The integration of hydrogen energy storage with renewable energy systems

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The integration of hydrogen energy storage with renewable energy systems

by

Rupert Gammon

Doctoral Thesis

Submitted in partial fulfilment of the requirements

for the award of

Doctor of Philosophy of Loughborough University

18th January 2006

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Abstract

This thesis concerns the design, implementation and operation of a hydrogen energy storage facility that has been added to an existing renewable energy system at West Beacon Farm, Leicestershire, UK. The hydrogen system consists of an electrolyser, a pressurised 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.

This work is being carried out through a project, conceived and overseen by the author, known as the Hydrogen and Renewables Integration (HARI) project. The purpose of this study 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. Effective models have been created and verified against the real-world operation of the system. These models have been largely completed, although some minor details remain unfinished as they are dependant upon studies linked to this one which are yet to be concluded. Subject to some fine tuning that this would entail, then, the models can be used to design a stand-alone, integrated hydrogen and renewable energy system, where only the load profile and weather conditions of a site are known.

Significant practical experience has been gained through the design, installation and two years' of operation of the system. Many important insights have been obtained in relation to the integration of the system and the design and operation of its components.

The efficiency of the hydrogen storage cycle (i.e. converting electricity to hydrogen and back to electricity again) at West Beacon Farm is calculated to be 16%. The overall system efficiency is found to be 44%, because some power goes directly from the renewable energy supply to the end-user loads, rather than through the energy storage system with its attendant losses. These apparently unpromising figures are the result of only the first attempt to integrate this complex and untried system at West Beacon Farm. From the lessons learnt in
this project, these efficiencies can be significantly improved upon through adjustment to the system and the redesign of various components.

It has been found that a battery is needed in support of the electrolyser to enable it to accommodate the dynamic and intermittent power input of renewable energy sources on a stand-alone system. This effectively exploits the complimentary characteristics of batteries and hydrogen to create a hybrid energy storage system. Balance of plant losses, particularly in power electronic components, and standing losses are found to play a major role in overall system efficiency. This can be mitigated by the use of power electronic devices with high efficiency, particularly at part load, and careful sizing of components. The state-of-the-art electrolyser at West Beacon Farm has proved to be ill-adapted to the dynamic and intermittent operation demanded by the system. This has been explored in more depth by Amitava Roy in a linked research study.

The capture of waste heat from the electrolyser can be employed as a means of increasing the overall system efficiency in a manner similar to that of a combined heat and power unit.

The exhaust water of the fuel cells is found to be pure enough to be recycled directly to the electrolyser. In bypassing the water purification process in this way, significant energy can be saved and the overall system efficiency improved.

The direct measurement of hydrogen store pressure has proved more unreliable than anticipated, due to complex thermal effects caused by the location of its pressurised cylinders. Instead, accumulated mass-flow measurements in and out of the store allow the store pressure to be calculated accurately.

In relation to health and safety issues involved in the handling of potassium hydroxide electrolyte solution, symptoms of severe tiredness and headaches have been noted, although these are not mentioned in the standard health and safety literature.

These findings have relevance to the future deployment of hydrogen and renewable energy schemes and, perhaps, the wider energy industry, but some insights gained through this research inform the debate about the nature and viability of a potential 'hydrogen economy'.
In this context, a notable lesson from the HARI project is that the round trip form electricity to hydrogen and back again carries a high efficiency penalty, which will have significant cost implications. This implies that the future role of hydrogen is in load management (for an electrical system with high renewable energy penetration) and fuel production (mainly for transport). The use of hydrogen for stationary power production in a post-fossil-fuel economy is not likely, therefore, to be broadly applicable. However, this does not rule out the important role of stationary fuel cells in the ‘partial’ hydrogen economy that is likely to evolve over coming decades before a full hydrogen economy is, maybe one day, reached.

Keywords: Hydrogen, renewable energy, energy storage, fuel cell, electrolysis, hydrogen economy.
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1. Introduction

1.a Aims and objectives

The broad aim of this study was to gain practical experience of designing, implementing and operating a hydrogen energy storage facility to be integrated with a renewable energy system. By its very nature, this is open-ended and does not necessarily suggest tightly defined objectives, because it recognises that much of the value of such field trials is in learning lessons that cannot be anticipated by theoretical studies alone. However, some specific objectives were defined at the beginning of the project to avoid the danger of such a large undertaking lacking focus and becoming unmanageable. These objectives were to:

- Design and install a hydrogen energy storage facility that to be integrated with the existing renewable energy system at West Beacon Farm, Leicestershire, UK

- Define a methodology for the design of integrated hydrogen and renewable energy systems

- Develop a software model for the design of integrated hydrogen and renewable energy systems

- Validate the software model by measuring the real-world performance of an integrated hydrogen and renewable energy system

- Assess the practical viability of hydrogen energy storage in conjunction with renewable energy systems

- Measure the efficiency of an integrated hydrogen and renewable energy system and its main components and explore ways of improving it

- Explore ways of improving the reliability, applicability and cost of integrated hydrogen and renewable energy systems

- To manage and operate an integrated hydrogen and renewable energy system on a year-round, day-to-day basis
- To gain practical experience and learn about operational issues relating to an integrated hydrogen and renewable energy system and its components

- To apply the lessons learnt to understanding wider issues about the future of sustainable energy systems in general, but particularly those containing hydrogen energy technologies and/or renewable energy supplies

While many of these issues have been explored in various studies and field trials previously, this aims to be the first complete, multi-sourced (i.e. being supplied by more than one renewable energy resource), stand-alone system of this type that operates continuously on a year-round in real world application.

Certain other sub-tasks or parallel studies are included as part of the Hydrogen and Renewables Integration (HARI) Project, such as those being carried out by Amitava Roy, John Barton and Matthew Little, which are alluded to in this thesis, but the objectives described above pertain specifically to the work carried out for this thesis.

1. b Scope of thesis

This thesis begins by briefly discussing the environmental, political and technical background behind the drive for clean, sustainable energy production. These are large and complex issues and this document cannot hope to do justice to the full depth and breadth of such arguments which have raged for many decades already. It is taken as read that the reader comes to this thesis by virtue of the fact that they already have formed opinions about such background issues.

A brief review is presented of the main technologies used in this research activity, known as the Hydrogen and Renewables Integration (HARI) project. An outline is then presented of the specific situation in which this project was launched, followed by a brief description of some of the most notable projects that have similarities with this one. This is followed by an explanation of how the main sub-systems, and various ancillary components, were selected and applied in this particular project.
The software models developed for this research are presented and their output analysed, particularly with reference to their verification against the real-world operation of the systems they represent. The lessons learnt from this practical experience are also discussed, as are their wider implications for both small- and large-scale sustainable energy systems, particularly in relation to the debate about the nature of a 'hydrogen economy'.

1.c Climate change

Many have described climate change as the greatest threat that humanity faces this century, or perhaps, ever (King 2004). Some increasingly rare exceptions on the other hand – most notably the Bush administration in the USA, which is the country that emits more greenhouse gases than any other (Leggett 1999; Piltz 2005) – resist the idea that it is caused by human activity, or even that it is happening at all. Ironically, the USA is also one of the world’s leaders in hydrogen and fuel cell related technological development and, at a regional level, there are many strong initiatives to promote it despite the attitude of central government. Meanwhile, the news media tend to qualify the term ‘climate change’ with words such as ‘controversial’ or ‘alleged’, in the interests of objectivity. This gives the false impression that opinion is evenly divided and, as such, could be considered a failure in their responsibility to communicate the veracity of the situation.

It is true that the contention that human activities are leading to climate change on this planet is not a proven one, however there is an extraordinary degree of consensus within the scientific community supporting the view that they are (McKee 2004). Indeed, it could be argued that proof is not desirable in this case anyway, as it is bound to come in the form of some fairly uncomfortable circumstances for humanity (Thomas, Cameron et al. 2004; Townsend and Harris 2004; Meehl, Washington et al. 2005; Wigley 2005). More importantly, since risk is quantified by combining the likelihood of something happening with the severity of outcome if it did (Figure 1-1) (Boltz, Döring et al. 1999), anthropogenic climate change must at least be considered a very high risk. If a company were to ignore such a level of risk, it would rightly find itself subject to claims of criminal negligence when the anticipated disaster materialised. It would be easy to blame our politicians for the lack of progress to confront this threat to the planet’s finely balanced ecosystem, but in a world dominated by rich democracies, the responsibility ultimately lies with those who elect the politicians. It is true that the technological challenges of dealing with the global warming
threat are formidable, but educating policy makers and the voting public on the issue may prove to be an even bigger battle. The main purpose of the research activity described in this thesis is, of course, to contribute to the technological progress in this field, but to the extent that it centres on the implementation of a demonstration project, it also aims to communicate the issues to a wider audience.

![Risk Matrix](Image)

**Figure 1-1:** Risk is a combination of the likelihood that something will happen and the severity of outcome if it does. Climate change is high risk.

### 1.d Energy Security

Besides environmental concerns, energy security is increasingly being recognised as another major problem in the modern world. This arises from a combination of political instability, particularly in the major oil and gas producing regions of the world, and the inevitability that fossil fuels will soon start to become more and more scarce (Schnurnberger, Hoyer et al. 2004).

On the other hand, a comment famously attributed to Sheik Yamani recognises that “the Stone Age came to an end, not because we had a lack of stones, and the oil age will come to an end not because we have a lack of oil”. What is more likely, of course, is that oil will become increasingly priced out of the market, which is a process that is expected to start from the point of “peak oil production” that many assume will be reached within a few short years (Campbell 2005; Hirsch, Bezdek et al. 2005). After this it will no longer be used for energy production, except in a few small niches, but more importantly, it will be used simply as the feedstock for certain industrial processes, such as in the production of plastics.
1.e Moving beyond fossil fuels

It is not within the scope of this volume to retrace the much-rehearsed arguments on these issues. Suffice it to say that these threats are treated as a reality and that they demand radical restructuring of the world’s energy systems. It is taken as read that these will ultimately rely heavily, if not solely, on renewable energy for their primary energy resource. Some would argue that nuclear power and “clean coal” technologies could be a part of the energy mix, but ultimately these, too, are finite resources. More importantly, the widespread implementation of “clean coal” faces severe technical hurdles (Klara, Srivastava et al. 2003) while the disposal of radioactive waste and other safety concerns continue to make nuclear deeply unpopular with the public. Both are likely to remain expensive options for the foreseeable future, whereas the falling prices of rapidly developing renewable energy technologies point to the potential for their universal deployment (Nemet 2005).

1.f Energy storage

This then begs the question of how the continuously fluctuating loads on an electrical system, which are difficult enough to manage on a grid fed by conventional, despatchable power supplies, will be met by these non-despatchable, intermittent renewable energy sources. Using nuclear power does not help this situation as the output from nuclear power stations can only be modulated to a very limited extent in response to varying demand (Miller and Duffey 2005). Whether or not nuclear power forms a part of a non-fossil fuelled energy future, there will be a significant need for load balancing mechanisms within the energy network as the penetration of renewables reaches beyond 10 – 15% of installed capacity. Meeting this challenge inevitably calls for the use of some kind of energy storage, much of it on large scales and over long time periods, but most energy storage technologies (e.g. flywheels, super-capacitors, batteries, superconducting magnetic energy storage) are only suited to short timescales or small capacities (Barton and Infield 2004). Others, such as pumped hydro storage or compressed air storage are very limited in the locations where they can be applied. Only redox flow cells or hydrogen are viable at larger timescales and capacities and, because of hydrogen’s adaptability and broad applicability, the concept of the ‘hydrogen economy’ has emerged.
1. The hydrogen economy

The term "hydrogen economy" is widely used, but is still not yet strictly defined. It probably means quite different things to different people, depending largely upon the area of expertise from which they approach it. To some, for example, it includes fossil fuels with carbon sequestration, while to others it precludes fossil fuels because it describes a post fossil scenario by definition. In recent months there has been increasing activity in the area of "hydrogen roadmapping" (US DOE 2002; McDowall and Eames 2005), and, in trying to plan a route to the hydrogen economy through such exercises, it has first been necessary to describe where that final destination is. It is therefore becoming obvious that a clear definition of what is meant by the term "hydrogen economy" is needed. One common misunderstanding, for example, is the assumption that the "hydrogen" component is simply about energy storage. Another is that renewable energy, not being mentioned by name, is not an intrinsic component of the concept.

It is vital that this idea is accurately defined because – as with any journey – knowing where your final destination is, informs every decision you make along the way about how to get there. Unless we know where we are ultimately headed, we will make many uninformed and costly mistakes and probably find ourselves in completely the wrong place. This does not rule out the option of only going part way along this road (at least the decision to compromise can be taken from a well-informed perspective) or reassessing the situation in response to the probability that the goalposts will move as the journey progresses.

There are three crucial areas where major progress is required before the hydrogen economy can really take off and these are the fuel cell technology, electrolysis technology and, perhaps most importantly, hydrogen storage methods.

Fuel cells currently suffer from high cost and short life expectancy, along with a range of other more minor limitations that are only be expected of a relatively new technology. Most of these should be dealt with by iterative development over the next few years, but the most important breakthrough will be in the cost reductions brought about by mass manufacture. This, though, is dependant upon there being a large market for fuel cell and other renewable energy products; however that market is unlikely to emerge until prices have fallen to competitive levels. Such "chicken-and-egg" situations are typical of the introduction of
many disruptive technologies (as exemplified by photovoltaics and others) and it usually requires the support of governments to unblock the logjam.

The drawback for electrolysis is currently the high cost of available systems, but their efficiency will become an increasingly important issue as they are integrated into energy systems dominated by renewables. While addressing the problems that fuel cells face is best left to the many established players in this field, the electrolysis issue has become a significant focus of studies related to this thesis. One of the most important outputs from the Hydrogen and Renewables Integration (HARI) project is that it Amitava Roy, one of its team members, has initiated a process whereby a new electrolyser technology will be developed that specifically addresses the issues of cost, durability and efficiency (Roy, Watson et al. 2005a).

The quest for a lightweight, compact and responsive hydrogen storage technique is, again, best left to the industrial and academic institutions qualified to deal with the subject, although some collaboration (in the form of providing real-world conditions in which to test the new technology) have been agreed as a later phase of this project.
2 Hydrogen energy storage system components

A range of different equipment may be appropriate where hydrogen technologies are integrated into energy systems, but in the particular circumstances where it is used for bulk electricity storage, there are three main components of relevance (although variations on this basic theme do, of course, exist). These are an electrolyser, the hydrogen store itself and one or more fuel cells. Since this is indeed the circumstance of the project under discussion in this thesis, only these three sub-systems of the hydrogen energy storage system will be considered in detail here.

2.1 Electrolysers

Electrolysis of salt water has been used extensively in the chlor-alkali industry over many years (Euro Chlor 2005) for the production of chlorine gas. Water electrolysis (i.e. using pure instead of saline water) is less common, but has been used to produce hydrogen in the food industry for hydrogenating fats, in the power industry for cooling generators, in the fertiliser industry for making ammonia and for applications in the electronics, metallurgy and glass industries for many years (Winter 2005). It is water electrolysis that is of interest in this study as this method produces hydrogen that can be used as a ‘clean’ fuel in energy systems.

Water electrolysis is simply the splitting of water into its constituent parts of hydrogen and oxygen by passing a DC electrical current through it. This process takes place within electrochemical cells that are placed end-to-end to make up what is known as a ‘stack’, or more commonly within the industry, the electrolyser ‘module’. These are electrically connected in series using bipolar electrodes, or in parallel using mono-polar electrodes. Between the two electrodes of each cell there is a membrane that allows ions in the electrolyte to pass, but not gas. Hydrogen collects on the surface of the negative electrode and oxygen on the positive. While kept separate by the membrane, these two gases are carried away from the stack and, in most cases, purified (to remove traces of water and electrolyte) before being collected for whatever end-use they are intended. Although research is being carried out to develop high temperature electrolysers (Hong, Chae et al. 2005) (which could potentially be more efficient in systems that are not intermittent), current designs operate at temperatures of around 70 – 90°C.
Electrolysers are generally considered a mature technology, but as the HARI project reveals, their particular application to hydrogen energy storage systems imposes specific conditions that demand a radical reassessment of the prevailing approach to the process (see section 4.a.iv below) (Roy and Woolf 2003; Roy, Watson et al. 2005c; Roy, Watson et al. 2005a; Roy, Watson et al. 2005b). There are currently two types of electrolyser technology available: alkaline and proton exchange membrane (PEM). Solid oxide electrolyzers are also expected to be developed in time; however it is only those available today that are of interest in this project.

2.a.1 Electrolyser types

Alkaline electrolyzers are currently the most common type and the more mature of the two technologies currently available. They employ potassium hydroxide (KOH) solution as a liquid electrolyte, typically at around 30% by volume (Divisek and Emonts 2003). This is a very hazardous substance, which imposes some practical limitations on its use due to the extreme care required in its handling (see Appendix for potassium hydroxide safety data sheet). In the normal course of events, however, this should present a minuscule risk as exposure to the electrolyte would only be necessary during maintenance, which must be carried out by trained personnel. The only significant hazard it might present to the public would be through accidental leakage.

Although a PEM electrolyser has a higher theoretical efficiency limit than an alkaline one (Rasten, Hagen et al. 2003; Barbir 2005), of the currently available systems, alkaline still tend to be the more efficient. Manufacturers of this type include major players such as Hydrogenics (who recently acquired Stuart Energy, who, in turn, had only just acquired Vandenborre Hydrogen Systems), Norsk Hydro, GHW, Accagen, ELT, Mitsubishi, MTU, Teledyne and GE, while there are many other small enterprises developing their own systems.

Having a solid polymer electrolyte, PEM electrolyzers have some safety advantages over alkaline ones and, needing no gas separating mechanism, they tend to have a smaller footprint (Kruse, Grinna et al. 2002). They currently suffer, however, from having lower efficiencies, much shorter life expectancy and being less mature as a technology (NREL 2004), but in the longer term have the potential for higher efficiencies and a greater tolerance of the kind of dynamic input supplied by REs. The solid electrolyte in a PEM cell is incorporated into the
membrane, which is itself combined into one piece with the electrodes, forming a membrane electrode assembly (MEA) similar to that found in a PEM fuel cell. The cost of PEM electrolysers is higher than that of alkaline, but at modest scales, there is a potential for prices to fall lower than alkaline devices.

There are only two manufacturers currently selling PEM electrolysers, these being Proton Energy and Hydrogenics. Since their availability is more limited than alkaline units, their efficiency currently lower, their lifetime shorter and their cost higher, PEM electrolysers have not featured strongly in this study. Unless stated to the contrary, therefore, comments within this thesis about electrolysers in general, will refer to alkaline electrolysers.

2.a.ii Intermittent and dynamic operation

The particularly arduous operational conditions imposed by an energy system like that of West Beacon Farm (WBF), present severe challenges to today’s off-the-shelf electrolysers. Such devices are designed to be connected to a steady mains supply and run constantly for most of their operational life. Their main purpose is to provide a reliable supply of hydrogen at a given pressure and flow rate and to do so extremely safely. Efficiency comes some way down the list of priorities, even though the cost of power is the most significant cost over the unit’s lifetime (Prince-Richard, Whale et al. 2005). Where the electrolyser is supplied by power from intermittent or highly dynamic sources, such as renewable energy generators like wind turbines and photovoltaic arrays, a number of important factors come into play. These relate particularly to the device’s durability, reliability and efficiency.

The effect of intermittency of operation will, over time, degrade the stack and thereby reduce its efficiency (Vanschoubroek 2003). This, therefore, means that intermittency significantly shortens the operational lifetime of currently available electrolyser technologies.

2.a.iii High pressure operation

The current trend in the industry is for higher and higher pressures within the electrolyser stack. Typically, they run at between 10 and 50 bar(g), but pressures of hundreds of bars are planned by some. The thinking behind this is based upon the misapprehension that the internal pressurisation is “for free”. In other words, if the flow of gas from the electrolyser is restricted, its production leads to an accumulation of pressure within the device and this
characteristic can be exploited to obtain pressurised hydrogen production without the need for a separate compressor. Of course nothing really is for free and so it should be no surprise that this internal pressurisation comes at a price in terms of efficiency, reliability and cost. Present day storage techniques demand much higher pressures than those provided by current electrolysers anyway, so an external compressor is usually needed to raise the pressure further and thus it is not eliminated from the process after all. The more valid argument for high pressure is to achieve a reduction in the size and possibly the cost of the stack. In reality this is far from proven, given the complex trade-off between strength, cost and efficiency. Through the HARI project it has been possible to investigate the issue of pressurisation in electrolysis and this has been done in detail by Amitava Roy, who discusses the relative merits of high and low pressure devices extensively in a number of publications (Roy and Woolf 2003; Roy, Watson et al. 2005c; Roy, Watson et al. 2005a; Roy, Watson et al. 2005b). Although this thesis covers the whole integrated hydrogen and renewable energy system at WBF and must therefore encompass a high-level overview of electrolysis, it is not within the remit of this author to delve into such matters in depth and so, for further information on the subject, the reader is referred to the work of Amitava Roy. One of the major findings of his PhD research is that pressurisation within electrolysers, particularly when RE powered, is counterproductive and he summarises it thus: “Pressurised electrolysers are less energy efficient, less durable, more costly and not compatible for renewable energy powered operation especially in stand-alone energy systems; these findings are opposite to the present industry trend which concentrates at the moment on developing very high pressurised electrolysers” (Roy, Watson et al. 2005a).

2.a.iv Efficiency

Efficiency is always the watchword in renewable energy systems. In fossil fuel energy systems, efficiency is not always of primary importance to its operators, even though each unit of wasted energy costs money and represents an unnecessary addition to the carbon dioxide already in the atmosphere. In renewable energy systems, however, each wasted unit of energy does not contribute to greenhouse gas emissions, but it does add extra expense to already capital-intensive installations.

Running an electrolyser at varying levels (as is the case where it is powered by renewables) means that, when it is running, it is usually at partial load. The efficiency of the electrolysis
process varies considerably according to what the power input is in comparison to its rated capacity. There is, therefore, an optimal range for the production of hydrogen, typically from around 20 – 100% of rated, beyond which the conversion efficiency is too low. Careful sizing of the electrolyser is needed to ensure that this operational range is set to give the maximum hydrogen production, but there are inevitably times where less than 20% or more than 100% of its rated power intake is available. To absorb these dips and peaks may require that a battery is also included in the system, which adds some losses to the overall process but it can also reduce the number of damaging on-off cycles. The sizing strategy that aims to maximise hydrogen production, however, does not necessarily give the best duty cycle and so concerns about the effects of intermittency may not be best served in this way.

Operating only intermittently, an electrolyser might be on standby for very long periods. It should be noted that there is a difference between switching off the unit completely and leaving it on standby. The former requires that, if it is a pressurised unit, the system be fully depressurised on shutdown and purged with nitrogen before re-pressurisation upon start-up. This is both time consuming and inefficient. Standby mode, by contrast, allows the system controller to regulate the electrolyte levels and other sensitive parameters. In this way, little pressure is lost and the stopping and starting of the hydrogen production process takes a matter of seconds, but the price paid for this is in the power required to monitor and operate the system while on standby. Although the controller itself might draw very little power (100 – 200W compared, for example, with the 36kW rated power consumption of the module in the electrolyser at WBF), over long periods this amounts to a significant energy consumption (on average, 3.6kWh/day). This is of particular importance in renewable energy systems where the duty cycle is such that the unit is on standby for much longer periods than it runs.

Where the losses are thermodynamic (as opposed to the gas losses), they are mainly manifested as waste heat. Much of this could be recuperated as useful energy if a similar technique is used to that of combined heat and power (CHP) systems. In this case it could be considered as combined heat and fuel (CHF), whereby the water in the electrolyser’s cooling circuit is used to provide heating services elsewhere. Although the author is not aware of any installed electrolyser systems that practice this, it is proposed that this method of optimising the overall efficiency of the system will be explored at West Beacon Farm. Low temperature differentials may make this expensive in some circumstances, but since the by-product heat
from the fuel cells at WBF is already being captured, integrating heat collection from the electrolyser into the same system is relatively easy.

Thermal management contributes to the system's efficiency and is adversely affected by intermittency. Even at full power, it can take over an hour for the process to climb from ambient temperature to reach its optimum level after start-up and, as will usually happen with renewable energy input, this will take much longer when operating at part rating.

Taking all the issues related to intermittency into account, it becomes clear that – like most devices – electrolyzers are built to be used. To put it bluntly: they do not like being switched off, especially not for long periods!

The water consumed in the electrolyser must be of very high purity (<5µSiemens conductivity) to avoid secondary reactions and the build-up of contaminants. To purify this water, usually by reverse osmosis (RO), consumes energy, thus further reducing the overall system efficiency.

2. b Hydrogen storage

Perhaps the biggest challenge facing the hydrogen and fuel cell industries is the search for a practical hydrogen storage method. With a higher heating value (HHV) of 39.7kWh/kg, hydrogen has a good energy to mass ratio, but a low energy to volume ratio of 3.57kWh/Nm³, since it is a gas (Larminie and Dicks 2003). The aim is to store the gas in such a way that it occupies a much smaller volume, but to do so using a mechanism that is not heavy, while also being able to charge or discharge the store rapidly in response to supply or demand for the hydrogen. There are four main options being pursued for hydrogen storage, all of which have severe limitations at the current state-of-the-art level of the technology. These are liquid hydrogen, pressurised gaseous hydrogen, solid-state hydrogen stores and chemical hydrogen carriers. The United States Department of Energy (DOE) has set a target of 9wt% (weight per cent) by 2015 (with an interim target of 6wt% by 2010) for the storage of hydrogen on board vehicles in order to allow a reasonable range between refuelling stops (assumed to be 300 miles) (US DOE 2005). No-one has developed an ideal and widely applicable solution to this problem and, of the few viable systems currently available, those that do work are suitable for only a limited number of situations. Metal hydrides and simple pressurised gas
storage are suitable for most stationary applications, for example, but the in majority of circumstances a hydrogen fuel of the future will be needed for vehicular or portable uses.

2.b.1 Liquid hydrogen

Liquefying hydrogen reduces its volume by 833, since 1 litre of liquid at 0bar(g) and -253°C provides 833 litres of gas at 0bar(g) and 15°C (Roach 2005), but it comes at a high cost in terms of the energy required in the liquefaction process. Present day methods consume between 25 and 45% of the energy content of the hydrogen being liquefied (Larminie and Dicks 2003), which dramatically reduces the attractiveness of this option in most situations. Furthermore, the plant required to perform the liquefaction task is bulky and complex, rendering it unsuitable to most of the applications envisaged in a future hydrogen economy. There are, however, significant niches where it may make economic sense to liquefy hydrogen; more for transportation purposes than for storage over long periods (Gretz, Baselt et al. 1990). Liquid hydrogen must be kept at a very low temperature (-253°C) and this requires that it be stored in highly insulated vessels that are bulky, heavy and expensive. Even with the use of these special containers, it is inevitable that a small amount of hydrogen will be continually boiling off, which seriously reduces its value as long-term energy storage. The boil-off gas may have to be vented unless a use can be found for it, as is the case, for example, in BMWs hydrogen powered internal combustion engine (ICE) cars, where it fuels a solid oxide fuel cell (SOFC) auxiliary power unit (APU).

2.b.2 Pressurised hydrogen gas

Compressing hydrogen is the most straightforward way of forcing it to occupy a smaller volume and is the most widespread method used today. This too consumes energy, but it is much less than that required for liquefaction. Of course, containing a gas at pressure demands a strong vessel which will also be heavy. A mild steel cylinder, for example, able to store 65Nm³ of hydrogen at 137bar(g), weighs about 1 tonne and is 4m long and ½m in diameter. The current state of the art for composite cylinders (carbon fibre wrapped aluminium) is for a storage ratio of 5.5wt%, which is close to the DOE’s 2010 target of 6wt%, but the volume and cost of the store is still well outside the DOE target. Attempts are being made to construct complex ‘conformable’ vessel shapes, beyond the standard cylinders or spheres, that will allow easier integration into vehicles (Hoogers 2002). There is some scope for strong, lightweight and non-hydrogen-porous composite vessels to be developed,
but there is a limited range of options to explore in trying to move this essentially mature technique forward.

Compressor technology has not, traditionally, been well suited to the requirements of the fuel cell industry, which demands extremely high purity hydrogen for its fuel. Contamination of the gas by, in particular, carbon compounds, is severely detrimental to today's mainly PEM fuel cell devices. The majority of compressors (e.g. centrifugal, screw, displacement/piston type) tend to be lubricated with oils containing carbon compounds, but new versions are now available that keep the lubricant isolated from the gas stream. A diaphragm compressor, on the other hand, uses intrinsically cleaner mechanisms, but is likely to suffer from lower reliability and cannot deliver the compression ratios required.

2.b.iii Metal hydrides and carbon nano-materials

Being such a small molecule, diatomic hydrogen can fit inside the interstitial spaces between the atoms of a metal and, in doing so, it forms a metal hydride. The ease with which the hydrogen is absorbed in this way, or is desorbed, varies according to the metal or alloy in question. This can vary in terms of timescale, heat input (or extraction), pressure, recoverability and repeatability. For a hydrogen energy store, the absorption and desorption processes should ideally happen quickly enough to respond to the input and output requirements of the hydrogen fuelling system and it should require little energy input, in terms of both heat and pressure, to make them happen. It should also allow the same amount of gas to be recovered that was put into the store in the first place and that this can be repeated over and over again. The reality is that no existing metal hydride store fulfils all these requirements at once, but some fulfil most of them reasonably well and so the aim is to strike the best balance between all these attributes. Research is also going on to find new alloys or system configurations (using zeolites or, perhaps, a multi-stage absorption or desorption process) to achieve these aims. The requirement that all this be achieved within a certain weight-percent ratio, however, means that the locations within the periodic table where suitable metals can be sought are limited to regions of low atomic mass.

The take-up of hydrogen in metals is a combination of absorption into the metal lattice structure and condensation of the gas on its surface. The latter process, known as adsorption (or, to make the distinction clearer in verbal conversation, physisorption) tends to have faster dynamics than absorption (or chemisorption) (Orimo, Zuttel et al. 2003). The same processes
Metal hydrides also offer a potential route to less energy intensive hydrogen compression. In a typical metal hydride system, hydrogen is introduced to the store at ambient temperature and very little pressure where the metal spontaneously absorbs it. The inevitable energy cost in this system comes in the desorption process as it takes considerably more persuasion to get the metal to release the hydrogen. This is usually done by heating it up (by happy coincidence, this can often be done using waste heat from the very fuel cell, or ICE, that the hydrogen is fuelling). If, upon heating the store, the hydrogen’s exit is restricted, pressure builds up within the vessel. Clearly, if this process is carefully controlled, it can be used, not so much to store the hydrogen, but to raise its pressure through a continuous charging and discharging cycle. There is one such metal hydride compressor already on the market made by Hera (DaCosta and Golben 2004).

2.b.iv Chemical hydrogen carriers

One form of hydrogen energy storage that has been in use for as long as man has harnessed the power of fire is in chemical hydrogen carriers. Hydrogen is bound up in chemical form within wood, coal, oil and natural gas. The historical trend from the use of solid fuels, through liquid oils, to today’s growing natural gas market, is characterised by a lowering of the carbon content and a rising hydrogen content of the fuel, until ultimately, the promise of pure hydrogen as the fuel of the future. Hydrocarbon fuels can, therefore, be seen as a
convenient energy storage mechanism for hydrogen. The problem, from an environmental point of view, is that the release of the carbon component of the fuel into the atmosphere, in the form of carbon dioxide, is a severe disadvantage. Had this carbon not been locked underground for millions of years, its sudden introduction would not have had such a deleterious effect. It is the avoidance of this problem that forms one of the major drivers to the introduction of pure hydrogen as a fuel. If, however, the carbon content of synthetically produced liquid or gaseous hydrocarbon fuels came from the carbon already in circulation in this ecosystem, there would be no harmful effect. Such would be the case where biofuels provided a source for hydrogen, because, as long as the resource is properly managed, they are carbon neutral. More radical, however, is the proposal that hydrogen produced by whatever 'clean' mechanism, could be combined with carbon (again, sourced from a 'carbon neutral' resource) and oxygen to make a liquid fuel such as methanol. Being liquid, methanol is easier to handle and has a greater energy density than pure hydrogen gas. This, of course, comes at some considerable energy cost and would, for example, require an on-board reformer in a car if it were to be used as a fuel. It is also very corrosive to certain components and, being a hazardous substance, requires great care in its handling.

Hydrocarbons are not the only way of binding hydrogen into a compact, portable form. Indeed, water does just that, but like all such methods, it requires energy to extract the pure hydrogen (e.g. in the form of electrolysis). What stops it being a fuel is its stability. The ideal hydrogen-containing fuel is stable, but only just, such that its release yields more energy than it took to release it. Sodium borohydride (NaBH₄) is one of the few examples of this that is available. It is produced by a company called Millennium Cell and uses a catalyst to release hydrogen from the NaBH₄ pellets in the onboard vehicle fuelling system, leaving a reusable sodium borate waste (which must continue to be carried to a refuelling/disposal point) (Millennium Cell 2005). Other chemical hydrogen storage methods being investigated include ammonia and hydride slurries (McClaine, Tullmann et al. 2004), but there is considerable way to go before they can become practical, commercial propositions.

2.c Fuel cells

The process that takes place inside a fuel cell is reverse electrolysis and, since it is the same process as that of an electrolyser except running backwards, there are predictably a number of similarities between the two technologies. Like an electrolyser, a fuel cell unit has at its heart
a stack made up of cells, each consisting of a membrane and two electrodes. In some cases, the same electrolytes are used and similar catalysts. A fuel cell combines hydrogen and oxygen (usually from the air) to make water and, in doing so, generates energy in the forms of electricity and heat. The mechanism by which this happens varies slightly depending upon the type of fuel cell in question, but in the case of a proton exchange membrane (PEM) device, shown in Figure 2-1 (Ballard 2005), it is as follows. Hydrogen entering the cathode side of the cell is persuaded by the action of a catalyst (typically platinum) to shed its electrons and to split into monatomic, positively charged hydrogen (H\(^+\)) ions, which are simply protons. Sulphonate groups within the solid electrolyte of this type of fuel cell attract the protons and encourage them to pass through it, across the membrane to the anode. Here the protons combine with oxygen atoms and the electrons, which have meanwhile travelled via an external electric circuit to reach the anode, to make water. In different fuel cell types the ions passing through the membrane may be different and the electrolyte may be liquid instead of solid, but the basic principle remains the same (Larminie and Dicks 2003). The various types of fuel cell fall into three main categories: high, medium and low temperature devices.

