Renewable Hydrogen Vehicles and Infrastructure Development in the UK

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***Abstract*- This paper considers the design and implementation of hydrogen vehicles and hydrogen storage along with hydrogen infrastructure development around the world, and in particular in the United Kingdom with reference to the work of the University of Glamorgan's (UoG) Sustainable Environment Research Centre (SERC). This work proposed a road map for hydrogen as an energy carrier for vehicle fuel by investigating current developments and future proposals relating to hydrogen energy and a hydrogen economy.**

Keywords*- *Hydrogen Vehicles; Energy Storage; Hydrogen Economy; Energy Management; Hydrogen Infrastructure

I. INTRODUCTION

Hydrogen fuel cell vehicles are considered to be an alternative potential replacement of conventional fossil fuelled internal combustion engine vehicles. However, there are several obstacles for the widespread application of hydrogen fuel cell vehicles, for example high capital and operating costs and lack of infrastructure. Research and development have a fundamental role to play in addressing issues that are acting as a barrier to the accelerated deployment of this energy technology. To this end, research and development are carried out to investigate and improve the performance, stability and reliability of hydrogen fuel cell vehicles, see for example [1, 2]. Furthermore, in Europe, in a large scale the Clean Urban Transport for Europe (CUTE) pilot project was carried out by DaimlerChrysler for the European Commission (EC), to evaluate the credibility of this new technology used by Citaro fuel cell buses [3]. CUTE project results indicated that the efficiency, reliability and durability of hydrogen fuel cell vehicles were good enough for rapid roll-out of hydrogen fuel cell vehicles throughout Europe.

In the specific case of UK development of hydrogen fuel cell vehicles and their deployment; the UK government is investing £400 million to support the development, demonstration and deployment of low and ultra-low emission vehicles by evaluating the potential for hydrogen as a fuel for ultra-low carbon vehicles in the UK. This programme is called UKH2 Mobility; its partners include Daimler, Hyundai, Johnson Matthey, Nissan, Scottish and Southern Energy, Tata Motors, Toyota and Vauxhall, as well as three UK government departments [4]. The objective of the programme is to position the UK to begin the commercial roll-out of hydrogen fuel cell vehicles in 2014/15 [5]. While we move closer to the implementation of this technology, it is important to improve the fuel economy and driving range of these hydrogen fuelled vehicles. To this end, several researchers have carried out different kinds of energy management studies in order to improve the performance of hydrogen vehicles, see for example [6-8]. In this aspect, research effort at University of Glamorgan's (UoG) Sustainable Environment Research Centre (SERC) lead to the development of new energy saving mechanisms for renewable hydrogen vehicles [9]. Research effort at the UoG has led to the development of the UK's first alternative renewable hydrogen energy refuelling facility at the University's Hydrogen Centre in Baglan along with the production of three hydrogen hybrid electric vehicles and an associated simulation toolbox which can be used for further investigation and analysis of problems such as energy management, system configuration, fuel consumption and hydrogen storage.

II. HYDROGEN VEHICLES

The growth and interest of hydrogen based technologies can be seen by the magnitude events and demonstration projects carried out around the world [10]. Hydrogen vehicles are increasingly being researched to satisfy the market need for a low emission means of transportation. Besides being a potentially green mode of transportation, hydrogen vehicles also promise efficient and quiet operation, which makes them an attractive proposition [10, 11]. The major challenges in using hydrogen for vehicle applications are the costs and the low energy efficiencies of conversion to hydrogen; therefore with low implementation into our society so far, successful solutions are needed for several challenges before hydrogen can be considered a viable energy carrier. However, several automobile manufacturers have committed to develop vehicles using hydrogen. The attraction of using hydrogen as an energy carrier is that, if hydrogen is prepared without using fossil fuel inputs, vehicle propulsion would not contribute to CO_2 emissions, along with its high energy concentration per unit weight. The drawbacks of hydrogen use are low energy content per unit volume, high tank weights, very high storage vessel pressures, the storage, transportation and filling of gaseous or liquid hydrogen in vehicles, the large investment in infrastructure that would be required to fuel vehicles, and the inefficiency of production processes.

