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Hydrogen Fuel Cell as an Intermittent Renewable Energy Fuel Source

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Abstract: This study present a number of experimental renewable energy systems with hydrogen energy buffering. The first generation of systems demonstrated that hydrogen could be generated from surplus renewable input power through water electrolysis and stored for both short-term and seasonal energy buffering. They illustrated that a continuous supply of power can be derived from an intermittent renewable energy source coupled to the appropriate hydrogen conversion devices. However, the test-beds were constructed primarily from custom components often one-off prototypes and were plagued with reliability issues. Energy self sufficiency was for the most part not obtained due to the limited energy generated from the renewable sources coupled with poor component efficiencies and large parasitic system loads. All of the demonstration projects report major operational problems with the fuel cells used in the regenerative subsystem. They revealed that significant advances in electrolyser, fuel cells, hydrogen storage and power conditioning technologies were required before reliable system operation could be achieved.

Key words: Hydrogen, fuel cells, intermittent, renewable energy, buffering, electrolyser

INTRODUCTION

Global concern over environmental climate change linked to fossil fuel consumption has increased pressure to generate power from renewable sources (Boyle, 1996). Although, substantial advances in renewable energy technologies have been made, significant challenges remain in developing integrated renewable energy systems due primarily to the mismatch between load demand and source capabilities (Leonhard, 2001). The output from renewable energy sources like photovoltaic, wind, tidal and micro hydro fluctuate on an hourly, daily and seasonal basis. As a result, these devices are not well suited for directly powering loads that require a uniform and uninterrupted supply of input energy.

Incorporating multiple renewable source types into the system design generally enhances resource availability (i.e., deployment of wind and solar or solar and micro-hydro, etc.) and aggregation of distributed renewable power generation mitigates short term (high frequency) variability (Milborrow, 2007). However, practical renewable energy systems require an energy storage media to bank excess energy when available to buffer the output during periods where load demand exceeds the renewable input. Furthermore, different types of storage media are required to service short-term transients and long duration time scales.

In remote off-grid locations, operation from renewable resources traditionally requires large lead/acid battery buffers to address the issue of supply fluctuations. The physical size, limited life span and initial capital cost of the battery bank coupled with transportation, maintenance and battery disposal issues imposes significant limitations on the load capacity (Palomino *et al*., 1997). Significant improvements may be possible by storing the energy in the form of hydrogen instead of using batteries. During periods when the renewable resources exceed the load demand, hydrogen would be generated through water electrolysis. Conversely, during periods when the load demand exceeds the renewable resource input, a fuel cell operating on the stored hydrogen would provide the balance of power.

Although, considerable advances in hydrogen related technologies (electrolysers, fuel cells and storage media) have occurred during recent years, significant barriers in system integration must be overcome before the potential of renewable resource/hydrogen buffered energy systems can be realized. The integration issues associated with the development of a hydrogen energy buffer are not well understood or documented in the literature. Experimental results detailing the energy balance within the system and quantifying the energy loss in various system components have yet to be reported in a unified manner. Furthermore and perhaps more importantly, the dynamic interactions between system components that occur while servicing real world loads remain unexplored. In general, a gap exists in experimental information available for validating the assumptions made in numerical simulations of renewable regenerative systems. Accurate data on the performance of the individual subsystems is required to inform and assist in the development of models to predict the performance of larger scale systems. A brief description of the challenges related to renewables, energy buffering and the history of hydrogen buffered renewable energy systems are discussed.

First generation hydrogen renewable energy systems: During the late 1980s' to mid 1990s', nine renewable energy test-beds employing hydrogen energy buffering appear in the literature. The basic system architecture is similar to or a minor variation of the one showed in Fig. 1. The scale of these projects range from small 1.3 kW proof of concept experimental platforms to large 270 kW multi million dollar corporate ventures. The projects mainly focused on fuel cell technology demonstrations but also

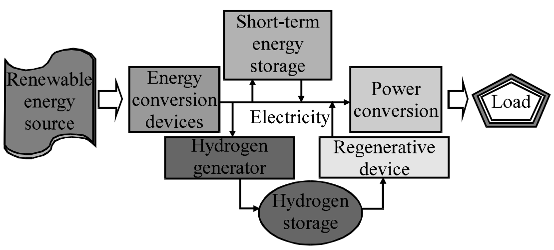

Fig. 1: Typical First Generation Renewable-Regenerative System Architecture

showed that hydrogen could be employed to buffer the daily and seasonal variations of an intermittent renewable energy source. A summary of the basic system parameters for the various projects is shown in Table 1.

