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A field application experience of integrating hydrogen technology with wind power in a remote island location

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Abstract

This paper aims to share the field application experience related to the development of an innovative stand-alone sustainable energy system known as the PURE project. The PURE project has been developed alongside a Knowledge Transfer Partnership (KTP) scheme, which is supported by the UK Department of Trade and Industry and executed by siGEN in collaboration with The Robert Gordon University. The system has been constructed within an industrial estate on the island of Unst in Shetland, 200 miles north of the Scottish mainland. The energy system now supplies five business properties with clean reliable power and utilises wind turbine and hydrogen technology to provide a sustainable energy source.

The stored hydrogen gas generated by the system is used as an energy source for periods when electrical demand within the business properties exceeds wind turbine production. The hydrogen is also utilised as a fuel source for transportation and as a transportable energy source for mobile power generation.

The paper therefore gives a detailed description of the PURE project and discusses the field experience accumulated during the development and installation of the system. It also shares a number of practical issues that had to be overcome during its integration and operation. The installation of the PURE project has resulted in a number of unexpected conclusions being identified and marks a significant step forward in the accessible deployment of this technology for community use.

Keywords: PURE hydrogen; PURE energy; Fuel cell; Renewable; Sustainable; Field experience

1. Introduction

Economical and environmental pressures experienced in recent years, and the steady increase of fossil fuel costs has led to an increased interest in promoting renewable energy sources and alternative energy carriers. A typical example of this can be seen in recent announcements by the European commission. They are working towards reducing carbon emission by scheduling a 20% penetration of renewable energy by the year 2020. The United Kingdom government has set targets of 10% and 20% of electricity from renewable sources (mainly wind power) by 2010 and 2020, respectively. The corresponding renewable energy targets set for Scotland by the Scottish Executive are very ambitious and amount to 18% and 40% [1].

Renewable energy resources are mostly available at rural and remote locations. It is at these locations that the presence of any electrical grid is normally at its weakest as the remote population is sparse and has little need for large transmission and distribution infrastructure. Therefore, a large number of electrical grids around the world that are located remotely cannot support the connection of renewable energy-based power plants, unless high cost network reinforcement is carried out. For example the majority of good renewable resources in Scandinavia and northern Europe exist around exposed remote or islanded locations that are not easily connected to the national electrical transmission systems [2]. Access to network therefore constitutes a significant barrier to achieving the ambitious targets stated above.

An example of the barrier towards the wide spread use of renewable energy is the Shetland Islands. A study conducted by Garrad Hassan and Partners has shown that the Shetland Islands have some of the best renewable energy resources in Europe

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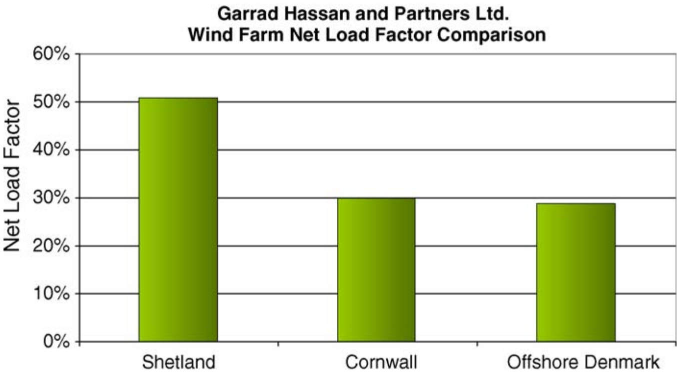

Fig. 1. Resource comparison highlighting abundance of wind energy in Shetland.

(see Fig. 1) [3]. Annual recorded wind turbine performance was shown to reach almost twice that of equivalent turbines elsewhere in the UK and Denmark.

The largest barrier to harnessing the abundant renewable energy available within Shetland is the difficulty in its effective delivery to the demand centres in central UK and Europe. The Shetland Islands are powered by one of the last major independent islanded electrical networks in the UK. As such there is limited capacity to absorb intermittent renewable energy sources.