Many researchers are investigating the issues relating to the development of new low emission hydrogen hybrid electric vehicles through the use of new technologies and materials along with the use of renewable energy to resolve the problems encountered. To this end, research efforts at the University of Glamorgan has led to the production of three hydrogen hybrid electric vehicles and associated simulation models [12, 13] to further investigate and alleviate problems such as energy management, system configuration, fuel consumption and hydrogen storage. These tools are also used to conduct an extensive study for control analysis, and math-based vehicle developments and controller design to improve system performance.

The hydrogen hybrid electric scooter vehicle is a small scale system designed to test the system configuration, reliability and applicability of the powertrain topologies and experimental setup. The test was conducted successfully [12] and the results lead to the production of the UoG, Faculty of Advanced Technology, Hydrogen Bus (UoGHB). The powertrain of UoGHB consists of a 12 kW PEM fuel cell stack developed by Hydrogenics, a 288 V, 132 Amp/hr lead-acid battery pack, 375 V, 63 F Maxwell ultracapacitor, and a 70 kW DC motor. This is an improved design based on the initial large scale MULE vehicle system, which was developed to test the same system configuration developed in the scooter vehicle on a larger scale. The vehicles were tested in various conditions to verify their performance while experimental data were collected from the vehicle components for further analysis.

It has been observed that the UoGHB achieved a range of 150 miles with a top speed of 55 mph. Compared to the MULE vehicle this was a significant improvement. In the case the MULE vehicle the range was 37 miles with a top speed of 40mph. Furthermore, for the UoGHB the maximum power output is 75 kW with a maximum power input for charging the battery of 45 kW, alongside a battery capacity of 72 Ah and a total energy store of 35.6 kWh. In contrast the MULE vehicle maximum power output is 22 kW with the maximum power input of 22 kW, alongside a battery capacity of 228 Ah and a total energy store 13.9 kWh. It is evident that the CO_2 emissions by these hydrogen based vehicles are lower than those by existing fossil fuel powered vehicles. For example, comparison results of the UoGHB's CO_2 emissions with a typical diesel van's CO_2 emissions for the same distance travelled with the same environmental and road conditions show that the CO_2 emissions of the UoGHB are significantly lower than the typical diesel van CO_2 emissions. In fact it was observed that the UoGHB CO_2 output is half of the typical diesel van CO_2 output. It is important to note that these vehicles have the potential to reduce carbon emissions and play a significant role in achieving UK carbon emission reduction targets [9].

Through these examples and pilot programs the commitment of developing vehicles using hydrogen has been addressed, specifically hydrogen fuel cell vehicles. However, hydrogen as a fuel still needs significant progress before being realized as an economically feasible and safe vehicle fuel. It is important to note that, as we begin to realise hydrogen as potential fuel, hydrogen does not exist naturally in quantity, and thus it needs to be generated from an energy input system such as steam reformation of natural gas, or electrolysis of water using renewable electricity. Thus, the utility of a hydrogen economy depends on issues of energy sourcing and sustainable energy generation and production. Due to the multiple possible energy sources from which hydrogen can be produced, hydrogen fuel cell technologies become more and more viable due to the limited amount of fossil fuels and the effects fossil fuels are having on the environment [14, 15]. The fuel cell is now considered as an alternative electrical power source for automotive, portable electronics and stationary applications. Fuel cells are able to provide large amounts of current and hence power, but the only requirement is the constant flow of reactants. It is this supply of reactants that presents one of the several challenges encountered by fuel cell system investigators. There are several types of fuel cells each using a different chemistry. Fuel cells are usually classified by the type of electrolyte they use. Some type of fuel cells work well for use in stationary power generation plants and others may be useful for powering a car [10, 16].

The growth in interest of hydrogen based technologies can be seen by the magnitude of the events and demonstration projects carried out around the world. For example, forklift trucks are ubiquitous around the world, enabling logistics companies to efficiently prepare goods for ProMat 2011, an international material handling show held in Chicago during March, four booths demonstrated fuel cell technology, including Plug Power, Nuvera Fuel Cells, Yale and the US Department of Energy. Industrial gas companies such as Air Products and Praxair were also present demonstrating their refueling solutions for hydrogen powered forklifts. In the niche transport sector, SFC Energy was exhibiting its DMFC technology. At Transport 2011 SFC partnered with Awilco Multiplex and at Nufam 2011, another commercial vehicle fair, had its own booth. It has also visited a leisure fair in Scandinavia with partner Mastervolt and plans to visit the Dutch Marine Equipment Trade Show in (METS-2011) November 2011. Stationary fuel cell systems are garnering increasing exposure too, for example, at the International Telecommunications Energy Conference, Intelec 2011, fuel cell tutorials and round table discussions formed part of the technical programme. The theme is the use of fuel cells for both backup and continuous power in telecoms applications. In the portable sector, Horizon Fuel Cell Technologies continues to promote its range of fuel cell recharging devices and toys at more than 30 consumer electronics shows, teacher conferences and toy fairs around the world. Furthermore, we have seen noticeable changes in certain hydrogen fuel cell companies that have been well established in the field; they have shifted focus from exhibition and demonstration projects themselves and are now directly targeting their end-users. This is an indicator of how successful and commercially viable hydrogen based fuel cell technology is becoming [17].