![Figure 2-1: Schematic of a PEM fuel cell (Source: © 2005 Ballard Power Systems Inc.)](image-url)
2.c.i Fuel cell types

Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFC) are high temperature devices that operate at between 600 and 1000°C (Larminie and Dicks 2003). The higher temperatures allow the electrochemical reaction to proceed more efficiently and produce high-grade heat that can be captured for use in many applications. It also means that reforming of hydrocarbon fuels to extract the hydrogen can take place within the stack itself, giving great flexibility in the fuelling of these devices. There are considerable technical challenges to constructing devices that operate at such high temperatures and, although far from being insurmountable, these have contributed to the slow introduction of high temperature systems into the market (Yokokawa and Sakai 2003). Because the heat output of these systems is at temperatures that are suitable for many industrial or commercial processes, some manufacturers of high temperature fuel cells are targeting the market for generators on the scale of 100s of kilowatts up to multi-megawatt systems, while some recognise that SOFC systems, at least, may well be useful at sizes of only a few kilowatts.

Phosphoric Acid Fuel Cells (PAFC) are medium temperature devices, operating at around 180 - 200°C (Larminie and Dicks 2003). This was the first type to be widely deployed, with hundreds being installed worldwide before other types were ready to be tested in even a handful of locations outside the laboratory. Such initial promise, though, has not been followed up, as the systems were expensive and showed little scope for of price reduction (King and Kunz 2003). Many thousands of hours’ operational experience have been gained by these units, which were almost all PC25 ONSI (later International Fuel Cells and now UTC Fuel Cells) 200kW systems made by United Technologies Company (UTC) using Ansaldo stacks. Many are CHP systems such as, for example, the UK’s first fuel cell system, which is installed at Woking in Surrey (Thameswey 2003).

The low temperature fuel cell types are Alkaline (AFC), Proton Exchange Membrane (PEM or PEMFC), sometimes known as a Solid Polymer (SPFC), and Direct Methanol (DMFC). The latter is generally designed for use in small portable appliances, such as mobile phones or laptop computers, as they offer the potential for longer ‘battery life’ than conventional batteries (Larminie and Dicks 2003). They use methanol as a fuel, which can easily be stored in small cartridges, and do not require any reformer to extract the hydrogen because the methanol can be used directly within the fuel cell.
Alkaline and PEM fuel cells operate at temperatures of between 70 and 90°C (Larminie and Dicks 2003). The former were the first to be developed and have been used extensively in the space industry ever since the Gemini missions of the 1960s (Cifrain and Kordesch 2003). PEM fuel cells were developed later and, due to their compactness, are seen as the best option for vehicular applications, which have provided the major impetus behind the fuel cell industry.

AFCs are intolerant of carbon dioxide (Tewari, Sambhy et al. 2006) (which is no problem in space missions where they use pure oxygen at the anode instead of air), they have a hazardous liquid electrolyte of potassium hydroxide (KOH) and a lower power density than PEMs. PEMFCs have a solid electrolyte, which is contained within a single-piece membrane electrode assembly (MEA). AFCs have the advantages of higher efficiency (theoretically, up to 60% (Kordesch, Gsellmann et al. 1999) compared to 55% for PEMs (Hubert, Achard et al. 2005)), simplicity of design (not requiring the complex humidification mechanism that PEMs do) and no need for expensive catalysts (such as platinum) (Larminie and Dicks 2003). With the automotive industry so squarely behind PEMFCs, the AFC has fallen somewhat out of favour in the industry. However, with the problem of carbon dioxide contamination now effectively dealt with (McLean, Niet et al. 2002; Gulzow and Schulze 2004; Astris 2005), they may well be the best option for many stationary applications and so a revival in their fortunes would be welcomed by many.

One potential variation on standard fuel cell designs that may have significance for energy systems like the one studied for this thesis, is an oxygen breathing version. Although used in space applications, pure oxygen breathing fuel cells are not commercially available since there is little perceived demand for them in the wider world. There are ones that are adaptations of air breathing fuel cells and their manufacturers claim a relative efficiency gain of 2-3% over their air breathing counterparts. Building a fuel cell that is specifically designed for pure oxygen feed to the anode, however, might increase its efficiency by 10% or more (Cifrain and Kordesch 2003) relative to an air breathing type. Such a unit would be potentially useful in an energy system like the one in this project because it could make use of the pure oxygen being produced by the electrolyser as a by-product of the hydrogen production. There are hazards associated with the storage of oxygen under pressure (BOC 2005), in addition to those already presented by the hydrogen storage, but the efficiency gains obtained may more than compensate.
3 The hydrogen and renewables integration (HARI) project

The Hydrogen and Renewables Integration (HARI) project is being undertaken by a team of four PhD student researchers from CREST (Centre for Renewable Energy Systems Technology), which is part of the Electronic and Electrical Engineering Department at Loughborough University, UK. Of these, the author of this thesis initiated the project and is studying the integration of the overall hydrogen and renewable energy system, Amitava Roy is studying in more detail the subsystems within this overall system, particularly the electrolyser, and Matt Little is researching and building the electrical system used to integrate the subsystems. The forth member of the team, John Barton, is less closely involved, but is looking at the wider issue of energy storage for use on grids with a high RE penetration.

3.1 Existing system

West Beacon Farm (WBF) is owned by Professor Tony Marmont and his wife, Angela. The 50 acre site is situated 4 miles outside Loughborough in Leicestershire, UK. Beyond the use of the fields for cattle grazing and some areas of biomass plantation that are currently not harvested, this is not a working farm, but is simply Tony and Angela’s domestic residence. Also associated with the site is a small office block nearby that is housed in some converted farm buildings. This office, at Whittle Hill, is the home of Tony Marmont’s company, Beacon Energy Ltd, and is directly connected to the electrical system of the West Beacon Farm site. For the purpose of this study, then, the energy system referred to throughout this thesis is taken to be that of both sites combined (Figure 3-1).

What makes these two sites unusual is that they incorporate a number of energy efficiency and renewable energy features. At Whittle Hill, the component of most relevance to this study is the 4kWp photovoltaic array that covers a glazed corridor at the front of the building. The other main renewable energy (RE) equipment of note is all at the WBF site. This includes two 25kW Carter wind turbine generators (WTGs), a 6kWp fixed photovoltaic (PV) array, three solar-tracking PV modules amounting to a 3kWp output and two micro-hydroelectric turbines with a combined output of 3.05kW. In addition, there is a 15kW_{\text{electrical}} 38kW_{\text{thermal}} Totem combined heat and power (CHP) unit that currently runs on LPG. A 10kW_{\text{thermal}} heat pump, circulating water from a coil at the bottom of an artificial lake, provides central heating in the house and (consuming 4kW_{\text{electrical}}) represents one of the most
significant electrical loads on the system. Further sustainable energy features at the sites include ≈5m² of 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 to either Whittle Hill or WBF and so rainwater is collected from the house’s roof and the Beacon Energy office roof. The former is used for washing, flushing and, since the installation of the hydrogen energy storage (HES) system, as a feedstock for the electrolyser.

The tracking PV modules are used to pump water from a 50m deep borehole into the lake, but they are not connected directly to the WBF power supply network. Only when the water from the lake flows through one of the hydro turbines is the energy fed into the electrical mini-grid for the two sites. The Whittle Hill PV array does not feed back to the WBF site, but only tops up the supply to the Beacon Energy office. The RE power supply from WBF, therefore, comes primarily from the wind turbines, with support from the fixed PV array, the micro-hydro turbines and occasionally from the Totem CHP unit. 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 hydrogen energy storage (HES) system, this has been carried out using a combination of batteries and the utility grid. A 120kWh lead acid battery accumulator has been used for energy storage over diurnal periods and the grid has been used as a ‘limitless store’. This allowed surplus electricity to be sold to the utility network, originally under a NFFO agreement, but with the help of the batteries, electricity is usually only imported from the grid at the cheaper night time rate. Figure 3-2 shows the West Beacon Farm site, with the location of the existing renewable energy technologies and the new hydrogen energy system components indicated.
Figure 3-1: Map of the West Beacon Farm and Beacon Energy offices (Whittle Hill Farm buildings).
Figure 3-2: Map of the West Beacon Farm site only, showing the location of the main hydrogen and renewable energy components.
3.b New components

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 as well as offering a response to the diminishing commercial returns of selling ‘green’ power back to utility companies that recent reforms to the electricity trading arrangements have brought about. Under a project entitled Hydrogen and Renewables Integration (HARI), such a system is being implemented and forms the basis of this and other PhD studies. Although clearly not necessary for a site in the heart of a modern industrialised nation, an autonomous energy system such as this could more practically be demonstrated and tested here as a prototype. The teething troubles associated with such early-stage development can be ironed out with the benefit of the electricity grid as a “safety net” in this situation, rather than deploying it at a location that is isolated from the electricity network, where such a learning curve would render it impractical. This site also benefited from the pre-existence of the RE system, financial and practical support from the site’s owner and easy access to a rich vein of expertise within various departments at Loughborough and other local Universities, most notably the Centre for Renewable Energy Systems Technology (CREST).

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 primary components of the newly installed HES system at WBF are a 36kW electrolyser that can produce 8Nm³/h of hydrogen at 25bar(g), pressurised hydrogen storage cylinders with a combined capacity of 2856Nm³ of hydrogen at 137bar(g), and two fuel cells with a combined electrical output of 7kW (one 2kW and one 5kW unit). Figure 3-3 shows a simplified schematic of the existing system and the new components that have been added for the HARI project.
Figure 3-3: Configuration of the West Beacon Farm energy system, showing the existing renewable energy system before the HARI project started and the additional components added to create a hydrogen energy storage system.

3.3 Comparison with similar projects

The idea that renewable energy and hydrogen energy storage could be combined to create a sustainable energy infrastructure was first proposed by J.B.S. Haldane in the 1920’s (NHA 2005), but gained much greater momentum in the 1970’s. The oil crises of 1973 and 1977 gave greater weight to the concept, however it was not until the late 1980’s that efforts were made to put it into practice. At first these were partial systems, that might feature a renewable energy source with an electrolyser or a fuel cell, but soon complete systems that included both hydrogen production and consumption within a renewable energy system were tried out. Even these, however, tended to be limited to short test runs that might use simulated loads, rather than the continuous operation of real-world energy networks.

The majority of integrated hydrogen and renewable energy projects in existence before the HARI project started were laboratory based and most of them were PV powered and/or grid connected. The number of projects that included wind power, which is more dynamic in output characteristics than solar, was small. Many of these projects claim to have proven that RE powered electrolysis, with highly variable inputs, is possible, but most have only done so
in relatively short-term tests, whereas the HARI project does so continuously on an ongoing, day-to-day basis. Various problems associated with using electrolysis in this way, that may not have been apparent in other projects, have been exposed by long-term, dynamic operation of components at WBF. Some comparatively good efficiency levels are claimed, much of them achievable by being able to keep small-scale, PV-based systems simple, but these often exclude balance of plant (BOP) losses. Although those that include wind power are necessarily more complex, which has an efficiency cost associated with it, this is compensated for by the higher energy density of wind installations.

The HARI project is the first field trial in the UK to bring together the elements of a hydrogen energy storage system with renewable energy sources into a complete sustainable energy system. It is the first in the world to use multiple renewable energy sources and to run continuously as a real-world energy system rather than simply as a test bed. By the end of the project, it is intended that the energy system at West Beacon Farm will be disconnected from the grid so that it will operate truly as a stand-alone system. Once this has been accomplished it will be genuinely unique and will pave the way for fully autonomous energy supply systems to be installed in a variety of applications around the world.

The following list of projects is not exhaustive, but it is representative of the more important research initiatives that have been undertaken in this field.

3.c.i HYSOLAR

Since 1989, the DLR (German Aerospace Research Establishment) in Stuttgart has been working on the HYSOLAR project (Schucan 2000f). This has taken place in phases, starting with investigations into various electrolyser concepts, leading to the development of their 10kW alkaline unit which is used as a test bed for electrolyser components under dynamic load. A 350kW solar-hydrogen project was then set up in Saudi Arabia, producing 463Nm³ of hydrogen per day by electrolysis (Almogren and Veziroglu 2004).

3.c.ii Fraunhofer House

The Fraunhofer Institute for Solar Energy Systems in Germany has been demonstrating a self-sufficient, solar powered, family house since 1992 (Schucan 2000f). A 4.2kW PV array is used to run a 2kW PEM electrolyser, which was developed by the institute in response to
the problems it experienced in using an alkaline one. The hydrogen is used in a 0.5kW Siemens PEM fuel cell and catalytic burners, used for cooking and space heating. The hydrogen store has a 15Nm³ capacity and there is also a battery for short-term electricity storage (Fraunhofer 2004). Disappointing system efficiencies (44%), caused by poor weather, PV outputs being less than predicted by the manufacturers and lower than expected hydrogen system efficiencies, have made it a very challenging task to remain self-sufficient.

3.c.iii  Stuart Renewable Energy Test Site (RETS)

A system located on the roof of the Stuart Energy Systems (SES) factory in Toronto, Canada, known as The Stuart Renewable Energy Test Site (RETS), has been in operation since 1991 (Schucan 2000a). It was set up to investigate low cost RE-hydrogen systems and included a 2.45 kW PV array, connected directly to an alkaline electrolyser supplied by the Electrolyser Corporation Ltd., with auxiliary loads (compressor and controls) supplied via a small bank of lead-acid batteries and a 420W PV array. The hydrogen was produced at almost atmospheric pressure and compressed to 7bar(g) for a store with a 17Nm³ capacity. This project particularly looked at the sizing of directly coupled electrolysers and found that “over-coupling” the cell module (i.e. having slightly more cells than is required to match the maximum power point of the PV supply, thus making it voltage limited), gave higher efficiency, however this reduces the cost effectiveness of the PV array. The electrolyser was controlled mainly by mechanical means, using switches activated by pressure and liquid levels.

3.c.iv  INTA Solar Hydrogen Facility

Running over three phases, from 1991 to 1996, the INTA (Instituto Nacional de Técnica Aeroespacial) solar hydrogen facility in Spain incorporated an 8.5kW PV array, a 2.2 kW alkaline electrolyser, a 24Nm³ metal hydride store, an 8.8 Nm³, 200bar(g) hydrogen store, a 10kW phosphoric acid fuel cell and two PEM fuel cells rated at 2.5 and 5kW (Schucan 2000e). The Metkon 6bar(g) electrolyser produced up to 1.2Nm³/h of hydrogen and was evaluated in three modes: connected directly to the PVs, but with a variable number of active cells in the electrolyser module, connected to the PVs via a MPPT, or powered from the mains by an AC-DC converter under steady-state conditions. The PAFC had a reformer, so that it could be tested with other fuels besides pure hydrogen. The electrolyser efficiency was
found to be 69% and was not significantly enhanced by varying the cell number in response to PV output.

3.c.v  **Schatz Solar Hydrogen Project**

The first components of the Schatz project at the Humboldt State University Telonicher Marine Laboratory in the USA were installed in 1990 (Schucan 2000j). A PV array of 9.2kW, with the support of a 1.3kWh battery, a 7.2kW electrolyser, a 5.7Nm³ hydrogen store and a 1.5kW fuel cell, powers an air compressor used to aerate the laboratory’s aquaria. The air compressor runs continuously, consuming a steady 600W. The electrolyser is a 7.9bar(g) alkaline one made by Teledyne Brown Engineering, which produces hydrogen at a rate of 1.2Nm³/h. Due to the lack of available fuel cells at the time, the Schatz team, in collaboration with Texas A&M University, built their own PEM device. The PV array is connected directly to the electrolyser, to avoid converter losses, and this requires careful management of the input, which is achieved through the switching on and off of parts of the array. In a similar way, power is distributed to the battery and load as necessary, with power being supplied by the fuel cell at times of low insolation. It is necessary sometimes to draw power from the grid when the hydrogen store is empty and to switch off parts of the PV array when it is full, suggesting that a larger hydrogen store might be required. Early failure of the original nickel-cadmium battery led to it being replaced with lead acid batteries that have proved more robust and cheaper. Problems experienced with the fuel cell, due to dehydration of the membranes after long periods without use, have resulted in its being decommissioned. An overall efficiency figure of 34% has been claimed for the storage system.

The Schatz Energy Research Centre (SERC) has become involved in a number of projects with integrated hydrogen and RE systems in the California area. Interestingly, in the Palm Desert RE-hydrogen transportation project (Schucan 2000g), they have included a hydrogen gas chiller to remove some of the water in the hydrogen produced by the electrolyser. This reduces the work to be done by the electrolyser’s driers, thus reducing hydrogen losses.

3.c.vi  **Markus Friedli House**

The hydrogen and PV system at the Friedli house in Switzerland (Hollmuller, Joubert et al. 2000; Schucan 2000k) is notable for being a privately funded, real-world application, rather than a laboratory based installation connected to a university or other research organisation.
Although the University of Geneva became involved later. The system, which was installed in 1991, consists of a 7.4kW rooftop PV array, lead-acid batteries, a 10kW, 2Nm³/h, 2bar(g) alkaline electrolyser (one of the Vandenborre forerunners of the one installed at WBF), a 19Nm³ metal hydride store and a hydrogen/gasoline powered minivan that also has a 16Nm³ metal hydride store onboard. The hydrogen produced by this system is not used to make electricity in a fuel cell, but to directly fuel the burner in a stove, the minivan and, at one time, a laundry machine. A controller and a DC-DC converter, with MPPT, are used to match the PV output to the electrolyser and to maximise the efficiency of battery charging. The batteries are used to store electricity from the PVs and are the sole source of electricity to the house. Some electricity is fed back into the grid and some is used in the control (and could be for the operation) of the hydrogen system. This system is unusual (outside the explicitly ‘hydrogen for transport’ projects), in that the hydrogen produced at the site is not converted back to electricity and the energy used in electrical loads is stored in the batteries. This conforms more closely to the findings of the HARI project, particularly in a solar dominated energy supply, where storage times are generally shorter than wind based systems. An electrolyser efficiency of 62% is quoted, although this does not include purification losses (both electrical and hydrogen) and compression, and a system efficiency of 51%.

3.c.vii Solar-Wasserstoff-Bayern, Germany

The Solar-Wasserstoff-Bayern Hydrogen (SWB) project at Neunburg vorm Wald, Germany, was an industrial-scale demonstration that integrated solar and hydrogen technologies installed in 1991 (Schucan 20001). Arrays of different PV types had a combined output of 340kW and there was one high pressure and two low pressure electrolyser, an alkaline, PEM and phosphoric acid fuel cell, two mixed natural gas and hydrogen burning boilers and a catalytic burner, a hydrogen fuelled absorption chiller and a liquid hydrogen vehicle filling station using imported LH₂. Much emphasis was placed, though, on the many peripheral subsystems that played an important role in the reliability, efficiency and cost of the overall system. The two low pressure electrolyser, one membrane type and one alkaline, had a combined rated output of 47Nm³/h and consumed 210kW. After initial teething problems, both performed well, but since their manufacturers ceased work on electrolysis, they were decommissioned for lack of spares. The high pressure electrolyser was a100kW alkaline type producing hydrogen at 32bar(g). It experienced a series of problems, mainly related to gas purity. The alkaline fuel cell used oxygen, instead of air, as the oxidant and demonstrated a
53% efficiency, however it suffered reversals of polarity in some cells, leading to repeated stack replacements, and was eventually decommissioned in 1994 when its manufacturer ceased work on this type in favour of PEM fuel cells. The PAFC suffered teething problems, but after these had been resolved it was tested successfully as a CHP generator with simulated loads running on both hydrogen fuel as well as the more commonly used reformed natural gas. A 10kW PEM fuel cell was also tested, in conjunction with a metal hydride store, on a forklift truck at the site. Being one of the earlier hydrogen demonstration facilities, most of the technologies tested in this project were prototypes and so, understandably, suffered many teething problems. These were largely overcome, leading to improvements in their design. Safety and licensing issues limited the unmanned operation of equipment at the site outside normal working hours, thus reducing its ability to replicate real-world applications. The project finished in 1999.

3.c.viii PHOEBUS Jülich Demonstration Plant

PHOEBUS, a laboratory-scale demonstration plant at the Research Centre in Jülich, Germany, has a PV array of 43kW, a 304kWh battery, a 26kW alkaline electrolyser operating at 7bar(g) and producing hydrogen at 6.5Nm³/h, a hydrogen store of capacity 300N³ at 120bar(g) and a Siemens 6.5kW alkaline fuel cell (Meurer, Barthels et al. 1999; Schucan 2000h). The oxygen produced by the electrolyser is also stored. Much emphasis in the PHOEBUS study has been placed on improving efficiency. One method of achieving this that has been investigated is to connect the PV system directly to the battery, without going via DC-DC converters. The 3 – 4% output lost by the omission of maximum power point tracking in the converter is more than compensated for by removing the 9% losses also resulting from the conversion. Unfortunately this strategy limits the flexibility of design and makes it particularly difficult to implement at larger scales. High leakage rates were experienced in the hydrogen storage infrastructure, but this was improved by the redesign of connecting flanges in the pipework. Two mechanical compressors used in the system proved unreliable, prompting work to develop a solar thermal powered metal hydride compressor as an alternative. A high pressure electrolyser, operating at 120bar(g), was also developed in a bid to make compressors redundant in the system. Work was carried out to build and test two 2.5kW PEM fuel cells, but was not completed successfully and the fuel cells were seen as a continuing weak point in the system. A 53% system efficiency is claimed, but it does not include the energy required to compress the air that was used to drive the original two
mechanical compressors. It was assumed to that the proposed elimination of DC-DC converters and compressors might raise this efficiency level to 65% as well as reducing costs. Although unable to include wind power in this project, the PHOEBUS team emphasise that its complementarities with solar power would be advantageous.

3.c.ix RAL/ENEA stand-alone wind-hydrogen study

In response to the lack of research on powering electrolysis from wind turbines, as opposed to solar power, a collaborative project was initiated in 1994 to investigate the matter (Dutton, Bleijis et al. 2000; Schucan 2000d). The partners were the Rutherford Appleton Laboratory (RAL), the University of Leicester, ENEA in Italy and DLR in Germany. The project made use of two existing WTGs: one was a 14kW North Wind L196 situated at RAL and the other was a 5.2kW Riva Calzoni M7S at ENEA's Casaccia Research Centre. A 2.25kW von Hoerner System 20 bar(g) alkaline electrolyser was installed at Casaccia as it was the nearest to the 1kW size that software modelling had predicted would be optimal. A 35.6kWh lead-acid battery bank, DC-DC converter and dump loads were also added along with pumps, valves, a controller and a water demineralisation unit that were to be powered from the grid instead of the wind turbine (as would be the case in a genuinely autonomous system). The electrolyser could be powered directly through the AC-DC converter from the on-site WTG, or via the controller using either output profiles from the remote turbine at RAL or other patterns of supply to emulate different sources. Since it was a small-scale project, whose scope did not encompass storage, the hydrogen generated was only kept in a temporary 50 litre store, used for monitoring the hydrogen production before it was released to atmosphere. A number of malfunctions, particularly leaks, occurred with electrolyser. Most of these were corrected, but at around 45%, it remained disappointingly inefficient. Large fluctuations in power input over periods of minutes had a detrimental effect on gas purity, but over seconds did not adversely affect it and there was no detectable damage caused to the electrolyser in response to dynamic power input. Smoothing of the output was, however, achieved through operating the wind turbine at variable speed and strong suspicion was expressed that the long-term effects would be noticeable; suggesting that further studies were needed to investigate if that would indeed be the case. Due to delays in getting the electrolyser to work properly, further testing was carried out on the 10kW Metkon electrolyser at DLR that had been used in the HYSOLAR project previously. This unit demonstrated an efficiency of 63%. It was suggested that the appropriate sized electrolyser would be 80% of the power rating of the
WTG it was connected to, or the same rating if batteries were also integrated with it to enable the electrolyser to run at part load, which was said to be more efficient. The results of the HARI project would, however, suggest a smaller electrolyser, even with batteries included, and that although the cell module itself may be more efficient at part load, the BOP losses more than cancel out this gain. Much of the future work called for in this project and concerns raised are addressed directly by the HARI project. Economic assessments were also carried for the viability of stand-alone wind-hydrogen systems, but given the degree of technical uncertainty rightly expressed, it is hard to see how the future economics of these technologies can be gauged yet.

3.c.x SAPHYS

Collaboration between ENEA (Ente per le Nuove Tecnologie, l'Energia e l'Ambiente) in Italy, IFE (Institutt for Energiteknikk) Norway, and KFA (Forschungszentrum Jülich) in Germany resulted in the SAPHYS (Stand-Alone Small Size Photovoltaic HYdrogen Energy System) project, which ran from July 1994 to June 1997 (Schucan 2000i). The main components, including a 5.6kW PV array, a 51kW lead-acid battery, a 300Nm³ (at 20bar(g)) hydrogen store, a 5kW electrolyser and a 3kW PEM fuel cell, were installed at the ENEA research centre. The electrolyser was an alkaline Metkon-Alyzer Model 0100, which produced hydrogen at 20bar(g), and the fuel cell was made by Ballard. A controllable load was use to simulate the demand of two houses and the system was intended to test the viability of a stand-alone energy installation. The project team claim to have proved the viability of dynamic solar powered electrolysis, although they conceded that further work needed to be done to investigate the long-term effect of intermittency on the device's performance. Efficiency was seen to be reduced due to the electrolyser never reaching optimum temperature and even more by inefficiencies in the DC-DC converter, giving an overall efficiency for hydrogen production of 54.7%. The many ancillary components (e.g. water purification, control PLC and the fuel cell's air compressor) were identified as adding undesirable complexity and cost to the system, increasing losses and reducing reliability, but the benefit of being able to purchase 'off-the-shelf' power electronic devices was noted. The battery's SOC was proven to be an effective parameter on which to base the system control. Analysis of the fuel cell operation over a normal year's supply and demand profile was not possible as, during the test period, the weather was unusually sunny. The view is expressed by the SAPHYS team that a single, reversible fuel cell and electrolyser unit would be
desirable, but this idea fails to take account of the conflicting requirements of optimising both devices that would inevitably demand compromises leading to reduced overall efficiency.

3. c. xi Grimstad Renewable Energy Park, Norway

Opened in June 2000, the Grimstad Renewable Energy Park in Norway has 20kW of photovoltaic power and an 85m² thermal array, which uses four 150m deep boreholes as heat stores and heat sources (Torstein Våland 2003). There is no wind power on site, but a data link to a separate wind installation is used to generate wind power profiles for use in research. A 50kW alkaline electrolyser, made by Norsk Hydro can produce up to 10Nm³/h of hydrogen at 15bar(g) for use in a 2.5kW ZeTek alkaline fuel cell and for tests on small gas turbines. The hydrogen is stored in two 4m³ tanks at 15bar(g). Energy crops are also grown at the site, which is primarily a demonstration project as well as a research centre connected to Agder University College. They claim that useful knowledge has been gained in relation to electrolyser design at high pressures, but further details on this are not provided.

3. c. xii University of Applied Sciences, Stralsund, Germany

The University of Applied Sciences at Stralsund in Germany is a laboratory based multi-source RE system, comprising a 100kW wind turbine, 10kW PV and biomass resources, integrated with an electrolyser, fuel cell, cogeneration unit, catalytic burner and a generator (Menzl - date unknown). The electrolyser is a 20kW Elwatek alkaline one, able to deliver 4Nm³/h of hydrogen at 25bar(g). The gas is stored at this pressure in a 200Nm³ tank, but a two-stage compressor is used for raising the pressure to 300bar(g) for transferring it to bottles. The Electrolyser can be powered from the WTG, PV or mains. The fuel cell is a 0.37kW PEM device (manufacturer not stated) and the Buderus catalytic burner has an output of 2kW. The cogeneration unit can be used to test hydrogen as a fuel, but normally runs on natural gas. This is one of the early projects that showed that dynamically powered electrolysis (using RE inputs) was possible in principle, but the analysis was not subtle enough to reveal some of the problems that this might entail.

3. c. xiii Hydrogen Research Institute, Canada

Similar in many ways to the HARI project, the Hydrogen Research Institute in Canada uses short term (batteries) and long term (hydrogen) storage to balance supply and demand on a stand-alone renewable energy system, although it is on a smaller scale than the one at WBF
The Institute is part of the Université du Québec à Trois-Rivières and has been running since May 2001. The system comprises a 10kw wind turbine, a 1kW PV array, 5kW Stuart Energy alkaline electrolyser with compressor, a 5kW Ballard PEM fuel cell, a 42kWh battery and a 10bar(g) 3.8m³ hydrogen store. Its electrical distribution system is centred on a 48V DC bus, while controllable loads and a power source are used to test the system. Apart from being on a smaller scale and being a low voltage system, it differs from the WBF system in that it is a laboratory installation rather than a real-world application with year-round operation. Much of the research centres on the operation of the power electronics and control methodology. Conflicts arising from both DAQ and control being carried out by the same processor have been identified and this reinforces the strategy of the HARI team of performing the two tasks on separate computers.

3.c.xiv Recent projects

Since the HARI project was instigated, other significant demonstrations of relevance have been launched. A project was launched in April 2004 on the island of Utsira in Norway (Bull-Hansen and Hammerstad 2003), another, on the island of Unst in Scotland, became operational in May 2005 (Gazey 2005), while a third was installed in Patagonia, Argentina, at around the same time (Inter Press Service 2005). Ten households on Utsira are connected to a wind-hydrogen system, which takes its power from one of two 600kW Enercon turbines on the island, while the other turbine exports power to the mainland. The 48kW alkaline electrolyser, made by Norsk Hydro, produces up to 10Nm³/h of hydrogen at 15bar(g). The hydrogen store has a 2400Nm³ capacity at 200bar(g) and electricity is generated from it via a 10kW fuel cell. The PURE project uses two 15kW Proven wind turbines to supply heating loads and to power an Accagen electrolyser on a small industrial estate in Unst. The hydrogen is produced at 50bar(g) pressure and used either in a 5kW Plug Power Gencore fuel cell (like the one at WBF) to generate electricity for heating, or to fuel a Riva electric/fuel cell hybrid vehicle. Few details are available yet about the Patagonian laboratory, but it aims to have enough wind and hydrogen capacity to serve the needs of 500 people by 2008. It is too early for any technical findings from these projects to have been published.

3.c.xv Renewable energy derived hydrogen transport projects

Besides the systems discussed above, there are a number of other projects that differ much more significantly in that they use the hydrogen produced from renewable resources for
transport applications, instead of for stationary power generation. Most notable of these are: the Sunline project (Rips, Clapper et al. - date unknown), Palm Desert project (Schucan 2000g), Clean Air Now (Schucan 2000b) and the Honda refuelling station (Schucan 2000c). These are all solar-hydrogen based transport systems, mainly demonstrating fuel cell fleet vehicles such as buses. The findings of the HARI project suggest that transport applications are far more appropriate for the use of RE-sourced hydrogen than stationary power generation, except in certain niche applications where specific conditions make them more viable. Although this assertion assumes that most will serve a grid balancing role as well as the task of fuel production in a ‘hydrogen economy’, it is recognised that, since such a scenario is still a long way off, this principle will necessarily be compromised in many situations as societies make steps towards truly low carbon energy systems. These examples of transport applications that use RE-generated hydrogen, then, rarely take account of their potential demand-side management role.

3.c.xvi Simulations

Numerous studies that investigated the integration of renewables with hydrogen energy storage were simulations only, with no actual installations of hardware that could be tested in real-world operation. Examples of such studies are: the TRNSYS simulations for solar-hydrogen systems carried out by the Institute for Energy Technology at Kjeller in Norway (Ulleberg and Mørner 1997), modelling of multi-source RE-hydrogen systems at the Politechnic of Turin (Santarelli, Calli et al. 2004), modelling of stand-alone hybrid energy systems at the Sandia National Laboratories (Vosen and Keller 1999), simulation of wind-hydrogen systems, by the Memorial University of Newfoundland (Khan and Iqbal 2005), life-cycle analysis of wind hydrogen systems at the Memorial University of Newfoundland (Khan, Hawboldt et al. 2005), the Hybrid2 simulation of RE-hydrogen systems at the Illinois Institute of Technology (Mills and Al-Hallaj 2004), modelling of RE-hydrogen systems for islands at the University of Zagreb (Duic and da Graca Carvalho 2004) and at Institute for Energy Technology, Norway (Glöckner, Kloed et al. 2002), to name but a small fraction of the total. While very instructive and a necessary precursor to the installation of real systems, these cannot anticipate the wealth of knowledge that can only be gained through the experience of implementing such schemes in the field.
4 System design for West Beacon Farm

4.a Sizing and procurement of HES system components

In advance of this PhD research, a feasibility study had been carried out by the author for an MSc project in 2001 (Gammon 2001). Using data collected on a daily basis by Prof Marmont, plus information contained in a PhD thesis on the WBF system five years previously (Child 1996), estimates were made on the approximate size of the main HES system components. At this time, little was known about the specific performance characteristics of the individual devices involved, the contribution of the battery accumulator was ignored and most of the data was available only as once-per-day measurements. Inevitably, therefore, the results of such a study offered merely a rough guide to the expected component sizes.

The proposed size of the fuel cell was such that it would cover the demand of the electrical system, which had been determined from a daily load profile of WBF (Child 1996), plus an estimation of the electrical demand of the Beacon Energy office. The fuel cell specification proposed was based on the availability of devices at that time. Using the daily supply and demand figures for the WBF electrical system, the size of the hydrogen store was determined by the amount of the gas needed to supply the fuel cell during the longest period of accumulated RE deficit. The same daily data was used to determine the size of electrolyser required to absorb the RE surplus. Although, at first sight, it might seem that the sizes of all these devices should be simply that which is required to meet the maximum demand on each, an analysis of the frequency of such extreme occurrences reveals that they are so rare that it may be more judicious to downsize each. Indeed, using a probabilistic analysis, it emerges that to meet the demands of the system in all but a very few hours in the year, various components can be significantly lower rated than those required to meet every extreme eventuality. Smaller capacity devices are generally less expensive and are likely to have a higher capacity factor (CF) as they will be used more often and at level closer to their rated capacity. This would tend, therefore, to give a better output per unit of cost.