The Shetland Islands also have among the highest energy costs in the UK. In particular the most northerly island of Unst where the price of road diesel has recently been recorded (at the time of writing this paper, October 2005) in excess of £1.09 per litre as demonstrated in Fig. 2. This is compared to 92 pence per litre average on the UK main land. Due to the remote northerly location of Unst the population are highly dependant on fuel for energy.

A recent energy balance study completed by the Unst Partnership Ltd. [4] found that over 50% of the islanders spend more than 20% of their household income on energy. The majority of this expenditure was found to be in the form of energy for heating and transportation fuel.

As a means to utilise the abundant renewable energy resource present within the islands, the community of Unst have commissioned the development of a sustainable energy system that can operate independently of the constrained electrical infrastructure. Surplus renewable captured energy is stored in the form of hydrogen for use in both transportation and the generation of ‘on demand’ electrical power.

2. Existing renewable hydrogen systems in the field

Currently there are many hydrogen production systems using renewable energy sources that have been designed and are either under implementation or are already operational. However most of these systems have been developed in the United States (US). For instance, the first solar hydrogen–fuel cell system in the US was installed at the Telonicher Marine Lab in Trinidad, California [5]. In Thousand Palms, solar energy is also used to supply an electrolyser [5]. Further to this, the Desert Research Institute has developed a wind/solar hydrogen production system [6] and the Chewonki renewable hydrogen project is about to install their electrolyser and fuel cell system [7]. The National Renewable Energy Laboratory has also shown an interest in building such a system for research purposes [8]. In Canada, the National Research Council Institute for Fuel Cell Innovation (NRC-IFCI) built a solar powered hydrogen production system [9].

There are also several systems in Europe and Scandinavian countries, though much less in numbers. For example, the Institute for Energy Technology based in Norway has been simulating solar and wind applications for several years. For the past couple of years, they have upgraded their facilities to incorporate a hydrogen electrolyser and a fuel cell [10]. Several large-scale hydrogen projects were built during the 1990s in Germany, Spain, Italy, Finland, and Switzerland with several small to large participating institutions. Another hydrogen project was designed and installed in the Kingdom of Saudi Arabia. These hydrogen projects have been the subject of several publications, some of which were directed by the International Energy Agency [11].

From year 2000 onward, three major renewable hydrogen projects have been completed in Europe showing the pace of the development in this technology. The first one is the Norwegian Utsira hydrogen project officially launched in July 2004 [12]. The second one is the HARI project at Loughborough in the UK, again opened in 2004 [13]. The third one is the PURE project in Unst (Shetland), opened in May 2005 [14].

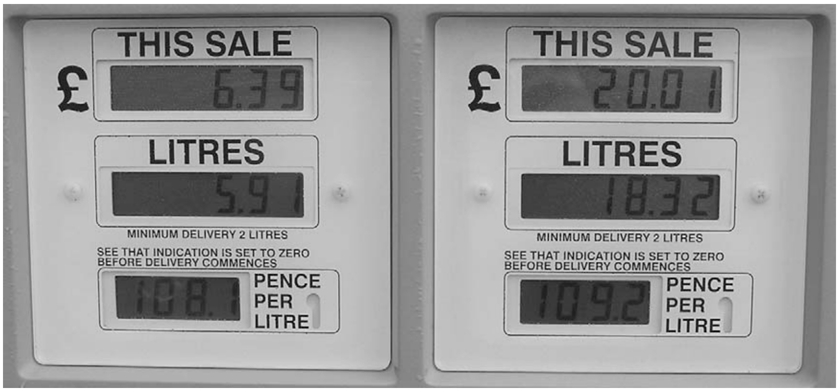

Fig. 2. Example of fuel costs on Unst during October 2005.

Fig. 3. Completed PURE energy system on Unst, Shetland.