The following section of the paper discusses hydrogen storage and production for the use of hydrogen vehicles and other applications.

III. OPTIMAL HYDROGEN STORAGE AND PRODUCTION

The literature on hydrogen futures contain a number of visions ranging from decentralized systems based on renewable through to centralized systems based on nuclear and carbon capture [18]. Centralized and decentralized hydrogen storage options may both be viable in a future hydrogen economy [19]. The transition to a hydrogen economy, if it occurs, will involve a large amount of investment and effort. It is likely that hydrogen will first be used in niche applications. One of these could be for energy balancing, which will drive technological innovations and will allow renewable energy generators to sell hydrogen for hydrogen economy uses.

Hydrogen may be produced renewably by using electricity generated by renewable resources as the power source for an electrolyser. In order for hydrogen produced by this route to achieve a large penetration as a fuel source, a number of technical and economic challenges must be overcome. These challenges are associated with the capital cost of components needed, operation with renewable energy sources, lifetime and reliability, and in the case of storage, weight and volume targets must be met. As well as these considerations, the design and control of renewable hydrogen systems must be considered in order to optimize the efficiency of hydrogen production and storage, as well is maximizing the life time of equipment.

Electrolysers are typically optimized to operate under a constant load. When operating with renewable resources the power source may be both intermittent and variable. This may lead to a reduction in efficiency, reduced lifetime and reduced hydrogen purity. In addition, dependent on the technology used, the electrolyser will not operate below a certain percentage of maximum load (e.g. 40%, alkaline electrolyser). The cost of electrolysers is likely to reduce as their production volume increases, but in order to bring costs down to a level which will make them economically feasible, other cost factors must be reduced. For example, PEM electrolysers often use platinum as a catalyst on their anode and cathode. Reducing costs through reducing platinum loading, or finding alternative non-Pt catalysts whilst maintaining performance, is an important research goal. Optimal electrolyser design for the biohydrogen production and hydrogen production by microbial water electrolysis (see Fig. 1) is also an active research area. Electrolysis is a key technology for the conversion of renewable energy to small scale-on site hydrogen production.

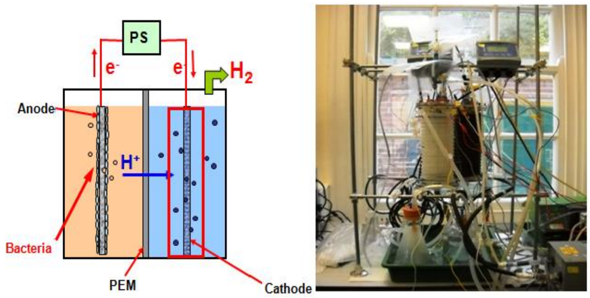

Fig. 1 Hydrogen production by microbial water electrolysis

As well as investigating the performance of individual components, the operation of the overall renewable hydrogen system should be studied. Stand alone renewable hydrogen systems tend to consist of a renewable source, electrolyser, battery/ultracapacitor and a fuel cell. These are connected, via appropriate power electronics devices to a DC bus bar. The role of the battery/ultracapacitor is to provide short term buffering of energy variations, as well as regulating the voltage of the DC bus bar. Sizing, control and interaction of the various components on the system should be optimised.

