HYDROGEN AND RENEWABLES INTEGRATION (HARI)

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1. PROJECT GOALS

This demonstration project comprises the design, implementation and operation of a hydrogen energy storage system that has been added to an existing renewable energy (RE) system at West Beacon Farm, Leicestershire, UK. The hydrogen system consists of an electrolyser, a pressurized gas store and fuel cells. At times of surplus electrical supply, the electrolyser converts electrical energy into chemical energy in the form of hydrogen. This hydrogen is stored until there is a shortage of electrical energy to power the loads on the system, at which point it is reconverted back to electricity by the process of reverse electrolysis that takes place within a fuel cell. The renewable energy sources, supplying electrical power to domestic and office loads at the site, are photovoltaic, wind and micro-hydroelectric.

The purpose of this project, known as the Hydrogen and Renewables Integration (HARI) Project, is to demonstrate and gain experience in the integration of hydrogen energy storage with renewable energy systems and, most importantly, to develop software models that could be used for the design of future systems of this type in a range of applications. In learning about such systems at this pilot scale, lessons can also be learned that have relevance to the future deployment of hydrogen and renewable energy schemes and to the wider energy industry, particularly the debate about the nature and viability of a potential ‘hydrogen economy’.

2. GENERAL DESCRIPTION OF THE PROJECT

Before the start of the HARI Project, the existing renewable energy devices at West Beacon Farm (WBF) and neighboring Whittle Hill Farm (WHF) included two 25 kW Carter wind turbine generators (WTGs), a 13 kWp of photovoltaics (PV) and two micro-hydroelectric turbines with a combined output of ≈3 kW. Further sustainable energy features at the sites include a 10 kW_{thermal} heat pump, circulating water from a coil at the bottom of an artificial lake to provide central heating in the house, a 15 kW_{electrical}, 38 kW_{thermal} Totem combined heat and power (CHP) unit that currently runs on LPG, evacuated tube solar thermal collectors for water heating, a conservatory used for passive solar space heating, biomass space heating, a battery powered car and a battery-petrol hybrid car. There is no mains water supply and so rainwater is collected from the buildings’ roofs for washing, flushing and, since the installation of the hydrogen energy storage (HES) system, as a feedstock for the electrolyser.

Of course, the combination of these supplies rarely matches the fluctuating demand of the system’s electrical loads and so some form of balancing mechanism is inevitably required. Until the arrival of the HES system, this has been carried out using a combination of batteries and the
utility grid. A 120 kWh lead-acid battery accumulator has been used for energy storage over diurnal periods and the grid has been used as a ‘limitless store’.

The addition of a hydrogen energy storage system to the existing RE supply network at WBF was proposed as a means of testing the feasibility of a stand-alone RE system. The three key elements that make up an HES system are a mechanism for converting electrical energy into chemical energy in the form of hydrogen (electrolysis), a means of storing the hydrogen and a method of reconverting the chemical energy of the hydrogen fuel back into electricity (fuel cell). The three primary components of the newly installed HES system at WBF are a 36 kW electrolyser, pressurized hydrogen storage cylinders with a capacity of 2856 Nm$^3$ of hydrogen at 13.7 MPa (137 bar), and fuel cells (of 2 kW and 5 kW). In Figure 1 a simplified schematic is shown of the existing system and of the new components that have been added for the HARI project.

![Figure 1: Configuration of the West Beacon Farm energy system](image)

West Beacon Farm (WBF) is a 200,000 m$^2$ site, located 6.5 km outside Loughborough in Leicestershire, UK, and is owned by Professor Tony Marmont and his wife, Angela. Besides this, their domestic residence, there is the office block for Beacon Energy Ltd at Whittle Hill Farm nearby that is connected to the site (Figure 2). The system referred to in this report serves both sites combined.

The core research team that have been working on the project are John Barton, who has been studying all forms of energy storage for use in combination with renewable energy (Barton and Infield 2004); Rupert Gammon, who conceived the Hydrogen and Renewables Integration (HARI) project as a means of investigating the integration of hydrogen and renewables and is
concerned with the overall system (Gammon 2001); Amitava Roy, who is investigating certain subsystems, particularly the electrolyser (Roy, Watson et al. 2003), and Matthew Little, who is investigating the system's electrical integration and implementing a new electrical distribution network for the site (Little, Thomson et al. 2005).

Figure 2: Map of the HARI project site
3. DESCRIPTION OF COMPONENTS

3.1 Electrolyser

The alkaline type electrolyser, manufactured by Stuart Energy Europe (formerly Vandenborre Hydrogen Systems VHS), is producing hydrogen at 2.5 MPa (25 bar). It was chosen on the grounds that it offered a high output pressure of 2.5 MPa and claimed a high stack efficiency of up to 3.9 kWh/Nm³.