Based on this feasibility study, the proposed fuel cell size would have been 15kW, the hydrogen store would have had a capacity of 2500Nm³ and the electrolyser would have been rated at 39kW. For the purposes of this PhD thesis and the actual implementation of the
scheme, however, a more accurate determination of the system specifications would be needed. In order to achieve this, a data acquisition system was required that would collect data at a much higher resolution. This data could then be applied to software models of the system to predict its performance in such a way that component sizes could be determined with more certainty.

4.a.1 Data Acquisition

The data acquisition (DAQ) system developed for a previous PhD research project (Child 1996) had been installed at WBF five years before the commencement of this work and had fallen out of use. Much of the equipment was not functioning, or was old enough to be obsolete if applied to today's technology. To revive the system, it was decided that the sensors and field wiring should be left in place, but that the data logger should be replaced by industry standard data logging software on a normal PC. The LabVIEW programme and a PCI6527 digital I/O data logging card from National Instruments have therefore been used for this task. The sensors, which measure power flow through various cables in the WBF electrical network, are digital ‘Klikmeters’ made by Sinergy Limited. They send a 120ms pulse to the DAQ card after a given amount of energy, usually 0.01 kWh, has passed along the cable (Figure 4-2). Table 4-1 lists all the parameters measured, but those in brackets were not actually used in this study. The time of each pulse is logged in a data file along with the channel number which identifies which cable it is flowing through. A Matlab programme (see Appendix) converts the difference between these time markers, \( dt \), to a power value, \( P \), at a time midway between \( t_1 \), the time of the first pulse, and \( t_2 \), the time of the second. These timed power readings are then put into a bar chart format, rather than a point-to-point line trace, because they denote power readings averaged across the time period between pulses and so are more accurately represented as such. These power values and times were fed into a Matlab Simulink model that simulated the behaviour of the hydrogen energy storage components (electrolyser, hydrogen store and fuel cell) operating under the measured electrical supply and demand on the system. This is discussed in more detail in Chapter 8. Initially, spurious high values were occasionally obtained for power flows in the network, indicating that the outputs from the wind turbines, or photovoltaic arrays, for example, were many times higher than their maximum rated output. Detailed investigation revealed that the pulses emitted from the Klikmeters would sometimes be followed immediately by a much shorter pulse as shown in Figure 4-5, particularly at higher pulse rates, which would give the
impression that two pulses followed each other in quick succession. Such a very small $\Delta t$ would therefore give a very high power reading. Although it was not established what was causing this effect, it was deemed unnecessary to do so anyway, as a simple filter in the Matlab programme would remove the false pulses. The calibration of the Klikmeters was checked by passing a known power (with current measured by a Tenma clamp meter and voltage with a Fluke voltmeter) through the relevant cable and measuring the time it took for a given number of pulses to be detected. These were also cross referenced with energy meters that are used to monitor accumulated energy flows on a daily basis at the site. Klikmeters that were found to be more than 2% outside their stated value were recalibrated.

<table>
<thead>
<tr>
<th>Digital pulses:</th>
<th>Analogue measurements:</th>
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</thead>
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<tr>
<td>Channel Number</td>
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</tr>
<tr>
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<td>(Grid Export)</td>
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<tr>
<td>2</td>
<td>Wind Turbines</td>
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<td>3</td>
<td>(Battery Charger Input)</td>
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<td>(CHP Electrical Output)</td>
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<td>(CHP Thermal Output)</td>
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<tr>
<td>6</td>
<td>(CHP Fuel)</td>
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<td>7</td>
<td>(Battery Charger Output)</td>
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<td>8</td>
<td>PV Array</td>
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<td>9</td>
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<td>(Battery Discharge)</td>
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<td>(Single Phase Inverter Input)</td>
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<td>(Three Phase Inverter Input)</td>
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<tr>
<td>14</td>
<td>Three Phase Inverter Output</td>
</tr>
<tr>
<td>15</td>
<td>(Spare)</td>
</tr>
</tbody>
</table>

Table 4-1: Parameters monitored by the data acquisition system at West Beacon farm. Items in brackets were not used in this study.

Once the hydrogen energy storage equipment had been installed a second phase of the data acquisition system was implemented. This used a National Instruments PCI6023E analogue card to log weather data and the inputs and outputs of the hydrogen energy storage components (Figure 4-3). Instead of the digital pulses of the first phase of the data acquisition system, this phase produced analogue values for each channel at regular 10s intervals (listed as Analogue measurements in Table 4-1). Figure 4-4 shows the LabVIEW
programme that records both analogue and digital data. Even though the anemometers gave digital pulses, these were detected by the analogue card and converted by the LabVIEW programme into wind speeds. As no meteorological mast was in place at the site, wind speed could not be measured at the hub height of the two wind turbines. Instead, an array of 4 anemometers was attached to the turbine’s tower, such that there was one at low level and one at high level on the side of the tower that was upstream of the prevailing wind and the there was a similar arrangement for the two on the downstream side. Having anemometers on both the upwind and downwind side of the tower allows for the tower’s ‘wind shadow’ effect to be ignored, as the wind direction indicator can be used to decide which pair of wind speed indicators are upwind (and therefore giving a more valid reading) at any given time. In this way, the two wind speed measurements from the upwind side can be used to predict the wind speed at hub height. This is calculated within Matlab, first by using the wind speed differential between the two anemometers to work out the surface roughness in each of twelve wind direction sectors and then to apply these to estimate the wind speed at hub height. The ambient temperature measurement requires two readings as it is calculated from the difference of the voltages across the two channels. The power consumption of the electrolyser is measured by the circuit shown in Figure 4-1 (Wildi 2000) and calculated within LabVIEW using Equation 4-1. All other parameters output by the analogue section of the data acquisition system are direct conversions from the voltages measured across the sensors.

![Figure 4-1: Power measurement of the three phase electrolyser power consumption.](image)

\[ P = (v_a \times i_a) + (v_b \times i_b) \]

Equation 4-1
Figure 4-2: LabVIEW screen for digitally recorded data

Figure 4-3: LabVIEW screen for analogue data
Figure 4-4: LabVIEW data acquisition programme used for monitoring weather conditions, electrical energy and hydrogen flows in the West Beacon Farm system.

The calibration of both current transformers and voltage transducers (see Appendix for manufacturer’s data sheets) were checked by passing known currents and voltages through the wires they were monitoring and comparing them with values recorded by a Tenma clamp meter and a Fluke voltmeter. Adjustments were made in LabVIEW, in the light of these calibration tests, to achieve accuracy within ±5%. In addition to the accuracy limits set out in the manufacturer’s data sheets, the two resistors used in the voltage measuring circuit (see Appendix) must be accounted for. These are rated at 5% for the primary circuit resistor and 0.1% for the secondary circuit resistor.
Calibration of mass flow meters (Brooks Instrument 2000), solarimeters, temperature sensors and pressure transducers all require specialist equipment and test conditions, which are available to their manufacturers but not at this project’s location. In reality, the effect of temperature on the hydrogen store pressure is very complex and it would not enhance the understanding of it or modelling of the system significantly, within the scope of this project, by having a more accurate measurement. The complexity arises from the variable rate of temperature change in different areas of the hydrogen store. Cylinders at the bottom tend to change temperature more slowly than at the top. This is more pronounced when bright sunshine creates a strong thermal effect and is more subtle on cloudier days. The temperature difference in various parts of the store is also greatly affected by the rate of ambient temperature change in response to diurnal and meteorological effects. Without an array of temperature sensors to monitor each cylinder individually, these issues cannot be clarified further. In fact, the quantity of stored hydrogen is better indicated by integration of the hydrogen production and consumption, as measured by the mass flow meters, over time.

Measurements of various parameters within the electrolyser itself are continuously recorded in an Access database file as an optional feature of the Vandenborre electrolyser installation. These include module current and voltage, electrolyte temperature, hydrogen pressure, gas purity, deoxo and drier temperatures, electrolyte levels and the operation of various switches and valves. These data can be recorded at various intervals from 5 seconds upwards. Some other parameters, such as the conversion energy and hydrogen production rate, are also recorded in the database, but these are calculated rather than being measured directly.
The data acquisition and control tasks are broadly, but not entirely, isolated by being performed by two separate computers so as to avoid conflicts and over-stretching either computer. The DAQ programme normally scans at a rate of 1kHz, but this may be increased to 10kHz for short periods of detailed monitoring in specific test runs. These rates are needed because the electrolyser's input power must be sampled at a frequency that reveals the detail of the voltage and current waveforms, particularly since the latter is not a simple sine wave. This sampling speed pushes the processor to its limit, so care must be taken to ensure that its memory does not get overloaded. If the speed of data processing begins to slow down, the computer must be re-booted to clear the memory. Because the analogue DAQ card does not have an in-built memory buffer, it requires that the data is managed by the main processor, which can in turn slow down the processing of data from the digital DAQ card. If this causes a delay of 120ms or more, there is a chance that one of the digital Klikmeter pulses might be lost. The computer allocated the control task is used primarily to switch the electrolyser and fuel cells on and off and to control their power levels, using a custom LabVIEW programme written by Matt Little, however it also runs the 'Vizimet' visualisation software for the electrolyser, shown in Figure 4-6. This programme provides a graphic user interface that allows detailed monitoring and control of the electrolyser and its subsystems, while also sending operational data from the electrolyser to a database file.

Figure 4-6: The 'Vizimet' graphic interface that allows detailed monitoring and control of the electrolyser.
4.a.ii Fuel Cell

High and medium temperature fuel cells were not, in general, considered to be appropriate for this project. MCFC systems on the market tend to be of the 100s of kW scale, as are PAFCs. They are better suited to industrial or commercial installations, where their high temperature heat can be can be made use of. Their start-up times are relatively long, as it takes longer to reach operating temperature than in low temperature systems and, those systems that are available, are designed to run on natural gas. Most SOFC devices are inappropriate to this project for much the same reasons, although there are some available at much smaller sizes. It is the low temperature, highly responsive PEM and AFC units that are generally considered to be suited to the modest scale, highly intermittent regime of a scheme such as that at West Beacon Farm.

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 to find any company that could supply a market-ready fuel cell. Approaches were made to a number of fuel cell manufactures and developers, but only two were prepared to even consider supplying a device for this study. Hydrogenics, the first of these, could only do so on the understanding that significant grant support would be available, as the price for the unit would include a sizable recuperation of their development costs. Intelligent Energy were the other option and even this company may only have been more amenable than most due to its strong connections to Loughborough University and the existing relationships between members of its staff and those involved in the HARI project. Two years later, when a second fuel cell unit was to be installed at West Beacon Farm, things had already progressed to the extent that one phone call to a supplier and system integrator that had by now become established in the UK, was sufficient to procure a Plug Power unit for commissioning within two weeks (See Appendix for table of potentially applicable fuel cell systems available in early 2004). At the time of placing an order for the original fuel cell unit at West Beacon Farm, however, Intelligent Energy was the only viable choice. This is not to say that it would not have been the preferred choice anyway. Indeed, although fresh out of the laboratory and barely tested in the real world, this was – and still is – considered by many to be one of the leading fuel cell technologies in the world. Its highly compact design (it has a higher power density than any other fuel cell stack) may not have been of prime importance in a stationary power application such as this, but its high efficiency (quoted at \( \approx 50\% \)) certainly was.
Intelligent Energy were only able to provide a unit (illustrated in Figure 4-7) with a 2kW rated output and so, as the preliminary feasibility study had already suggested that this would be nowhere near large enough, no sizing exercise was carried out ahead of procuring the device. Furthermore, because a radical rationalisation of the electrical distribution system at West Beacon Farm was proposed as a separate part of the HARI project to this study, it would be very difficult to assess with any real accuracy the impact it would have on the amount and pattern of electrical demand on the system. It was hoped that this restructuring would bring about significant efficiency gains, thereby generally lowering the electrical demand on the system, but to try to quantify these improvements was not within the scope of this study. What is clear is that effect of this change would be more apparent to the fuel cell than the electrolyser as it would represent a much higher percentage difference of the latter’s rated output. For the purposes of assessing the electrolyser size, then, this uncertainty was ignored, whereas, had a similar assessment been carried for the fuel cell, it would have been more important to take account of it. At this stage, however, the procurement of any fuel cell device at all was an achievement in itself and there was no choice over its rated capacity. To increase the capacity of power supply from fuel cells at the site would require the installation of further units at a later date, thereby building up the capacity on a modular basis.

Figure 4-7: The Intelligent Energy 2kW PEM fuel cell CHP system installed at West Beacon Farm as first installed. The hot water tank was later replaced with a plate heat exchanger to link it into the heating system. (Source: © 2004 Intelligent Energy)
Half a year after the Intelligent Energy fuel cell was installed at West Beacon Farm, a second one was purchased, but this time it was a 5kW Gencore® unit, pictured in Figure 4-8, made by Plug Power and supplied by SiGen. Again, no accurate sizing assessment was carried out as the range of units on offer was still very limited and, with the addition of this device, the total fuel cell capacity at West Beacon Farm would still fall short of the predicted requirement.

A further fuel cell unit is planned to be added to the system and, on that occasion a proper sizing exercise will need to be undertaken, since this extra device will bring the overall fuel cell capacity up to the required amount. This will take place after the rationalisation of the electrical distribution system has been completed and so an accurate assessment will then be possible.
Of the two fuel cell units currently installed at the site, only the Intelligent Energy one is configured for CHP output. The Plug Power unit is due to be converted from electricity-only output to CHP capability at a later date. At 2kW, the thermal output of the Intelligent Energy appliance is the same as its electrical output. It is actually capable of supplying up to 4kW of electricity for short periods (of around 15 minutes). This is made possible because it is a parallel hybrid system. Most fuel cell systems in the 0.5 - 10kW range are hybrids, because they incorporate some degree of battery storage to cope with quick start-ups and severe transients. The Gencore is a series hybrid, in which the batteries feed the load, while the fuel cell stack keeps the batteries charged. The parallel hybrid system employed by Intelligent Energy’s unit, however, allows the fuel cell to feed the load directly and, for short peaks, both battery and fuel cell to do so, hence giving a peak output twice that of its continuous output.

Unlike the Intelligent Energy fuel cell, which has no load associated with it while it is switched off, the Gencore consumes a small amount of power while on standby. This is because it was originally designed as a UPS system, where security of energy supply far outweighs concerns about efficiency. As such, there are ancillary systems within the unit, such as heaters, control electronics and battery chargers (as the lead acid cells in the unit gradually self-discharge) that draw small amounts of power (estimated to average 100 - 200W) even when the fuel cell itself is switched off. It could be argued that, for this reason, Plug Power’s Gencore system is not well suited to this particular application, but it is a common problem with pioneering endeavours like this that the closest fit, from what technology is available at the time, is often a long way short of ideal. This is not a criticism of the device itself, but simply recognises that, given the limited range of fuel cell products on the market at the time (and another IE fuel cell would not have been available), this seemed like a reasonable choice. Indeed, the subtleties of the system’s operation were neither understood nor discussed to the level of detail where such potential problems would have been raised before its installation. It has emerged, after 1½ years of very low availability, in which only 44 hours of run-time was achieved, that the problem lies with the integration of the power electronics used to manage its output. The Gencore unit has an inbuilt DC-DC converter and battery charger, an external DC-AC converter was needed to condition the power out of the device as well as to maintain charge within its internal batteries, as is typical of a UPS system. Unfortunately, both these converters were too ‘intelligent’ to be compatible with each other as each fought to be the master in what should have been a master-slave relationship. This interaction became highly unstable as their conflicting control algorithms
caused the fuel cell to switch on and off rapidly (i.e. every 30 seconds, or so). This, of course, damaged the cell stack, which was never able to maintain its humidity levels and consequently the stack was so severely damaged that it needed to be replaced. The solution, therefore, would be to replace the external DC-AC converter with a simpler one that does not confuse the control algorithm of the internal DC-DC converter. Since this combination of devices will be rendered obsolete under the new electrical system, this particular route to solving the problem in the short term has not been pursued as the long-term solution will be implemented within a few weeks of the time of writing this thesis.

4.a.iii Hydrogen store

Of the three main categories of hydrogen storage, liquid hydrogen was ruled out at the beginning of the project. The energy cost of the liquefaction system would be too great and the complexity and financial cost of the necessary plant, particularly at this small scale, would be prohibitive.

Storage within metal hydrides would be very attractive for this system as it would significantly reduce the footprint, by comparison with pressurised hydrogen gas and, being stationary, would not suffer from the drawback that hydride stores are very heavy. Unfortunately, metal hydride stores were not commercially available at that time; however plans were put in place for one to be tested at a later date in collaboration with a team of researchers, led by Professor Rex Harris, at the University of Birmingham. In the meantime, the only viable option for this project would be pressurised storage of gaseous hydrogen.

In the early part of this study, attempts were made to find a novel, low-cost means of storing hydrogen. It had been hoped, by the owner of the site, that storage tanks could be placed underground where they would be unobtrusive in this domestic location, but to reduce costs an alternative was sought to a buried standard steel tank. One idea put forward, for example, was that of driving steel tubes into the ground, using a technique known to be effective for other applications, such that the support of the ground surrounding them would provide structural support the tubes, thereby reducing the strength of tube required. Ultimately, this idea appeared unfeasible for a variety of reasons. The amount of support afforded by the surrounding ground, for example, would vary with depth, such that no reduction in wall-thickness of the tubing would be achieved at near the ground surface. It would also be difficult to seal the ends of the tubing, let alone in a way that would reliably contain such a
leaky gas as hydrogen. In considering this and other options, it was necessary to research the effect of storing very pure hydrogen at pressure within containers of a various materials. Hydrogen is known to cause embrittlement to a number of metals under certain conditions and it would be important to establish if the conditions encountered in this project were similar to those that might cause this effect (Han, He et al. 1998). Although little is known about this effect, except in its relation to metal fabrication and treatment processes, it appeared that it would not be a problem at the temperatures and pressures encountered in this setup. It soon became clear that no simple solution would be found to this quest and that, with so much else to deal with on a tight schedule, it would be beyond the scope of this study to investigate the issue further. After discussions with commercial gas suppliers (Linde and BOC), the simple solution of storage in standard cylinders was accepted as a viable option, albeit one that was more visually intrusive than was ideal. Indeed, this could be achieved at a cost that was lower than had been initially anticipated.

The cylinders that were available from BOC were mild steel cylindrical tanks, with a water volume of 0.475m³ each. At 3.7m long and 0.475m in diameter, with a wall thickness of 38mm, they each weigh around 1 tonne. The optimal size of the hydrogen store, as predicted by the initial feasibility study for this project, would be 2500Nm³. To have a store that contained this amount of hydrogen at 25bar(g) would require 202 of these cylinders. It was agreed, therefore, to initially install around ¼ of this number and, after a more accurate assessment of the store’s optimum size had been ascertained through experience gained with the system in actual operation, the full (probably amended) number would be installed. After this had been agreed, the idea of incorporating further compression into the scheme, which had initially been rejected as an extra energy cost that should be avoided, was proposed. This option was taken up on the advice of BOC, who suggested that the energy cost would be modest while the benefit of reduced footprint of the store would be considerable, thus making the pay-off worthwhile. It was by this slightly arbitrary process, therefore, that a final storage capacity of 2856Nm³ would be achieved using 48 cylinders (because they would be stacked in multiples of 4), in which the hydrogen could be compressed at up to 137bar(g). The hydrogen store is shown in Figure 4-9.
4.4.4 Electrolyser

There are not a large number of manufacturers or developers of electrolysers and, of them, there are few that were at the time able to supply commercial units of a size that would be relevant to this project. There has recently been much activity in the industry, with new players coming into the arena and some mergers and acquisitions, but at the time that an electrolyser was being sought for this field-trial, there were only four that were worth considering. These were Teledyne Energy Systems, Stuart Energy Systems, Proton Energy and Vandenborre Hydrogen Systems (now Hydrogenics) and all claimed that their devices were suitable for connection to renewable energy systems.

The main criteria used to choose between these four were output pressure and – most importantly – efficiency. The output pressure was important because, initially, the plan was to avoid having a compressor as this would represent a significant extra load on the system.
that would reduce its overall efficiency. It was intended that the hydrogen be stored at whatever pressure the electrolyser produced it. The higher the output pressure of the electrolyser, therefore, the smaller the volume would be of a given amount of hydrogen stored. Each manufacture quoted an efficiency for their process, usually expressed as a stack efficiency that ignored balance of plant losses. The preferred option, based on these parameters, was the Vandenborre Hydrogen Systems IMET unit, which claimed an output pressure of 25bar(g) and conversion energy quoted at 3.9kWh/Nm³, beating the others on both counts.

Following discussions with Vandenborre, it was possible to construct a software model of the device using the information obtained from them about its performance characteristics. Although this was not as clear a picture as was to be derived later from its real-world performance, it was the best estimate of the size of electrolyser required that was possible at the time. Section 5.e (Electrolyser sizing model design) shows the Matlab Simulink model used for sizing the electrolyser. The conversion efficiency curve was estimated, but subsequent operation of the unit confirmed quite a different one, as shown in section 5.d (Electrolyser model verification). Balance of plant losses were assumed as an average quoted by the manufacturer, although clearly (and as subsequent operational experience confirmed), the true picture would be far more complex than this.

There are two approaches that can be used to define the optimum size of electrolyser for this system: the first would be in terms of capacity factor (Roy 2003 - 2006), whereby the most usage was obtained for a given cost of appliance. This is a common way of establishing the desired rating for a piece of equipment, since it minimises the time that the device is standing idle and maximises the use one gets from it compared to its cost. The second definition tries to achieve the maximum hydrogen production for a given cost, thus minimising the cost per unit of hydrogen. The latter approach was considered to be the most appropriate for this scheme, even though it might lead to the unit being on standby for long periods. Given that this was the chosen route, the model was run with a range of stack sizes, using actual renewable energy supply and electricity demand data for the West Beacon Farm site over a period of a typical windy winter’s day. This period was chosen because, firstly, there was a limited amount of reliable data available at this stage and secondly, because the wind energy (which is the predominant renewable energy source at the site) would be strongest at this time of the year. If the electrolyser were big enough to cope with the wind input from this period
it would be able to cope with any other time of the year and, although wind power might be harvested at any time, its overall contribution at other times would be modest compared to this period. Ideally, though, a whole year – or better still – three to five years’ worth of data would give a more accurate assessment, but given that the information available from Vandenborre was limited and, therefore, so was the accuracy of the model, it was deemed that this exercise would be adequate in the circumstances. There are two electrode sizes available from Vandenborre and so two curves were produced of hydrogen output against the number of cells in the stack: one for the 1000cm² electrodes and one for the 300cm² electrodes. The highest hydrogen yield was achieved by a 44 cell stack, comprised of 1000-Series electrodes (see 5.f Electrolyser sizing model results below). This result was in agreement with John Barton, another member of the research team involved in the HARI project, who used a different Matlab time-stepping model. Modest differences in stack size would produce very little differential in the price of a unit, because the majority of cost is in the complex balance of plant, therefore a decision was made on purely technical, rather than financial, grounds.

After this exercise, it was revealed by Vandenborre that the module would be degraded by excessive on-off cycling, which would reduce its efficiency. They could, it transpired, only guarantee the appliance’s output for up to 2500 on-off cycles, which the models predicted would be reached within two years of installation unless there were radical modifications of the overall system and its control strategy. Since Vandenborre’s customers are usually seeking to meet a demand for hydrogen more-or-less continuously at a given flow rate (with efficiency being only a secondary consideration) the company’s policy was to add a small number of extra cells to ensure this could be guaranteed even if the stack degraded a little. For this reason they advised that two extra cells should be included in the module, even though the operation of the system is driven by very different criteria to almost all Vandenborre’s other customers. A unit with a 46-cell stack was therefore ordered from them. A far more effective strategy for mitigating module degradation caused by intermittency would be to use a battery to reduce the number of switching cycles that the electrolyser would experience. The limited operational range of the electrolyser means that there would be peaks of surplus RE power that were 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.
Figure 4-10: The electrolyser power supply (EPS) unit. 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 some of the power electronics required in the upgrade of the electrical network at West Beacon Farm.

Figure 4-11 (left): Inside the main compartment of electrolyser process unit and Figure 4-12 (right): the deoxo and drier units in the other part of the electrolyser process unit.
4.b Ancillary systems

Although not central to this study, there are a number of ancillary issues that it was necessary to deal with as part of the overall HARI project. Some of these fell under the responsibility of other PhD research students that were part of the project team; however others were overseen by the author of this thesis who, due to the overarching nature of this study, became the de facto team leader and project manager.

4.b.i Batteries

The operational limitations of the electrolyser mean that some form of short-term energy storage is required. There is already a battery accumulator at the West Beacon Farm, consisting of ten lead-acid submarine cells, with an effective capacity of around 120kWh. These are nearing the end of their lifetime and will be 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 will have a capacity of 20kWh and, being able to deliver the required 620V, will be able to connect directly to the DC bus without any DC-DC conversion, whereas the lead acid batteries only deliver 120V. The existing battery capacity is sufficient for providing up to two days’ worth of power at the site (as compared with the HES system’s three weeks’ worth), but the new Zebra battery will be required mainly to moderate the variability of supply to the electrolyser. Further batteries may be added on a modular basis, should this prove necessary, but the models suggest this will be unlikely. Without the Zebra battery, some peaks of power input from the wind turbines could not be absorbed by the electrolyser, but more importantly, the electrolyser would be switching on and off so frequently that its effective lifetime would be drastically reduced.

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 round-trip efficiency of batteries over short periods can be >80%, but charge leakage reduces this efficiency over time, whereas hydrogen – having no standing losses – is more effective at greater timescales. The Zebra battery has a coulombic efficiency of 100%, but maintaining its temperature represents a loss similar to that of more conventional batteries. Although this standing loss is lower than that of a lead-acid battery, it still means that – like any battery – it will eventually become fully discharged, which would ultimately result in a 0% efficiency! That is not to say that the hydrogen method does not
4.b.ii Compressor

It was originally intended that the use of a compressor in this installation should be avoided on the grounds that it would lead to more parasitic losses in the system. Furthermore, it is frequently seen as a being troublesome piece of equipment (Schucan 2000h), that could be obviated by the use of high pressure electrolysis. On the other hand, the practicalities of reducing the size of the plant, while meeting its capacity requirements, became a higher priority than the potential efficiency saving of omitting the compressor, or concerns about its unreliability. Clearly, even with some pressurisation within the electrolyser, in most applications further compression will still be required until electrolysers operating at hundreds of bars of pressure can be successfully developed. It is this thinking that is behind the drive for ever higher electrolyser pressures, but as has been already discussed, this is seen by the HARI project team as being a severe miscalculation (Roy, Watson et al. 2005b). The experience at WBF has been that the compressor is one of the more reliable devices in the HES system. It suffered some malfunctions in the early months of the project, but after initially requiring frequently administered taps with a hammer to coax a stuck valve to work, the compressor has settled into functioning smoothly and reliably. Its efficiency is, however, yet to be analysed.

The compressor chosen for WBF, shown in Figure 4-14, was a Hydro-Pac C03-05-2550LX-V with a compression ratio of 1:8 that can pump up to 11Nm³/h at a feed pressure of 25bar(g). Since the input flow rate into the compressor might be varying between 2 and 8Nm³/h, it was also necessary to put a buffer tank (with a water volume of 37.85 litres) between it and the electrolyser. This means that the compressor is started by a pressure switch when the pressure in the tank reaches 19bar(g) and is switched off by another at around 16bar(g). If the pressure inside the main hydrogen store is lower than the higher of these two set points, the gas will pass directly through the compressor without it running. The compressor consumes 3.75kW of power in operation at its rated conditions.
4. b. iii  Pipework infrastructure

The infrastructure 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. Having many years of experience in managing industrial gases, BOC were in a far better position to deal with the many hazards associated with this scheme than the research team and site owners who were new to this field. This infrastructure, shown in Figure 4-15, consisted mainly of pipework and safety mechanisms associated with hydrogen gas.
4.b.iv Building and layout

A new building, shown in Figure 4-16, 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. There were a few important restrictions to be placed upon the design of the new 'hydrogen building' due to the domestic location of the scheme. Although both residents of West Beacon Farm are environmentalists, it is Mr Marmont that is interested in the technological aspects, while Mrs Marmont is a naturalist who is more concerned about the flora and fauna at the site. Such differing approaches often call for careful compromise and so any structures relating to this project would have to be acceptable to both parties. With this in mind and, given that part of the purpose of the project 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 (i.e. following the line of the garages),
it would need to be built partially underground (Figure 4-17). Normally, a building housing equipment containing an explosive and pressurised gas like hydrogen would need to be constructed in a lightweight manner that would easily release the pressure of a potential explosion. However, being partly underground, this building would need to be constructed of substantial, reinforced concrete walls. Even the roof would have to be of the same construction as it was intended that it have a small garden on top of it. This dichotomy was neatly solved by Jerry Tzeng, the project’s architect (who received an award for work he had previously carried out for Prof Marmont). He proposed that the building be divided into two zones: a safe zone and a hazardous zone. The hazardous zone would be further subdivided into three rooms: one containing the electrolyser, one the fuel cells and the other the compressor, buffer tank, nitrogen cylinders (used for purging the electrolyser and operating the main hydrogen safety shut-off valve) and most of the pipework. These three rooms would have a lightweight skylight (running the length of the building) above them, which would blow out easily if there were a hydrogen explosion within any of the hazardous-zone rooms. The main room, which makes up the non-hazardous area, would not be expected to ever have hydrogen in it. This would be ensured by the passive ventilation mechanism resulting from the building’s layout, which would be reinforced by an active ventilation system that would be called into operation should a leak be detected (Figure 4-18 and Figure 4-19). The hazardous areas are all Ex-2 Explosion Rated, which means that any electrical devices or connections within them must not be able to create any sparks. This also necessitates the separation of the electrolyser’s power supply and control unit (EPS) from the electrolysis process unit, with the former being located in the safe zone while the latter is in a hazardous zone. The hazardous zone has a red coloured floor (the pink shaded area in Figure 4-16) and the safe area a green floor (the green shaded area in Figure 4-16) to emphasis to those using the building what precautions are appropriate while working in each area.
Figure 4-16: Layout of the “hydrogen building” at West Beacon Farm. The pink area is the hazardous zone and the green area the safe zone.

Figure 4-17: Exterior view of the hydrogen building (foreground right hand side), garages (foreground left hand side) and the house (behind) at West Beacon Farm.
Figure 4-18: Passive and active ventilation in the hydrogen building at West Beacon Farm.

Figure 4-19: Air bricks above and behind the water storage tanks, just beneath the skylights, in the electrolyser room of the hydrogen building at West Beacon Farm. These provide passive ventilation.
4.b.v Safety

Safety is of the utmost importance in the design and operation of any system involving a high quality fuel, such as hydrogen. Hydrogen already has a somewhat unfair reputation in the public’s perception for being dangerous, due mainly to the Hindenburg airship disaster and the H-bomb. The fact that the fabric of the Hindenburg’s gas envelope contained a substance not dissimilar to solid rocket fuel and that the people killed in the incident died from falling debris, jumping from too high up, or being doused in burning diesel fuel, is swamped by the concern that hydrogen is a highly combustible gas. Equally, the H-bomb was so named (mainly to distinguish it from the standard atom bomb) because it used deuterium and tritium, which are exotic forms of hydrogen that have little to do with the normal hydrogen under discussion here.

It is true that any high quality fuel is dangerous by definition in some way or other; otherwise it would not be much good as a fuel! Hydrogen, therefore, carries with it certain risks, some of which are worse than with other fuels and some of which are less so. It is difficult to say whether it is more or less dangerous, but it is certainly ‘differently dangerous’ to other fuels (See Appendix for hydrogen safety data sheet). The fact that it is so buoyant is often an advantage when dealing with hydrogen leaks, or that its hot flame is actually not very radiant, whereas its very wide flammable range or its almost invisible flame can be real disadvantages. One classic illustration of the potential safety benefits of using hydrogen as a fuel in vehicles is shown by a video that used to be displayed on the US Department of Energy website (Swain 2001). The clip shows two cars, one with a petrol tank and one with a hydrogen tank, both of which are ruptured and ignited. A jet of flame shoots straight upwards and burns for 2 – 3 minutes from the hydrogen powered car, while the petrol vehicle burns for around ten times as long. Anyone trapped within the passenger compartment of the hydrogen vehicle would have been unaffected by the burning fuel as very little of its heat reached the interior of the car, but the petrol spilt onto the ground and would have caused severe, if not fatal, burns to the car’s occupants if they were unable to escape. Furthermore, recent events witnessed at the Buncefield fuel depot in Hertfordshire, UK (BBC News 2005), would have been very different and, arguably, less damaging and difficult to control had it been a store for pure hydrogen rather than liquid hydrocarbon fuels.
Oxygen, too, is produced in the electrolysis process and has a number of safety risks associated with it. It is highly corrosive and readily reacts (sometimes violently) with many materials. As the oxygen produced in the WBF system is not collected or stored for any purpose, there are few risks relevant to this situation, as long as it is vented carefully to atmosphere (particularly at a safe distance from any hydrogen vent).

Failure to pay enough attention to safety in this project would expose the occupants of West Beacon Farm and other staff and visitors to the site to unacceptable risk as well as threatening to cause a significant setback to the reputation of hydrogen-based energy systems at a particularly vulnerable time in their development. Safety issues were therefore given precedence at every stage of the design, installation and operation of the scheme. The Health and Safety Executive were consulted closely and were involved at all stages of the project, as they too wanted to learn from this groundbreaking field trial, while BOC was given responsibility for overseeing risk assessment and HAZOPs, safety planning and implementation. One of the challenges in the fuel cell and hydrogen industries is to bring what are currently considered industrial processes and substances into domestic and public environments and to develop codes, standards and practices to allow that to happen safely across a range of extremely diverse situations.

Hydrogen and oxygen sensors, supplied by Dräger, have been located in all the hazardous zones and hydrogen sensors in the safe zone of the hydrogen building. Should hydrogen be detected at 10% of its lower explosion limit (LEL), the active ventilation system will be switched on, which – it is hoped – would contain the problem until it can be fixed. If this is not effective and the hydrogen concentration rises to 20% of LEL, all systems within the building will be shut down, depressurised and the gasses vented to atmosphere. Warning lights indicate when it is safe to enter the building. The gas sensors are checked and recalibrated by Dräger engineers every six months. A smoke test has been conducted to test whether the ventilation system in effective. It showed that the passive ventilation works, but there is a small amount of leakage from around the edges of the doors back into the safe area during active ventilation. To remedy this, draft proofing devices are being fitted to the doors.