Work at the University of Glamorgan's Hydrogen Centre will focus on improving electrolyser performance under variable load, either by changes in electrolyser design, changes in control methodology, and combination with short term energy storage (e.g. battery/ultracapacitor). The Baglan Hydrogen centre has a 20 kWp PV array, 10 NM^3/hr alkaline electrolyser, 10 barg intermediate storage cylinders together with 200 barg compressor and associated storage cylinder, 12 kW PEM fuel cell with additional battery storage, along with a hydrogen/CNG vehicle refuelling station. The structure of the solar powered hydrogen production/storage system is demonstrated in Fig. 2. By using a power source emulator, it will be possible to investigate the operation of different electrolyser technologies with various renewable sources. Optimizing the process efficiency of round trip hydrogen storage as well as hydrogen generation for vehicle use will also be investigated. The centre also operates as a demonstration centre.

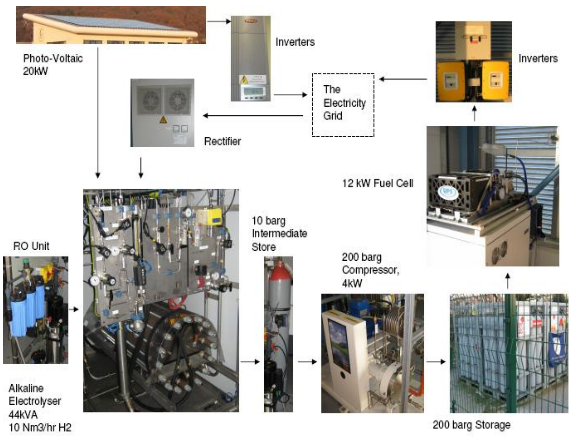

Fig. 2 Structure of solar powered hydrogen production and storage system installed in UoG Baglan Hydrogen Center

Biohydrogen production from renewable biomass or waste can be another option for on-site hydrogen generation. Hydrogen production by using fermentative bacteria can use various feedstocks such as agricultural and food waste, thereby reducing waste treatment cost whilst simultaneously generating renewable hydrogen [20]. Two pilot scale biohydrogen reactors are being operated by SERC: Aberystwyth two-stage pilot plant using crop (Fig. 3a), and Barry biohydrogen plant using wheat feed (Fig. 3b).

(a) (b)

Fig. 3 UoG-SERC's biohydrogen plants using crops and wheat feed

IV. HYDROGEN INFRASTRUCTURE

Development of a hydrogen infrastructure includes setting standards such as supporting laws and regulations, and construction of a delivery and transportation infrastructure as well as efficient hydrogen production discussed in the previous section. Transportation of hydrogen from production plants to distribution stations is an essential part of a hydrogen economy as it comprises one of the main costs of the final hydrogen fuel. Central hydrogen production and construction of delivery systems (pipeline or transportation) are being planned and developed with governmental support. Additionally, local production of hydrogen using renewable energy based on fermentation and wind and solar might contribute to save transportation costs, and can diversify and stabilize hydrogen supply systems. Construction of infrastructure for hydrogen fuel is of interest as it can increase economic feasibility of clean energy as well as it contributes to further technical advancements.

There are over 100 hydrogen filling stations in operation around the world, mostly located in USA, Germany and Japan. In Europe, filling stations have recently been built in 10 cities to support hydrogen powered buses in the EC funded CUTE project in order to reduce the consumption of fuel and energy in the whole transportation system [21]. In order to expedite implementation of hydrogen fuel for transportation and energy systems in UK, the Energy Research Centre (UK ERC) has supported the Supergen Sustainable Hydrogen Energy Consortium (SHEC) which includes renewable hydrogen production including biohydrogen, storage, and social impacts and integration including transportation.

The Welsh Assembly Government also supports R&D programs (e.g. H2Wales) for infrastructure and for ultimate market growth in order to create an extensive renewable refuelling infrastructure in the UK. Wales has an existing hydrogen infrastructure to build on, and demonstration projects such as H2Wales which focus on coalescing of individual research projects with existing infrastructure in SERC and other University based research centres. This program aims to construct a "hydrogen highway" along the M4 corridor in South Wales and West England as a UK flagship for hydrogen based transportation (see Fig. 4). Baglan Hydrogen Energy Centre facilitates the implementation by providing a demonstration centre and refuelling station, as well as research and testing facilities.