From information provided by VHS about the performance characteristics of the device, software models were constructed, although these required significant adjustment later in the light of monitoring their real-world performance. Based on the information available at the time a unit with a 46-cell stack was ordered from them. VHS warned that they expected the number of on/off switching cycles for the electrolyser to be limited to 2500 before its performance started to degrade appreciably. To mitigate this problem it was necessary to incorporate a battery, which reduced the number of switching cycles. The limited operational range of the electrolyser (20 – 100% of rated power) means that there would be peaks of surplus RE power too big for it to absorb and troughs where the surplus supply is beneath the range. These can be captured by the battery and used to fill in short periods of non-operation thus reducing its switching cycles.

The electrolyser power supply (EPS) unit is shown in Figure 3a. To the right of it is the cabinet containing a computer used for controlling the electrolyser and fuel cells and for viewing the electrolyser’s ‘Vizimet’ graphic interface. In this installation, the EPS unit is twice the normal size, as the right hand side must accommodate the power electronics required in the upgrade of the electrical network at West Beacon Farm. An inside view of the main compartment of the electrolyser process unit and the deoxo and drier units are shown in Figures 3b and 3c, respectively.

3.2 Hydrogen storage

Storage within metal hydrides would be very attractive for this system, but since none were commercially available at that time, the only viable option for this project was pressurized...
storage of gaseous hydrogen. Plans are, however, in place for a hydride store to be tested at the site in 2006 in collaboration with the University of Birmingham.

The pressurized hydrogen store at WBF consists of 48 mild steel cylinders (Figure 4), leased from BOC, with an internal volume of 0.475 m$^3$ each. At 3.7 m long and 0.475 m in diameter, with a wall thickness of 38 mm, they each weigh around 1 ton. Their total storage capacity is 2856 Nm$^3$ when the hydrogen is pressurized to its maximum level of 13.7 MPa (137 bar). This gives an equivalent storage capacity of 3.8 MWh when the hydrogen is converted to electricity via the fuel cells, allowing the electricity supply to survive for around three weeks without any RE input.

![Figure 4: The pressurized hydrogen storage cylinders at West Beacon Farm.](image)

The operational constraints of the electrolyser mean that some form of short-term energy storage is required. The old 120 kWh lead-acid battery accumulator at the West Beacon Farm is being replaced with a “Zebra” battery, which is a high temperature (250+°C) sodium/nickel chloride (NaNiCl) battery developed by Beta Research and Development Ltd. This is able to operate at the required voltage for the new electrical system and will have a capacity of 20 kWh. It is required mainly to moderate the variability of supply to the electrolyser.

![Figure 5: The 2kW, high temperature, nickel sodium chloride (NiNaCl) Zebra battery](image)

This hybrid approach to storage exploits the relative merits of the two technologies: batteries provide efficient short-term, low-volume energy storage, while the hydrogen system provides longer-term, bulk storage. The 20 kWh Zebra battery at WBF (Figure 5) has an energy density of
145 kWh/m³. A battery storage capacity equivalent to that of the hydrogen energy storage system would require 190 these Zebra batteries, costing £3.8M, with a volume of 26.3 m³ and standing losses of 20 kW.

### 3.3 Fuel Cells

It is a mark of the speed with which this industry is developing that, in the early stages of this project (2001-02), it was very difficult obtain a market-ready fuel cell and yet, two years later, when a second fuel cell unit was to be installed at West Beacon Farm, it simply took one phone call to the supplier to procure a unit for commissioning within two weeks. Initially, though, it was only the close links already established between the parties involved that meant Intelligent Energy were amenable to providing the first fuel cell.

The Intelligent Energy 2kW PEM fuel cell CHP system first installed at West Beacon Farm is shown in Figure 6a. The hot water tank was later replaced with a plate heat exchanger to link it into the heating system. Half a year later the second unit was purchased, but this time it was a 5kW Gencore® unit, pictured in Figure 6b, made by Plug Power and supplied by SiGen. There is provision for a further fuel cell unit to be added to the system.

![Figure 6a: Intelligent Energy 2kW fuel cell](image)

![Figure 6b: Plug Power Gencore® 5kW fuel cell](image)

Of the two fuel cell units currently installed at the site, only the Intelligent Energy one is set up to provide CHP output. The 5 kW Plug Power unit is due to be converted from electricity-only output to CHP capability at a later date. At 2 kW, the thermal output of the Intelligent Energy appliance is the same as its electrical output, but it is actually capable of supplying up to 4 kW of electricity for short periods of around 15 minutes.

### 3.4 Compressor

The compressor chosen for WBF to raise the hydrogen pressure to up to 13.7 MPa is shown in Figure 7. It is a Hydro-Pac C03-05-2550LX-V with a compression ratio of 1:8 that can pump up to 11 Nm³/h at a feed pressure of 2.5 MPa. Since the input flow rate into the compressor might be varying between 2 and 8 Nm³/h, it was also necessary to put a buffer tank (with a volume of 37.85 liters) between it and the electrolyser. This buffer tank is shown in the foreground of the picture.
3.5 Infrastructure

The infrastructure, shown in Figure 8, relating directly to the hydrogen appliances was designed and installed by BOC. They also led the hazard and operability studies (HAZOP) and advised on the safety aspects of handling hydrogen.