3. PURE—the first community owned renewable hydrogen system in the world

The PURE (Promoting Unst Renewable Energy) project shown in Fig. 3 is a pioneering project on the windswept island of Unst, the most northerly island in the British Isles. The PURE project is a demonstration project that shows how wind power and hydrogen technology can be combined to provide the energy needs for a remote rural industrial estate. It has been developed by the Unst Partnership Ltd., a community development agency established by the Unst Community Council to support local economic development and regeneration. This is the first community owned renewable energy project of its kind in the world, and represents an important milestone in the development of green energy systems. The Unst Partnership, siGEN Ltd., and the Robert Gordon University through the Department of Trade and Industry (DTI)'s Knowledge Transfer Partnership (KTP) scheme worked together to deliver the hydrogen system.

Significant differences between the PURE project and other hydrogen energy systems deployed around the world are the scale and the low budget within which it has developed. The PURE project has uniquely been developed with a comparatively small project budget of approximately £350,000. This budget also included all the engineering and consultancy works surrounding the project, as well as the hardware.

4. Description of the PURE energy system

At present wind turbine technology offers the most cost effective method for the generation of clean electrical energy. As such this technology has been deployed as the primary power source within the PURE project system. However the PURE energy system was uniquely designed so that any type of renewable resource could be connected to it such as wave, tidal, solar, or even the grid in case green tariffs are being solicited.

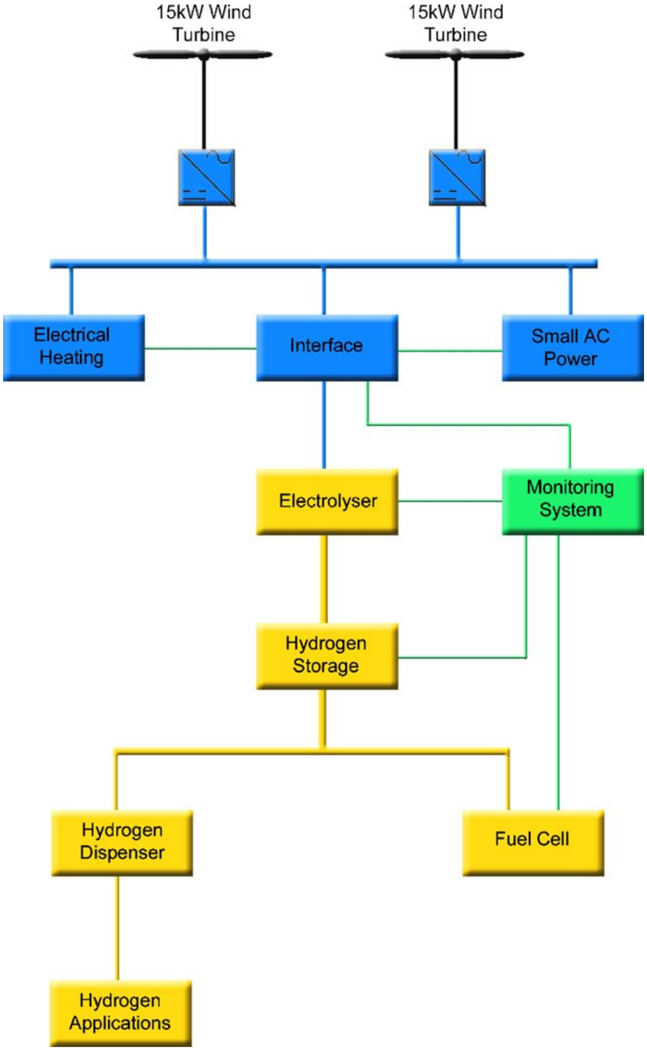

Fig. 4. Simplified schematic diagram of the PURE energy system.

The PURE project as shown in Fig. 4 consists of two 15 kW wind turbines whose design is based on the concept of using a permanent magnet generator (PMG) and a direct drive. It has a 3.55 Nm^3 per hour high-pressure hydrogen electrolyser, high-pressure hydrogen storage, and a hydrogen dispensing facility to fill hydride cylinders. The cylinders are used in a fuel cell/battery hybrid vehicle and other hydrogen applications as an alternative to fossil fuels.