The electrolyte used in the electrolyser is a 30% (by weight) potassium hydroxide (KOH) solution, which is a strong alkali that is very corrosive to the skin and can cause blindness if it comes in contact with the eyes (See Appendix for potassium hydroxide safety data sheet).
long as it remains sealed within the electrolyser itself, it presents no hazard to personnel at the site, however should it leak, particularly at high temperature (the optimal stack temperature being around 60 – 70°C) or pressure (up to 25bar(g)), it could be very dangerous. Normally, therefore, only trained personnel, wearing the appropriate protective gear (safety goggles or visor, gloves, boots and apron) are allowed to be in the electrolyser room with the cabinet doors open when it is running, however additional acrylic safety screens were fitted to the electrolyser to enable the interior of the unit to be visible to visitors. Eye baths and a shower are also provided in the building for use in case of an emergency. Since it has become necessary during this project to carry out repairs and maintenance on parts of the electrolyser containing electrolyte, experience 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 4-20.

Figure 4-20: Safety-ware being used by members of the HARI project team while handling potassium hydroxide electrolyte at West Beacon Farm.
The other major safety risk comes from the use of electricity on the site. Three phase power is supplied to the electrolyser's EPS unit, which in itself is more hazardous than normal domestic single phase power, and it is converted to DC power at around 75 – 80V and up to 440A. The electrical distribution network for the site has at its heart a DC bus bar that operates at voltages between 560 and 800. All these, of course, would only be accessible to trained personnel.

All these hazards demand that clear and specific warning signs are displayed in all relevant areas, that only authorised personnel have access to certain areas and that 'hot works' forms are signed by visiting engineers to ensure that they are aware of the specific hazards and take the necessary precautions.

4.b.vi Electrical distribution system with 600V DC bus

The electrical distribution network for West Beacon Farm and the Beacon Energy offices has evolved over several 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 ask the question "If one were to build this system 'from the ground up' today, what would it ideally be like?". The answer to this question provides the basis for the design of a rationalised electrical system, illustrated in Figure 4-4, that is being implemented as part of the project, not by the author of this thesis, but by a Matthew Little, PhD student colleague on the team (Little, Thomson et al. 2005). The new network will be centred around a 600V (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. These are used to connect individual loads or groups of loads and AC power sources to the DC bus. However there are DC power sources (e.g. fuel cells, batteries and solar PV) for which a DC/DC converter design has been developed in-house. Several of these are being built so that they can be used on a modular basis to serve these different sized DC devices. The electrolyser stack itself is a DC load but it would require a radical redesign of the off-the-shelf device to bypass its standard AC input configuration and, even if this were done, the conversion of the DC power from the bus level to that required (at varying levels) by the stack would be complex, time consuming and expensive and would still involve some AC step in the process. A DC-AC inverter will, therefore, be used to connect the electrolyser to the DC bus.
4.b.vii Off-grid wind turbines

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 (except for a few small-scale devices) rely upon the grid to provide the electromagnetic excitation of induction generators as well as to provide synchronisation with the network. Ironically, this means that if there is a power cut on the grid during a windy period, no electricity can be generated by the wind turbines, in spite of the ample supply of wind energy, as there is no support being given by the grid. However, in the situation at West Beacon Farm (and potentially many other locations), they will be required to 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', such that it would appear to them that they are indeed connected to a grid (Kemsley 2002). This is done by converting the power supplied from the DC bus to an AC input to the turbines using a standard converter with some minor modifications to its control. This will also allow the turbines to run at variable speed in order to capture more power at lower wind speeds. This technique demonstrates a widely applicable method for running WTGs on stand-alone energy systems.
4.b.viii Thermal management

There are some material losses in the system, such as vented hydrogen from the electrolyser or waste water from the reverse osmosis unit, but most energy losses manifest themselves as waste heat. Judicious thermal management measures can therefore be employed to increase the overall efficiency of the system. The Intelligent Energy fuel cell unit is configured for CHP output and it is planned that the Plug Power Gencore unit will be converted to CHP operation too. The former will provide a thermal output of around 2kW to raise its quoted 50% electrical efficiency to an overall efficiency of more than 90%. 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). In fact any device that features a water cooling loop as standard can easily be converted to dispose of its ‘waste’ heat in a useful manner. With its in-built water cooling loop, therefore, the compressor can also provide useful heat. It is proposed that a phase-change heat store will be installed at West Beacon Farm to store the heat output from all the aforementioned devices so that the heat can 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. The separator tanks, cell stack and interlinking pipework within the electrolyser cabinet can be thermally lagged to reduce the heat lost when on standby. In normal industrial operation, the heat must be removed from the continuous exothermic reaction, but since the operation is far from continuous in this particular situation, the temperature rarely reaches its optimal level and therefore heat rarely needs to be removed from the vessels. In continuous operation the emphasis is on preventing overheating, but in intermittent operation the emphasis is on reaching the most efficient temperature as quickly as possible upon start-up. Again, within the electrolyser’s power supply unit, there is a need to cool the transformers, power electronics and control circuitry, however these are rarely in danger of overheating in intermittent operation. Putting thermostatic control on the fans that cool the electrical equipment in the cabinet, which normally run permanently, will save the energy wasted on their unnecessarily use.

4.c System costs

Table 4-2 shows the indicative cost of components in the hydrogen and RE system at WBF. The Intelligent Energy fuel cell and the hydrogen storage cylinders are leased, but the rest
have been purchased. The cost indicated 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 include shown include VAT, but no
discounted terms that may have been applied.

There are two main reasons why no further economic analysis or modelling has been
undertaken for this study. The first is that there was simply not enough time and the second
is that it is too early in the development of some of these technologies to make realistic cost
projections for the future.

The first and most important task in understanding these systems and their practical
application is a technical one. This thesis must answer the simple question: “Do these
systems work and, if so, how well?” Questions that follow, but which lie outside the scope of
this thesis, might be: “Now that the system is proved to work, how much will it cost?”,”Now
that it has been proven on a small scale, what are the implications of a significant scale up?”
and “How will financial considerations affect the direction that future development of such
systems might take?”. An analysis, for example, of the relative capital costs, capacity factor,
and resultant payback times of the relevant technologies (and those they compete with),
would be a worthwhile undertaking. Where some technologies are still pre-commercial, it
might be assumed that their costs will fall dramatically in order to reach a commercial
market. What this project already reveals, however, is that the current path taken by some
manufacturers is unlikely to result in a successful commercial product and that getting the
fundamentals of operation must be tackled before working out how to make the device
commercially viable. This is not to say that economic analysis is meaningless or worthless at
this stage, it is just that it the technical questions must be answered first and time does not
allow the consequent priority of financial considerations to be tackled within this study.
<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Manufacturer/Supplier/Model Designation</th>
<th>Rated Performance</th>
<th>Indicative Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyser</td>
<td>Hydrogenics (formerly, Stuart Energy Europe and Vandenborre Hydrogen Systems)</td>
<td>8Nm³/h of H₂, 34kW, 25bar(g)</td>
<td>143,000</td>
</tr>
<tr>
<td>Fuel Cell (1)</td>
<td>Intelligent Energy, CHP Unit</td>
<td>2kW Electrical, 2kW Thermal, 24V DC</td>
<td>25,000</td>
</tr>
<tr>
<td>Fuel Cell (2)</td>
<td>Plug Power GenCore® supplied by SiGen Ltd.</td>
<td>5kW Electrical, 48V DC</td>
<td>20,000</td>
</tr>
<tr>
<td>H₂ Compressor and Infrastructure</td>
<td>Pipework, valves, fittings and Hydro-Pac compressor supplied by BOC</td>
<td>11Nm³/hour, 3.75kW, 8:1 compression ratio</td>
<td>59,000</td>
</tr>
<tr>
<td>H₂ Storage</td>
<td>Supplied by BOC</td>
<td>48 cylinders (0.475m³ each) 137bar(g) Max pressure, 2856Nm³ total H₂ capacity</td>
<td>112,000</td>
</tr>
<tr>
<td>Wind Turbines</td>
<td>Carter Wind Turbines</td>
<td>2 x 25kW two bladed stall-regulated, pitch over-speed.</td>
<td>50,000</td>
</tr>
<tr>
<td>Solar PV</td>
<td>BP</td>
<td>13kW total, mixed polycrystalline and monocrystalline</td>
<td>60,000</td>
</tr>
<tr>
<td>Hydro-electric</td>
<td>Installed by Dulas</td>
<td>850W Cross-flow (2m head) 2.2kW Turgo (25m 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>
<tr>
<td>TOTEM (CHP engine)</td>
<td>Fiat</td>
<td>LPG fuelled CHP system, 15kW electrical, 38kW thermal</td>
<td>5,000</td>
</tr>
<tr>
<td>Zebra Batteries</td>
<td>Beta Batteries</td>
<td>32Ah, 640V DC nominal</td>
<td>20,000</td>
</tr>
<tr>
<td>Lead Acid Batteries</td>
<td>SEC Industrial Battery Co.</td>
<td>1296Ah, 120V DC nominal</td>
<td>19,000</td>
</tr>
<tr>
<td>DAQ System</td>
<td>National Instruments and Loughborough university</td>
<td>National Instruments DAQ cards, LabVIEW software</td>
<td>1,000</td>
</tr>
<tr>
<td>Total system</td>
<td>-</td>
<td>-</td>
<td>630,000</td>
</tr>
</tbody>
</table>

Table 4-2: Indicative costs of existing and new components in the HARI project.
5 Modelling of the WBF system and subsystems

5.1 Renewable energy model design

Meteorological information was collected by the 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 (see Appendix).

Wind speed measurements at two different heights below the hub height of the turbines are used to calculate what the wind speed (in m/s) should be at the hub height itself using the 'log law' equation (Equation 5-1) (Infield 2000), where $U(z)$ is the wind speed at hub height, $z$ is the hub height, $z_1$ is a reference height, $U(z_1)$ is the wind speed measured at the reference height and $z_0$ is the surface roughness length (in m). All heights are in metres.

$$U(z) = U(z_1) \left[ \frac{\ln(z/z_0)}{\ln(z_1/z_0)} \right]$$

Equation 5-1

First, by rearranging this to obtain Equation 5-2, the surface roughness length, $z_0$, can be calculated, where $U(z_{hi})$ is the wind speed measured at height $z_{hi}$ and $U(z_{lo})$ is the wind speed measured at height $z_{lo}$.

$$z_0 = \exp \left[ \frac{U(z_{hi}) \ln z_{lo} - U(z_{lo}) \ln z_{hi}}{U(z_{hi}) - U(z_{lo})} \right]$$

Equation 5-2

This is done for each of 12 direction sectors, to take account of the different topology in each direction, and is a one-time calculation. A surface roughness length appropriate to the wind direction, measured simultaneously with the wind speeds at the two heights, is then applied to Equation 5-1 to calculate the wind speed at hub height. Finally, the wind turbine's power curve (Child 1996) is used to convert the hub-height wind speeds into power outputs.
Table 5-1 shows the heights of the anemometers and the WTG's hubs. Table 5-2 shows the surface roughness lengths for the 12 direction sectors. Measurements were used from the two anemometers that are downwind of the prevailing winds for direction sectors 1 – 6 and the upwind anemometers for sectors 7 – 12. Typically, surface roughness lengths for the type of landscape found at WBF are assumed to be between 1 and 3 metres, due to features that could cause surface friction and turbulence such as trees hedges walls, buildings and the local topography (Lawson 2002), so the values obtained here fit well within such predictions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 5-1</td>
<td>Equation 5-2</td>
</tr>
<tr>
<td>Hub height</td>
<td>Z</td>
</tr>
<tr>
<td>High level anemometer</td>
<td>Z_h</td>
</tr>
<tr>
<td>Low level anemometer</td>
<td>Z_lo</td>
</tr>
</tbody>
</table>

Table 5-1: Anemometer heights

<table>
<thead>
<tr>
<th>Sector number</th>
<th>Bearing (° from North)</th>
<th>Surface roughness length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-30</td>
<td>1.9401</td>
</tr>
<tr>
<td>2</td>
<td>30-60</td>
<td>1.8976</td>
</tr>
<tr>
<td>3</td>
<td>60-90</td>
<td>1.933</td>
</tr>
<tr>
<td>4</td>
<td>90-120</td>
<td>1.8986</td>
</tr>
<tr>
<td>5</td>
<td>120-150</td>
<td>1.9797</td>
</tr>
<tr>
<td>6</td>
<td>150-180</td>
<td>1.9787</td>
</tr>
<tr>
<td>7</td>
<td>180-210</td>
<td>2.0319</td>
</tr>
<tr>
<td>8</td>
<td>210-240</td>
<td>1.9159</td>
</tr>
<tr>
<td>9</td>
<td>240-270</td>
<td>1.8677</td>
</tr>
<tr>
<td>10</td>
<td>270-300</td>
<td>1.8465</td>
</tr>
<tr>
<td>11</td>
<td>300-330</td>
<td>1.8132</td>
</tr>
<tr>
<td>12</td>
<td>330-360</td>
<td>1.8804</td>
</tr>
</tbody>
</table>

Table 5-2: Surface roughness values for different directions

The solar irradiance readings measured by the in-plane solarimeters are used to predict the power generated by the PV arrays. The efficiency of a solar cell varies according to how close it is to standard test conditions (STC) (Child 1996) and so, as well as the simple scaling of the output in relation to irradiance, this change in efficiency is also factored in. Using Equation 5-3, some additional adjustment is made for ambient temperature, where $P_{PV}$ is the
actual power generated by the photovoltaic array, $P_{PV_{nom}}$ is the power it would generate at STC, $\theta_{PV}$ is the ambient temperature and $\theta_{PV_{nom}}$ is the temperature at STC. Normally, $\theta_{PV}$ would be the temperature of the PV module itself, but since this measurement was not available, the ambient temperature reading was used. Although far less than ideal, this at least it goes part of the way towards compensating for thermal effects, which is better than no adjustment at all. No inverter was included in this model, because on the WBF system the PV arrays feed directly to the 120V DC battery bus bar. However, conversion losses are accounted for in the overall system model, which describes the electrical distribution network at the site as it will be when the HARI project is complete rather than as it is now.

$$P_{PV} = P_{PV_{nom}} \left[1 - 0.004 \left(\theta_{PV} - \theta_{PV_{nom}}\right)\right]$$

Equation 5-3

Although hydro electricity is generated at WBF, it has not been included in this modelling exercise yet, however there are plans to include it at a later date. There are two reasons for its omission: firstly, its contribution to the overall energy harvest at the site is relatively small and secondly, sensors have not yet been fitted to the cables carrying its output, although they will be added during the electrical system upgrade. To incorporate the hydro electric model into the system, in the same way the wind and solar resources are, will also require rainfall measurements and analysis of the dynamics of the reservoir (i.e. the lake) and its feed-water sources (i.e. rainwater run-off from Beacon Hill and the water pumped up from a borehole). This would allow its output to be predicted from measurement of local weather conditions in the same way that the other two RE sources are assessed. This in itself is a considerable modelling task, which time does not allow being included in the study and, since the aim is to develop a model that is widely applicable, it was considered that the two most important RE sources to model for this purpose would be the wind and solar resources.

The other energy source at the site that is left out of this modelling exercise is the Totem CHP unit. Once the electrical system upgrade is complete, a model of the overall energy system at WBF can be verified, but since it will not be ready in time for the completion of this study, the Totem — like the hydro turbines — will be omitted from the model.
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5. b Renewable energy model results

The verification of the RE models was carried out over a period of 44 days, from 7\textsuperscript{th} June 2005 to 20\textsuperscript{th} July 2005 and simple Simulink routines (Figure 5-1 & Figure 5-2) were used to compare the results predicted by the models with measured values of RE output.

The accumulated output of the wind turbines over this period that was predicted by the model is 1333kWh, which is 68% higher than the measured output of 792kWh. From the graph in Figure 5-3, it is clear that this is in no small part due to a difference in the switching on of the wind turbines in reality compared to the model. The wind turbines have been at WBF for 18 years and their design, and much of the technology in them, is even older. It would not be surprising, therefore, if both the control electronics and some of the mechanical elements of the WTGs were to have become less efficient and reliable in recent years. However, the turbines are rigorously repaired and maintained, with worn parts being carefully repaired or replaced as new ones are needed, so there has been very little mechanical degradation of the
devices over time. In recent months, however, problems have been encountered with the control gear and this is clearly reflected in the comparison of actual wind power output achieved with that predicted by the model. There are times when there is a high enough wind speed for the turbines to start generating, but due to problems with their controllers, either one or both of them have not. From the graph of accumulated output, it is apparent that, for the first 11½ days (~1x10^6 seconds), the controllers are working well and the turbines are generating very much as predicted. Figure 5-4 shows a 5¾ day period (from 5x10^5 to 1x10^6 seconds) where the predicted and measured outputs agree very closely, with any slight variation largely attributable to the controller not switching the turbines on and off entirely as predicted.

Figure 5-3: Unadjusted wind model results comparing wind power predicted from weather monitoring (yellow) with measured wind power output (magenta).
During the rest of the test period, it appears that both turbines often fail to switch on during periods of moderate wind speed and, even when some wind power is being generated, it is only being produced by one turbine (as the gradient of the accumulated output is about half what it should be). The validity of this assumption can be tested by setting the model to predict the output from only one turbine, as shown in Figure 5-5. Here, it can be seen that, in the last 1¾ days (=1.5x10^6 seconds) of the test period, the lines of predicted and actual output do indeed agree very closely.
Figure 5-5: Wind model results comparing wind power predicted from weather monitoring (yellow) with measured wind power output (magenta). The output predicted from one turbine fits with the measured output at points where the controller works properly.

Once the new electrical system at WBF has been completed, the turbines will be controlled by new power electronic devices, which – it is assumed – will make their operation far more reliable. Based on this assumption, therefore, no adjustment needs to be made to the model to predict the future wind energy harvest. On the other hand, changes in the turbines’ efficiency (once they have been measured) will have to be taken account of, because the new power electronic controllers will also allow them to operate at variable speeds.

Graphs of the verification of the PV model, covering the same period as was used for the wind model, are shown in Figure 5-6. It has been necessary to include a correction factor (see ‘Adjustment’ block in the Simulink programme) as the measured output was only 91% of that predicted by the model. There are a number of possible causes that this might be attributable to. Firstly, there is bound to be some degradation to the PV arrays over the years that they have been installed at WBF. Some of this is caused by ageing of the cells themselves and some by the accumulation of dirt on them. There are at least two ‘hot spots’ visible on the arrays where individual cells have, for some reason, burnt out. This reduces the output of the damaged cell itself and also causes mismatch losses in the rest of its string. Mismatch effects, caused by slight incompatibilities in the two types of cells used, will also arise from the combination of the two sub-arrays, because one is comprised of
monocrystaline cells and the other of polycrystalline. This leads to a slight reduction in their overall combined output. Another loss of efficiency in the system arises from the lack of a maximum power point tracker (MPPT) in the PV system at WBF. In the early days of the installation, one was fitted, but was subject to reliability problems, so it was removed. Advances in the electronics for such devices means that a new MPPT is likely to benefit this system and one is indeed being fitted as part of the electrical system upgrade. In the meantime, however, the predicted output from this PV array is bound to be a little higher than will be actually achieved without the MPPT.

![Figure 5-6: Photovoltaic model results comparing solar power predicted from weather monitoring (yellow) with measured wind PV output (magenta).](image)

There are two ways in which the DAQ system itself is currently less than ideal, although these will be remedied shortly. The first of these is that no temperature measurement is obtained for the PV cells themselves, only the ambient temperature of the air nearby is recorded. Although there is free movement of the air around the arrays that will help cool them, they are still likely to be well above ambient on sunny days and cell temperature will affect their output. The second slight deficiency of the DAQ system for the photovoltaic area is that the irradiance sensors are positioned at one end of the array. This means that the shading of a tree in early morning gives the sensors a low reading, while most of the array is already experiencing good exposure to the sun. Conversely, in late afternoon, much of the
array is shaded by trees on the other side of the array, but the sensor is still receiving unimpeded sunlight. During the middle of the day, however, which is the most important part (because the sunlight is at its strongest), the correlation between the sensors and the array is good. It can be seen from Figure 5-7 that the shading effects at either end of the day also tend to cancel each other out over time. The repositioning of the irradiance sensors and the addition of temperature measurement for the cells, due to be implemented shortly, will reduce these sources of inaccuracy significantly.

![Figure 5-7: Photovoltaic model results comparing solar power predicted from weather monitoring (yellow) with measured wind PV output (magenta) showing how shading discrepancies tend to cancel each other out over the day.](image)

Given the issues discussed, the accuracy of the model is within acceptable limits. Without the correction factor now incorporated into the model, the predicted energy accumulated over the sample period would be 624.9kWh, which is 9.9% higher than the measured amount of 568.8kWh. With the anticipated improvements in data acquisition and the electrical system, it is only mismatch and ageing effects that will continue to reduce the theoretical efficiency of the PV system at WBF. This means that the correction factor that reduces the model's predicted output to 91% of its unadjusted level, may be reduced in the future.
5.c Electrolyser verification model design

A test run was carried out on 26th September 2005 to validate the software model of the electrolyser. The unit was controlled manually for 1¼ hours, to ensure that a range of power levels were tested and that its optimal temperature was reached, and then it was left to run automatically in response to energy supply and demand on the system for a further 7½ hours. Figure 5-8 shows the Simulink model derived as a result of this test run.

Figure 5-8: Simulink model used in the electrolyser verification exercise.

5.c.i Rectifier and other electrical losses

The main electrical losses in the electrolyser are from the rectifier, while much smaller losses are associated with control, monitoring, safety, thermal management and other ancillary systems. To quantify these losses, module power consumption is subtracted from the overall power demand of the electrolyser unit.

The DC power being fed to the module is measured directly within the electrolyser as knowing both current and voltage levels of the cell stack is vital to the control and management of the system. At the same time, the 3-phase power being supplied to the EPS, which feeds the whole electrolyser unit, is monitored by the LabVIEW DAQ system. The data was gathered at 1s intervals as the test run proceeded, but was averaged over 20s to improve synchronisation between the data sets produced by the two DAQ programmes and to
smooth out the short-term (< 3s) time lag between current and voltage response of the module. The data was then sorted in order of ascending module power values to show the corresponding power level demanded by the whole electrolyser system. In spite of this, there is still a wide scattering of the data and it is not yet clear what caused such variation. It is likely that the answer lies predominantly in the performance of the power conditioning rather than in the more minor BOP components.

The difference between these two power measurements represents all the balance of plant (BOP) loads (Figure 5-9) and so, to differentiate between what is included in the total electrolyser power consumption and what is not, it is important to know which intermittently operated components are operational at the time a power measurement is made. However, it would be extremely difficult and — for the purposes of this study — entirely unnecessary to monitor every valve and minor circuit in the BOP. Over the period of a test run, an average BOP power is sufficient to cover all these, with the exception of one component: the drier. Because the regeneration of the drier consumes ≈1kW for a period of 5 hours with a gap of at least 23 hours of electrolyser run-time in between, it is unlikely to be averaged over a typical test run. In this case, therefore, it is important to know the status of the drier during any test run and to account for it separately within the software model.

In the test carried out on the 26th October 2005, the drier’s heater was not operational and so the BOP power measured was a good representation of typical running conditions. The deoxo unit, which also consumes ≈1kW, was switching on for brief periods, which would have had a significant effect on the instantaneous power measurements, but amounted to relatively small energy consumption over time. In effect, then, the major electrical loss observed would have been due to inefficiencies in the power electronics of the AC to DC conversion. This ranged from about 2.5kW at low power inputs up to about 5kW at rated power, equating to 28% and 11% of the total power input respectively. Typically, the AC/DC conversion process would be expected to be around 90% efficient (Divisek and Emonts 2003), but this could be anything up to 98%, for the best converters, (Control Techniques 2005) at a device’s rated power, with efficiencies falling at part load. This confirms that almost all (≈90%) of the BOP losses are taken up by this process.
5.c.ii Deoxo and drier losses

After 225 m³ H2 has passed through the drier, the silica bed is saturated and cannot absorb any more water. It therefore needs to be regenerated and this requires that it is heated up to drive out the absorbed moisture. In the meantime, the other drier is used to dry the hydrogen being produced by the electrolyser. The drying task is thus alternated between the two driers, such that, while one is being regenerated, the other is operational (Vandenborre Hydrogen Systems 2003).

The regeneration process begins with the depressurisation of the drier. Having a volume of 0.06 m³ (Roy 2005b) and operating at 20 bar(g) pressure, this means that 0.06 x 20 = 1.2 m³ of hydrogen is lost each time.

The total regeneration process takes approximately 12 hours. Throughout this process a flow of gas is required to carry the desorbed moisture out of the drier vessel. For this purpose about 10% of the hydrogen produced at rated output is used (i.e. 0.8 m³/h) (Roy 2005a). This amounts to 0.8 x 12 = 9.6 m³ for the regeneration of each drier.
Adding these two together, a total volume of 10.2 m$^3$ of hydrogen is lost. This equates to 4.53% of the total hydrogen production. There are no gas losses associated with the deoxo unit.

The deoxo unit and the driers each consume 1.058 kW of electrical power while they are switched on. For the driers, this is a period of about 5 hours during each regeneration process, equating to 5.29 kWh consumed for each 225 m$^3$ of hydrogen produced, or 0.0235 kWh/m$^3$.

The precise amount of electrical energy that the deoxo unit consumes over time has not been measured separately. It is, however, incorporated into the total power consumed by the electrolyser during the validation test run and is averaged over time along with the other electrical BOP losses (excluding the driers, which were dealt with separately).

During the 26th September 2005 test run, one of the driers was part-way through the regeneration process. It was not being heated, but was venting hydrogen, which means that the software modelling of that period needed to omit the 1.085 kW power of the heater but include the 0.8 m$^3$/h hydrogen loss. For general, longer term modelling, though, these should be incorporated as averaged values of 0.0235 kWh/m$^3$ and 4.53% of the hydrogen produced respectively.

5.c.iii Module conversion energy

The conversion energy (or 'specific consumption' as it is known by Hydrogenics) is calculated by the unit's controller and recorded in the Access database. By running the unit, this has been confirmed as an accurate predictor of hydrogen output from the module; however it does not reflect the hydrogen output from the overall system as there are losses associated with the BOP that must also be accounted for. It is because of these that other methods of predicting the output (such as trying to fit a curve to the plot of hydrogen production against module power) have proved less accurate. Using the Hydrogenics database, the conversion energy can be predicted from an almost linear relationship with the module current (Figure 5-10). The average cell voltage can also be obtained by fitting a curve to the plot of voltage against current measured during the test run (Figure 5-11). In this way, everything can be derived from the one parameter that is used to control the electrolyser: the module current. Correlating the voltage to the current by this method also
has the advantage that it takes into account the condition of the module itself. A side effect of the intermittent operation of the electrolyser at WBF is that the cell stack has degraded slightly. This manifests itself as a rise in cell voltage for a given current, which means that an assessment of the conversion energy should take account of this. The conversion energy value is related to the module power in the model, as is the system power, and used to predict the hydrogen production rate.

![Conversion energy relative to current density](image)

**Figure 5-10:** Conversion energy relative to current density.

The effect of temperature and many other subtleties of electrolysis (such as leakage current, pressure effects, bubble removal, etc) are beyond the scope of this study, but are being studied in detail by Amitava Roy, who is also working on the WBF system (Roy 2003 - 2006; Roy, Watson et al. 2005a; Roy, Watson et al. 2005b). These are likely to have effects on the system efficiency of a few percent over the timescales of this logistical modelling exercise. For the 26th September 2005 test run, the temperature, which is the most significant of the aforementioned parameters, climbed from ambient at the beginning of the test period to optimal by the end of the manual operation. It remained within the optimum zone throughout the automatically controlled period, thus the electrolyser spent 80% of the test period at
optimal temperature. Because the electrolyser has been seen to spend a good deal less time at this temperature in normal operation, the model may slightly overestimate, by a few percent (<5%), the average efficiency and, therefore, the hydrogen output predicted.

Another criterion that will have affected the predicted conversion energy on the date of the test run is the concentration of the electrolyte. Normally its concentration should be at 30% KOH by volume, however due to a leak in the module this level had fallen to 21%. The effect of this is expected to reduce the hydrogen output by 2-3% (Roy 2005a).

5.d Electrolyser model verification

The graphs in Figure 5-12 show how the model predicted an accumulated hydrogen production value that was 4.9% higher than that which was measured by the mass flow meters. This is entirely within the ±6% margin of error allowed for in the power measurement, on top of which there may be an additional inaccuracy of up to ±0.7% in the mass flow meters. Some inaccuracy is to be expected from the combined effects of deviation from optimum thermal conditions during part of the test run, the reduced electrolyte
concentration and the degradation of the cell stack. A small correction factor could be introduced into the conversion energy to account for the effect of stack degradation, as this is a permanent feature of the system (which, thankfully, appears to have stabilised after 1½ years’ operation) (Roy, Watson et al. 2005a). The electrolyte concentration can be ignored as repairs that are currently underway will eliminate this inaccuracy. The thermal effects must be ignored in this model, because to incorporate them would introduce a whole new level of complexity that would be inappropriate to this type of logistical model and would only be of minor significance to the end result.

Figure 5-12: Electrolyser performance predicted by the Simulink model (yellow) 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.

The predicted pressure rise in the hydrogen store is far less accurate, showing a predicted pressure rise of 1.59bar, which is 11% below the measured value of 1.78bar(g), but given the complexities and uncertainties encountered in measuring the store’s temperature (Barton 2005), this is also not surprising. Furthermore, in all the calculations relating to this model, hydrogen is treated as an ideal gas, because its behaviour deviates only slightly from one. Greater accuracy would be achieved (of the order of 1-1.5%) if this approximation was removed and the gas was modelled in finer detail. For these reasons, it is not advisable to use the store pressure as anything more than a rough guide to the amount of gas stored. It is far
better, where practicable, to calculate this by integrating the hydrogen production and consumption rates (as measured by the mass flow meters) over time, to get an accurate value. In terms of the absolute pressure measurement, in contrast to the change in pressure ($\Delta P$), the accuracy is within 1.5%.

Measured data, rather than purely theoretical calculations, were used to derive the predicted power consumption of the electrolyser. This approach was taken due to the complex nature of the BOP in the unit. To theoretically quantify each load and its duty cycle is well outside the scope of this project. The total power consumed by the whole electrolyser is therefore measured directly, as is that of the module (which the control system requires by default). Both are related by curves that fit the measured data to the one controllable input to the system: the current density set point. Although these curves were fitted to data points with a fair amount of scatter, it has been possible to do so with a good degree of success. The accuracy with which the model predicts the accumulated energy use is, consequently, as close as 1.1% from the measured amount, which is seen in Figure 5-13. This is smaller than the ±6.1% margin of error allowed for in the measuring devices, such as current transformers and voltage transducers.

The conversion energy of the module was found to be 4.38 kWh/Nm³, which is 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 combined effects of not being at optimum thermal conditions during part of the test run, the reduced electrolyte concentration and the degradation of the cell stack will have reduced this efficiency in this validation test run of the electrolyser at WBF.
5. e Electrolyser sizing model design

The Hydrogenics electrolyser module can be constructed with a different number of cells in it to give a different power consumption rating (or hydrogen output rating) to the device. An electrolyser sizing model, which incorporated a conversion energy curve estimated by Amitava Roy (Roy 2003), was therefore designed to determine what would be the optimum number of cells in the unit to be purchased for WBF.

Because the electrolyser can only generate hydrogen at 20 – 100% of its rated level, it is not possible to have one that covers the full range of expected inputs in a dynamically powered situation such as this. It might be possible to have an electrolyser that absorbed the maximum predicted surplus energy, but it would not be able to absorb the lower levels expected, which form the bulk of the input. Likewise, if it were designed to cover more of the lower power levels (and even this range could not go all the way to zero), it would be too small to take the peaks. In other words, there is an optimum range somewhere in between, where some peaks are not absorbed and some low level inputs are also lost. Finding the highest hydrogen production over time, therefore, is a way of locating this optimum range.
This is not the only way of making a judgement over the device's ideal size, however. It may be considered that the best return on one's investment is to get the most possible use out of the appliance, thus the size that gives the longest run time, or highest capacity factor, might be the best option. If so, the module size might be smaller, as the most frequent power input levels are relatively low (Roy 2003 - 2006). Another approach might be to base the decision on the highest efficiency (lowest conversion energy) production of hydrogen. The first option was chosen, however, because maximising the quantity of hydrogen produced was considered to be the more important outcome for this particular device. In addition, the actual number of cells used had little effect on the overall price of the unit and so there is a natural tendency to 'get the most for your money', meaning that if there were any ambiguity over size there would be a temptation to err on the side of over-sizing rather than under-sizing the module.

Two different sizes of electrolyser cell were available: 300cm$^2$ and 1000cm$^2$, so simulation runs were carried out for each of the two types with various numbers of cells in the module. The module is divided into two halves so that the voltages across both can be monitored and compared with each other to reveal any imbalance (and, therefore, any fault) in the stack. Due to this, the number of cells in the module must always be an even number. An average of 600W for the BOP electrical load was quoted by Vandenborre, but it was not clear whether this included standby periods or only operational periods. The original sizing model, shown in Figure 5-14, assumed the latter, since Vandenborre were not accustomed to their electrolyzers being on standby for long periods. It should be noted that, at the time of this initial sizing exercise, the HARI team had not yet been informed that there is a limitation to the number of on/off cycles that the module could tolerate. Once this was made apparent, the need for a battery became obvious and it was included in subsequent models, however at this stage, the battery was not a feature of the model.
Wind power provides the bulk of the RE input to WBF and so would be the most important source of energy for the electrolyser with solar and hydro power only making a modest contribution. Data for the 14th January 2003 (Figure 5-15) was therefore used for the initial sizing exercise as this was a day that experienced a broad range of wind speeds in a distribution that would be typical of a windy winter's day when the electrolyser would be called upon to operate.

Figure 5-14: Original electrolyser sizing model in Simulink.