![Figure 7: The compressor used at West Beacon Farm.](image)

![Figure 8: Flow schematics of the hydrogen pipe work and infrastructure at West Beacon Farm (Source: BOC)](image)
A new building was required at the site to house the major components of the hydrogen energy storage system, except the gas store that would necessarily be placed outdoors. Given that one of the HARI project’s aims is to demonstrate these technologies within a broadly domestic environment, it was very important to avoid the construction of anything too closely resembling an industrial plant. To fit in, therefore, with its surroundings, the hydrogen building would need to follow the style and layout of existing buildings at the site and, in doing so, it would need to be built partially underground. This posed some design challenges, which were solved by dividing the building into two zones: a safe zone and a hazardous zone (Figure 10). The hazardous zone has three rooms: one containing the electrolyser, one the fuel cells and the other the compressor. A passive ventilation mechanism results from the building’s layout. This would be reinforced by an active ventilation system that would be called into operation should a leak be detected. These mechanisms ensure that any potential hydrogen leaks are managed safely.

Figure 10: Layout of the West Beacon Farm ‘Hydrogen building’.

The pink shaded area is the hazardous zone and the white area the safe zone.

3.6 Summary

A summary of the main parameters of the HARI subsystems is shown in Table 1, including the names of manufacturers and/or suppliers, rated performances and indicative costs in GB pounds sterling (£). The Intelligent Energy fuel cell and the hydrogen storage cylinders are leased, but
the rest have been purchased. The cost shown for the Intelligent Energy fuel cell covers the full two-year lease period and the cost of the hydrogen storage cylinders, supplied by BOC, is for the full five-year period of their lease. The prices shown include tax, but no discounted terms that may have been applied.

Figure 9: Exterior view of the Hydrogen Building (foreground right), garages (foreground left) and house (background) at West Beacon farm.

Table 1: Summary of HARI Sub-Systems

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Manufacturer/Supplier/Model Designation</th>
<th>Rated Performance</th>
<th>Cost (in £) (indicative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyser</td>
<td>Hydrogenics (formerly Vandenborre)</td>
<td>8 Nm³/hour of H₂, 34 kW, 2.5 MPa (25 bar) rated</td>
<td>143,000</td>
</tr>
<tr>
<td>Fuel Cell (1)</td>
<td>Intelligent Energy, CHP Unit</td>
<td>2 kW (el), 2 kW (th), 24 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>25,000</td>
</tr>
<tr>
<td>Fuel Cell (2)</td>
<td>Plug Power GenCore, supplied by SiGen Ltd</td>
<td>5 kW (el), 48 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>20,000</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; Compressor</td>
<td>Hydro-Pac supplied by BOC</td>
<td>11 Nm³/hour, 3.75 kW, 8:1 compression ratio</td>
<td>59,000</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; Storage</td>
<td>Supplied by BOC</td>
<td>48 Cylinders, each 0.475 m&lt;sup&gt;3&lt;/sup&gt;, 13.7MPa (137 bar) max pressure, 2856 Nm³ total H&lt;sub&gt;2&lt;/sub&gt; capacity</td>
<td>122,000</td>
</tr>
<tr>
<td>Wind Turbines</td>
<td>Carter Wind Turbines</td>
<td>2 x 25 kW two bladed stall-regulated, pitch over-speed</td>
<td>50,000</td>
</tr>
<tr>
<td>Solar PV</td>
<td>BP</td>
<td>13 kW total, mixed polycrystalline and monocrystalline</td>
<td>60,000</td>
</tr>
<tr>
<td>Hydro-electric</td>
<td>Installed by Dulas</td>
<td>850 W Cross-flow with 2 m head; 2.2 kW Turgo with 25 m head</td>
<td>67,000</td>
</tr>
<tr>
<td>Integration System</td>
<td>Control Techniques and bespoke converters from Loughborough University</td>
<td>Various</td>
<td>49,000</td>
</tr>
</tbody>
</table>
4. INTEGRATION OF COMPONENTS

The electrical distribution network for site has evolved over many years in a piecemeal fashion, as more and more sustainable energy components were added, and this has created a system that is far from ideal. Part of the HARI project has been to rationalize the electrical system, as illustrated in Figure 11. The new network will be centered around a 600 V\textsubscript{nominal} DC bus, which, being at the voltage of rectified three phase mains, allows standard power electronic converters to be purchased at relatively low cost. DC/DC converters on the system, however, must be developed in-house and are being implemented on a modular basis.

![Figure 11: Schematic of the new electrical distribution network (Source: Matthew Little)](image)

Another novel feature of the proposed system will be to convert the existing wind turbines to operate in isolation to the utility grid. Under normal circumstances, WTGs need a live grid to function, but at WBF they must run without a grid connection. A method has therefore been developed, as part of the HARI project that provides the turbines with a ‘virtual grid’ in a way that could be widely applicable for stand-alone energy systems.