Solar-Wasserstoff-Bayern (SWB) GmbH test-bed: Szyszka (1998, 1992) outlines the development of the 1st large-scale solar-hydrogen-fuel cell demonstration project located in Neunburg Vorm Wald, Germany which commenced in 1986. The project was a joint venture between the German government and a conglomerate of companys (notably Bayernwerk AG, BMW, Linde AG and Siemens AG) with a mandate to develop and test industrial scale hydrogen energy system components. The array of first generation prototype equipment assembled for this project was both impressive and diverse.

The total reported capital investment over the 13 years project was approximately 80 million US dollars. A block diagram for the overall plant is shown in Fig. 2. Solar collectors of monocrystalline, polycrystalline, amorphous silicon and advanced monocrystalline were employed in multiple fields connected to a common DC bus by various styles of power conditioning modules. In addition, several collector fields were tied directly to the 3-phase grid via DC-AC inverters. A variety of

Table 1: Component data for first generation Renewable-Regenerative Systems

Components	Solar-wasserstoff-bayern	Helsinki hydrogen energy test-bed	Schatz Solar Hydrogen Project	Freiburg solar house	University of Oldenburg	INTA solar hydrogen facility	Friedli solar hydrogen house	PECS Energy Conversion System	PHOEBUS
Year initiated	1986	1989	1989	1989	1990	1990	1991	1992	1993
Location	Germany	Finland	USA	Germany	Germany	Spain	Switzerland	USA	Germany
Solar input	370 kW_p	1.3 kW_p	9.2 kW_p	4.2 kW_p	6.2 kW_p	8.5 kW_p	4.5 kW_p	0.15 kW_p	43 kW_p
Wind input	None	None	None	None	5 kWp	None	None	None	None
Battery storage	None	14 kWh @24 VDC	5 kWh @24 VDC	19 kWh @24 VDC	Size not specified	None -	38 kWh @24 VDC	None -	303 kWh @220 VDC
Electrolyser	211 kW_{el} @1 bar 100 kW_{el} @31 bar	0.8 kW_{el} @25 bar	5.8 kW_{el} @8 bar	2 kW_{el} @30 bar	0.8 kW_{el} -	5.2 kW_{el} @6 bar	10 kW_{el} @2 bar	0.095 kW_{el} @6 bar	26 kW_{el} @7 bar
H_2 storage	5000 m^3 @30 bar	200 Nm^3	5.7 m^3 @30 bar	15 m^3 @30 bar	30 Nm^3	8.8 m^3 @ 200 bar+ 24 m^3 MH	0.5 m^3 @ 29 bar MH	2.6 Nm^3 MH	27 m^3 @ 120 bar
O_2 storage	500 m^3 @30 bar	None	None	7.5 m^3 @30 bar	Size not specified	None	None	None	20 m^3 @70 bar
Fuel cell	6.5 kW_{el} AFC 10 kW_{el} PEM 79 kW_{el} PAFC	0.5 kW_{el} PAFC	1.3 kW_{el} PEM	0.5 kW_{el} AFC	0.6 kW_{el} AFC	10 kW_{el} PAFC 5 kW_{el} PEM 2.5 kW_{el} PEM	None	Size not specified	6.5 kW_{el} AFC 5 kW_{el} PEM 2.5 kW_{el} PEM
Load	Public grid	0-0.5 kW DC resistive	0.6 kW AC	0.35 kW combined	Size not specified	Public grid	Stove/mini van	Size not specified	15 kW local grid
Notes	Industrial size system- US$80 million investment	Direct bus connection (no dc-dc converters)	Long-term continuous operation	Solar heating systems employed	Limited system data available	Direct PV electrolyser connection	Project funded by home owner	Limited system data available	Large-scale high visibility demonstration project
Primary reference	Szyszka, 1998, 1992	Vanhanen *et al*., 1998, 1997	Lehman *et al*., 1997	Goetzberger *et al*., 1993	Ghosh *et al*., 2003	Schucan, 2000	Hollmuller *et al*., 2000	Hollenberg *et al*., 1995	Ghosh *et al*., 2003