Figure 5-15: Wind power generated at West Beacon Farm on 14th January 2003, used for the original electrolyser sizing study.
5.f Electrolyser sizing model results

Intuitively, one might expect that hydrogen production is simply proportional to module size, but in reality, a maximum level is reached, beyond which the output starts to fall with the increasing number of cells. The limited range of the electrolyser's operation (e.g. from 20 – 100% of rated) demands that a compromise be reached between the ability to capture more peaks, but less low power inputs, as the module size increases. This leads to an optimum module size being reached, beyond which the gains at the high power end of the range are outweighed by the losses at the low power end. The optimum for the WBF system was determined by the model to be 44 of the 1000cm² cells. The graph in Figure 5-16 implies that there may, in fact, be a better hydrogen output from the '300-series' (i.e. 300cm²) cells, but it would require an unfeasibly large stack if that cell area were used. For reasons that were not revealed by Vandenborre, it was not possible to build the module with a 44 cell configuration and so they stipulated that a 46 cell unit would be supplied instead. This may have been related to the problem that was revealed later about the anticipated degradation of the module from intermittent operation. Since the requirement for most of their customers (in standard applications) is for a steady supply of gas at a given flow rate and pressure, Vandenborre may have added extra cells to ensure that the specified flow rate would be maintained in spite of some cell degradation. This is a precaution that they are known to take with the sizing of the unit's power electronics, which are designed to accommodate the rising power consumption that a slightly degraded module would cause. Indeed, it is when this spare capacity in the rectifier and its transformer are fully taken up by this increased power consumption, that the device is deemed to have reached the end of its life. Later, another simulation was carried out using data that covered a 98 day period from 12th December 2002 to 19th March 2003, which is typically a windy period of the year and is therefore a time when the electrolyser is likely to be at its most active. Figure 5-17 shows how this simulation varies from the original model in its assessment of the optimum module size by only two cells and, coincidentally, suggests a 46 cell configuration too.
Figure 5-16: Results from the original sizing model, using data for 14th January 2003 only. The amount of hydrogen produced over the 1-day simulation is shown relative to the number of cells in the electrolyser module. The 1000-series cells have an area of 1000cm² and the 300-series have 300cm².

Figure 5-17: Results from the original sizing model, using data from 12th December 2002 to 19th March 2003.
Once installed, the performance of the electrolyser was monitored and analysed to see how closely the model represented its real life operation. Over time, as anticipated, module voltage did rise as the switching cycles started to degrade the stack. When first installed, the electrolyser was rated at 36kW, but over two years of operation, the power demand of the module at rated hydrogen production has risen to 39kW. 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 43kW (with its drier heating on) and now its maximum power demand is 45kW.

5.9 Updated electrolyser sizing

Part of the challenge of the HARI project has been in dealing with the mindset of design and operational strategies established to serve more conventional uses of the equipment. Misunderstandings were therefore a frequent feature of discussions with suppliers of this system's components, as they grappled with 'thinking outside the box' about technology that they felt they understood so well. More than for any other device, this was true of the electrolyser. As a result of this, the actual performance of the device was at some considerable variance to that expected of it. Given the later knowledge gained through experience of the electrolyser's real-world performance, it is interesting to see what the outcome of a revised sizing model would be. Figure 5-18 shows an updated version of the model that takes account of new information gained about the size of parasitic loads and hydrogen losses in the electrolyser. The assumption is made that the AC-DC conversion accounts for almost all the electrical losses in the electrolyser and that the other parasitic loads are negligible by comparison. It is also assumed that the power electronics for this conversion can be sized to an infinitely variable degree to match the module size, whereas in reality, there is bound to be some degree of quantisation in the range of devices available. On the basis of these two conditions, all but the first sizing model adjust the BOP losses according to the number of module cells.

It should be noted that the updated sizing models are based on the performance of the electrolyser at WBF as it currently stands after two years of operation. This means that the current power consumption and conversion energy have increased due to degradation of the module since it was commissioned and this will also affect the hydrogen production figures. Although the sizing exercise is designed to specify what plant needs to be purchased, it
should take account of the performance of a device throughout the majority of its lifetime, not just how it functions immediately after installation. It is still unclear at this stage of the HARI project how the performance of the electrolyser will change throughout its whole lifespan, but recent evidence suggests that – despite early rapid deterioration – the module efficiency may have stabilised or, at least, be degrading much less rapidly (Roy, Watson et al. 2006). The module efficiency currently stands at a level 7% lower than that quoted by the manufacturer when it was new. Given that the current data on its operation is the best available to date, this is used in the sizing models to give an indication of its general performance rather than that of a brand new unit. Care must be taken, therefore, if specifying a device for purchase by its power rating and the appropriate adjustment from mid-life performance to as-new performance must be made. If specifying it by cell number, however, this is not an issue and so is a better way of defining the electrolyser size.

Figure 5-19 shows that, when data for the same 98-day modelling period is fed into this model, it concludes 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 (3345W compared to 600W) than the original model, but suggest a reduction in the optimum cell stack size of only 27%. In the revised modelling exercise, the conversion energies of different module sizes are assessed along with the hydrogen production. The conversion energy for a 32 cell module would be 4.5kWh/Nm³, or 4.9kWh/Nm³ if standing losses for the 98-day period are included. It would be rated as a 25kW electrolyser module, but the maximum system power demand would be 30kW. The 300cm² cells are not simulated in this updated model as verification of these and their associated BOP subsystems is not possible at WBF.

Amitava Roy has also performed sizing exercises for the electrolyser with another approach incorporating detailed information about the electrolyser, which includes the capacity utilisation factor of the device, stack degradation due to on-off cycling, stand-by losses, parasitic losses, probability of excess wind power and optimisation between the current density, Faraday efficiency and stack-energy consumption. This approach does not include the battery, compressor or other sub-systems external to the electrolyser itself, but it aims to optimise the total hydrogen production at minimum electrolyser cost and its results suggest that both 15kW and 20kW modules have the same utilisation factor. A 15kW module was therefore chosen by him for its cost, efficiency and durability (Roy 2003 - 2006).
Figure 5-18: Revised version of the original electrolyser sizing model. This takes account of new knowledge gained through operational experience of the device.

Figure 5-19: Results of the revised electrolyser sizing exercise, showing the amount of hydrogen produced by the 1000-series cells over the 98-day period simulated. Conversion energy values are also shown.

A further revision of the electrolyser sizing model, shown in Figure 5-20, includes an estimation of the compressor’s power consumption (although this has not been fully verified yet) and takes account of the battery that it has proved necessary to install in support of the electrolyser. This is, in fact, a variation on the model used to describe the overall system at
WBF, but the fuel cells have be omitted (by giving them a rated size of 0kW) so that only the hydrogen production side of the system is assessed.

The purpose of the battery is to reduce the number of on/off switching cycles experienced by the electrolyser. It does this by absorbing energy from the peaks above the electrolyser’s operational range and storing them until a trough below the operational range needs to be filled in order to prevent the unit switching off for a brief period, only to switch back on again moments later. The battery liberates the electrolyser from operating only within a limited range of power inputs, thus rendering meaningless the previously used method of determining the optimum module size. Ultimately, the criterion that defines the best configuration in this instance is the quantity of hydrogen generated relative to the energy consumed by the system used to produce it. This is the conversion energy and is measured in kWh/Nm$^3$. The lower this is, the more efficient the process is. Figure 5-21 shows how, in the new model, the conversion energy varies with the number of cells in the electrolyser module when combined with different sizes of battery. The best conversion energy is consistently achieved with a module of 28 – 30 cells, regardless of the battery capacity. The bigger the battery, however, the lower the conversion efficiency of the system becomes, due to the standing losses in the battery (Table 5-3). Clearly, from the point of view of efficiency

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**Figure 5-20**: Final version of the electrolyser sizing model that includes the battery and compressor.
and cost, the smaller the battery is, the better. On the other hand, if the battery is too small it is unable to reduce the switching cycles to an acceptable level.

Figure 5.21: Variation of conversion energy (kWh/Nm³), with the number of cells in the electrolyser module for different battery capacities.

<table>
<thead>
<tr>
<th>Battery size (kWh)</th>
<th>Number of cells</th>
<th>Loss Rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>120</td>
<td>65.05</td>
</tr>
<tr>
<td>15</td>
<td>180</td>
<td>85.51</td>
</tr>
<tr>
<td>20</td>
<td>240</td>
<td>105.96</td>
</tr>
<tr>
<td>25</td>
<td>300</td>
<td>126.41</td>
</tr>
<tr>
<td>30</td>
<td>360</td>
<td>146.87</td>
</tr>
<tr>
<td>35</td>
<td>420</td>
<td>167.32</td>
</tr>
<tr>
<td>40</td>
<td>480</td>
<td>187.78</td>
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<tr>
<td>45</td>
<td>540</td>
<td>208.23</td>
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<td>600</td>
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<td>55</td>
<td>660</td>
<td>249.14</td>
</tr>
<tr>
<td>60</td>
<td>720</td>
<td>269.60</td>
</tr>
</tbody>
</table>

Table 5-3: Standing loss rate for Zebra batteries. *(Source: Beta Research & Development Ltd)*
Interestingly, Figure 5-22 shows that the highest hydrogen output over the 98-day simulation run does not necessarily correspond to the most efficient conversion energy. This is because better conversion efficiency is likely to be achieved by the electrolyser operating closer to its rated power more often, whereas the highest hydrogen yield will come as a result of balancing the hydrogen production range of the electrolyser with the power input profile. It is essential, therefore, in defining the best system configuration, to decide which is the most important outcome: maximum efficiency or maximum hydrogen yield. In this exercise, efficiency is treated as the most important indicator.

Vandenborre quoted a life expectancy of 5000 switching operations (zero crossings) before they expect the performance to deteriorate to a level that became unacceptable (i.e. about below 90% of its original conversion energy). The switching cycles must, therefore, be limited by the required lifetime of the electrolyser and so, if a 10 year life expectancy is specified, the average number of switches allowed per day would be 1.37 (or 0.685 on/off cycles). At this rate the appliance could tolerate 134 switches over the 98-day simulation period and this imposes an upper limit in the module’s cell number for a given battery capacity.
capacity. Figure 5-23 shows how the switching cycles vary with module size for a range of battery capacities. Other criteria may also be of interest when considering the sizing of these components. The capacity factor of a device is defined in Equation 5-4. It is normally expressed in terms of power (e.g. for a WTG or PV system's energy production), but since it is hydrogen production that is of interest in this case, the capacity factor (unless stated otherwise) is assumed to be expressed here in terms of hydrogen output. The capacity factor of the electrolyser reduces with battery size, as does its duty cycle (the proportion of time for which it runs). These are significant because, if the electrolyser were to only operate for very brief periods, as signified by a low percentage duty cycle or capacity factor, it is unlikely to reach its optimum operating temperature and, although thermal parameters were not included in this model, it is clear that the conversion energy would rise as a result. It is beneficial, therefore, to re-introduce the criterion that was rejected as being unnecessary in the initial sizing model: that is, the amount of run time the electrolyser experiences (i.e. its duty cycle), which in turn, affects the capacity factor. In fact, both these follow the same trend as the conversion energy, thus reinforcing the benefits of keeping the battery size to the minimum possible.

\[
\text{Capacity Factor} = \frac{\text{Actual output during } t \text{ hours}}{\text{Rated output } \times t \text{ hours}}
\]

Equation 5-4

Figure 5-24 illustrates where the balance is struck between the desire for a smaller battery to increase efficiency and a big enough battery to ensure the required limitation of switching cycles. This puts the optimum Zebra battery capacity at 16kWh (20% smaller than the existing Zebra battery) and electrolyser module size at 28 cells (39% smaller than the existing module at WBF), giving the best duty cycle (12.6%), capacity factor (7.7%) and conversion energy (6.6kWh/Nm³) that the switching limit allows. Over the 98-day simulation period this would have produced 854Nm³ of hydrogen. This would be a 24kW rated module (agreeing with Amitava Roy's model (Roy 2003 - 2006)) and have a maximum power demand of 27.5kW, based on the current performance of the electrolyser at WBF. In fact this would equate to a 22kW rated module at the time of purchase with a maximum consumption of 26kW, before any deterioration of the module.
Figure 5-23: Variation of the number of on/off switches over the 98-day test period with the number of cells in the electrolyser module for different battery capacities.

The actual combination in the WBF system has a larger than ideal module size of 46 cells and battery capacity of 20kWh. As expected, this configuration results in a higher conversion energy value and, as illustrated by Figure 5-25, a lower hydrogen yield than the optimum would have produced. Although it performs better than the specified optimum for the 46-cell module described in Figure 5-26, it violates the maximum switching condition and therefore lies outside the allowable range of battery capacities. To fulfil this criterion, the battery capacity would have to be 28kWh, which would produce 797Nm³ of hydrogen, with a conversion energy value of 6.9kWh/Nm³ and a 12.6% capacity factor.
Figure 5-24: The number of on/off switches, during the 98-day test period, compared to conversion energy (kWh/Nm³), CE, capacity factor, CF, and duty cycle (%), DC, in relation to the size of battery to be used with a 28-cell electrolyser module.

The reason the electrolyser and battery combination actually installed at WBF fails to comply with the limitation of switching cycles is that when the modelling exercise for ascertaining the battery capacity was undertaken, the full extent of the BOP losses in the electrolyser had not been revealed by Vandenborre to the HARI project team. With the knowledge available at the time, the simulation had assumed a BOP loss of 600W in the electrolyser, leading to a predicted number of 124 on/off switches over the 98-day period. This was slightly lower than was required, but since the battery was bought as an off-the-shelf item that came in a range of standard sizes, the 20kWh version was the closest to the requirements of the WBF system. Having later revised the mean BOP losses to 3.3kW, the number of on/off switches with this battery capacity and module size is now predicted to be 196 during this period. This number of allowable switching operations is, however, based on a daily average across the year, with no weighting for seasonal variation. The period being modelled is at one of the more windy times of the year, which is likely to cause a greater number of switching cycles for the electrolyser than at less windy periods, since the input to the electrolyser at this site is dominated by the wind resource. Re-running the simulation with a whole year’s data, would
provide a better indication of whether the size of this battery is sufficient, but time has not allowed such an exercise to be undertaken for this study. With the new electrical system in place, operational experience will be gained that would also provide such confirmation, but better still, it would take account of how the loads on the network will have changed in response to the new arrangement.

Using the operational knowledge so far from this project, an optimized specification for the electrolyser and battery would achieve a 2.5% improvement in conversion energy, produce 2.9% more hydrogen and have a 69% higher capacity factor than the existing system, while bringing the switching cycles within the target for a ten year electrolyser life. On a like-for-like basis (i.e. allowing the same 196 cycles that the existing WBF system would go through), the gains would have been 4% in conversion energy, 3.3% in hydrogen produced and 70% in capacity factor.

![Figure 5-25: Comparison of hydrogen yield for the ideal sized module of 28 cells, with the actual module size at WBF of 46 cells, in relation to battery capacity. The minimum battery capacity allowed by the switching limitation is shown for each module size.](image-url)
Figure 5-26: Determination of the best battery capacity to match the 46-cell electrolyser module at WBF.

The average conversion energy of the overall electrolyser-battery-compressor system at WBF over the 98-day simulation period was 6.74kWh/Nm³, which equates to an efficiency of 48.8% (using HHV at NTP). Its capacity factor, defined in terms of hydrogen output, was 4.56%, but had it been defined in terms of energy consumption, the CF would have been 4.97%. Such a low CF as this is not surprising given that power from the RE sources tends to be delivered in short bursts with relatively long gaps in between and that the system must have the capacity to absorb large peaks of power while at the same time accommodating the far more frequent low power inputs. The average length of time between hydrogen generating periods was 10.8 hours.

The overall conversion energy of the system is 60% higher than that quoted by the manufacturer for the module alone (of 4.2kWh/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 operation. The main contributor to these BOP losses, though, is the conversion from AC to DC power, in which the amount consumed ranges from 12% of the electrolyser’s power at rated output to 30% at
It should be noted that this is a purely technical model and so financial considerations have not been included. In reality, price would be the overriding concern in the specification of most installations, but these technical models propose solutions which would minimise cost by default. The most up-to-date sizing model clearly defines an optimal configuration that uses the smallest possible battery and electrolyser module to fulfil the necessary parameters, while achieving the best performance possible within those operational constraints.

5.h Fuel cell models

A number of factors have made it difficult to carry out detailed analysis of the fuel cells' performance. These have been issues of access, due to commercial sensitivity and warranty agreements, technical barriers that have limited the size of load that could be connected to them for testing and, in the case of the PPFC, the very limited availability of the unit.

Due to concerns over the protection of intellectual property relating to its technology, Intelligent Energy is extremely careful about the degree of access it gives to its customers. The fact that their fuel cell is being leased by WBF, instead of being owned outright, allows IE to strictly regulate this (although, had it been purchased, the risk of invalidating the warrantees would also have prevented much interference with the device). Only IE technicians can, for example, open the fuel cell cabinet and data on the operation of the unit and its subsystems is carefully filtered (to remove any commercially sensitive information) before being passed on to the HARI project team. The limit of the HARI team's interaction with the unit is merely to switch it on or off, supply hydrogen to it and draw whatever load is required from it.

The performance data that IE makes available to the HARI team is the voltage and current of the cell stack and its power output, the current and power supplied to the load and the auxiliary voltage. Of these, it is the power supplied to the load that is of most interest to this study, which, when compared with the hydrogen consumption rate (as measured by the mass flow meter), can be used to calculate the hydrogen required to generate each kWh of electricity. Although this is very unsophisticated, it provides a system efficiency figure for
the fuel cell unit and is sufficient for the logistical modelling exercise being carried out here. Until the electrical system upgrade is complete, the IE fuel cell is usually given a 1 hour test run each day using a steady load of ≈1.5kW. This is 75% of the unit’s continuous rated output of 2kW (although it is capable of short 4kW peaks). Intelligent Energy claim that their system (not just the stack) consumes between 0.6 and 0.9 m³ for each 1kWh of electricity generated. The lower of these two figures is when running at part load (although the exact level is not stated) and the higher value is assumed to be at its maximum (i.e. continuous rated output, as the short peak output is boosted by internal batteries). Using the characteristic efficiency curve of a hydrogen fuelled PEM fuel cell (Kreutz and Ogden 2000), it can be assumed that the lower of these values occurs at about 20% of rated power and the higher at 100% and that between these two the relationship is almost linear. This would imply that the fuel consumption at 75% of rated output should be approximately 0.81m³ of hydrogen per kWh. Test runs carried out at WBF show that for approximately the first six minutes of each operational period, the hydrogen consumption is slightly higher as the fuel cell reaches its optimum running conditions, but for the rest of the time it remains steady in response to the steady load that is typically applied to it at this site. Since it more accurately reflects the expected run time of the device when the electrical system upgrade is complete, the results used to verify the fuel consumption rate were obtained over a 1½ hour test run and used to get an average value. From this test run, however, the hydrogen consumption is 0.69m³ per 1kWh of electricity when the unit is supplying power at a rate of 1.5kW, which is 15% less than expected. This either suggests that the manufacturer’s quoted fuel consumption rate is overly cautious (which is unlikely), or that the fuel cell stack does not run at a part-load as low as 20% of rated. If the latter were true, it is likely to be as a result of the control strategy of the device, which might be designed to rely on its internal battery for low load levels, rather than by running the stack at such a low output rate. Alternatively, it could be a characteristic of the unit’s BOP that the gains in stack efficiency at low output levels are partly offset by other losses that increase at these levels. As the details of such matters are considered commercially sensitive, they cannot be revealed to the HARI project team and so it is not possible to know what internal conditions lead to the discrepancy between measured and expected consumption values. An accurate fuel consumption rate cannot be measured for this device yet, because it cannot be tested at its maximum output level until the electrical upgrade is complete.
Access to the Plug Power fuel cell was easier, although (due to the restrictions of the warrantee agreement) it was still limited. However this did not mean that monitoring of the unit was any more detailed as, once again, the parameters of real interest to this study were the hydrogen consumption and its relationship to the power output. Two hydrogen consumption rates quoted by the manufacturer (Plug Power 2004) are 4.5Nm³/h at its rated power of 5kW and 2.4Nm³/h at a part-load output of 3kW. Until the electrical upgrade at WBF is complete, however, it has only been possible to test the PPFC at up to 1.5kW output. The average conversion energy for the fuel at these low power levels was measured at 0.788Nm³/kWh, whereas the information provided by the manufacturer suggests that it should be around 0.71Nm³/kWh, which is a discrepancy of 10%.

There is a great deal of noise in the data and it only covers output levels from 20 – 35% of rated, so without a known power curve for the device, this cannot be considered an accurate predictor of its performance at full power. For the time being, then, Plug Power’s stated fuel consumption rates are taken at face value for use in the software model, but can be adjusted accordingly after further testing.

In addition to the data recorded during test runs of the Gencore, its standing losses must also be accounted for in the models. Since the standby load is fed from the electrical network, not the fuel cell itself, this must be accounted for by electrical consumption rather than hydrogen. The Intelligent Energy fuel cell does not consume any power while it is switched off and so there are no standing loads associated with it.

5.1 Overall system model design

Finally, a Simulink model, shown in Figure 5-27, was developed, which is designed to describe the eventual configuration of the overall hydrogen and electrical system at WBF as it will be after the upgrade of the electrical system is complete. This does not, therefore, simulate the system as it has been up until now. With the electrical distribution network at the site currently in the process of being upgraded, it is not possible to verify the model as a whole yet; however its major subsystems have been validated separately. These include the electrolyser, RE sources, fuel cells and hydrogen store. The battery and control model can only be fully validated once the whole system is in place. While the system is still connected to the grid, for example, the switching on and off of the electrolyser and the setting of its
power level is predicated upon the flow of energy to and from the grid. The aim is to reduce the flow in either direction to a minimum, but since the measurement of that flow can only be reacted to in retrospect by the control programme, it cannot be eliminated altogether. This will no longer be relevant after the electrical system upgrade.

Figure 5-27: Model for the complete hydrogen and electrical system at West Beacon farm.

This model of the energy system at WBF does not include the thermal aspects of the system, such as the heat output of the devices that is captured, stored in a phase-change heat store and used for space heating in the house. It does not include any modelling of the thermal properties of the electrolyser or fuel cells; although it is expected that there will be an impact on their performance. This area is being analysed in detail by another research student as part of a complementary study within the wider HARI project. To go into such details is beyond the scope of the study described in this thesis, which is intended to produce a logistic model giving information suitable for system design and operation, rather than a dynamic one, which might be used of electrolyser or fuel cell design purposes.

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. In this situation, the electrolyser and fuel cells are switched on and off in response to the state of charge (SOC) of the battery. This is given as a percentage of the full range of charge levels that it can accommodate rather than an
absolute charge level. In fact, with the Zebra battery, this is effectively the same level as its whole capacity range can be used. In this case, from being fully charged (100% SOC) to its lowest allowable depth of discharge (0% SOC), the battery can supply 20kWh of electrical energy. The control strategy is such that when this relative SOC reaches 90%, the electrolyser switches on and a current density set point signal, which is proportional to the SOC, is sent to the electrolyser to control the level at which it operates. The electrolyser continues to run until the SOC has reached 50%. The Intelligent Energy fuel cell (IEFC) is switched on when the SOC falls to 30% and continues to run, charging the battery at a rate of 2kW, until the SOC is raised to 50%. If the IEFC is not able to charge the battery fast enough, the SOC will fall further and at 20% the Plug Power fuel cell (PPFC) will be switched on instead (i.e. the IEFC is turned off). The PPFC will charge the battery at a rate of 5kW until it reaches 50% SOC, at which point the fuel cell will be switched off. If this is not a fast enough charge rate and the SOC falls to 10%, the IEFC is switched back on again, so both fuel cells charge the battery at a combined rate of 7kW until the SOC reaches 50%.

Under this control regime, both fuel cells only run at their rated output and never at part load, so the maximum fuel consumption rate must be assumed for each. In both cases, this has been taken as 0.9Nm³/kWh, which is the figure quoted by both manufacturers. The values implied by the tests carried out thus far at WBF are slightly more optimistic for the IEFC and slightly more pessimistic for the PPFC, but the accuracy of these can be improved upon as the new electrical system allows and the model can be adjusted with relative ease.

The effectiveness of this control mechanism in real-world operation is difficult to gauge accurately, because there are bound to be subtleties in the system's behaviour that the simulation does not yet incorporate, but it works satisfactorily in the Simulink model thus far. Once the system is able to be tested in real life, these control parameters will, no doubt, need some fine tuning, however this is a relatively simple task to accomplish in the model.

Other minor improvements could be made to the model in future, as time allows. The compressor, for example, could be analysed in more detail by the addition of a sensor to measure its power consumption. A theoretical average power consumption figure is currently used for this device in the model. Also, the RO water treatment unit is currently left out of the model. Again, the addition of power consumption monitoring for this device would be beneficial; however, advice received from Hydrogenics suggests it might be dispensed with.
altogether, as the low flow rates demanded at this location mean that a filter bed process would be sufficient. As this method only consumes filter materials, not electrical energy, the electrical load of the water purification process would removed. Furthermore, it has been established, through tests carried out on the exhaust water from the fuel cells, that it is pure enough to be fed straight back into the electrolyser filler tank. Only a small proportion of water will be lost in the electrolysis and reverse electrolysis (i.e. fuel cell) processes, so by recycling this water, the demand for water from the purification system will be significantly reduced. Although these modifications are due to be implemented at WBF shortly, it would still be useful for the software model to include a reverse osmosis component to make it applicable to the design of other similar systems.

The Matlab models of the RE devices are designed to produce data files that fit into the Simulink models in the same place as the data files previously used in the sizing and verification exercises. Instead of measured RE outputs, therefore, the Simulink model now contains the RE outputs predicted from weather measurements by the Matlab programmes. In this way, a complete model of the overall system can be simulated before any devices are installed. Knowing only the relevant weather and electrical load data, then, this model can be used to design a stand-alone energy system, based on wind and/or solar energy supply, with hydrogen and battery energy storage.

System efficiency is hard to determine because it can be defined in a number of different ways. In theory, if the cycle from RE electricity to hydrogen and back to electricity is completed in a very short period of time, the energy consumed in making it is less, because time-related losses are negligible. Since the whole point of using the hydrogen system is for storage over long time periods, however, this is not an ideal way of quantifying its efficiency. On the other hand, it does at least give a simple round trip efficiency, which is derived from averaged conversion factors in the model. These indicate that 1Nm³ of hydrogen takes 6.8kWh to produce (but if the battery is included, this is slightly improved at 6.74kWh, due to the higher efficiency of battery storage over short cycles during the 98-days sampled) and electricity generated in the fuel cells from this hydrogen is 1.1kWh, so the round-trip efficiency is only 16%. Standing losses in the electrolyser, fuel cell, battery and control systems add a little to this over time at a rate of about 300 – 400W.
Another way of assessing the system efficiency is to look at the total energy that is supplied to the system 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 of running the overall system model with supply and demand data over a 23 day period from 3rd to 26th January 2003 (part of the 98 day period used for the earlier sizing exercise) are shown in Figure 5-28. 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). In Figure 5-29, a Sankey diagram illustrates the results of this simulation run and reveals the energy flows though each stage of the overall system from input (energy supplies) through to output (energy delivered to loads). From this, the efficiency of various processes in the system can be calculated, but it is particularly useful in understanding how to estimate the overall efficiency of the system.

*Figure 5-28: Results of a simulation of the West Beacon Farm hydrogen and electrical system as it will be when the electrical network upgrade is complete. The magenta line is the state of the batteries (%), the yellow line is the electrolyser power consumption (kW), the cyan line is the fuel cell power generation (kW) and the red line is the amount of hydrogen in the store (Nm³).*
If the total energy input, including the depletion of energy that was already stored, is compared with the output, the overall system efficiency is 42.7%. If only the RE input were considered, the efficiency would be 48%, but this ignores the fact that energy that was stored before the start of this test run has also been introduced into the system. To properly take account of this, an allowance must be made for this external input and its effect must be eliminated. Of course, it would be easier to carry out another test simulation where the stored energy is the same at the beginning and the end, but in this instance time constraints demand that the existing data is used. To eliminate the input from the pre-stored energy, the proportion (25%) of fuel cell output that results from it must be subtracted from the energy output of the system. This then leads to an efficiency of 43.4%, which is marginally better than the value produced by the comparison of total energy input with energy output.

This model can be used to design energy systems of a similar nature (i.e. stand-alone RE systems with integrated HES), using only weather and load data for the location in question. A design methodology has been developed whereby the following steps are taken. First, the fuel cell size is derived from the load profile. Next, the electrolyser and battery size is determined that achieves the best conversion efficiency for producing hydrogen during periods of surplus RE output. The required hydrogen storage capacity is then contingent on accommodating these two parameters. Finally, the capacity of RE devices must be scaled to supply the whole system. The design process requires some trial and error and a certain amount of feedback between the different stages. This is particularly true of the balance...
between the combined electrolyser and battery capacities and the scaling of the RE devices. The gaps in RE supply change little with the scale of generation capacity (a 100kW wind turbine produces no electricity when there is no wind, just as a 10kW one does) and the size of hydrogen store is largely dependant on the length of such gaps, so the iterations are not as complex as it might at first appear. The process of refining the Simulink model will continue indefinitely as more experience is gained of this and other systems, so that it constantly evolves and improves. However, with the proviso that ongoing tests will lead to minor adjustments, the overall system model can be considered to be complete and operational.
6 Lessons learnt and suggested improvements to the system

6. a Data acquisition

The establishment of a reliable and accurate data acquisition system proved to be one of the major challenges of this project. This began with the learning of the fundamentals of the process and how to use the LabVIEW software and National Instruments DAQ cards, followed by the installation and calibration of the transducers and their associated circuitry and wiring. As this was proceeding in parallel with the design, installation and day-to-day operation of this complex energy system, some parts of the DAQ system were not complete and fully functioning until the later stages of this research period. Indeed, had time allowed, other parameters would ideally have been monitored, such as the compressor and RO unit's power consumption. Despite the size and difficulty of the task, the importance of establishing a good quality DAQ system cannot be overemphasised as it underpins the accuracy of the modelling exercise and is required for certain system management and control tasks.

6. b Efficiency

The theoretical round trip efficiency of using hydrogen for electricity storage is not impressive and this, and other projects like it, emphasise 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, that it is unviable or, indeed, that there is any better alternative. 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 and so the challenge, then, is to make this goal achievable at lower cost and higher efficiency. It is extremely difficult to estimate what the combined effect would be of including all the efficiency and other measures discussed here, because each change would affect the others and, in some cases, demand a radical restructuring of the sizing and control strategies of the system. 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 thesis. To carry out a full assessment of these issues would be a lengthy and complex study in itself, so it is hoped that
what has been initiated here will be taken up by other researchers who will continue to work on the WBF system.

6.b.1 Matters for further Investigation

One of the first issues to be addressed, as soon as the upgrade of the electrical network at WBF is complete, is to analyse the performance of the two fuel cells. Until now, it has not been possible to test them at their full range of power outputs and to use this for an accurate hydrogen consumption profile. It is quite possible that, following such an exercise, the overall system efficiency figure will prove to be higher than the currently available data suggests. It will not be lower, because the most conservative values for both fuel cells have been assumed in the simulations for this study.

The most important ongoing task for the HARI project will be a full and careful assessment of the system management and control strategy. Might the efficiency of the electrolysis process, for example, be maximised by ensuring that it always operates at its most efficient power level, even though this would demand more short-term electricity storage in the battery? As it stands, the system is designed for maximum robustness and reliability and little has been done so far to investigate the subtleties of alternative control methodologies that might be applied to it; however this is a foundation upon which efficiency improvements can be built through more intelligent system control and management. This should start with a detailed energy audit of the system, including monitoring the power consumption of the compressor, the RO unit and other subsystems that have not had their performance analysed yet. The intention is to reveal where inefficiencies arise and which have the potential to be significantly improved. Such improvements may be accomplished through hardware modifications and control methodologies. One way of achieving efficiency improvements, for example, might be the use of demand-side management techniques, such as the deferred or opportune use of non-critical loads, which avoids unnecessary use of energy storage. This second phase of the HARI project has significant value as a learning opportunity for this research group and for others working in this field and could be seen as the most worthwhile part of the project. Up until now, the work carried out under the HARI project might be seen as mere preparation to establish a research facility for the ongoing drive to improve the efficiency, reliability, durability, size and cost of theses systems and their components.
One potentially fruitful area for investigation is that of the water purification for the electrolyser. Currently this is carried out by a reverse osmosis (RO) unit, which is known to have relatively high energy consumption (although this has not yet been accurately quantified at WBF). It has been suggested by Hydrogenics that, because the flow rates encountered at this site are low, it might be possible replace this energy intensive purification method with a filter bed system. The latter consumes only material resources instead of electrical energy and would therefore help improve the overall system efficiency.

Another potential improvement in system efficiency could be achieved, in the longer term, by making use of the oxygen that the electrolyser produces, which is currently vented to atmosphere. The efficiency of a fuel cell that breathes pure oxygen is theoretically up to 30% more efficient (Larminie and Dicks 2003) than one that breathes air. To realise this full efficiency gain, however, would require that the fuel cell be designed specifically for this mode of operation. Simply adapting a standard air-breathing device does not achieve anything like the same efficiency gain and, since an oxygen breathing cell can only be used in a small number of niche applications, they are not being developed by manufacturers who are currently more eager to break into early markets with broad applicability. Until the wider fuel cell market takes off, such niche applications will not be addressed, but when oxygen breathing fuel cells eventually do become available, it might become appropriate for one to be installed at WBF, thus making use of the oxygen that is currently wasted and improving the overall system efficiency. A further line of enquiry in relation to potential fuel cell upgrades could be the use of a SOFC. These have the potential to be more efficient than low temperature fuel cell types, but their high temperature operation inevitably leads to slower start-up times and less responsiveness to and tolerance of dynamic loads (Hamnett 2003). With further development, though, these shortcomings may be improved upon to the extent that SOFCs may one day be applicable to situations like that of WBF. An AFC might be a more readily accessible addition to the WBF system and, due to its higher efficiency (compared to a PEMFC), this too has the potential for improving the system efficiency.

It is perhaps typical of an experimental and pioneering venture like the HARI project many of the subsystems and components are bound to be less than ideal for the purpose for which they are employed in the scheme. The components used are frequently the nearest fit for the job, not the exact fit. Because new and different roles are often being demanded of plant that may have been designed for similar, but subtly different tasks, it is like "trying to fit a square peg
in a round hole”. As the market for these types of applications opens up, so products
designed for the specific functions involved will become available (and they will owe much
to projects like this for their development). This will improve their durability and reliability
and boost the overall efficiency of this type of system. As these products become available,
they may replace those currently in use at WBF, particularly as some reach the end of their
life, and so the system will become more efficient. This has already proved true for some of
older power electronic devices used at the site, which are now being replaced by improved
versions, and will be particularly relevant in the cases of the electrolyser and Plug Power fuel
cell. The former indicates that much work is needed in order to allow dynamic and
intermittent operation of electrolysers to work effectively, while the latter illustrates how a
UPS system (with its static load) is less well suited to this system than a fuel cell like the
Intelligent Energy one, that consumes no power while switched off.