Judicious thermal management measures are being employed to increase the overall efficiency of the energy system. One of the fuel cells is operating as a CHP unit and it is planned that the other will do so in due course. By applying the same principle to the electrolyser, the heat extracted by its cooling system can also be captured and made use of. Instead of CHP, this might be termed CHF (i.e. combined heat and fuel). The thermal outputs will be fed into a phase-change heat store to be used for space heating within the home. In addition to these measures, steps can be taken to avoid heat loss within the devices themselves or unnecessary cooling where appropriate.
4.1 Simulation

Meteorological information was collected by a data acquisition (DAQ) system so that the energy production from the wind turbines and photovoltaic arrays could be predicted from environmental conditions alone. The Matlab models of the wind and PV devices converted the raw weather data into power outputs for each. Surface roughness values, appropriate to the wind direction, are determined by wind speed measurements at two different heights. This is then used to calculate wind speeds at hub height, which are converted into power outputs using the wind turbine’s power curve. The solar irradiance readings, measured by the in-plane solarimeters, and temperature measurements are used to predict the power generated by the PV arrays. The hydro electricity generated at WBF has not yet been included in the software models; however there are plans to include it at a later date. Simulink routines were used to compare the results predicted by the Matlab models with measured values of RE output.

Measurements taken during test runs of the electrolyser allowed software models to be verified against its real-world operation. This led to radical adjustments of the original models, particularly as the BOP losses turned out to be much greater than initial briefings had suggested. The graphs in Figure 12 show how the validated software model predictions compare with measured real-world parameters. The conversion energy of the module was found to be 4.38 kWh/Nm³, corresponding to an efficiency of 75.2% (using HHV at NTP). The manufacturer quotes a conversion energy value of between 3.9 and 4.2 kWh/Nm³, depending at what level the electrolyser is being operated. The average conversion energy of the overall electrolyser-battery-compressor system at WBF is 6.74 kWh/Nm³, which equates to an efficiency of 48.8% (using HHV at NTP). The overall conversion energy of the system is 60% higher than that quoted by the manufacturer for the module alone (of 4.2 kWh/Nm³) because it incorporates substantial BOP losses. It should also be noted that this varies slightly with time, as there are small standing losses associated with the standby periods between electrolyser operations.

When a new sizing exercise was carried out for the electrolyser, based upon the revised and validated models, it concluded that the optimum module size should be 32 cells, which is 12 less than that proposed by the original model. The average BOP losses in the revised model are 5½ times greater (3345 W compared to 600 W) than the original model, but suggest a reduction in the optimum cell stack size of only 27%. The revised model includes an estimation of the compressor’s power consumption and takes account of the battery that it has proved necessary to install in support of the electrolyser. The optimum Zebra battery capacity was found to be 16 kWh (20% smaller than the existing Zebra battery) and the electrolyser module size would be optimized at 28 cells (39% smaller than the existing module at WBF), which gives a conversion energy of 6.6 kWh/Nm³. This would be a 24 kW rated module and have a maximum power demand of 26 kW. This agrees with a parallel modeling exercise for the electrolyser that incorporated the capacity utilization factor, stack degradation, stand-by and parasitic losses, excess wind power probability and optimization between current density, Faraday efficiency and stack-energy consumption for maximization of hydrogen production at minimum cost (Roy, Watson et. al. 2005).
The prediction by the Simulink model (yellow) is compared with measured, real-world performance of the device (magenta). The short-term effect of the compressor on the hydrogen flow rate measurement makes comparison of the instantaneous production rate difficult, but the accumulated hydrogen output allows easier comparison, since the effect is cancelled out over longer periods.

A Simulink model was developed to describe the final configuration of the overall hydrogen and electrical system at WBF as it will be after the upgrade of the electrical system is complete. Central to the model of the hydrogen and electrical system for WBF is the control of the network as it will be when running autonomously.

One way of assessing the system efficiency is to look at the total energy that is supplied and subtract the useful energy that has been obtained from it, which includes that used by the loads and the amount still remaining in the two types of energy store. The results over a 23-day period from in January 2003 are shown in Figure 13. Here the SOC of the batteries can be seen (magenta line), compared with the electrolyser power consumption (yellow line), fuel cell power generation (cyan line) and amount of hydrogen in the store (red line). The overall losses in the system over the period can be calculated by Equation 1, where $\Delta RE$ is the accumulated RE supply, $\Delta Batt$ is the change in energy stored in the battery, $\Delta FC$ is the electrical energy that could be generated by the fuel cells using the hydrogen accumulated in the store, and $\Delta Load$ is the accumulated consumption of the electrical loads. The values obtained for these by the model are given in Table 2. The losses amount to 3024 kWh, which is 56% of the total RE input over the period, giving an overall system efficiency of 44%.
Figure 13: Results of a simulation of the West Beacon Farm hydrogen and electrical system as it will be when the electrical network upgrade is complete.

\[ \Sigma \text{Losses} = \Delta \text{RE} - \Delta \text{Batt} - \Delta \text{FC} - \Delta \text{load} \]

Equation 1

Table 2: Results obtained by simulation of the WBF system for a 95-day period in winter.