A back-up power supply was also installed. This takes the form of a 5 kW fuel cell and an inverter. The hydrogen used by the fuel cell is produced from the electrolyser. The inverter was installed to convert the output power of the fuel cell from direct current (DC) into mains equivalent alternating current (AC).

A wind to heat system was designed and implemented to heat the five business properties. This system essentially consists of two AC/DC rectifiers that are used to convert the unregulated AC electric power generated by the two wind turbines into DC. This is then fed under electronic control to the electrical storage heating elements. It has been found that the best use of the wind power is to directly connect the corresponding generated electric power to the heating system to warm up the buildings.

The main reason behind this design approach is the direct correlation between high wind speeds and the need for increased heating energy. Therefore, when the wind speed increases, storage heater units are activated to produce heat. The storage heaters also store thermal energy for future use in the location that the thermal energy is required.

In addition to the above a novel intelligent electronic management system was developed to minimise the losses between all elements of the system. Detailed monitoring and analysis of performance of the system are being performed to maximise learning opportunities and further developments.

A battery based electric vehicle was converted to run with a hydrogen fuel cell. This electric/fuel cell hybrid car is now fuelled exclusively by the PURE system, using hydrogen produced from the renewable source. This makes this electric car the only one, which is 100% carbon free vehicle on the British roads.

5. The field integration experience

During the design and construction of the PURE energy system a number of key lessons have been learned.

Key to the successful implementation of the project within the available budget was a significant reduction of the on-demand power requirements. The graph shown in Fig. 5 demonstrates the significant reduction in on-demand power requirements achieved prior to the implementation of the new energy system.

The reduction of the on-demand power requirements was achieved by implementing a number of energy efficiency measures. This included substantial improvement in building insulation and removal of on-demand heating from the main power system. These measures have reduced the need for on-demand power by 55%. The same measures are also expected to deliver a further 20% reduction in annual energy consumption. The on-demand heating has been replaced by storage heaters whose thermal output can be manually controlled by the users as the need arises. The energy used to charge the storage heater system is delivered directly from the wind turbines, as mentioned earlier, with the balance being shared between the small AC power and the electrolyser.

Economically this is considered the first major field experience. This exercise has resulted in £40,000 savings in the capital costs of additional renewable energy production by spending only £3000 on energy efficiency measures.

One of the most unexpected findings during the early stage of design was the gap in the wind turbine market between 6 and 300 kW. It was found after an extensive market survey that no manufacturer could offer turbines within this power range suitable for the strong wind conditions, which comply with the IEC 61400 class I [15]. It was also found that most of the recent innovation in wind turbine technology that makes modern commercial machines dependable has not been fed back to smaller community scale turbines. The main area of development missing from community scale wind turbines appears to be the use of active yaw and pitch controls. Such controls provide a regulated power output in turbulent wind conditions and also facilitate the execution of a controlled shutdown in extreme wind speeds, usually in excess of 55 miles per hour.

Consequently it was decided to select two commercial prototype wind turbines for the two 15 kW units that provide the primary system power. They were selected with an agreement drafted for the PURE project site to be the UK test site for the turbines. As the turbines were commercial prototypes, the project team have also been involved in developing the 15 kW wind turbine shown in Fig. 3. Such involvement helped to ensure that the developed prototypes can withstand operation under extreme wind conditions where the wind speed can gust as high as 140 miles per hour as seen in Fig. 6.

Due to the prototype nature of the wind turbines a number of system faults have been recorded over the course of the project. It should be noted that the wind turbines have been operating since April 2004, prior to the installation of the electrolyser. This is highlighted in Fig. 7, which shows a large proportion of system faults are attributed to wind turbine failure. After every wind turbine failure was recorded, a significant improvement was made in the wind turbine design and implementation. From November 2005 onwards it is anticipated that the implemented improvements will significantly reduce future wind turbine failures.