6.b.i Electrical efficiency

From the lessons learnt so far in this project, it is clear that there are a number of more
immediate ways that efficiency could be enhanced in this system. Firstly, obtaining the
optimal match between the battery capacity and the number of cells in the electrolyser
module ensures the best hydrogen production and most efficient conversion energy. This
could increase the efficiency of the process that converts surplus power to hydrogen by 3.3%
and produce 4% more hydrogen.

As most of the parasitic losses (as opposed to the thermodynamic losses of the
electrochemical reaction itself) are in the power conversion electronics, it would make sense
to focus on improving these. It should be possible to obtain power electronic devices to
perform the AC-DC conversion in the electrolyser with efficiencies of up to 98% at full load
and, of particular importance in this case, with improved part-load efficiencies. This could
boost the electrolyser's efficiency by at least 8% to give a hydrogen conversion efficiency of
53%, or higher.

The hydrogen compressor at WBF uses ≈0.34kWh/Nm³ to raise the pressure from 25bar(g) to
200bar(g), although, with the reduced flow rates and inlet and outlet pressures used at the
site, this is slightly reduced. At its rated throughput, this would add 5% to the energy
required in the hydrogen production. The HARI team, in collaboration with the Metallurgy
and Materials department at the University of Birmingham, are hoping to investigate the use
of metal hydrides for hydrogen compression to see if it proves a more efficient method than the mechanical compression currently in place. By careful thermal management of a metal hydride store, the output pressure can be raised to many times that of its input pressure. As well as the potential for efficiency gains in the compression process itself, the integration of the heat flows associated with it into the existing thermal energy management scheme at WFB provides further opportunities to enhance the overall system efficiency.

6.b.iii Thermal efficiency

Although not explored in any depth in this thesis, it is recognised that thermal management is key to the optimisation of the WBF energy system. The by-product heat from the HES components (e.g. electrolyser, fuel cells and compressor), will be captured for domestic space heating. The space heating task at WBF is normally carried out by a water-source heat pump, which is the most demanding load on the electrical system. By making use of the HES ‘waste’ heat, the heat pump’s work-load is reduced, thus leading to a larger surplus energy supply for the electrolyser to absorb. Furthermore, thermal management measures within the electrolyser itself will improve its performance. The electrolyser power supply (EPS) cabinet, for example, has cooling fans on the front to ensure that the power electronics and other components inside do not overheat. Since the unit runs continuously in most applications, these fans are also set to run continuously. However, in the circumstances of intermittent operation encountered at WBF, overheating is rarely likely to occur, so running these fans continuously is simply a waste of energy. One of the first modifications made to the EPS upon installation at WBF, therefore, was to fit a thermostatic switch to the unit to ensure that these fans only operated when needed. In the main process unit of the electrolyser, thermal lagging will be fitted to the cell module, separator tanks and associated pipework to reduce temperature losses between operational periods, which cause the electrolyser to run less efficiently. The thermal lagging will also help it reach optimum conditions quicker upon start-up and reduce mechanical stresses cause by thermal cycling of components.

6.b.iv Hydrogen gas losses

Hydrogen venting, both operational and unscheduled, accounts for further inefficiencies. The unplanned losses are due to leakages in joints and valves. During the first year of operation at WBF, very large amounts of hydrogen – estimated to be more than half the total produced
were lost in this way! Hydrogen is more difficult to contain than any other gas except helium, which is the only one to have smaller molecules than hydrogen, so leaks are always particularly difficult to eliminate with this gas. The quality of joints used in the pipework should have been high enough to eliminate such problems, so it is not entirely clear what gave rise to such leakages. A bedding-in period might be expected at the beginning of an installation's life, but the problems at WBF persisted longer than anticipated. Certainly, intermittent operation may impose extra stresses on joints from thermal cycling, but the quality of hardware used was such that the risks from this should have been negligible. The leakage through valves came about through two different mechanisms. The first was due to a grain of silica from the electrolyser's drier being carried through in the gas stream until it became lodged in a valve seat. This was an understandable teething problem, which once it had been traced (after the loss of large amounts of hydrogen), was quickly fixed and filters were introduced to prevent a reoccurrence of this fault. The second instance of leakage through a valve is less easy to eliminate permanently. It occurred due to small amounts of KOH being entrained in the product hydrogen, which can form crystals in the pipework. If, as happened in this case, a crystal gets stuck between a valve seat and its outlet port, it will prevent it sealing properly when closed. This can be fixed, but there is no guarantee that the problem will not recur.

Unintentional hydrogen losses from leaks may, with careful construction and maintenance of hardware, be eliminated, however hydrogen venting that is intrinsic to the operation of the electrolyser presents more of a challenge. In the Hydrogenics IMET electrolyser, the process of topping up the electrolyte with fresh water necessitates the release of hydrogen, as does the regeneration of each of the driers, which require a stream of hydrogen to carry away the water vapour. It is the high pressure operation of this electrolyser that compounds this unavoidable loss by a factor equal to the outlet pressure. Reducing this loss, which amounts to 8% of the hydrogen produced in a 25bar(g) electrolyser, is one of the arguments in favour of carrying out this process at as close to ambient pressure as possible (Roy, Watson et al. 2005a). Another way of reducing the water filling loss might be to inject the water under pressure using a pump, but this would consume electricity and go against the manufacturer's desire to reduce mechanical devices in the electrolyser (Roy 2003 - 2006; Roy, Watson et al. 2005a).
6.b.v Electrolyser design

Conducting the electrolysis process at ambient pressure, or at least as close to ambient as is practicable, has other advantages besides reducing hydrogen venting losses. It would help to reduce the propensity of hydrogen to escape through leakage and, because it would require a much simpler system infrastructure, would have fewer joints and valves from which the gas might have the opportunity to escape. As well as hydrogen leaks, there are other types of inefficiencies to consider. To deal with these issues in detail is beyond the scope of this thesis; however, they are being investigated in considerably more depth by Amitava Roy (Roy 2003 - 2006; Roy, Watson et al. 2005a), who is a member of the HARI project research team, and his findings will be presented in a PhD thesis in 2006.

Even the electrochemical water-splitting reaction itself would be more efficient at lower pressure. In such a case, the system includes a compression stage external to the electrolyser, but the energy consumed by the compressor is less than that saved by electrolysis at low (i.e. close to atmospheric) pressure. Roy calculates the difference in total system efficiency to be between 8% at 50bar(g) hydrogen output and 17% at 700bar(g) (Roy, Watson et al. 2005a). The more complex control, monitoring and safety mechanisms required by high pressure operation of the electrolyser contribute to the BOP losses, which reduce the overall system efficiency (Roy, Watson et al. 2005a).

It is a proud boast of the electrolyser manufacture that the number of mechanical systems in the IMET system has been minimised (Hydrogenics 2005), but its high pressure operation simply reintroduces a level of complexity that their exclusion aims to remove. The need for a compressor has not been eliminated, for example, since storage at much higher pressures than 25bar(g) is required for most applications. In fact, far from being the troublesome piece of equipment that Hydrogenics imply, the compressor has emerged as one of the more reliable devices at WBF. During the first few months of its operation the compressor suffered from an intermittently sticking valve, but this would be freed-up with a tap from a hammer. It became necessary to do with less and less frequency until it eventually worked trouble-free.

6.c Reliability

The reliability of various components has been an issue at WBF and many of these have already been discussed in this thesis. Such problems are to be expected, given the
experimental nature of some of the components and the pioneering nature of the project. In addition to those mentioned previously, there are other difficulties of note, particularly those encountered by the Plug Power Gencore fuel cell. Over the one and a half years since its installation, only forty hours of operational time have been recorded for this device and its cell stack has been replaced twice, its batteries replaced twice and an air compressor replaced once. The latter was an upgrade that has been required by all Gencores in current operation due to a design fault in that particular component (Graham 2005a; Graham 2005b). The replacement of the batteries and the cell stack is, however, of more concern and is believed to be related to the way in which the Gencore was integrated into the electrical system (Little 2005). An inverter/battery charger was used to connect it to the electrical network so that AC power could be exported from the unit, but DC power could be imported into it to keep its internal batteries topped up while the fuel cell was on standby. These lead-acid batteries supply power to the onboard system management during standby periods and are subject to self-discharge as well. Since the Gencore is designed as a UPS unit, such a standby load is to be expected. After many long struggles to achieve consistent and reliable operation it became apparent that the inverter/charger, which is an intelligent device, was acting in conflict with the Gencore unit’s internal DC-DC converter and battery charger, which is also an intelligent device. It proved impossible to adjust the various set points on the external inverter/charger in such a way that the two power electronic devices could work in harmony. Clearly, what would have worked more effectively would have been if the external inverter/charger had not been an intelligent device so that a simple master-slave relationship could have been operated. The result of this conflict has been that, in a struggle to find equilibrium, the Gencore would switch on and off in rapid succession as its batteries discharged slightly and were then quickly recharged. Such rapid cycling never allowed the fuel cell stack to be properly humidified and so its membranes were damaged by dehydration and, consequently, the stack was destroyed. A clear understanding of this issue has only recently been gained and, since the upgrade of the electrical system that will make the existing inverter/charger redundant is underway, there is considered no reason to address this issue by changing the existing set up. Instead the Gencore will remain out of service for a matter of weeks until the new system is in place. Long lead times on replacement parts and the fact that the supplier and manufacturer are both located at some considerable distance from this test site, led to significant delays in analysing and understanding matters relating to the Gencore and carrying out the appropriate repairs and adjustments to it. By contrast, in the case of the Intelligent Energy fuel cell, much greater availability has been achieved. This is
due partly to them being based only four miles from the test site; however some credit must also be taken by Intelligent Energy for the quality of their technology. In both cases downtime has been the result almost entirely of BOP and ancillary systems failures rather than the fuel cell technology itself.

Initial difficulties with the electrolyser centred mainly on hydrogen leaks, which appear to have been successfully remedied, but in recent months it has encountered further reliability problems. After 1½ years in use, leakage of KOH electrolyte from both pipework and (more alarmingly) the module has become a major problem in the HARI system. The electrolyser cell stack has been returned to the manufacturer for a complete rebuild and, at the time of writing, is awaiting reinstallation. Hydrogenics is currently in the process of preparing a report on why a major electrolyte leak could have occurred in this system, but its findings are not available yet. At the risk of pre-empting the report, though, it is clear that the intermittency of operation may have been a factor, due to thermal cycling, and that any leakage problems can only have been exacerbated by high pressure operation.

6.d Safety

Safety is of paramount importance in a research and demonstration project such as this, from the point of view of personnel 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 have been provided by BOC who routinely deal with pressurised hydrogen gas in various applications. Matters relating to this in the particular context of the HARI project have already been discussed in this thesis, but issues raised by the HARI project team's experience with the handling of KOH solution are also worth highlighting. It is well documented in the standard safety literature for potassium hydroxide (See Appendix for potassium hydroxide safety data sheet) that it is a strong irritant to the skin, airways and most particularly to the eyes, however it is not mentioned that inhalation of its fumes may also cause headaches and tiredness. These last two symptoms were experienced by members of the HARI project team
on each occasion that they were exposed to KOH vapour for any appreciable length of time. In addition to good ventilation, alkali-resistant overalls, protective headgear, gloves and footwear, breathing masks were also necessary during handling of the solution.

6.e Future developments

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 5.6Nm³ prototype metal hydride store in December 2005, 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 (Hydrogen Solar Ltd 2005). They plan to install one of their first prototype systems at WBF for testing, where it can be integrated with the existing hydrogen infrastructure. They estimate that a 100m² array of their cells can produce enough hydrogen each day in summer to run one car. The disadvantage of this system is that it does not fulfil the demand-side management role that conventional RE-powered electrolysis does (i.e. where the electrolyser is required to fulfil a demand for fuel production, but can be operated as a controllable load on the grid). 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 2kW PEM fuel cell and a small compressed hydrogen cylinder is expected to double this range. A hydrogen refuelling 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. An electrical conversion efficiency of ≈30% is anticipated and an overall CHP efficiency of ≈95%. 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.

Provision has been made at WBF for the installation of a third fuel cell. Modelling of the system is based upon current energy demand at the site, but with expected efficiency gains afforded by the new electrical distribution network, it is hoped that demand will fall slightly. Even so, the simulations suggest that further fuel cell capacity might be needed. When the Totem is converted to run on hydrogen, it will perform the same task, but far less efficiently and so should only be called upon as a last resort. Furthermore, life expectancy for present day fuel cells is not high. Lifetimes of 1500 hours are routinely quoted by manufacturers for PEM fuel cells, although these estimates appear to be conservative, due mainly to suppliers being reluctant to expose themselves to the risk of not meeting guaranteed performances. Experience of many PEM systems in the field, suggests that lifetimes of twice this length and more are achievable in many situations. Such experiences notwithstanding, the issue of replacement of the existing fuel cells at WBF must be considered. The Intelligent Energy fuel cell, for example has come to the end of its lease period and it is still unclear under what arrangement it might continue to be operated there. It is still working, with around only ¼ of its guaranteed lifetime of 1500 hours used up, and so there are no plans to replace it yet. Whether as a replacement, or to increase the installed capacity of fuel cell plant at WBF, there may be a requirement for another fuel cell in due course. At this point the opportunity presents itself to compare the PEM technology, currently in place, with another fuel cell type. The option of a pure oxygen breathing type has already been discussed, but this is unlikely to be available for the foreseeable future. A solid oxide type might also be considered, since it has high efficiency and its high temperature conditions could provide useful high quality heat for integration into the thermal management network at the site. This high temperature operation may, however, also prove to be a major drawback in relation to the device’s intended intermittent operation, since it makes start-up times very long. Perhaps the best contender, then, is an alkaline fuel cell. These have a better life expectancy, a higher efficiency and are less expensive than other types. The cell stack of an AFC has a lower power density than PEMFCs and SOFCs, but with a simpler BOP its footprint may not be all that much different. The disadvantages associated with this type of fuel cell, such as weight, size and the use of a liquid electrolyte (KOH) are of little concern for stationary applications like that of the HARI project and there may even be some compatibilities with the alkaline
electrolyser used at the site. This type of fuel cell has fallen out of vogue in recent years, due in part to concerns over carbon dioxide poisoning, which have since been allayed. However, there seems little reason why they should not experience a renaissance and, indeed, one of these might prove to be the most appropriate for WBF.

The final upgrade under consideration is the replacement of the two existing 25kW Carter wind turbines with a single turbine of similar capacity. As an exact equivalent is not available, the closest match is likely to be a 100kW device, which would give a higher renewable energy harvest for the site due to its greater power rating and, possibly, because a different location may be found for it within the WBF site that will have a better wind regime. It was planning constraints at the time they were commissioned, eighteen years ago, that prevented the Carter turbines being installed in the best location; however the planning environment in the region has changed considerably since that time and the same limitations are no longer expected to apply. The reason that replacement of these turbines is being considered is simply that they are old. Wind power technology of that period was still in relative infancy (their design is 25 years old) and so these turbines have lasted remarkably well, although a twenty year life span should easily be expected of today’s models. They owe their longevity to careful maintenance and the good supply of spare parts, but this supply is becoming increasingly difficult to sustain as time passes. Certainly, they are not as quiet and aesthetically pleasing as modern turbines. These points are of some importance at WBF, because it is a demonstration scheme that is intended to promote the virtues of sustainable energy technologies to a wide audience through a range of outreach activities. From the point of view of the HES, the main advantage of such an upgrade (if it were to happen) is that more hydrogen would be produced to serve the growing demands for its use at the site (e.g. the range extender on the car, the conversion of the Totem and a potential extra fuel cell). It is not clear yet whether total energy self-sufficiency is attainable at WBF, but a better assessment can be made after the electrical system upgrade, which in itself is likely to improve the overall system efficiency. Certainly, based on current information, it will at the very least be a challenge to achieve full autonomy. A further advantage of a larger WTG would be that it would make the currently oversized electrolyser at the site more appropriate in scale, which would improve the overall system efficiency.

Moving beyond West Beacon Farm itself, the experiences of the HARI project and particularly the findings of Amitava Roy have resulted in a proposal to develop a new low
pressure electrolyser. He and the author intend to commercialise an electrolyser technology that will be appropriate to integration with renewable energy power sources. There is considerable scope to improve the efficiency of such a device and, furthermore, the simpler architecture of a low pressure electrolyser system would naturally lead to reduced capital cost, as would the lower specification materials that it would demand. The fact that the cost of the Hydrogenics electrolyser varies only slightly with module size indicates that the BOP plays a disproportionate role in the high cost of the device compared to the module, which is the heart of the system. In a simpler design, the cost of the unit would be far more closely related to the module itself, thus the customer is appropriately “getting what he/she pays for” in terms of function and capacity. Hydrogenics and other electrolyser manufacturers claim to be particularly keen on pursuing the new market for renewable energy powered electrolysis that is expected to emerge, especially as the existing market is fairly static, and yet it is the experience of the HARI project team that they are struggling to adjust their technology to the very different operational environment that this imposes.

The work carried out so far in the HARI project has incorporated only limited financial analysis, as there has been a strong emphasis on technical issues, however there is considerable value in investigating financial aspects of the technologies involved (and competing technologies) in the light of the knowledge gained here. It is anticipated, therefore, that such matters will be tackled in future as part of the ongoing work of the HARI project.
7 Modelling of the hydrogen economy

7.a Round-trip efficiency

One of the clear messages that come out of the experience of the HARI project is that the efficiency of passing through the cycle from electricity to hydrogen and back to electricity is (typically, at 30% or less) poor. This, in itself, is no great revelation. Indeed, many have pointed out that this is the major flaw in the hydrogen economy concept (Bossel 2004; Hammerschlag and Mazza 2005). What is more surprising, perhaps, is the degree to which this is true when theory is put into practice. The HARI project does not claim to have attained the best levels of efficiency achievable by such a system, yet. To date efforts in this project have focussed simply on getting all the parts of this complex system to work together in the first instance. Only then can the real task of getting them to do so with optimum efficiency begin. Even so, the round-trip efficiency of 16% that the model suggests will be attained on the WBF system, shows how much improvement there needs to be and to what extent the reality is more challenging than many hydrogen visionaries might suggest.

All this is not to imply that the hydrogen economy idea is wrong or unworkable, but it should add a strong note of caution to some of the evangelising that is carried out in support of it, since some of the arguments put forward tend to downplay the harsh thermodynamic realities of the situation (Lovins and Williams 2001; Rifkin 2002). There are many variations on the basic theme of the hydrogen economy and the term can mean different things to different people (depending, mainly, upon the area of their expertise or vested interest), but the purist's version might be that the hydrogen economy is one in which all primary energy resources are renewable and carbon neutral and that the energy currencies are electricity and hydrogen. Other versions (Cherry 2004) may to a greater or lesser extent include nuclear power and fossil fuels with carbon sequestration; however, for the purposed of this discourse, the term 'hydrogen economy' will be used to refer to the former definition. Widening the discussion to include the latter 'partial' hydrogen economy will be relevant only after the core idea has been dealt with.

The efficiency of the overall electrical and hydrogen energy system simulated for WBF shows a marked improvement, at 43%, 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. Judicious use of deferrable and opportune loads, reduced consumption through energy efficiency and other demand-side management measures may be used in the future to reduce the storage requirement further, thus improving system efficiency. Optimisation of the HES sub-systems, too, will allow efficiency gains, but the clear lesson is that, wherever possible, electricity should remain as electricity in the system until it is consumed by the end-user appliance. Indeed, it implies that 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). What hydrogen should do in a hydrogen economy, however, is to provide fuel and (via electrolysis) a controllable load by which the supply and demand on the utility grid can be balanced. Quite simply, the conversion of energy from one form to another is wasteful and so should be avoided where possible. This means that – from an efficiency viewpoint – conversion, even of biofuels to hydrogen, is not necessarily beneficial, although there may be other, more compelling reasons to do so. Indeed, efficiency is not often considered the most important imperative in the application of most technologies, but financial return on investment usually is. Efficiency, though, underpins the financial drivers of most technologies and its influence will be increasingly felt as we are forced to end the profligacy brought about by artificially cheap energy supplies. Environmental concerns and energy security issues are likely to necessitate the internalisation of what are currently considered external costs (Klaassen and Riahi) before too long. This will create a more robust financial case for environmentally benign technologies and make them less sensitive to efficiency concerns, since inefficiencies in non-polluting energy technologies do not exacerbate the problems of climate change like they do in conventional plant. They do, however, still lead to higher costs, even when the source of energy is essentially ‘free’ (e.g. wind, solar, wave, etc), because they still entail higher capital and operational expenditure.

7.a.1 A new hydrogen economy model

There may be a tendency for commentators on the hydrogen economy to look at the transport or power sectors in isolation (depending on their area of expertise), resulting in arguments that were weakened by the thermodynamic realities they overlook. The hydrogen economy concept only makes sense when a holistic view of the total energy system is encompassed
and there are encouraging signs that more integrated overviews are now gaining currency (Colella, Jacobson et al. 2005; Granovskii, Dincer et al. 2006; Poudenx and Merida 2006). What the HARI project’s findings can add to this debate is a clearer understanding of the role of hydrogen as both fuel production and grid management mechanism.

In a ‘pure’ hydrogen economy, all energy sectors must draw on the primary resource of renewables. This includes heat loads, portable power, remote power and all forms of transport as well as the electricity grid. 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.

This does not mean that there will never be a shortfall of supply for the grid, but it does mean that the frequency and duration of such deficits are reduced, which in turn reduces the need to store electricity. Less electricity that was converted to hydrogen, therefore, tends to get reconverted back to electricity (except for motive power in vehicles). Furthermore, where it does, the electricity should at least be generated in CHP plants to maximise the overall efficiency of the process. Indeed, CHF (combined heat and fuel production) should be applied on the hydrogen production side of the process (electrolysis), as well as the consumption side, to maximise efficiency. Redox flow cells could be used as an alternative in this instance, because – at around 70% efficiency (Ponce de Leon, Frias-Ferrer et al. 2006) – they offer a more efficient electricity storage method than hydrogen; however this depends upon the successful development of commercially viable redox flow cell systems. Of course, the most efficient large-scale energy storage technologies in this situation would be pumped hydro and pressurised air systems (Kondoh, Ishii et al. 2000), but these are only deployable in very rare locations that have the appropriate topology or geology, in contrast to hydrogen, which is highly adaptable and widely applicable.

In this scenario, when viewed from the point of view of the power sector, electrolysis is mainly a load-balancing mechanism that happens to produce hydrogen fuel as a by-product, whereas from the transport sector’s perspective, it is simply the source of non-polluting fuel. Hydrogen will most likely be generated largely at the point of use, the vast majority of it in forecourt electrolysers (Kaul and Edinger 2004; Huang and Zhang 2006). For electrolyser
operators, revenue may be earned both by selling fuel at the garage forecourt and for the
provision of grid management services to utility companies. This can be done by modulation
of hydrogen production in response to the frequency of the electricity grid. Through an MSc
research project at CREST, this principle has been investigated in relation to fridges and their
potential (when aggregated across the UK) to provide a significant controllable load for use
in grid management (Short 2004). When applied to electrolysis, the aggregation of such a
network of controllable loads, allows the modulation required for grid balancing purposes to
be far more gentle than those experienced on a small scale system like that of WBF. This
means that the electrolysers can all be operated relatively close to their optimal level, leading
to much higher efficiencies. The aggregation of the various primary energy resources on the
grid will also be significant, thereby also reducing the modulation required by the electrolyser
load. The most expensive lifecycle cost of electrolysis is the energy input (Mercuri, Bauen et
al. 2002; Wietschel, Hasenauer et al. 2006), but in a load balancing capacity this cost is, by
definition, very low – maybe even free – because the electrolyser is absorbing surplus grid
power. Indeed, some have argued that an economic case can be made for applying this
already (Pritchard 2005).

7.b Scenario building and roadmapping

As with any journey, it is important to know the destination before embarking upon it,
otherwise the traveller cannot make an informed decision about the direction of each step
along the way. This does not mean sticking to a rigid plan or being unresponsive in changing
conditions. On the contrary, it ensures the traveller does not meander aimlessly, simply
taking the path of least resistance with no reference to the final goal. It is important when
planning a sustainable energy future that we define the desired end point before deciding on
how to get there, particularly if we are to avoid costly mistakes and technical cul-de-sacs.
With this in mind, the author is undertaking further work in this area to define end-point
scenarios and subsequently use a process of back-casting to draw up a roadmap for how to
get there. It is not necessary at this stage to define a date for reaching the final destination
scenario, as this is down to the will of policy makers industry and the public, although it is
the belief of this author that the urgency imposed by the threat of climate change clearly
indicates that the sooner the destination is reached the better.
7. b. 1 Aggregation of supply and demand

The basic principles of balancing supply and demand by means of energy storage on a RE based system are clearly illustrated at WBF, but were this to be applied at larger scales, the aggregation of loads and RE resources would reduce the severity of such dynamics (Barton and Infield 2004). Being a very small-scale system, WBF represents an extreme case (Figure 7-1), however in moving to community, regional and, ultimately, national scales, the aggregation effect increases with size. This means that system efficiencies will also improve with scale as a result of diminishing storage requirements. Loads on energy networks are smoothed by aggregation, since all users on the system are unlikely to switch on loads entirely in unison (except, famously, when everyone puts the kettle on at half time in the World Cup final). Wind, solar, wave and – to a certain extent – hydro power sources are obviously affected by passing weather systems, but if their deployment is spread across a large geographical area (as would be the case for national systems, even in a small country like the UK); different generating regions are hours, even days, out of synchronisation with each other. This means that, though it might be calm in Cornwall, it may be quite windy in Scotland. Even tidal power, which is unchanged by the weather, shows asynchrony in different regions as the tidal surge moves through a country’s national waters. Furthermore, with a broad mixture of renewable generation technologies installed, aggregation between the various energy resources is achieved, because if the sun is not shining, for example, at least the wind might be blowing, there might be some water in the reservoir after the previous day’s rain and there will always be some despatchable supply from the biomass resources. All this leads to a more constant supply, a degree of predictability and a significant reduction in the need for storage.
Further work is being undertaken by the author to investigate the effect of load and supply aggregation, using a range of renewable energy sources, on a national scale across the UK. To this end the author has recently supervised an undergraduate student carrying out research in this area (Forrester 2005) and is himself conducting ongoing research on the subject. This is intended to firstly answer the question “Is it technically possible for the UK to self-sufficiently exist as a pure hydrogen economy and, if so, what form (or forms) would such a scenario take?” Several questions that might follow on from that will also be investigated, such as: “If this is not possible, what compromises would be needed?” “What more pragmatic options are possible or are likely to be pursued (on political or economic grounds)?”, “What routes could be, or should be, taken to reach this (and any alternative) scenario?” Qualitative answers to some of these questions can already be anticipated. Nuclear power, ‘clean’ coal and other fossil fuel supplies (coupled, it is hoped, with carbon sequestration) are bound to be included for the foreseeable future (DTI 2003). Also, the need for self-sufficiency may be a more strict stipulation than reality demands, but it is explored on the assumption that all nations will struggle to supply their own needs in this way, let alone have energy to export to others. Any international energy trading would therefore be more likely based on the exploitation in time-zone related demand displacement and less on the
selling of energy surpluses. The continuation of this line of enquiry, though, aims to provide quantitative answers to these questions, as well.

In the Forrester study, two scenarios for supplying the UK's energy from REs were analysed. The 'Practicable' scenario, shown in Figure 7-2, took a reasonably pragmatic, modestly ambitious view, while the 'Maximum' scenario, in Figure 7-3, explored what would be possible by stretching the UK's RE potential to its limits (requiring some very tough political decisions). In the Practicable scenario, there was a considerable shortfall of RE supply, which would have to be supplemented with major efficiency gains (energy efficiency should be considered "the first renewable"), nuclear power and fossil fuels. The variation in primary energy supply was such that there were substantial periods of oversupply, even though the yearly average fell far short. A simplified version of the Maximum scenario, illustrated in Figure 7-4, shows that there would only have been 4 hours of supply deficit in the whole year. Although this is an extreme case, it serves to demonstrate how the role of electrolysis fits into a renewable energy system, where grid electricity storage through hydrogen has been minimised. In this hydrogen economy scenario (and in variations on this basic theme), the gap between the combined supply line (blue) and the electrical demand line (magenta) would be filled by electrolysis. The point is emphasised more clearly in Figure 7-5 (an adaptation of the Michael Forrester graph), 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 by electrolysis, which is a controllable load, used for grid balancing, and 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 primary (renewable) energy conversion device, even – if possible – in the 4 hours of deficit, which might be accommodated by other storage technologies besides hydrogen. Once converted to hydrogen, the energy remains in that form until used on board vehicles, but does not get converted back to grid electricity. Figure 7-6 shows how supply and demand variations would be smoothed by averaging over monthly periods. The ideal scenario, which has not been modelled yet, would be somewhere between these two where the supply and demand balance over timescales that are dictated by the storage capacity in the system. Taking the Maximum scenario as a starting point, the installed capacity of REs on can be reduced until an acceptable storage period is reached (i.e. somewhere between the hourly variation in Figure 7-3 and the monthly variation of Figure 7-6). This storage period will be largely dictated by the capacity of hydrogen stored at garage forecourts, which is
assumed be the main outlet to the end user. 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 7-2: “Practicable” renewable energy scenario. (Source: Michael Forrester)

Figure 7-3: “Maximum” renewable energy scenario. (Source: Michael Forrester)
Figure 7-4: Simplified version of the “Maximum” renewable energy scenario, showing combined renewable energy supply and the load on the electricity grid. (Source: Michael Forrester)

Figure 7-5: In a hydrogen economy 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. (Adapted from data supplied by Michael Forrester)
Although this work is in its early stages, early indications are that it might be technically possible to achieve a pure hydrogen economy in the UK, but at enormous cost, and that political and economic pressures will make a much more mixed partial hydrogen economy scenario likely, even in the long term. Assuming it were eventually possible on a pragmatic level to achieve a pure hydrogen economy, there would still remain many years in the meantime in which bridging technologies, such as hydrogen powered ICE’s instead of fuel cells, fossil-fuel derived hydrogen instead of ‘green’ hydrogen, hythane in the gas network, and so on, will be used. What is evident, though, is that a hydrogen distribution network is unlikely to replace an electrical distribution grid. There are a number of reasons for this. Firstly, the electricity grid is a reasonably efficient method of moving energy around, being on average 75 – 85% efficient (Hammerschlag and Mazza 2005), whereas hydrogen pipelines are best suited to high flow, short distance applications (Joffé 2006). Secondly, the majority of the electrical infrastructure is already in place, although certain parts of it will need to be reinforced and extended to bring power from the areas where the bulk of the RE resource is located to regions of high energy consumption (Dondi, Bayoumi et al. 2002; Alberg Ostergaard 2003). Finally, there is no extensive hydrogen pipeline network and the existing natural gas network would need extensive refurbishment if it were to be used. Pipelines in
the USA already leak up to 2.2% of the natural gas they carry (Dedikov, Akopova et al. 1999) and hydrogen is even more difficult to contain than methane (Jasionowski, Pangborn et al. 1980), as has been highlighted by the experiences of the HARI project, which suffered significant leakage in its early stages and still does experience minor leaks.

7.b.ii Energy infrastructure

Electricity is an excellent means for the spatial displacement of energy, whereas hydrogen is a good means of achieving temporal displacement of energy, so in a future energy system the complimentarity of these two energy currencies can be exploited. This means that the notion of most houses having a hydrogen powered fuel cell CHP unit, fed by a national hydrogen grid is may be unlikely in the pure hydrogen economy scenario (Hoogma 2006). In the meantime, however, it is quite possible that this will be a bridging technology, where a combined reformer and fuel cell unit will be used in the domestic environment for CHP generation. Since hydrogen will be injected into the natural gas supply, these could be fuelled by hythane.

Most of today’s heating loads that are served by burning liquid or gaseous fuels could equally be fed by electricity and, in some cases, more efficiently so. Again, in a post-fossil-fuel economy this means that the electricity generated by the primary RE sources does not undergo any further wasteful conversion process before reaching the heat load. In the rare situations where a fuel is still required, that fuel can be hydrogen and the heat generating technology may be a catalytic burner. Almost all the hydrogen produced should therefore find itself used as a transport fuel, or in portable and certain niche stationary-power applications. It should also be recognised that there is a strong argument for extensive use of batteries in light vehicular transport, since most car journeys are comparatively short (more than 75% of them being less than 10 miles (Department for Transport 2005)) and can be served more efficiently by battery power alone. Hydrogen’s role here becomes predominantly one of range extension in light-duty vehicles, but more universal in larger vehicles, and might even warrant the use of different vehicles for different journey lengths. It is tempting to postulate a number of potential directions that the future of transport infrastructure and technologies might take, but since it is a huge subject in itself with a vast range of potential scenarios, it is beyond the scope of this discourse to discuss this in any more depth (McHenry 2004; Kempton and Tomic 2005; May, Allsop et al. 2005; Curry,
Hodgson et al. 2006). This cursory analysis does, however, underline the basic principle that batteries represent one of the few potential threats to the idea of a hydrogen economy. Even so, it will require a step-change advance in battery technology for it to displace hydrogen as the leading contender in the quest for large-scale, long-term, adaptable and widely applicable energy storage. Although storing energy by means of hydrogen carries a heavy efficiency cost, the charge leakage that most batteries experience means that, over long periods, their efficiency eventually reduces to zero. The other major alternative to the widespread use of renewables for clean, indigenous energy production would be extensive use of coal in conjunction with carbon capture and sequestration. This, at least this is a dispatchable power supply and so reduces the need for energy storage, but one of the main contenders for the carbon capture process involves gasification of the coal to make hydrogen, which is burned in the power station (Chiesa, Consonni et al. 2005; Stiegel and Ramezan 2006). Moreover, the requirement for a clean transport fuel still needs to be fulfilled, so in the end, it is hard to see sustainable energy system for the future that does not contain a sizable hydrogen component.