<table>
<thead>
<tr>
<th></th>
<th>Conversion</th>
<th>Rated</th>
<th>Initial</th>
<th>Final</th>
<th>Change</th>
<th>Units</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulated RE supply</td>
<td></td>
<td></td>
<td></td>
<td>5417</td>
<td></td>
<td>kWh</td>
<td>( \Delta \text{RE} )</td>
</tr>
<tr>
<td>Battery SOC</td>
<td></td>
<td>50</td>
<td>11.6</td>
<td>-38.4</td>
<td>%</td>
<td>( \Delta \text{SOC} )</td>
<td></td>
</tr>
<tr>
<td>Energy stored in battery</td>
<td></td>
<td>20</td>
<td></td>
<td>-7.7</td>
<td>kWh</td>
<td>( \Delta \text{batt} )</td>
<td></td>
</tr>
<tr>
<td>Hydrogen in store</td>
<td></td>
<td>1140</td>
<td>952.7</td>
<td>-187.3</td>
<td>Nm³</td>
<td>( \Delta \text{H2} )</td>
<td></td>
</tr>
<tr>
<td>Electricity from hydrogen</td>
<td></td>
<td>1.11</td>
<td></td>
<td>-207.9</td>
<td>kWh</td>
<td>( \Delta \text{FC} )</td>
<td></td>
</tr>
<tr>
<td>Accumulated electricity consumption</td>
<td></td>
<td></td>
<td>2599</td>
<td>( \Delta \text{load} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
<td></td>
<td>3034</td>
<td>kWh</td>
<td>( \Sigma \text{losses} )</td>
<td></td>
</tr>
<tr>
<td>System efficiency</td>
<td></td>
<td></td>
<td></td>
<td>44</td>
<td>%</td>
<td>( \eta_{\text{system}} )</td>
<td></td>
</tr>
</tbody>
</table>
5. PERFORMANCE AND OPERATIONAL EXPERIENCE

Initial assumptions that were used in models for designing the system and sizing its components were found to require significant adjustment in the light of real-world operation of the plant. Through actual operational experience it has therefore been possible to develop much more accurate tools for the design of future systems and so the importance of such field trials is clearly apparent.

The lessons learnt in this project suggest that there are a number of ways that efficiency could be optimized when designing similar systems. Firstly, it is important to obtain the most appropriate equipment at the optimal size. Obtaining the ideal match between the battery capacity and the number of cells in the electrolyser module, for instance, ensures the best hydrogen production and most efficient conversion energy. Another example is illustrated by comparing the fuel cells installed at WBF. The Intelligent Energy fuel cell has no standing load when switched off, but the Plug Power one does, as it was originally designed as a UPS system. As such, it is not best suited to this particular application. However, it is typical of pioneering endeavors like this project that the closest fit available at the time is often a long way short of ideal. Furthermore the electrical integration of the Gencore proved difficult until it was realized that the power electronics connected to it were too sophisticated to operate in the master-slave relationship that was required. Interaction between the FC unit and the external device became highly unstable and caused severe damage to its internal components. This will be remedied by the electrical system upgrade that is currently (early 2006) being undertaken at the site.

The most important ongoing task for the HARI project will be a full and careful assessment of the system management and control strategy. As it stands, the system is designed for maximum robustness and reliability and little has been done yet to improve component and system efficiencies beyond their default levels. A detailed energy audit is required to reveal where inefficiencies arise and where improvements may be accomplished through hardware modifications and control methodologies. The upgrade of the new DC-bus based electrical network being undertaken by Matthew Little, which links various components, interfaces and control systems and includes detailed measurement of energy flows around the system, is expected to improve its overall efficiency. Demand-side management techniques, such as the deferred or opportune use of non-critical loads, could be employed to avoid unnecessary use of energy storage. Energy can be saved, for example, in the water purification process for the electrolyser feed by reducing or eliminating the reverse osmosis (RO) load. By recycling the exhaust water from the fuel cells directly back to the inlet for the electrolyser, very little water is wasted. Due to the very low volumes and flow rates required, this can be topped up by a filter bed purifier instead of RO. Equally, though not explored in great depth yet at WBF, thermal management will also be important in the optimization of the WBF energy system, as it captures byproduct heat and reduces heat loss or cooling requirements. Early on in the project, for example, it became obvious that the EPS cabinet’s cooling fans were rarely needed and so they were fitted with a thermostatic switch to avoid unnecessary use. Thermal insulation of components within the electrolyser would also improve efficiency by allowing it to reach optimum temperature quicker, by reducing thermal cycling and by capturing more of its byproduct heat. Thermal management could even be used to turn a metal hydride store into a compressor, because heat can be used to raise the output pressure of the store. This is being investigated in collaboration with the Metallurgy and Materials department at the University of Birmingham.
Various losses are associated with control, monitoring, safety, thermal management and other ancillary systems, but by far the most significant parasitic losses (as opposed to the thermodynamic losses of the electrochemical reactions themselves) were found to be in the power conversion electronics. The rectifier required for AC-DC conversion in the electrolyser wastes about 2.5 kW at low power inputs, rising to about 5 kW at its rated power. This equates to 28% and 11% of the total power input respectively. Typically, the AC-DC conversion process would be expected to be around 90% efficient at a device’s rated power (Divisek and Emonts 2003), but efficiencies fall significantly at part load. Unfortunately, an RE powered electrolyser in a stand-alone system will spend almost all its operational time at part load, so finding a way around this problem would be the key to radically improving the efficiency of the process and must be considered a priority in the drive for improving the viability of these systems.