The benefit to the PURE team's involvement in the development and testing of the wind turbines was a greater understanding of the turbines dynamic performance in all weather conditions. This enhanced understanding has led to the development and construction of an intelligent electrical interface

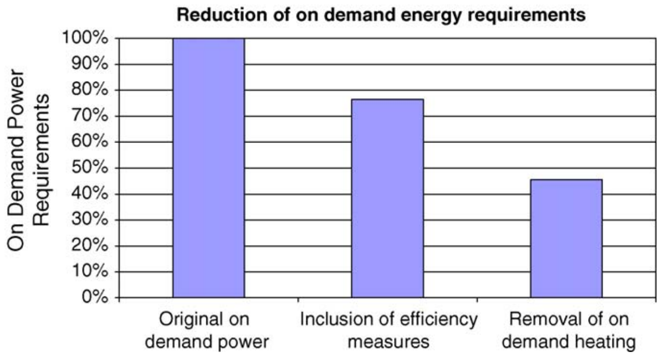

Fig. 5. On-demand power reductions achieved.

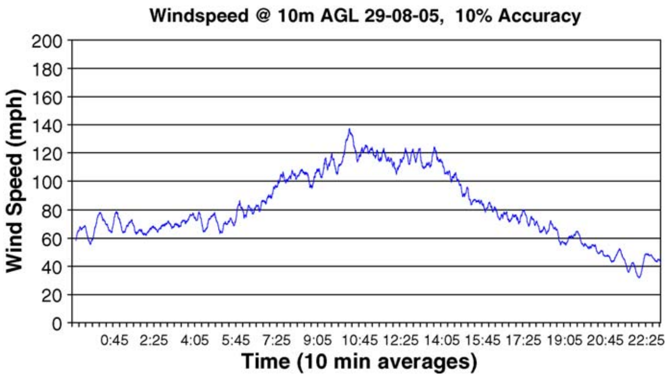

Fig. 6. Example of extreme wind conditions recorded at project site.

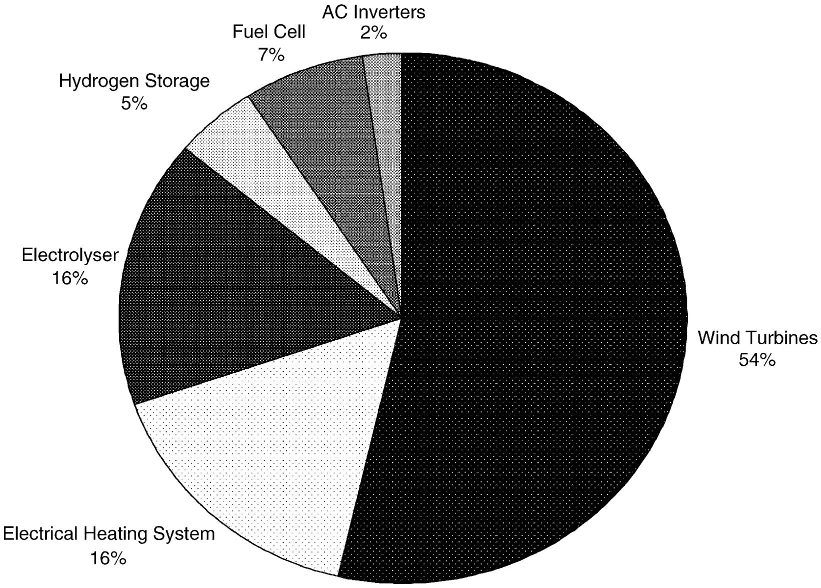

Fig. 7. Historic fault log overview.

system between the wind turbines and the electrolyser. This is aimed at further improving the overall system performance. This makes it possible to capture a further 18% increase in the total energy available from the wind turbine, which is equivalent of up to 21 MW h per annum in the wind conditions recorded at the project site.