The hydrogen economy concept can justifiably be criticised for its various flaws. Hydrogen is, for example, inefficient if used to store grid electricity without heat capture and utilisation and much of the technology associated with hydrogen energy systems is still immature (as experienced in the HARI project) and therefore very expensive. In its favour, though, few technologies look close to challenging it in offering a serious alternative. The efficiencies of most conventional energy technologies are worse than those of hydrogen energy systems when performing comparable tasks (e.g. fuel cells versus coal fired power stations or internal combustion engines, etc) (Hart and Hormandinger 1998; Ahluwalia, Wang et al. 2004). With few moving parts, hydrogen based devices tend to be quieter, vibration-free and suffer less mechanical wear. The technology (electrolysers, fuel cells and various methods of storage) is extensively modular, making it highly adaptable to a huge range of applications from scales of watts to megawatts, from small-scale portable devices up to large-scale stationary plant and all forms of transport (except, most likely, motive power for aeroplanes). In a hydrogen energy storage system, charge rate, discharge rate and storage capacity are all independently variable, unlike batteries, which gives hydrogen further flexibility. Once these technologies reach a critical-mass in the market place, their universality is bound to become self-propagating as prices fall. They may even be applied in situations where they do not provide the best technical solution, in the same way that, for example, car batteries are sometimes used in PV installations (in spite of their lack of tolerance for deep discharge cycling), simply
because their ubiquity makes them the cheapest most easily obtainable solution (Huacuz, Flores et al. 1995). Furthermore, in some respects, hydrogen may become an important part of the future energy mix, not necessarily because it is the best solution (the example of Betamax versus VHS illustrates how the best technology does not always win), but because decisions are taken by industry and policy makers that it will (Armason and Sigfusson 2000; The White House 2003; AFX News Limited 2004; Schwarzenegger 2004). Indeed, Romano Prodi, when he was European Commission President, compared the implementation of the hydrogen economy to the US space race of the 1960's (Miller and Duffey 2005), where a similarly daunting technological quest was driven by a political decision. The major difference between that situation and this, though, is there is far less money coming from governments to back up the intention (Dunn 2002). It is important, therefore, that decisions about the deployment of these technologies are well informed, in order to avoid costly mistakes. The fact still remains that, for all its flaws, hydrogen is probably the only viable option for the bulk energy storage role in a future sustainable energy system, even though it may come at a high energetic or financial cost. The prize of large-scale, long-term widely applicable energy storage is — like anything of such high value — bound to come at a price. Were this not the case, it would surely seem too good to be true!

The potential resurgence of nuclear power, or — if it is ever proved viable — the introduction of nuclear fusion, does little to reduce the need for hydrogen, since both technologies have very limited load-following capabilities (El Osery 1984). This explains the enthusiasm for hydrogen shown by many in the nuclear industry. Some in the renewable energy arena attack the concept of hydrogen energy and the importance given to research in this area for drawing much needed resources away from renewables (Cherry 2004), however many of the arguments levelled at renewables, centre on their intermittency, their unpredictability and claims that their capacity must be matched with spinning reserve. Unless the ambitions for REs go no further than a 10 — 20% penetration (Milborrow 2000), the only way to counter such attacks is by calling on energy storage in their defence. Far from threatening renewables, then, hydrogen helps to promote them. Before long, situations will arise where the further deployment of REs depends directly upon their integration with hydrogen energy storage capabilities. Already, advice has been sought from the HARI project team, where the installation of a wind farm would be prevented by the unwillingness of the utility company to reinforce the grid to accommodate it. The proposed solution was to use electrolysis to absorb peak outputs, thereby producing hydrogen to fuel a local bus service (in preference to the
regeneration of grid electricity). The symbiosis between REs and hydrogen is clearly of mutual benefit to both. Indeed, the challenge of global warming appears so great that the problem will require that we throw everything that we have got in our arsenal at it (King 2004). This means that these different energy technologies should not be seen as being in competition with each other, but rather as part of a mutually supportive network all striving for the same end (as members of a team must pull in the same direction).

Significant advances are needed before hydrogen becomes truly practical in most energy applications envisaged for its future use. Iterative advances in hydrogen and fuel cell technologies are required to stimulate a number of early-adopter markets, but a quantum leap—particularly in finding a compact, light-weight hydrogen storage method—is necessary before hydrogen can become ubiquitous. It currently suffers from the chicken-and-egg problem, (seen in the past, for example, in the wind industry (Kobos, Erickson et al. 2006)) that a market does not exist because prices are so high, but prices will not fall dramatically until the market takes off. If left purely to market forces this situation will surely not change, therefore government support in these early stages could be vital to unlocking the potential of hydrogen for future energy sustainability.

7.b.iii Early adopters

Today, 2 billion people still do not have access to grid electricity (Rodriguez Monroy and San Segundo Hernandez 2005). While this represents a huge potential market for integrated hydrogen and RE systems, it is also true that the vast majority of people in this situation are desperately poor and even less able to afford this technology than anyone else. Despite this, there are still many market opportunities for this technology in less deprived situations. Early adopters for such systems are largely in portable power applications, remote (Iqbal 2003; Shakya, Aye et al. 2005; Coince - date unknown), or island (Glöckner, Kloed et al. 2002; Gómez-Gotor, Lymberlopoulos et al. 2003; Bechrakis, McKeogh et al. 2006) communities with weak or non-existent grid connections, remote telecommunications (Peter Lehman) and remote monitoring. Even in some urban communities, particularly in the developing world (Muneer, Asif et al. 2005), where electricity supplies can be unreliable or intermittent, or where the cost and pollution associated with more conventional fuels is a problem, hydrogen may soon be able to play a role in the improvement of energy services. Certain specialist transport applications (Adamson 2005), such as forklift trucks, golf buggies and boats (where
the weight of the storage medium makes good ballast), fleet vehicles (e.g. delivery vans and busses) provide early opportunities for hydrogen ICEs or fuel cells to be deployed. RE-powered electrolysis may, even at this early stage, prove to be the best source of hydrogen for these in some situations. In Unst, for example, where there is already a hydrogen and renewables demonstration project that follows the HARI model, petrol is extremely expensive, due to its remote location. The potential for further exploitation of the technology to answer this problem has been highlighted and met with great approval from the local community (Brown and Marter 2005).

7.b.iv Stand-alone and national systems

Many of the early adopters are expected to be stand-alone applications like the one demonstrated at WBF. These will not have the 'safety net' of being able to reconnect to the grid in an emergency, which is a luxury that WBF will retain, so it is important that initiatives like the HARI project are able to prove the reliable operation of such systems before they are deployed 'in anger' in the real world. Initially, these installations will tend to be at the small scale, perhaps at community level (Bull-Hansen and Hammerstad 2003; Gazey 2005), but as the penetration of REs onto all energy networks increases, they may start to look ever more like larger versions of this scheme. The major difference, though, that this discussion anticipates, is that the wider implementation of such systems would tend to favour hydrogen as a transport fuel rather than the stationary power application for which it is currently employed in the HARI project. Ultimately, national and international energy networks are just very large autonomous energy systems (even if they amount to planet-wide ones), for which the same basic principles will probably apply. As has been discussed, the experiences of the HARI project may offer important lessons for sustainable energy networks of all scales.

Due to the high levels of wind energy penetration already established on the Danish grid, studies have been undertaken to investigate the efficacy of hydrogen energy storage in that region (Sharman 2004; Sorensen, Hauge Petersen et al. 2004). These suggest that, in Denmark at least, the introduction of bulk hydrogen energy storage may become a reality sooner than many people expect. The Danes might be followed quickly by the Spanish and Germans, who also have large installed capacities of wind power. Already on some Spanish and Greek (Gómez-Gotor, Lymberlopolous et al. 2003) islands, wind power is in danger of
being curtailed at periods of high output, where hydrogen could provide a more productive grid management technique.

7.c Economic modelling

Economic (and, no doubt, social, political and environmental) considerations are bound to force adjustments to this basic hydrogen economy model to be made, however they must be founded upon a sound technical case, too. As this research progresses, it is intended that financial modelling will be incorporated into the analysis, but time has not yet allowed this. Furthermore, as has been discussed already, the economic case must logically proceed only after the technical case has been fully understood. In view of this, no economic assessment of potential hydrogen economy scenarios is presented in this thesis.
8 Conclusion

The aims of this project have been broadly achieved and the success, or otherwise, of the stated objectives are discussed below along with any conclusions that are drawn from this study.

A hydrogen energy storage (HES) system has been successfully designed and installed as part of a research programme known as the Hydrogen and Renewables Integration (HARI) project, which was initiated and overseen by the author of this thesis. The HES system comprises an electrolyser, compressor, pressurised hydrogen storage cylinders and two fuel cells. This was successfully integrated into an existing renewable energy (RE) system at West Beacon Farm (WBF), Leicestershire, UK, to provide long-term energy storage. The HES system absorbs energy when there is a surplus of RE output to meet loads on the system and provides energy when there is a shortfall. The absorption of energy is carried out by the electrolyser as it uses electricity to produce hydrogen by the disassociation of water. The hydrogen is stored under pressure and used to create electricity, when needed, via fuel cells.

A methodology has been developed for the design of integrated hydrogen and renewable energy systems based on the application of a software facsimile of the combined hydrogen and RE system at WBF. This model has been built in Matlab and Simulink and validated against the real-world operation the HARI system. It encompasses the complete energy system at WBF (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.

Since some subsystems are in the process of being upgraded as part of a separate but integrated study, it has not been possible to verify the battery model and only a limited verification of the fuel cell model has been possible. Certain other components, such as the hydrogen compressor and water purification plant, have not been monitored accurately yet, but the models would clearly benefit from more detailed characterisation of these devices. Software models of the other major components have, however, been validated against their real-world performance and, once the data becomes available for the those that are not fully validated yet, only modest adjustments will be needed to complete the model. The complete model of the system, then, cannot be said to be fully verified yet, due to the limited time that
has been available to undertake such a large project and because some aspects are dependant upon the completion of parallel research activities being carried out by other PhD students.

Data initially used for the sizing of components at the design stage of the project suffered from significant inaccuracies due to the very limited nature of information made available by the manufacturers, but were improved considerably through the subsequent operational experience gained. This is particularly true of the electrolyser, which was later shown to be oversized for its task at WBF by 39%, on account of the wrong information initially being supplied about the power consumption of its balance of plant (BOP). Also, it was only revealed part-way through the procurement process that 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 into a hybrid energy storage system.

This project demonstrates that an HES system can be integrated with RE devices to create a stand-alone energy network. It is fair to say, however, that there were significant challenges above and beyond those anticipated. To operate on a stand-alone basis, it is necessary to upgrade the electrical system (which is being carried out for another PhD study), but this process is only partially complete at this stage, so the system is yet to operate continuously in this mode. The current status of some of the technologies involved is such that they are not ideally suited to the tasks required of them in the HARI system. Of these, the most notable are the Hydrogenics IMET electrolyser and Plug Power Gencore fuel cell. The electrolyser is designed to operate on a continuous, steady-state basis, whereas it must operate dynamically and intermittently at WBF. The Gencore is designed specifically as an uninterruptible power supply (UPS) rather than for the general power supply purposes demanded at WBF.

The electrolyser operated less efficiently than the manufacturer's quoted performance level because it is designed to work more-or-less continuously at close to rated capacity (i.e. with a very high capacity factor), whereas the situation at WBF demands that it usually runs at part load and spends the majority of its time on standby. This resulted in a mean conversion energy being measured, for the electrolyser module itself, of 4.38kWh/Nm³, which is an efficiency of 75.2% (using HHV at NTP). This represents a conversion energy of 4% higher than that quoted by the manufacturer for rated capacity (or 12% higher than optimum level).
A part of this, it should be noted, is due to a certain amount of stack degradation that had occurred through the intermittency of its operation over almost two years in use. Furthermore, due to an electrolyte leak, there was with a reduced potassium hydroxide (KOH) concentration when the validation test was being conducted. The latter (which might account for up to 2% loss of efficiency) can be fixed, but the degradation of the module is a permanent feature of the device. Fortunately, this deterioration, which was rapid at first, seems to have stabilised in recent months.

At WBF, as in most situations, a compressor must be included in the system to boost the pressure of the hydrogen if the store pressure is above that of the electrolyser's output. A battery must also be included in support of the electrolyser, due to the intermittency of operation and the frequently low levels of energy (i.e. periods of surplus RE supply) available to it. The battery can reduce the amount of on-off cycling (which degrades the cell stack) and it can absorb energy at levels that fall outside the electrolyser's input range. The module efficiency is therefore not a good guide to the real conversion energy of converting electricity to compressed hydrogen, as it ignores BOP losses. A more accurate measure of conversion energy in the WBF system, which includes the electrolyser, battery and compressor, was found to be 6.74kWh/Nm³. This equates to an efficiency of 48.8% (using HHV at NTP) and represents a 60% lower efficiency than that claimed by the manufacturer for the module alone at rated capacity (or 73% compared to its quoted optimum level). This study highlights the point that the claims of manufacturers - and conversion efficiencies that are quoted more generally - should be treated with a great deal of caution. With such an emphasis on module efficiency, even the manufacturers themselves may not be clear about the level of BOP losses.

The round-trip efficiency of the cycle from electricity to hydrogen and back to electricity again, is shown by the model (using experimental data) to be 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 43% This 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. Furthermore, considering the groundbreaking nature of this work, it is challenging enough to get the whole system functioning at all in the first instance, so to getting it to work with high levels of efficiency must realistically be conceded as a subsequent undertaking.

It should be noted, therefore, that the work carried out so far in the HARI project represents only the first phase in what is intended to be ongoing research. This phase has merely laid the foundation for the perhaps more valuable later stages, by establishing a high quality and unique research facility. It is hoped that the next phase will focus on continued operation, in-depth monitoring, performance analysis and accurate modelling of the system over the long term. This should begin with a full energy audit of the complete WBF energy system (including thermal energy). The final phase should be concerned with implementing the improvements to hardware and system management that will bring the ultimate benefits of greater efficiency, durability and reliability of these systems and reduce costs.

Since the majority of the losses (that ranged from 11 – 28%, depending upon operating level) in the electrolyser system were in the conversion from AC to DC, particularly where the power electronic devices were operating at part load, this might be one of the most fruitful areas for further investigation if significant improvements are to be made in system efficiency.

One of the main improvements in hardware proposed by Amitava Roy, a member of the research team currently working on the HARI project, is for the development of a new electrolyser specifically designed for use with RE power inputs. This device should be able to withstand intermittency without degradation in performance; it should be much more efficient, durable, reliable and simple in design and — above all — significantly less expensive. One major factor in meeting these stipulations will be that the new electrolyser will operate at low (near to ambient) pressure, which goes against the current trend in the industry.

One of the significant BOP loads in an electrolyser system is the water purification plant, which is typically a reverse osmosis (RO) type. It must produce water of very high purity and this consumes considerable amounts of energy and water resources. Where there is a fuel cell also in the system, very pure water is being produced. In the case of the HARI project, this by-product water from the fuel cells has been tested and its purity is high enough for it to
be pumped directly to the water feed tanks for the electrolyser. This can save energy and water. Like many situations where a system like the HARI scheme would be appropriate, WBF is not connected to a water main and so water is a precious resource that has to be collected as rainwater. Even if the water were not pure enough to be recycled in this way, it is possible that the low flow rates required of the water supply system at WBF, would allow purification by a filter bed process alone, but this requires further investigation.

The principle of combined heat and power (CHP) is well established, but the waste heat from the HARI project's electrolyser also represents a potential source of useful energy. By capturing and using this heat, the notion of combined heat and fuel (CHF) can be implemented. To do this effectively would involve insulating parts of the electrolyser, which would have the additional benefit of keeping it closer to optimum temperature during dynamic and intermittent operation.

Economic questions have not been dealt with in any depth in this study, due largely to time limitations; however this aspect is clearly a very important part of assessing and improving the viability of HES, RE and stand-alone energy systems. Indeed, the emphasis placed on technical performance and, in particular, efficiency throughout this thesis ignores the common tendency to measure efficiency, not in technical terms, but as return on investments. However, since technical viability must be a prerequisite of commercial viability, it makes sense to pursue financial considerations in subsequent research, which the author is planning to undertake.

In this project, an integrated hydrogen and renewable energy system has been operated for two years on a year-round, day-to-day basis. Availability of components has been variable, but this is only to be expected of pioneering endeavours such as this. The majority of devices that suffered low availability did so because they were being asked to perform tasks that were not exactly what they were designed for, but for which they were the closest fit available on the market at the time of procurement for this project. Day-to-day management of the system requires careful monitoring, therefore, for signs of potential malfunctions of sub-systems and components.

Significant experience has been gained, giving valuable insights into issues relating to the design, installation and operation of integrated hydrogen and RE systems. One of the first
and most important lessons to emerge from this project has been the realisation that the limited operational range (typically 20 – 100% of rated capacity) of current electrolyser technology demands an integrated battery store to support it when used in the context of a stand-alone RE system. In fact, this serves to emphasise the benefits of incorporating both battery and HES capacity in such a system, since this hybrid configuration exploits their complementary characteristics.

Leakage of hydrogen proved to be a major issue in the early months of operation. Hydrogen, having such small molecules, is more prone to leaking than all other gas except helium. It should, therefore, be no surprise that its containment would be a challenge, but the scale of the problem was not anticipated. Detection of leaks was difficult, particularly where it was outdoors or through valves into vent pipes rather than into rooms, for example, where hydrogen detectors were situated. Leakage is best minimised by keeping the number of joints in pipework and the extent of high pressure areas to a minimum.

Pressure measurement in the hydrogen store also proved surprisingly tricky. The 48 cylinders were situated close to a high wall which reduced air circulation around the installation and shaded most of the cylinders from the sun. A complex relationship between weather conditions and the temperature of each individual cylinder became evident, such that a simple measure of aggregated pressure corrected for an ambient temperature measured close by, did not give an accurate guide to the amount of hydrogen in the store. A more accurate assessment was made from the cumulative production and consumption of hydrogen measured by mass-flow metres.

The quality of data acquisition (DAQ) is crucial to a project like this and it took about 2½ years to design and implement the monitoring system used for this study. Even then, more parameters would ideally have been recorded (e.g. photovoltaic cell temperature, hydropower generation, energy consumption of water purification and hydrogen compression, individual hydrogen cylinder temperatures, etc.) and adjustments made to existing DAQ components (e.g. to improve the positioning of solar irradiance sensors). Indeed, even the computer used for DAQ purposes struggled to cope, such that it had to be monitored itself to ensure that it did not crash as a result of memory overload. Particularly demanding was the power monitoring for the electrolyser as it necessitated a fast scan rate (on a DAQ card with no internal buffer) to show the detail in the complex waveform of the current. Although the
energy system, including HES components, has operated more-or-less continuously for over 2 years, only relatively short periods of reliable data have been available for some aspects of this study. The electrolyser model verification, for example, is based mainly on about one day's operational data, while the longer-term renewable energy and overall-system modelling uses around 3 months' worth of data.

The Gencore suffered from poor reliability and, while on standby, created a standing load estimated to average 100 – 200W. Over long periods, this amounted to an accumulated consumption of significant amounts of energy (4.8kWh/day). These problems are not necessarily a criticism of the device itself, but are largely a result of employing the device for general power supply purposes when it was designed specifically as a UPS unit. The Intelligent Energy fuel cell did not suffer these disadvantages. Standing losses are also a feature of the electrolyser, battery, monitoring and control system and power conversion devices. Although they appear small on an individual and instantaneous basis, the aggregated energy loss can be substantial. This is particularly apparent for equipment that consumes power during long periods in standby mode. It is intrinsic to the nature of RE-based systems that many devices will have low duty cycles, because RE resources tend to arrive in short, intense bursts, with long gaps in between. Typically, a windy period may last for 2 – 3 days with a week's gap before the next windy period arrives, for example. Reducing standing losses and, where possible, designing systems to consume no power in standby mode (as the Intelligent Energy fuel cell manages to achieve), can therefore significantly enhance a stand-alone energy system such as this.

Safety issues have naturally featured strongly in this project, both in relation to the handling of large quantities of pressurised hydrogen gas and the handling of KOH electrolyte solution. In the case of the hydrogen, careful liaison was maintained with the Health and Safety Executive throughout the planning and implementation stages of the scheme and careful consultation was carried out in cooperation with BOC who have extensive experience in the handling of hydrogen. While the flow of knowledge in relation to hydrogen safety issues was almost entirely inwards for the HARI project team, some of the knowledge gained about the handling of KOH may be important to share with a wider audience. The standard information sheets for KOH mention a number of hazards associated with it, such as its corrosive nature, irritant effect on the skin, airways and – most importantly – the eyes, but none mentions that it may cause headaches or tiredness. However, it was the experience of
members of the HARI team that severe headaches and tiredness resulted from exposure to KOH fumes over a matter of hours.

Lessons have also been learnt through this project that relate to the wider debate on the nature of a potential hydrogen economy. Further work is required to add substance to the basic principles expressed here and so the author plans to undertake continued research in this area as time allows. Meanwhile, the ideas presented here could be considered speculative, since they are founded upon the experience of the HARI project, but are extrapolated beyond its immediate scope.

The knowledge gained through this research offers a note of caution to some 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 obvious alternative has yet been proposed. However, what it does suggest 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. Sometimes, for example, the efficiency values given for electrolytic production of hydrogen fail to take account of the substantial balance of plant (BOP) losses in the process. Such omissions lead to misunderstandings that fundamentally affect some of the more short-term assumptions, predictions and decisions made about how we might take steps towards creating a sustainable energy industry, as well as the longer-term projections about future energy scenarios. Failure to fully comprehend the technical issues will inevitably lead to costly mistakes which we can ill afford.

Clearly, converting energy from electricity to hydrogen and back to electricity again is a wasteful cycle, which must be considered only as a last resort, but which may be unavoidable in certain situations. This inefficiency is due to the inherent losses associated with converting energy from one form to another, a process that is undergone twice in this sequence. This indicates that, 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 therefore be used in applications, such as transport and remote or portable power generation, where only a fuel is able to do the job. Contrary to many ideas proffered about the nature of the hydrogen economy, this emphasises
the point that hydrogen is unlikely to be viable for the storage of grid electricity. In a post-
fossil-fuel energy system, the primary RE (and, maybe, nuclear) 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 generating grid electricity alone. The substantial controllable load
that will be required to balance energy supply and demand on such a network is likely to be
electrolysis (where a demand for fuel exists), largely at garage forecourts, providing fuel to
hydrogen powered vehicles. Revenue can then be earned by the operators of such
electrolysers from selling fuel and also from grid management services. This scenario would
reduce the incidence of the wasteful energy conversion cycle and implies that hydrogen
production will be at the point of delivery to end users. The electricity grid will probably
remain the predominant method of energy transmission, rather than a hydrogen pipeline
network (except in certain specific circumstances). The assumption is, in effect, that energy
will tend to be displaced spatially by electricity and temporally by hydrogen, thus playing to
the strengths of both these energy currencies. It also means that it will be necessary to have a
substantial installed capacity of electrolysis plant (for grid management purposes) and
hydrogen storage facilities (providing transport fuel). Fuel cells may be used widely in
portable power, remote power and transport applications, but their use for stationary power in
a ‘pure’ hydrogen economy is likely to be limited to particular niches. The number and
breadth of such niches will, at least, be enhanced where the fuel cells’ by-product heat is
made use of in CHP or tri-generation (CHP and cooling) systems or in combined-cycle
generation, such as that envisaged for Rolls Royce’s fuel cells. That is not to say that fuel
cells for stationary power generation will not find substantial markets as a ‘bridging’
technology on the long path to establishing a full hydrogen economy. This slow transition is
anticipated to provide substantial markets for many bridging technologies over the decades to
come and, in reality, we may never reach beyond some form of ‘partial’ hydrogen economy;
however the extreme case of a pure hydrogen economy highlights the fundamental principles
that underline the partial version.
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### Appendix

**Fuel cell availability in 2004 (for sizes appropriate to HARI project)**

<table>
<thead>
<tr>
<th>Company</th>
<th>Model</th>
<th>Size</th>
<th>Specification /Comments</th>
<th>System Price (£)</th>
<th>Price /kW (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEM</strong></td>
<td></td>
<td></td>
<td><strong>Type</strong></td>
<td><strong>£</strong></td>
<td><strong>£</strong></td>
</tr>
<tr>
<td>Anuvu</td>
<td>Power-X</td>
<td>1.5kW</td>
<td>Stack only - NO BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballard</td>
<td>Nexa</td>
<td>1.2kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCS Fuel Cells</td>
<td>72 cell, Forced Flow</td>
<td>3kW</td>
<td>Stack only - NO BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogenics</td>
<td>HyPM 10 Power Module</td>
<td>10kW</td>
<td>BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IdaTech</td>
<td>FCS NG, FCS 1200</td>
<td>4.6kW, 1.2kW</td>
<td>Ballard Stack, Reformer, BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intelligent Energy</td>
<td>2kW</td>
<td></td>
<td>BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lynntech</td>
<td>0.5kW</td>
<td></td>
<td>Not Available yet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manhattan Scientifics</td>
<td>3kW</td>
<td></td>
<td>Not Available yet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matsushita (Panasonic)</td>
<td></td>
<td></td>
<td>Not Available yet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallic Power</td>
<td>1kW</td>
<td></td>
<td>Complete UPS system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuvera</td>
<td>H2e</td>
<td>1 - 6kW</td>
<td>AC or Raw DC, BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ovonic</td>
<td></td>
<td></td>
<td>Not Available yet (also Hydrides)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palcan</td>
<td></td>
<td>1kW, 5kW</td>
<td>Not Available yet (also Hydrides)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug Power</td>
<td>GenCore 5T</td>
<td>5kW</td>
<td>BOP [0.9m³/kWh]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton Motor</td>
<td>PM1 Stack</td>
<td>7kW</td>
<td>BOP</td>
<td>110,000</td>
<td>15,700</td>
</tr>
<tr>
<td>Relion (Formerly Avista)</td>
<td></td>
<td>1kW</td>
<td>Hot-swap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sigen</td>
<td>Various</td>
<td>5kW Plug Power, 1kW</td>
<td>Avista</td>
<td>BOP</td>
<td>8,800</td>
</tr>
<tr>
<td>Teledyne</td>
<td>Perry NG1000 / NG2000</td>
<td>1.8kW, 7.2kW</td>
<td>BOP available (also electrolysers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UTC Power</td>
<td>5kW, (1kW Toshiba)</td>
<td></td>
<td>Not Available yet</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AFC</strong></td>
<td></td>
<td></td>
<td><strong>Type</strong></td>
<td><strong>£</strong></td>
<td><strong>£</strong></td>
</tr>
<tr>
<td>Apollo Energy Systems</td>
<td>Models 102-C / 104-C / 101-B / etc</td>
<td>2.88kW / 4.3kW / 11.5kW / etc</td>
<td>BOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astris</td>
<td>E8 Portable</td>
<td>2.4kW</td>
<td>BOP, 2000hrs only</td>
<td>26,000</td>
<td>10,800</td>
</tr>
</tbody>
</table>

152
<table>
<thead>
<tr>
<th>Company</th>
<th>Model</th>
<th>Size</th>
<th>Specification /Comments</th>
<th>System Price (£)</th>
<th>Price /Nm³/h (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM</td>
<td>Hydrogenics</td>
<td>HyLYSER</td>
<td>5kW, 1.2Nm³/h, 7bar(g), 4.1kW/Nm³</td>
<td>BOP</td>
<td></td>
</tr>
<tr>
<td>Proton Energy Systems</td>
<td>Hogen H series</td>
<td></td>
<td>2-6 Nm³/h, 10 Nm³/h, 13bar(g)</td>
<td></td>
<td>BOP</td>
</tr>
<tr>
<td>Alkaline</td>
<td>Vandenborre Hydrogen Systems (acquired by Stuart Energy in 2003)</td>
<td>IMET 10/30/60</td>
<td>40kW, 10Nm³/h, 4.6Nm³/kWh / 100kW, 30Nm³/h, 4.8kW/Nm³ / 200kW, 60Nm³/h, 4.8kW/Nm³ All 10-25bar(g),</td>
<td>BOP</td>
<td></td>
</tr>
<tr>
<td>Teledyne</td>
<td>Titan HM50 / HM100 / HM125</td>
<td></td>
<td>17kW, 2.8Nm³/h, 7bar(g), 6.1Nm³/kWh / 32kW, 5.6Nm³/h, 5.7kW/Nm³ / 40kW, 7Nm³/h</td>
<td>BOP</td>
<td></td>
</tr>
<tr>
<td>Norsk Hydro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Too big</td>
</tr>
</tbody>
</table>

Electrolyser availability in 2004 (for sizes appropriate to HARI project)
Matlab programmes:

Programme for converting in-plane irradiance measurements into photovoltaic power outputs.

Calculates the solar (PV) power output based on analogue in-plane irradiance and ambient temperature measurements.

%Directory assignement
DirectoryName = 'C:\WBFData';
DirectoryListing = dir([DirectoryName '/*.dat']);
ExistingData = [DirectoryName DirectoryListing(3).name];

DateTimeSec, Temp, HorizIrr, InPlnIrr, DWZLo, UWZLo, DWZHi, UWZHi, WDir, HyProd, HyCons, HyPress, ElyPwr = textread(ExistingData, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', -1, 'delimiter', ',', 'headerlines', 1);

for FileNumber = 4:length(DirectoryListing);
    NewData = [DirectoryName DirectoryListing(FileNumber).name];
    nDateTimeSec, nTemp, nHorizIrr, nInPlnIrr, nDWZLo, nUWZLo, nDWZHi, nUWZHi, nWDir, nHyProd, nHyCons, nHyPress, nElyPwr = textread(NewData, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', -1, 'delimiter', ',', 'headerlines', 1);
    DateTimeSec = [DateTimeSec; nDateTimeSec];
    Temp = [Temp; nTemp];
    HorizIrr = [HorizIrr; nHorizIrr];
    InPlnIrr = [InPlnIrr; nInPlnIrr];
    DWZLo = [DWZLo; nDWZLo];
    UWZLo = [UWZLo; nUWZLo];
    DWZHi = [DWZHi; nDWZHi];
    UWZHi = [UWZHi; nUWZHi];
    WDir = [WDir; nWDir];
    HyProd = [HyProd; nHyProd];
    HyCons = [HyCons; nHyCons];
    HyPress = [HyPress; nHyPress];
    ElyPwr = [ElyPwr; nElyPwr];
end

StartDay=floor(DateTimeSec(:,1)); % Finds the start day
TimesInDaysFromStart=DateTimeSec-StartDay; % Converts the times into times in days from time=0

TimesInSecsFromStart=TimesInDaysFromStart.*(24*3600); % Converts the 'times in days from t=0' into 'times in seconds from t=0'

RatedOutputMonoC = 2.86*1000; %Rated Output of sub-array in Wp
RatedOutputMultiC = 2.9*1000; %Rated Output of sub-array in Wp
RatedOutputArray = RatedOutputMonoC + RatedOutputMultiC; %Rated Output of whole array in Wp

ArrayOutputFromActualIrrad = RatedOutputArray.*(InPlnIrr./1000);
% Adjust efficiency for actual Irradiance (from DC graph). Gives the %age of STC output expected at a given irradiance

\[
\text{IrradAdjustmentLoFilter} = (\text{InPlnIrr} > 0 \& \text{InPlnIrr} \leq 100); \quad \% \text{Uses (binary) filter to select Irradiances between 0 and 100W/m}^2
\]

\[
\text{IrradAdjustmentHiFilter} = (\text{InPlnIrr} > 100 \& \text{InPlnIrr} < 1000); \quad \% \text{Uses (binary) filter to select Irradiances between 100 and 1000W/m}^2
\]

\[
\text{IrradAdjustmentMaxFilter} = (\text{InPlnIrr} \geq 1000); \quad \% \text{Uses (binary) filter to select Irradiances higher than 1000W/m}^2
\]

\[
\text{LoIrradArray} = \text{IrradAdjustmentLoFilter} \cdot \text{InPlnIrr}; \quad \% \text{Array of Irradiances between 0 and 100W/m}^2
\]

\[
\text{HiIrradArray} = \text{IrradAdjustmentHiFilter} \cdot \text{InPlnIrr}; \quad \% \text{Array of Irradiances between 100 and 1000W/m}^2
\]

\[
\text{MaxIrradArray} = \text{IrradAdjustmentMaxFilter} \cdot \text{InPlnIrr}; \quad \% \text{Array of Irradiances higher than 1000W/m}^2
\]

% Adjust irradiances using (low and high portions of) DC's graph to take account of variance from STC irradiance value. Above STC irradiance value \%(1000W/m^2) it is assumed to be 100%. Adjustments calculated as percentages of STC values.

\[
\text{LoIrradAdjustedPercent} = -
(0.0000000000000611111 \cdot (\text{LoIrradArray}^6)) + (0.000000000134167 \cdot (\text{LoIrradArray}^5)) -
(0.0000000118194 \cdot (\text{LoIrradArray}^4)) + (0.000053375 \cdot (\text{LoIrradArray}^3)) -
(0.0130619 \cdot (\text{LoIrradArray}^2)) + (1.67783 \cdot (\text{LoIrradArray})) + 0.0000000967648;
\]

\[
\text{HiIrradAdjustedPercent} = -
(0.00000000000000125 \cdot (\text{HiIrradArray}^6)) + (0.00000000000454167 \cdot (\text{HiIrradArray}^5)) -
(0.00000000660096 \cdot (\text{HiIrradArray}^4)) + (0.0000492263 \cdot (\text{HiIrradArray}^3)) -
(0.00200733 \cdot (\text{HiIrradArray}^2)) + (0.442458 \cdot (\text{HiIrradArray})) + 51.5333;
\]

\[
\text{HiIrradAdjustedPercentCleanedFilter} = (\text{HiIrradAdjustedPercent} > 52); \quad \% \text{Binary filter that eliminates spurious values (HiIrradAdjustedPercent returns a value of 51.5333 at zero)}
\]

\[
\text{HiIrradAdjustedPercentCleaned} = \text{HiIrradAdjustedPercentCleanedFilter} \cdot (\text{HiIrradAdjustedPercent});
\]

\[
\text{LoIrradAdjustment} = \text{LoIrradAdjustedPercent} / 100; \quad \% \text{Converts from percentages to simple multiplier}
\]

\[
\text{HiIrradAdjustment} = \text{HiIrradAdjustedPercentCleaned} / 100; \quad \% \text{Converts from percentages to simple multiplier}
\]

\[
\text{IrradAdjustmentFactor} = (\text{LoIrradAdjustment} + \text{HiIrradAdjustment} + \text{IrradAdjustmentMaxFilter})
; \quad \% \text{Puts all adjusters into one array (because IrradAdjustmentMaxFilter returns 1s at relevant points and one is the conversion factor required for these, the binary values are used)}
\]
% Adjust for this array's size and efficiency
ArrayOutputAdjustedForActualIrr = IrradAdjustmentFactor .* ArrayOutputFromActualIrr;

% Adjust for ambient temperature (NB: this is NOT cell temperature, but ought to be really!)
% Ppv = Ppvnom (1 - 0.004(Temppv - Temppvnom))
SolarPower = ArrayOutputAdjustedForActualIrr .* (1 - 0.004*(Temp - 25));
TimedPVPowers = [TimesInSecsFromStart SolarPower];

% Now need to create an array of all the power points repeated so that a
% bar graph style output can be created.
ArraySize = length(SolarPower) * 2;
PVPowersDoubled = [SolarPower'; SolarPower'];
PVPowerLevels = reshape(PVPowersDoubled, [ArraySize 1]);
PVPowerLevels = [0; PVPowerLevels; 0];  % This adds a zero as the first and last point to
give a sharp edge to the data

% Each data reading has been averaged over the previous 10s.
TimePeriodStarts = (TimesInSecsFromStart - 9.99999999999999999);  % This finds the
beginning of each 10s period that this power level refers to, but with 0.000000000000000001
added.
TimeDoubled = [TimePeriodStarts'; TimesInSecsFromStart'];
TimePeriodsUnsorted = reshape(TimeDoubled, [ArraySize 1]);
TimePeriodsUnsorted = [(TimesInSecsFromStart(1) - 10); TimePeriodsUnsorted; (TimesInSecsFromStart(end) + 0.000000000000000001)];  % This
adds a time for the zero at the beginning and end

TimePeriods = sort(TimePeriodsUnsorted);
TimedWPVPowerBars = [TimePeriods PVPowerLevels];
PVPwrOutputData = [TimePeriods'; PVPowerLevels'];

save SolarPowerFileForSimulink.mat PVPwrOutputData;

plot (TimePeriods, PVPowerLevels, '-b')
hold on
plot (TimesInSecsFromStart, InPlnIrr, '-r')
hold on
Programme for converting wind speed measurements into wind power outputs.