Leakage of hydrogen and KOH electrolyte has proved to be a major problem in this project. Occurrences of the former can be expected during the initial bedding-in period of an installation, but these prevailed for a surprisingly long period at WBF. Hydrogen leaks occurred at various joints in the piping infrastructure, which, once located (a feat in itself), were usually quite easily rectified. They also arose due to KOH crystals accumulating on a valve seat and from a grain of the drier’s desiccant obstructing the valve, which was easily remedied by the introduction of a filter. Electrolyte leakage appears to have been due partly due to misalignment of components during transit and a manufacturing fault. These have now been corrected, but it is also necessary to regularly check the torque of the module tensioning bolts to ensure that KOH leakage does not recur.

Over time, as anticipated, the electrolyser module’s efficiency declined as the switching cycles started to degrade the stack, but it appears that this may now be stabilizing. When first installed the electrolyser was rated at 36 kW, but over two years of operation, the power demand of the module at rated hydrogen production has risen to 39 kW. The rating of an electrolyser is determined by the module power, excluding the BOP. In fact the electrolyser at WBF, when first installed, could draw anything up to 43 kW (with its drier heating on) and now its maximum power demand is 45 kW.

In the long term, a re-design of the electrolyser could lead to significant efficiency, reliability and cost improvements. Amitava Roy has been investigating the development of a new low cost electrolyser technology optimized for renewable energy powered operation by using dynamic modeling that incorporates the fundamentals of electrochemistry, thermodynamics, heat and mass transfer and Faraday efficiency of the stack (Roy, Watson et al. 2005).

6. SAFETY ISSUES

Safety is of paramount importance in a research and demonstration project such as this, from the point of view of those on-site and also because a major incident could be disastrous for the reputation of these nascent technologies at a critical time in their emergence into the wider consciousness. Much has been learnt through the HARI project about safety issues relating to the use of potentially hazardous materials, such as hydrogen and potassium hydroxide, particularly when introduced into a domestic environment. Close liaison has been maintained with the Health and Safety Executive throughout this project and close consultation, including extensive HAZOP (hazard and operability studies) procedures, has been provided by BOC who routinely deal with pressurized hydrogen gas in all its applications.
The electrolyte used in the electrolyser is a 30% (by weight) potassium hydroxide (KOH) solution, which is a very strong alkali. This is very corrosive to the skin and can cause blindness if it comes in contact with the eyes. Eye baths and a shower are, therefore, provided in the building for emergencies. Experience of carrying out maintenance and repairs has taught that it is prudent to use full chemical resistant overalls, hoods, boots and gloves for such tasks. Furthermore, members of the HARI project team who were exposed to KOH fumes for long periods experienced throat irritation and, although not listed as symptoms on safety sheets for this chemical, intense headaches and tiredness. The use of specific alkali-resistant breathing masks has, therefore, also been necessary, as shown in Figure 14.

![Figure 14: Safety-ware being used by members of the HARI project team while handling potassium hydroxide electrolyte at West Beacon Farm](image)

7. MODELLING OF THE HYDROGEN ECONOMY

The term “hydrogen economy” means different things to different people, but in its purest sense, it describes an energy system that relies on renewable energy for its primary resource and hydrogen for energy storage.

One of the clear messages that come out of the HARI project is that the efficiency of passing through the cycle from electricity to hydrogen and back to electricity is (at typically around 20% or lower) poor. The efficiency of the overall electrical and hydrogen energy system at WBF shows a marked improvement, at 44%, compared to the 16% efficiency of just the HES system. This is because, where possible, electricity that is generated by the renewables is used directly as electricity in the loads, or stored briefly as electricity in the battery. Only as a last resort is it converted to hydrogen for storage before being reconverted back to electricity again. The clear lesson is that, wherever possible, electricity should remain as electricity in the system until it is used at the end-point appliance. Indeed, hydrogen should not be used for storage of electricity, except where specific conditions dictate that no practical alternative exists (e.g. in remote, off grid applications). Instead hydrogen should provide fuel and, via electrolysis, a controllable load by which the supply and demand on the utility grid can be balanced.
In the ultimate hydrogen economy scenario, all energy sectors must draw on the primary resource of renewables. All too frequently, future projections about the possible nature of a hydrogen economy tend to look at the transport or power sectors in isolation and the thermodynamic imperatives undermine their validity. The concept only makes sense when a holistic view of the total energy system is encompassed. In this scenario, there is usually more than enough power to feed the electricity network alone, because - of necessity - it is also required to go into fuel production. In other words, the installed capacity of primary (renewable) energy resource required to feed the whole energy system is much greater than would be required simply to supply the electricity grid.

Figure 15: The renewable energy supply (yellow) and electrical demand (magenta), both in kW, on the West Beacon Farm system over a 23-day period.