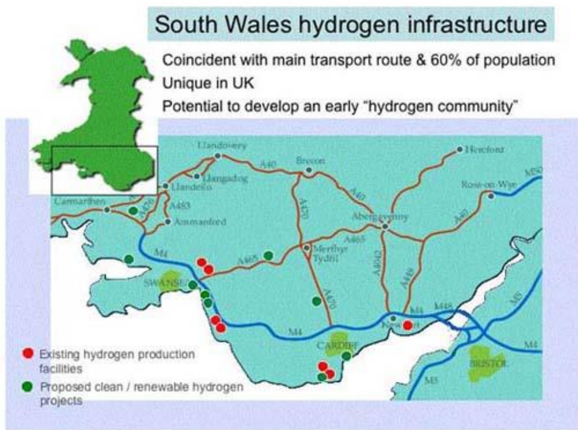

Fig. 4 Hydrogen infrastructure: South Wales

The hydrogen fuelling station is an important part of the infrastructure for a hydrogen economy. For a station dispensing delivered hydrogen (e.g. a small refueller), the final cost of hydrogen is dependent on the price of delivery. However, the cost is also dependent on the capital investment of the plant and the cost of electricity production for large scale filling stations and grid-electrolysis [22]. Development of efficient hydrogen delivery systems in compressed gas storage and liquefaction would require further R&D advancement. In addition, local on-site generation by electrolysers with sustainable electricity, and biohydrogen production based on local biomass and waste can reduce transportation cost and improve energy efficiency [23].

V. FUTURE RESEARCH CHALLENGES

A. *Technological Challenges*

For the production of hydrogen from renewable sources, low temperature electrolysers are considered most suitable. This is due to the intermittent, variable nature of the renewable resource. High temperature electrolysers operate at poor efficiencies during the transient warm up period, and the effect of multiple heating and cooling cycles may affect lifetime [24]. For low temperature electrolysers, alkaline and proton exchange membrane (PEM) electrolysers are the two most viable current technologies. Alkaline electrolysers are a mature technology, whilst PEM electrolysers have been more recently developed, and are now commercially available. For both technology types, when used with variable renewables, thermal management, gas mixing at low loads and uncertainty over the long term effect of intermittent variable operation need to be considered. These problems are greater for alkaline electrolysers [25]. Electrolysers exhibit greater efficiency at low loads, due to reduced current densities decreasing ohmic losses, so maximising efficiency is an important challenge. Similar conclusions to the above can be drawn for the reverse operation – e.g. fuel cells. In all cases, cost reduction is an important challenge. For PEM electrolyser, reduced platinum loading of catalysts, or alternative catalysts are being researched, along with membrane technology. Increased efficiency, reduced costs and increased lifetime are the main research goals, as well as volumetric and gravimetric power densities (inclusive of the hydrogen store) for vehicular use [26].

B. Hydrogen Systems Research

Electrolysers and fuel cells are often combined with short term storage devices, and interfaced with power electronics. The purpose of this is to increase system efficiency, reduce the variability seen by the electrolyser/fuel cell, and provide suitable voltage/current levels and profiles. Systems could include stand alone storage systems, grid integrated systems, and hydrogen production facilities, and vary in size from domestic to utility scale. Research challenges in this area include system design, component selection and sizing, control design, power electronic interface design, and overall management strategies [27-29].

C. Future Scenarios Research

Defining the role of hydrogen storage and a hydrogen economy in future energy systems is a major research challenge. There is no consensus on whether increased storage will be necessary in future systems with renewables, although the majority view is that it will be to some extent [30], [31]. Defining the role of storage, the level of renewable penetration/system characteristics at which it becomes beneficial or necessary are important areas of research. Along with this, system design and control of energy systems with storage are major research challenges [32, 33]. The overall outlook of a hydrogen economy, including production, transportation, end used and overall system design is an active area of research, with a large number of competing visions for the future [34, 35].

VI. CONCLUDING REMARKS AND DISCUSSION

In this paper an investigation of the development of renewable hydrogen vehicles, hydrogen storage, and hydrogen infrastructure in the UK is carried out with reference to the work of the University of Glamorgan's Sustainable Environment Research centre. Analyses are based on the overall progress in the development of hydrogen energy and its future. The growth and interest of hydrogen based technologies can be seen by the magnitude of the events and demonstration projects carried out around the world. The research challenges which need to be overcome before a hydrogen economy is realized are outlined. Furthermore, it has been observed that, hydrogen infrastructure in the UK is still in the early development stage and compared to the other leading nations such as Germany, USA, and Canada, the UK will need to do more to achieve its full potential in order to realize hydrogen as an alternative energy carrier.

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