% Uses calculated Zo to convert hub height wind speeds from analogue measurements to predicted wind power outputs of ONE WIND TURBINE.

% Creates a .mat file of times and predicted wind power outputs called "WindPowerFileForSimulink.mat".

load 'WindSpeedFileForSimulink.mat'
DateTime = TimedZHubWindSpeeds(:,1);

% TimedZHubWindSpeeds is the array in the .mat file
WSpeed = TimedZHubWindSpeeds(:,2);
StartDay=floor(DateTime (1,:)); % Finds the start day

TimesInDaysFromStart=DateTime-StartDay; % Converts the times into times in days from time=0

% SynchedTimesInDaysFromStart=TimesInDaysFromStart+1; % Synchronises with digital data (USE ONLY IN B.S.T.)

WindPowersLo = -(0.000560897.*((WSpeed.^5))+(0.0113529.*(WSpeed.^4))-(0.0370582.*((WSpeed.^3))+(0.19228.*(WSpeed.^2))+(2.09878.*WSpeed)-4.36798;
WindPowersMd = -(0.000956825.*((WSpeed.^5))+(0.0652681.*(WSpeed.^4))-(1.747668.*(WSpeed.^3))+(22.6378.*(WSpeed.^2))-(137.283.*WSpeed)+317.549;
WindPowersHi = (0.00921165.*(WSpeed.^3))-(0.612282.*(WSpeed.^2))+(13.2359.*WSpeed)-60.8394;

LoWindFilter = (((WSpeed > 3) & (WSpeed < 10));
MdWindFilter = (((WSpeed >= 10) & (WSpeed < 15));
HiWindFilter = (((WSpeed >= 15) & (WSpeed <= 25));

LoWindPowerFiltered = (LoWindFilter.* WindPowersLo);
MdWindPowerFiltered = (MdWindFilter.* WindPowersMd);
HiWindPowerFiltered = (HiWindFilter.* WindPowersHi);

AllWindPowers =(LoWindPowerFiltered + MdWindPowerFiltered + HiWindPowerFiltered);

CutInToCutOutFilter = (((WSpeed >= 3) & (WSpeed < 25));

% GeneratingArray = [WSpeed CutInCutOutFilter]
WindPowerOutput = (CutInToCutOutFilter.* AllWindPowers);
WPowerOutputW = WindPowerOutput.* 1000; % Converts wind power from kW to W

% WindSpeedToPowerArray = [WSpeed WindPowerOutput]
TimedWindPowers = [TimesInSecsFromStart WPowerOutputW];

% Now need to create an array of all the power points repeated so that a bar graph style output can be created.
ArraySize=length(WPowerOutputW)*2;
PowersDoubled=[WPowerOutputW;WPowerOutputW];
PowerLevels=reshape(PowersDoubled,[ArraySize 1]);
PowerLevels=[0;PowerLevels;0];  % This adds a zero as the first and last point to give a
sharp edge to the data

% Each data reading has been averaged over the previous 10s.
TimePeriodStarts=(TimesInSecsFromStart-9.999999999999999999);  % This finds the
beginning of each 10s period that this power level refers to, but with 0.000000000000000001
added.

TimesDoubled=[TimePeriodStarts';TimesInSecsFromStart'];
TimePeriodsUnsorted=reshape(TimesDoubled,[ArraySize 1]);
TimePeriodsUnsorted=[(TimesInSecsFromStart(1)-
10);TimePeriodsUnsorted;(TimesInSecsFromStart(end)+0.000000000000000001)];  % This
adds a time for the zero at the beginning and end

TimePeriods=sort(TimePeriodsUnsorted);
TimedWindPowerBars = [TimePeriods PowerLevels];
WPwrOutputData=[TimePeriods';PowerLevels'];

save WindPowerFileForSimulink.mat WPwrOutputData;

plot(TimePeriods,PowerLevels,'-');
hold on;
xlabel('Time');  % Change to 'Date' for longer timescales
ylabel('Wind Power (W)');
Voltage transducers used for the measurement of electrolyser power

Voltage Transducer LV 25-P
For the electronic measurement of voltages: DC, AC, pulsed... with a galvanic isolation between the primary circuit (high voltage) and the secondary circuit (electronic circuit).

**Electrical data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{P,w}</td>
<td>10 mA</td>
</tr>
<tr>
<td>L_{P}</td>
<td>0..±14 mA</td>
</tr>
<tr>
<td>R_m</td>
<td></td>
</tr>
<tr>
<td>with ±12 V</td>
<td>@ ±10 mA_max</td>
</tr>
<tr>
<td>with ±15 V</td>
<td>@ ±10 mA_max</td>
</tr>
<tr>
<td>I_{P,n}</td>
<td>25 mA</td>
</tr>
<tr>
<td>K_n</td>
<td>2500:1000</td>
</tr>
<tr>
<td>V_S</td>
<td>±12..15 V</td>
</tr>
<tr>
<td>I_C</td>
<td>10 mA@±15 V±I_{P,n} mA</td>
</tr>
<tr>
<td>V_e</td>
<td>2.5 kV</td>
</tr>
</tbody>
</table>

**Accuracy - Dynamic performance data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_A (Overall Accuracy) @ I_{P,w}, T_A = 25°C</td>
<td>±0.9 %</td>
</tr>
<tr>
<td>E_L (Linearity)</td>
<td>&lt;0.2 %</td>
</tr>
<tr>
<td>I_o (Offset current) @ L = 0, T_A = 25°C</td>
<td>±0.15 mA</td>
</tr>
<tr>
<td>I_{T} (Thermal drift of I_o)</td>
<td>0°C.. +25°C</td>
</tr>
<tr>
<td>+25°C.. +70°C</td>
<td>±0.10 mA</td>
</tr>
<tr>
<td>t_r (Response time @ 90 % of V_{P,w})</td>
<td>40 μs</td>
</tr>
</tbody>
</table>

**General data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_a (Ambient operating temperature)</td>
<td>0..±70 °C</td>
</tr>
<tr>
<td>T_s (Ambient storage temperature)</td>
<td>-25..+85 °C</td>
</tr>
<tr>
<td>R_p (Primary coil resistance @ T_f = 70°C)</td>
<td>250 Ω</td>
</tr>
<tr>
<td>R_s (Secondary coil resistance @ T_f = 70°C)</td>
<td>110 Ω</td>
</tr>
<tr>
<td>m</td>
<td>22 g</td>
</tr>
</tbody>
</table>

**Standards**

- EN 50178 (97.10.01)

**Features**

- Closed loop (compensated) voltage transducer using the Hall effect
- Insulated plastic case recognized according to UL 94V-0.

**Principle of use**

- For voltage measurements, a current proportional to the measured voltage must be passed through an external resistor R, which is selected by the user and installed in series with the primary circuit of the transducer.

**Advantages**

- Excellent accuracy
- Very good linearity
- Low thermal drift
- Low response time
- High bandwidth
- High immunity to external interference
- Low disturbance in common mode.

**Applications**

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Power supplies for welding applications.

Notes:

- Between primary and secondary
- R = 25kΩ (L/R constant, produced by the resistance and inductance of the primary circuit).

981009/14

LEM Components www.lem.com
Dimensions LV 25-P (in mm. 1 mm = 0.0394 inch)

Mechanical characteristics
- General tolerance ± 0.2 mm
- Fastening & connection of primary 2 pins, 0.635 x 0.635 mm
- Fastening & connection of secondary 3 pins Ø 1 mm
- Recommended PCB hole 1.2 mm

Remarks
- I_p is positive when V_p is applied on terminal +HT.
- This is a standard model. For different versions (supply voltages, turns ratios, unidirectional measurements...), please contact us.

Instructions for use of the voltage transducer model LV 25-P
Primary resistor R_p: the transducer's optimum accuracy is obtained at the nominal primary current. As far as possible, R_p should be calculated so that the nominal voltage to be measured corresponds to a primary current of 10 mA.

Example: Voltage to be measured V_m = 250 V
a) R_p = 25 kΩ / 2.5 W, I_p = 10 mA, Accuracy = ± 0.5 % of V_m (T = ± 25°C)
b) R_p = 50 kΩ / 1.25 W, I_p = 5 mA, Accuracy = ± 1.6 % of V_m (T = ± 25°C)

Operating range (recommended): taking into account the resistance of the primary windings (which must remain low compared to R_p) in order to keep thermal deviation as low as possible and the isolation, this transducer is suitable for measuring nominal voltages from 10 to 500 V.

LEM reserves the right to carry out modifications on its transducers, in order to improve them, without previous notice.
Current transducers used for the measurement of electrolyser power

**Current Transducer HT 200 to 500-SBD**

For the electronic measurement of DC, AC and pulsed currents, with a galvanic isolation between the primary (high power) circuit and the secondary (electronic) circuit.

### Electrical data

<table>
<thead>
<tr>
<th>Type</th>
<th>Primary nominal DC or Rms current $I_{pn}$</th>
<th>Primary current measuring range $I_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT200-SBD</td>
<td>200 A</td>
<td>0.. ± 400 A</td>
</tr>
<tr>
<td>HT300-SBD</td>
<td>300 A</td>
<td>0.. ± 600 A</td>
</tr>
<tr>
<td>HT400-SBD</td>
<td>400 A</td>
<td>0.. ± 800 A</td>
</tr>
<tr>
<td>HT500-SBD</td>
<td>500 A</td>
<td>0.. ± 1000 A</td>
</tr>
</tbody>
</table>

- $I_0$: Overload capacity (Ampere Turns) 30000 A
- $V_{out}$: Analogue output voltage @ $I_{pn}$ ±5 V
- $R_L$: Load resistance >10 kΩ
- $V_S$: Supply voltage (± 5 %) ±15 V
- $I_S$: Current consumption (max) 20 mA
- $V_a$: Rms rated voltage 50 V

### Accuracy - Dynamic performance data

- $X$: Accuracy @ $I_{pn}$, $T_a$ = 25°C, $V_S$ ± 15 V ±1 %
- $E_L$: Linearity ± 0.5 %

- $V_{off}$: Electrical offset voltage @ $I_{pn}$, $T_a$ = 25°C ±20 mV
- $V_{res}$: Residual offset voltage @ $I_{pn}$, $T_a$ = 25°C < 6.25 mV
- $V_{th}$: Thermal drift of offset voltage $T_a$ = 0.. + 70°C ±3 mV/K
- $T_{ce}$: Thermal drift of gain $T_a$ = 0.. + 70°C ±0.05 %/K
- $t_r$: Response time @ 90 % of $I_p$ < 7 µs
- $f$: Frequency bandwidth (-3 dB) DC.. 50 kHz

### General data

- $T_a$: Ambient operating temperature 0.. + 70 °C
- $T_s$: Ambient storage temperature -10.. + 85 °C
- $m$: Mass 160 g

**Features**
- Open loop transducer using Hall Effect
- Panel mounting
- Split core design for easy installation
- Insulated plastic case to UL 94-HB.

**Advantages**
- Very good linearity
- Very good accuracy
- Low temperature drift
- Wide frequency bandwidth
- Very low insertion losses
- High immunity to external interference
- Current overload capability
- Low power consumption
- Wide dynamic range 200 to 500 A in one package.

**Applications**
- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptable Power Supplies (UPS)
- Switched Mode Power Supplies (SMPS)
- Power supplies for welding applications.

**Notes:**
- For use on SELV systems or with insulated conductors on higher rated systems
- Excludes the electrical offset
- Refer to derating curves in the technical file to avoid excessive core heating at high frequency

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Dimensions HT 200 to 500-SBD (in mm, 1 mm = 0.0394 inch)

**Secondary terminals**
- **RED**: supply voltage + 15 V
- **BLUE**: supply voltage - 15 V
- **WHITE**: output
- **GREEN**: 0 V
- **SCREEN**: NC

**Mechanical characteristics**
- General tolerance: ± 0.5 mm
- Primary through-hole: Ø 23 mm
- Connection of secondary: Via 4 core screened PVC cable 1.5 m in length
- Enclosure: Moulded ABS plastic

**Remarks**
- $V_{out}$ is positive when $I_p$ flows in the direction of the arrow.
- Temperature of the primary conductor should not exceed 90°C.
- This is a standard model. For different versions (supply voltages, secondary connections, unidirectional measurements, operating temperatures, etc.) please contact us.

LEM have a policy of continual product improvement and the company reserves the right to revise the above specification without prior notice.
Safety data sheet for hydrogen

**BOC**

**High Purity Hydrogen**

**PRODUCT:** HYDROGEN MSDS NR: 352-00-0012 BOC VERSION: 1.02 DATE: 17/4/02 PAGE: 1/2

1 IDENTIFICATION OF THE SUBSTANCE/ PREPARATION AND OF THE COMPANY

- **Product name:** Hydrogen
- **Chemical formula:** H₂
- **Company:** see footer
- **Identification number:** see footer
- **Emergency phone number:** see footer

2 COMPOSITION/INFORMATION ON INGREDIENTS

- **Substance/Preparation:** Contains no other components or impurities which will influence the classification of the product.
- **CAS Nr:** 1333-74-0
- **EEC Nr:** 215-605-7 (from EINECS)
- **Specification:** High Purity Hydrogen 99.995% minimum

3 HAZARDS IDENTIFICATION

- **Hazard Identification:** Extremely flammable. Compressed gas.

4 FIRST AID MEASURES

- **Inhalation:** In high concentrations may cause asphyxiation and death. Symptoms may include loss of mobility/consciousness. Victim may be unaware of asphyxiation. Remove victim to uncontaminated area wearing self contained breathing apparatus. Keep victim warm and rested. See doctor. Apply artificial respiration if breathing stopped.
- **Ingestion:** Ingestion is not considered a potential route of exposure.

5 FIRE FIGHTING MEASURES

- **Specific hazards:** Exposure to fire may cause containers to rupture and explode. Inform fire Brigade.
- **Hazardous combustion products:** None
- **Suitable extinguishing media:** All known extinguishers can be used.
- **Specific methods:** If possible, stop flow of product. Move away from container and cool with water from a protected position. Do not extinguish a leaking gas flame unless absolutely necessary. Spontaneous/explosive re-ignition may occur. Extinguish any other fire.
- **Special protective equipment for fire fighters:** In confined space use self-contained breathing apparatus.

6 ACCIDENTAL RELEASE MEASURES

- **Personal precautions:** Wear self-contained breathing apparatus when entry is necessary. Ensure area is safe. Evacuate area. Ensure adequate ventilation. Eliminate ignition sources. Post warning signs (including no smoking).

Leak not ignited

- Extinguish all sources of ignition in the immediate area. Close the cylinder valve. If necessary tighten the gland nut. If leak continues, evacuate the area and avoid sources of ignition and minimize personal risk move the leaking cylinder to a safe outside area. Notify BOC. Post warning signs and prevent access to the area.
- DO NOT Attempt to tighten the cylinder valve in the body of the cylinder. DO NOT tamper with the safety devices.

Leak ignited

- Raise fire alarm. Close cylinder valve if safe to do so. Call fire brigade. Evacuate the area. If possible apply copious quantities of water from a hose to the affected cylinder(s) from a protected position until the cylinder(s) are cold. DO NOT Move cylinders until cold.

Environmental precautions

- Clean up methods: Ventilate area.

7 HANDLING AND STORAGE

- **Handling and storage:** Ensure equipment is adequately earthed. Shut off gas from cylinder before introducing gas. Do not allow backflow into the container. Use properly specified equipment which is suitable for the product, its supply pressure and temperature. Hydrogen diffuses rapidly and may leak from a system gas tight for other gases. Use non-spark equipment. Contact BOC in doubt. Keep away from heat and ignition sources (including static discharges). Store cylinders outside in the open air. Separate from oxidizing agents and other combustible materials. Keep container below 50°C in a well-ventilated place. Ventilation equipment should be hydrogen safe.

8 EXPOSURE CONTROLS/ PERSONAL PROTECTION

- **Personal protection:** Ensure adequate ventilation, Do not smoke while handling product. Before connecting the cylinder for use, the cylinder valve should be checked for cleanliness. Do not touch cylinder valve with wet hands. If there are any signs of dirt, blow it out with a jet of clean compressed air or nitrogen. Action in the event of a flashback: Close the cylinder valve. Check equipment. If cylinder becomes hot take action as in ignited.

9 PHYSICAL AND CHEMICAL PROPERTIES

- **Molecular weight:** 2
- **Melting point:** -259 °C
- **Boiling point:** -252 °C
- **Critical temperature:** -240 °C
- **Relative density, gas:** 0.07 (air=1)
- **Relative density, liquid:** 0.07 (water=1)
- **Vapour Pressure 20°C:** Not applicable.
- **Solubility in water:** 1.6 mg/l
- **Appearance/Colour:** Colourless gas
- **Odour:** Non.
- **Autoignition temperature:** 560 °C
- **Flammability range:** 4.75 vol% in air.
- **Other data:** Burns with a colourless invisible flame.

Please photocopy if further copies required.
10 STABILITY AND REACTIVITY
Stability and reactivity can form explosive mixture with air. May react violently with oxidants.

11 TOXICOLOGICAL INFORMATION
General
No known toxicological effects from this product.

12 ECOLOGICAL INFORMATION
General
No known ecological damage caused by this product.

13 DISPOSAL CONSIDERATIONS
General
Do not discharge into areas where there is a risk of forming an explosive mixture with air. Waste gas should be flared through a suitable burner with flash back arrestor. Do not discharge into any place where its accumulation could be dangerous. Contact BOC if guidance is required.

14 TRANSPORT INFORMATION
UN Nr 1049
Class/Div 2.1
ADR/RID Item Nr 2.1
ADR/RID Hazard Nr 23
Labelling ADR Label 3: flammable gas

Other transport information:
Avoid transport on vehicles where the load space is not separated from the driver's compartment. Ensure the driver is aware of the potential hazards of the load and knows what to do in the event of an accident or an emergency. Before transporting product containers ensure that they are firmly secured and:
- cylinder valve is closed and not leaking.
- valve outlet cap nut or plug (where provided) is correctly fitted.
- valve protection device (where provided) is correctly fitted.
- adequate ventilation.
- compliance with applicable regulations.

15 REGULATORY INFORMATION
Number in Annex I 001-001-00-9
EC Classification F+ A12
Labeling of cylinders
-Symbols
-Label 3: flammable gas
-Risk phrases R12 Extremely flammable.
-Safety phrases S9 Keep container in well ventilated place.
S16 Keep away from ignition sources - No smoking.
S33 Take precautionary measures against static discharges.

16 OTHER INFORMATION
Ensure all national/ local regulations are observed.
Ensure operators understand the flammability hazard. The hazard of asphyxiation is often overlooked and must be stressed during operator training.
Users of breathing apparatus must be trained.
Before using this product in any new process or experiment, a thorough material compatibility and safety study should be carried out.
Always leak check cylinders when first collected, delivered or used, using an approved leak detection fluid.
Details given in this document are believed to be correct at the time of going to press. While proper care has been taken in the preparation of this document, no liability for injury or damage resulting from its use can be accepted.
For further safety information please refer to "Safe Under Pressure" and "Safe handling, storage and transport of industrial gas cylinders", both of which are available from your local BOC outlet.

NOTES
1. In case of leak or release of cylinder may be toxic from all sections.
2. Do not discharge into areas where there is a risk of forming an explosive mixture with air.
3. In the event of fire ensure a suitable fire extinguishing agent is used. Use water only if the fire is small and the cylinder can be cooled rapidly. The operation is a device at each cylinder and is ICPC.
4. The forced ventilation indicator pales to prevent all contaminated in a single area.

BOC
A member of The BOC Group

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For product and safety enquiries please phone
In the United Kingdom: 0800 111 333
In the Republic of Ireland: 1850 333 435

BOC Gases
Customer Service Centre
Priestley Road, Worsley
Manchester M28 2UT
Fax: 0800 111 555

BOC Gases
P.O. Box 201
Bluebell, Dublin 12
Fax: 01 409 1801

SFI/00729A/AF060221(M/15)

Please photocopy or further copies required

SAFETY DATA SHEET

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Safety data sheet for potassium hydroxide solution

Material Safety Data Sheet
Potassium Hydroxide Solution 30% To 50%
MSDS# 19430

Section 1 - Chemical Product and Company Identification
MSDS Name:
Potassium Hydroxide Solution 30% To 50%
Catalog Numbers:
P/5645/17, SP/0465, SP/0468, SP/0475
Synonyms:
None
Company Identification:Fisher Scientific UK
Bishop Meadow Road, Loughborough
Leics. LE11 5RG
For information in Europe, call:(01509) 231166
Emergency Number, Europe:
01509 231166

Section 2 - Composition, Information on Ingredients

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<th>Chemical Name</th>
<th>%</th>
<th>EINECS#</th>
<th>Hazard Symbols</th>
<th>Risk Phrases</th>
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<td>Potassium hydroxide</td>
<td>30-50</td>
<td>215-181-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7732-18-5</td>
<td>Water</td>
<td>50-70</td>
<td>231-791-2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Text for R-phrases: see Section 16

Section 3 - Hazards Identification

EMERGENCY OVERVIEW
Harmful if swallowed. Causes severe burns. Corrosive.
Potential Health Effects
Eye:
Causes eye burns. Contact may cause ulceration of the conjunctiva and cornea. Eye damage may be delayed. Causes redness and pain.
Skin:
May cause deep, penetrating ulcers of the skin. Causes severe burns
with delayed tissue destruction. Causes redness and pain.

Ingestion:
May cause severe and permanent damage to the digestive tract. May cause circulatory system failure. May cause perforation of the digestive tract. Causes severe digestive tract burns with abdominal pain, vomiting, and possible death. May cause systemic effects.

Inhalation:
Irritation may lead to chemical pneumonitis and pulmonary edema. Causes severe irritation of upper respiratory tract with coughing, burns, breathing difficulty, and possible coma. Causes chemical burns to the respiratory tract. Inhalation may be fatal as a result of spasm, inflammation, edema of the larynx and bronchi, chemical pneumonitis and pulmonary edema. May cause systemic effects.

Chronic:
Prolonged or repeated skin contact may cause dermatitis. Prolonged or repeated eye contact may cause conjunctivitis. Effects may be delayed.

Section 4 - First Aid Measures

Eyes:
Get medical aid immediately. Do NOT allow victim to rub eyes or keep eyes closed. Extensive irrigation with water is required (at least 30 minutes).

Skin:
Get medical aid immediately. Immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash clothing before reuse. Discard contaminated clothing in a manner which limits further exposure. Destroy contaminated shoes.

Ingestion:
Do not induce vomiting. If victim is conscious and alert, give 2-4 cupfuls of milk or water. Never give anything by mouth to an unconscious person. Get medical aid immediately.

Inhalation:
Get medical aid immediately. Remove from exposure and move to fresh air immediately. If breathing is difficult, give oxygen. Do NOT use mouth-to-mouth resuscitation. If breathing has ceased apply artificial respiration using oxygen and a suitable mechanical device such as a bag and a mask.

Notes to Physician:

Section 5 - Fire Fighting Measures

General Information:
As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and full protective gear. During a fire, irritating and highly toxic gases may be generated by thermal decomposition or combustion. Wear appropriate protective clothing to prevent contact with skin and eyes. Wear a self-contained breathing apparatus (SCBA) to prevent contact with thermal decomposition products. Use water with caution and in flooding amounts. Non-combustible, substance itself does not burn but may decompose upon heating to produce irritating, corrosive
and/or toxic fumes.

Extinguishing Media:
Substance is noncombustible; use agent most appropriate to extinguish surrounding fire. Cool containers with flooding quantities of water until well after fire is out.

Section 6 - Accidental Release Measures

General Information:
Use proper personal protective equipment as indicated in Section 8.

Spills/Leaks:
Absorb spill with inert material (e.g. vermiculite, sand or earth), then place in suitable container. Neutralize spill with a weak acid such as vinegar or acetic acid. Avoid runoff into storm sewers and ditches which lead to waterways. Clean up spills immediately, observing precautions in the Protective Equipment section. Provide ventilation.

Section 7 - Handling and Storage

Handling:
Wash thoroughly after handling. Remove contaminated clothing and wash before reuse. Do not breathe dust, vapor, mist, or gas. Do not get in eyes, on skin, or on clothing. Keep container tightly closed. Do not ingest or inhale. Use only in a chemical fume hood. Discard contaminated shoes.

Storage:
Keep container closed when not in use. Store in a tightly closed container. Store in a cool, dry, well-ventilated area away from incompatible substances. Keep away from strong acids. Corrosives area.

Section 8 - Exposure Controls, Personal Protection

Engineering Controls:
Facilities storing or utilizing this material should be equipped with an eyewash facility and a safety shower. Use adequate ventilation to keep airborne concentrations low.

Exposure Limits
CAS# 1310-58-3:
United Kingdom, WEL - STEL: 2 mg/m3 STEL
Belgium - STEL: 2 mg/m3 VLE
France - VLE: 2 mg/m3 VLE
Japan: 2 mg/m3 Ceiling
Malaysia: 2 mg/m3 Ceiling
Spain: 2 mg/m3 VLA-EC
CAS# 7732-18-5:

Personal Protective Equipment

Eyes:
Wear chemical splash goggles and face shield.

Skin:
Wear appropriate protective gloves to prevent skin exposure.

Clothing:
Wear appropriate protective clothing to prevent skin exposure.
Respirators:
A respiratory protection program that meets OSHA's 29 CFR 1910.134 and ANSI Z88.2 requirements or European Standard EN 149 must be followed whenever workplace conditions warrant respirator use.

Section 9 - Physical and Chemical Properties

Physical State: Liquid
Color: clear to slightly turbid
Odor: odorless
pH: 12.0 (0.1 M sol.)
Vapor Pressure: 2.6 mm Hg @ 20 C
Viscosity: 3.7 cP
Boiling Point: 271-293 F
Freezing/Melting Point: 48 deg F (8.89 C)
Autoignition Temperature: Not available.
Flash Point: Not available
Explosion Limits: Lower: Not available
Explosion Limits: Upper: Not available
Decomposition Temperature: Not available
Solubility in water: Completely soluble in water
Specific Gravity/Density: 1.51
Molecular Formula: Solution
Molecular Weight: 0

Section 10 - Stability and Reactivity

Chemical Stability:
Stable at room temperature in closed containers under normal storage and handling conditions.

Conditions to Avoid:
Excess heat.

Incompatibilities with Other Materials
Metals, strong acids.

Hazardous Decomposition Products
Irritating and toxic fumes and gases, oxides of potassium.

Hazardous Polymerization
Has not been reported.

Section 11 - Toxicological Information

RTECS#:
CAS# 1310-58-3: TT2100000
CAS# 7732-18-5: ZC0110000
LD50/LC50:
CAS# 1310-58-3: Draize test, rabbit, skin: 50 mg/24H
Severe; Oral, rat: LD50 = 273 mg/kg. 
CAS# 7732-18-5: Oral, rat: LD50 = >90 mL/kg.

Carcinogenicity:
Potassium hydroxide -
Not listed as a carcinogen by ACGIH, IARC, NTP, or CA Prop 65.
Water -
Not listed as a carcinogen by ACGIH, IARC, NTP, or CA Prop 65.
Other:
See actual entry in RTECS for complete information.
Section 12 - Ecological Information

Ecotoxicity:
Fish: Mosquito Fish: LC50 = 80.0 mg/L; 24 Hr.; Unspecified

Section 13 - Disposal Considerations

Products considered hazardous for supply are classified as Special Waste and the disposal of such chemicals is covered by regulations which may vary according to location. Contact a specialist disposal company or the local authority or advice. Empty containers must be decontaminated before returning for recycling.

Section 14 - Transport Information

IATA
Shipping Name: POTASSIUM HYDROXIDE, SOLUTION
Hazard Class: 8
UN Number: 1814
Packing Group: II

IMO
Shipping Name: POTASSIUM HYDROXIDE, SOLUTION
Hazard Class: 8
UN Number: 1814
Packing Group: II

RID/ADR
Shipping Name: POTASSIUM HYDROXIDE, SOLUTION
Hazard Class: 8
UN Number: 1814
Packing Group: II

USA RQ: CAS# 1310-58-3: 1000 lb final RQ; 454 kg final RQ

Section 15 - Regulatory Information

European/International Regulations
European Labeling in Accordance with EC Directives
Hazard Symbols: C
Risk Phrases:
   R 22 Harmful if swallowed.
   R 35 Causes severe burns.

Safety Phrases:
   S 26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
   S 36/37/39 Wear suitable protective clothing, gloves and eye/face protection.
   S 45 In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible).

WGK (Water Danger/Protection)
CAS# 1310-58-3: 1
CAS# 7732-18-5: Not available

Canada
CAS# 1310-58-3 is listed on Canada's DSL List
CAS# 7732-18-5 is listed on Canada's DSL List

US Federal
TSCA
CAS# 1310-58-3 is listed on the TSCA Inventory.
CAS# 7732-18-5 is listed on the TSCA Inventory.

Section 16 - Other Information
Text for R-phrases from Section 2
MSDS Creation Date:
6/21/1999
Revision #7 Date
10/05/2004

The information above is believed to be accurate and represents the best information currently available to us. However, we make no warranty of merchantibility or any other warranty, express or implied, with respect to such information, and we assume no liability resulting from its use. Users should make their own investigations to determine the suitability of the information for their particular purposes. In no event shall the company be liable for any claims, losses, or damages of any third party or for lost profits or any special, indirect, incidental, consequential, or exemplary damages howsoever arising, even if the company has been advised of the possibility of such damages.

-------------------------------------------------------------------------------------------------
**Glossary of terms and abbreviations**

**AFC** – alkaline fuel cell

**Back-casting** – the opposite of forecasting. Used in ‘roadmapping’ exercises. After a future scenario is built, back-casting can be used to plan a path to such a destination. Follows from the assumption that, until the intended destination of a journey is defined, informed decisions cannot be made about the steps required to get there, even in the short term.

**BOP** – balance of plant

**Bridging technology** – Some technologies and processes (e.g. reformation of fossil fuels to make hydrogen) are not seen as playing a role if an eventual ‘pure’ (i.e. post fossil) hydrogen economy, but are bound to play an important role in the meantime in taking us towards a one– a process which will take decades. These are known as ‘bridging’ technologies.

**Cell stack** – stack of electrolytic cells at the heart of the electrolyser or fuel cell system, where the actual electrochemical reaction takes place. Used interchangeably with “module” when referring to the electrolyser.

**CF** – capacity factor = actual output / maximum possible output (i.e. running full time at rated level)

**HARI** – Hydrogen and Renewables Integration project

**HAZOP** – hazard and operability studies

**HHV** – higher heating value (for hydrogen this is 39.7kWh/kg). This is considered to be a more accurate measure of the energetic content of a material than lower heating value (LHV) (Bosse! 2003) and so is used throughout this thesis

**Hythane** – a mixture of hydrogen and methane (an example of a bridging technology)

**ICE** – internal combustion engine

**IEFC** – Intelligent Energy fuel cell

**LH2** – liquid hydrogen

**MPPT** – maximum power point tracker

**Module** – stack of electrolytic cells at the heart of the electrolyser, where the actual electrochemical reaction that splits water into hydrogen and oxygen takes place. Used interchangeably with “cell stack”.

**Nm³** – normal metres cubed

**NTP** – normal temperature and pressure (20°C, 1atm, or 1.01325bar). The energy density of hydrogen at NTP is 3.29kWh/m³ (HHV).

**PEM** – proton exchange membrane

**PEMFC** – proton exchange membrane fuel cell

**PPFC** – Plug Power fuel cell

**PV** – photovoltaic or solar (electric) power

**Roadmapping** – planning a route, or routes, forward towards a projected future scenario or destination.

**SOFC** – solid oxide fuel cell

**STC** – standard test conditions. Used to measure the nominal output of PV devices at a light intensity of 1000W/m², a temperature of 25°C and an air mass of 1.5.

**STP** – standard temperature and pressure (25°C, 1bar). The energy density of hydrogen at STP is 3.20kWh/m³ (HHV).

**Vandenborre** – Vandenborre Hydrogen Systems, subsequently merged with Stuart Energy and then Hydrogenics. Used where references to the company relate specifically to the time before they merged, when they were still trading as Vandenborre Hydrogen Systems.

**WBF** – West Beacon Farm

**WTG** – wind turbine generator
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