This may not eliminate all periods of supply shortfall for the grid, but it dramatically reduces the frequency and duration of such episodes, thus reducing the need to store electricity. Electricity that was converted to hydrogen does not, therefore, tend to get reconverted back to electricity and, where it does, the electricity should at least be generated in CHP plants to maximize the overall efficiency of the process. In this scenario, electrolysis is a load-balancing mechanism that produces hydrogen fuel as well. Hydrogen will be generated largely at the point of use, the vast majority of it in forecourt electrolysers. Electrolyser operators earn revenue by selling fuel at the garage forecourt and for the provision of grid management services. This can be done by modulation of hydrogen production in response to the frequency of the electricity grid and, due to aggregation, electrolysers can all be operated relatively close to their optimal level, leading to much higher efficiencies. The most expensive lifecycle cost of electrolysis is the energy input, but in a load balancing capacity this cost is, by definition, very low (maybe even free) because the electrolyser is absorbing surplus grid power.
The point is emphasized more clearly in Figure 16, which illustrates that in this scenario the difference (blue area) between aggregated renewable energy supply and the electrical load on the grid (purple area) is absorbed mainly by electrolysis, which is a controllable load, used for grid balancing, and a fuel production process for transport applications. Energy consumed in the purple region has remained in the form of electricity, undergoing no other transformation, since the point of generation in the renewable energy device. The ideal scenario, which has not been modeled yet, would be to have the primary energy resource adjusted to a level dictated by the capacity of hydrogen stored at garage forecourts. If this is still too challenging a target, supplemental nuclear, fossil fuels and other sources can be added to reduce the amount of REs required to match the same storage limits.

![Figure 16: Comparison of aggregated renewable energy supply and electrical load on the grid (adapted from data kindly supplied by Michael Forrester)](image)

Since such a scenario is still a long way off, there are many years in which bridging technologies will be used. What is evident, though, is that a hydrogen distribution grid will not replace an electrical distribution grid. There are a number of reasons for this. Firstly, the electricity grid is an efficient method of moving energy around. Secondly, the majority of the electrical infrastructure is already in place (although certain areas will need reinforcement). Finally, there is no extensive hydrogen pipeline network and the existing natural gas network would need considerable refurbishment if it were to be used. Electricity is an excellent means for the spatial displacement of energy, whereas hydrogen is a good means of achieving temporal displacement of energy. In a future energy system the complementarities of these two energy currencies should be exploited appropriately. Only where very large-scale storage of hydrogen is needed, and transmission-level infrastructure required to support it, might hydrogen pipelines be used.
8. FUTURE PLANS

A number of future developments are being considered for WBF that will add to or improve the existing facilities at the site. The first of these will be the installation of a 5.6 Nm³ prototype metal hydride store, in the Spring of 2006, provided by the Metallurgy and Materials department at the University of Birmingham. If initial tests with this are successful further capacity may be installed at a later date.

Hydrogen Solar is a company that is developing a double-layer, integrated PV and Graetzel cell system that combines solar electricity generation and electrolysis in one device. They plan to install one of their first prototype systems at WBF for testing, where it can be integrated with the existing hydrogen infrastructure. The disadvantage of this system is that it does not fulfill the demand-side management role that conventional RE-powered electrolysis does. It simply produces hydrogen from solar energy in isolation from the electricity supply network; however it will play a complimentary role in certain niche applications.

A fuel cell range extender is planned for installation in a battery-powered car already in use at WBF. The vehicle uses nickel metal hydride batteries and has an effective range of around 60 miles. The addition of a 2 kW PEM fuel cell and a small compressed hydrogen cylinder is expected to effectively double this range. A hydrogen refueling station will be installed at WBF to service this vehicle and two fuel cell powered Smart cars that the department of Aeronautical and Automotive Engineering at Loughborough University are hoping to build.

An existing ‘Totem’ CHP engine at WBF currently runs on LPG fuel; however it is intended that this will be converted to run on hydrogen fuel using a specially designed spark plug that allows simple conversion from fossil fuel operation. If this proves successful it paves the way for easy conversion of internal combustion engines to run on hydrogen, which, although less efficient than fuel cells, provide a bridging technology for the growth of a future hydrogen economy.

9. CONCLUSION

A hydrogen energy storage (HES) system has been successfully designed, installed and operated for two years at West Beacon Farm (WBF), Leicestershire, UK as part of a research initiative known as the Hydrogen and Renewables Integration (HARI) project. The HES system comprises an electrolyser, compressor, pressurized hydrogen storage cylinders and two fuel cells. This was successfully integrated into an existing renewable energy (RE) system to provide long-term energy storage. Software models of the combined hydrogen and RE system have been built in Matlab and Simulink and verified against their real-world operation. These models encompass the complete energy system at West Beacon Farm, excluding thermal energy subsystems, and could be applied to the design of future hydrogen and RE installations where weather and load profile data are available. Significant experience has been gained, giving valuable insights into issues relating to the design, installation and operation of integrated hydrogen and RE systems. Lessons have also been learnt that relate to the wider debate on the nature of a potential hydrogen economy.