An additional unexpected lesson learnt during the project design was the inability of conventional alkaline electrolyser technology to effectively use an intermittent energy input. Again after completing an extensive market survey it was revealed that there was only one electrolyser manufacturer available that could guarantee continued electrolysis efficiency when used with an intermittent renewable power source. Their patented alkaline electrolyser technology has removed cyclic degradation in hydrogen production efficiency and consequently extended expected electrolyser life to more than 20 years.

Proton exchange membrane (PEM) electrolyser technology was considered for use in this project and was included in the market survey. From the market survey it was found that this technology could potentially out perform conventional alkaline technology in a number of important areas. One potential benefit of PEM technology compared with conventional alkaline technology was its ability to reach output gas purities typically in the region of 99.999% both for H_2 and O_2 without using any post gas production purification. Another benefit is that PEM technologies ability to operate at high pressure has been proven and the need for auxiliary gas compression is then considerably reduced. Also PEM technology avoids the requirement of circulating a large amount of liquid electrolyte and showed the ability to operate at higher current densities than alkaline electrolysers, with conversion efficiencies ranging from 50 to 90%. This gives PEM technology the intrinsic ability to cope with transient variations in electrical power input a lot better and more responsively.

However, commercially available PEM technology cannot yet reliably achieve high efficiencies at high current densities, with premature stack failure occurring under extended high power usage. This results in market ready PEM technology holding only small 6–12 month warranties with expected stack lifetime ranging from 3000 h up to a maximum of 5 years at lower efficiency and current densities. As the PURE project is expected to operate for an extended period of time the PEM technology will cost significantly more to operate over the long-term due to premature stack failures. As such alkaline technology was selected for use in this instance.

The long expected operational life from the selected alkaline electrolyser technology has resulted from the high quality materials and components used in the electrolyser construction. After extensive field trials of the electrolysis material technology there have been no failures through the correct operation of the electrolyser. Another significant advantage between the chosen technology and that of other alkaline technologies is its ability to reduce electrode corrosion from dissipated and parasitic electric currents. This minimises the formation of electrolyte sludge containing metal deposits from electrode degradation.

By minimising the build up of electrolyte sludge, the need for periodic wash cycles to remove the sludge is removed. Also addressing the cause of electrode degradation removes the need to replace the electrolyser stack in the short to medium time frame. This results in a maintenance saving of approximately 40–50% of the cost of a new electrolysis plant and a life expectancy of up to 20 years.

A detailed comparison of the selected electrolyser technology against that currently available has shown that the new design can also deliver improved efficiency gains. The chart shown in Fig. 8 highlights the improved efficiency gains expected from the optimised design of the new electrolyser that is currently used in the PURE project. The manufacturer has recorded figures for electrolyser efficiency over a long period of operation with a variable power source. The data presented represents the average figures of efficiency when the electrolyser system is in operation and has reached its nominal values for operating temperature.

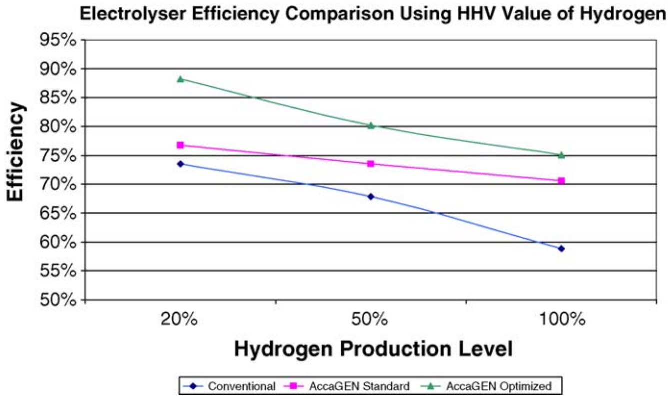

Fig. 8. Nominal electrolyser efficiency comparison.