Models used for the sizing of components at the design stage of the project suffered from significant inaccuracies due to the shortage of information made available by the manufacturers, but were significantly improved through the operational experience gained. This is particularly true of the electrolyser, which was shown by later experience to be oversized by 39% for its task at West Beacon Farm (WBF) on account of the limited information initially supplied about its
balance of plant (BOP) power consumption. The lifetime of the electrolyser would be severely limited by repeated on/off switching cycles and as a result of this, it became necessary to use a battery in support of the electrolyser. This turns out to be an appropriate combination of complimentary short-term and long-term energy storage methods.

The conversion energy of the electrolyser module itself was found to be 4.38 kWh/Nm³, corresponding to an efficiency of 75.2% (using HHV at NTP). This conversion energy value is around 8% higher than that quoted by the manufacturer, but after almost two years’ operation, a certain amount of stack degradation had occurred through the intermittency of its operation. For the whole electrolysis process, where BOP losses such as those of the compressor, battery, power electronics and gas drier are included, the conversion energy was found to be 6.74 kWh/Nm³, which equates to an efficiency of 48.8% (using HHV at NTP). The round-trip efficiency of the cycle from to electricity to hydrogen and back to electricity again, is 16%. The efficiency of the overall electrical and hydrogen system (i.e. the complete energy system after electricity has been generated within the RE devices and not including thermal energy flows) is shown by the model to be 44%, which relies upon electricity being used directly, without passing through the HES system, wherever possible. Although these are not reassuring levels, they reflect the harsh thermodynamic reality of achieving a goal as challenging as that of long-term, large-scale energy storage. On the other hand, using the lessons learnt in this project, it is anticipated that these efficiencies could be significantly enhanced by advances in component design and improved system integration and control.

Safety issues have featured strongly in this project, both in relation to the handling of large quantities of pressurized hydrogen gas and the handling of KOH electrolyte solution. In relation to the latter, it is important to note that the standard information sheets for KOH do not mention that it may cause severe headaches and tiredness, whereas the experience of the HARI team is that exposure to KOH fumes over a matter of hours does indeed cause such symptoms.

The knowledge gained through this research brings a note of caution to many of the visions expounded about a potential ‘hydrogen economy’ for the future. It plainly highlights the limitations of using hydrogen for energy storage, although it by no means suggests that the hydrogen economy is not a practical proposition. Indeed, it remains the case that no workable alternative has yet been proposed. What it does suggest, however, is that some ideas that have been put forward about the shape and configuration of a hydrogen economy fail to incorporate some of the thermodynamic realities of the situation.

Clearly, converting energy from electricity to hydrogen and back to electricity again is a very wasteful cycle, which must be considered only as a last resort, but which may be unavoidable in certain situations. Wherever possible, the electricity that is hard-won from renewable (or any other) sources should remain as electricity until it is consumed by the end-user appliance. Once converted to hydrogen, the energy should only be used in applications, such as transport and remote or portable power generation, where only a fuel is able to do the job. In a post fossil fuel energy system, the primary RE resources must be relied upon to supply all energy sectors including grid, electricity, thermal loads, portable power and all forms of transport. This will demand a much greater installed capacity of renewables than is normally considered for the generation of grid electricity. The substantial controllable load that will be required to balance energy supply and demand on such a network will be electrolysis, largely at garage forecourts, providing fuel to hydrogen powered vehicles. Revenue will be earned by the operators of such electrolysers from selling fuel and also from grid management services. This scenario eliminates the wasteful energy conversion cycle and implies that hydrogen production will be at the point of
delivery to end-users. The electricity grid will remain the predominant method of energy transmission and distribution, not a hydrogen pipeline network (except in certain specific circumstances). In effect, energy will be displaced spatially by electricity and temporally by hydrogen, thus playing to the strengths of both these energy currencies.

The theoretical round-trip efficiency of using hydrogen for electricity storage is not impressive. This project, and others like it emphasize that putting the theory into practice with currently available technologies and know-how makes its performance even less impressive. This is not to say that it cannot be improved upon or that it is unviable. Any 'holy grail', like the search for a practical large-scale, long-term energy store, is by definition extremely challenging and, therefore, expensive. In this case, the cost is both financial and energetic. The challenge, therefore, is to make this goal achievable at lower cost and higher efficiency. Much has been learnt through the HARI project that addresses these questions and much more is still to be discovered as the project progresses from the initial phase described in this report, to the next phase.

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11. CONTACT INFORMATION

The HARI project was conceived by Rupert Gammon, a PhD student researcher at CREST (Centre for Renewable Energy Systems Technology), Loughborough University, who is responsible for the system overview. Other members of the team, who are also PhD students at CREST, include Amitava Roy, who is focusing on electrolysis powered by renewables, Matt Little, who is researching the power electronics required in the integration of the system and John Barton, who is studying a range of energy storage methods for use with renewables.

The project is being supervised by Prof David Infield, Director of CREST, and is sponsored by Prof Tony Marmont, the owner of West Beacon Farm.

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12. REFERENCES