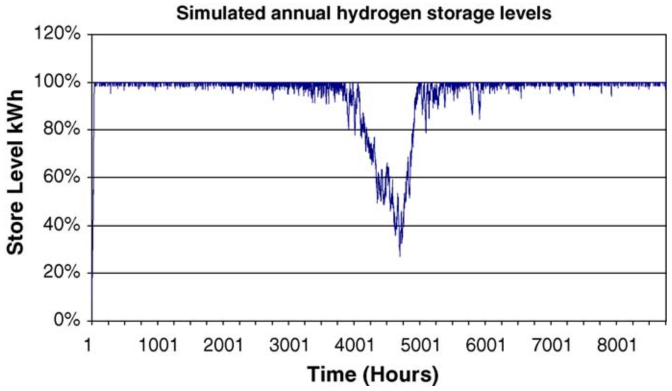

Fig. 9. Example of hydrogen storage level simulation results.

During the early design stages of the PURE energy system it was identified that there was a lack of system modelling tools that could simulate the use of hydrogen as a long-term energy storage medium. This has led to the development of proprietary modelling tools to assist in the sizing of the system components [16]. As seen in Fig. 9 this enabled annual simulations to be performed to assess the system performance against the renewable resource available.

It was also found that codes and standards relating to fuel cells and hydrogen as an energy carrier were in their infancy and therefore little or no information could be found. This has necessitated the establishment of a close working relationship with the Health and Safety Executive (HSE). In particular it was found extremely important to consult with the HSE on the layout and ventilation requirements for the installation of a hydrogen system in a community location.

6. Wider identified benefits

The high profile nature of the project, the islands demographic profile, and the infancy of the technology used resulted in a number of important indirect benefits to the wider local community of approximately 650 people.

One of these has been the custom it has provided to local businesses involved in its implementation. This is estimated to be over £60,000 spent within the Unst community alone. In a specific example visitors to the PURE project have generated over 150 bed-nights of additional tourist accommodation trade on the island since its official opening in May 2005. This equates to over £7000 of additional income to the local economy.

Local ownership over the entire project development process has meant the Unst community is now in a position to capitalise and benefit from the lessons learnt and skills acquired, by establishing its own PURE Energy Centre. The PURE project has demonstrated that a community can control the management of an innovative hydrogen project by seeking and acquiring the relevant technical and management skills. This has necessitated the forging of links and partnerships with a wide variety of academic institutions, businesses, and public agencies that have facilitated skills and knowledge transfer.

Since completion, the PURE project has created a number of highly skilled jobs, which were almost non-existent before within Unst. The project has attracted several young engineers to return to Shetland after graduation and become involved in the highly rewarding and innovative work in Unst. This has contributed to helping reverse the decline in population and job opportunities. High quality jobs have already been created for seven individuals, with potential for more as the PURE Energy Centre develops.

One direct benefit to Shetland communities resulting from this project that has already entered its implementation phase is the deployment of 16 wind-to-heat systems to heat 16 public buildings. The deployment of this system will be executed by local contractors and will reduce overheads for the public amenities making them more accessible to the wider community.

7. Conclusions

This paper has described the PURE project and outlined the field experience gained so far from getting involved in the design, implementation, and operating the system.

It can be concluded that the PURE project has been a success from a community perspective due to the additional and sustained income that it has generated for local business.

It has also shown that PEM electrolyser technology has the potential to provide a better solution for the production of hydrogen from renewable energy in the long-term. However, based on today's commercially available technology it has been found that alkaline electrolysis technology could provide the most reliable and cost effective solution to hydrogen production from an intermittent renewable energy source. Advances in the alkaline technology used in the PURE project have also significantly improved its ability to work with intermittent power sources whilst retaining and improving efficiency and reliability.

The implementation of this project has also highlighted the need for development of reliable community scale wind turbines that are classified for IEC 61400 class I wind areas.

8. Further work

In order to understand the actual operation of this type of energy system in more detail it will be necessary to conduct detailed data logging. After implementation of the wind turbine modifications it is planned to begin the detailed data logs required. From the recorded information it will also be possible to accurately understand system efficiency losses. The recorded data will also make it possible to improve the modelling tools that have been developed.

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