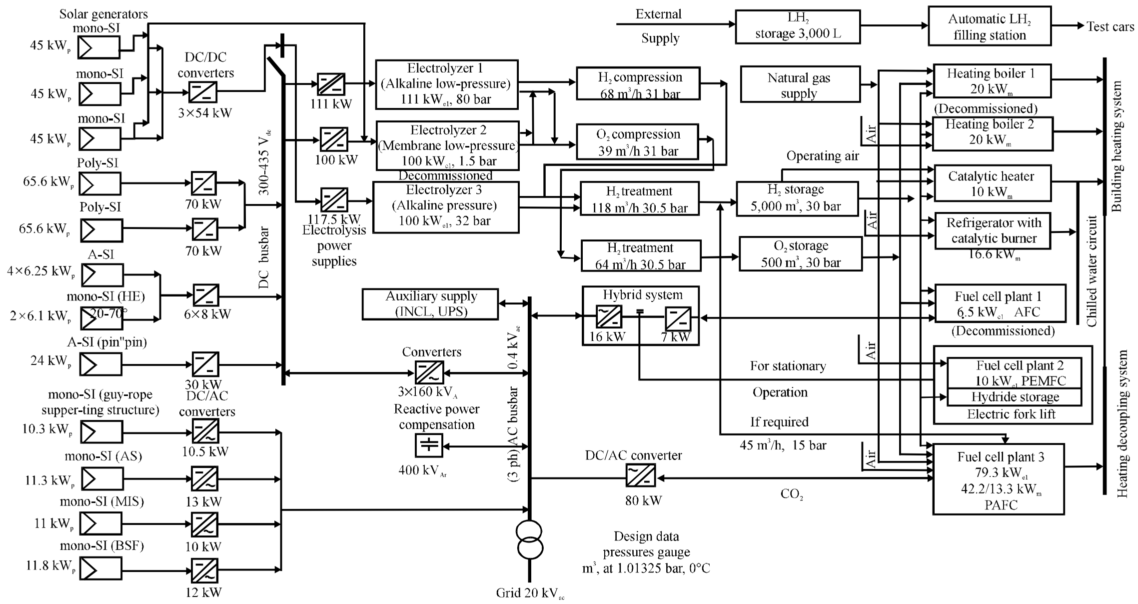

Fig. 2: SWB solar hydrogen facility block diagram

electrolyser technologies were tested including both low and high pressure alkaline and low pressure membrane types. Hydrogen production was controlled by limiting electrolyser input power. Extensive purification and compression stages were implemented for both the hydrogen and oxygen streams. Primary storage was in compressed form at 30 bar. Multiple fuel cell technologies were tested including alkaline, phosphoric acid and proton exchange. The fuel cell electrical output was used locally or coupled to the grid via appropriate DC-AC inverters. In addition, hydrogen and oxygen was also utilized in various boilers, catalytic heaters and absorption refrigeration technologies under investigation. The experimental program at SWB generated a significant database of information for the industrial partners involved but limited results are reported in the public domain. The technical aspects benefited component manufacturers involved unfortunately many are no longer active in the field of hydrogen energy systems. Researches by Szyszka indicate that considerable delays in commissioning subsystems was a common occurrence and that components often required complete redesigns. The SWB project reinforced the fact that significant advances in component reliability and performance were required before hydrogen systems for energy conversion could be realized on a commercial scale. It also illustrated that integration of hydrogen components was often more difficult than commonly believed.

University of Helsinki hydrogen energy experiment: Kauranen *et al.* (1994) and Vanhanen *et al.* (1997, 1998) report on the development of a small photovoltaic hydrogen energy test-bed at the Helsinki University of Technology.

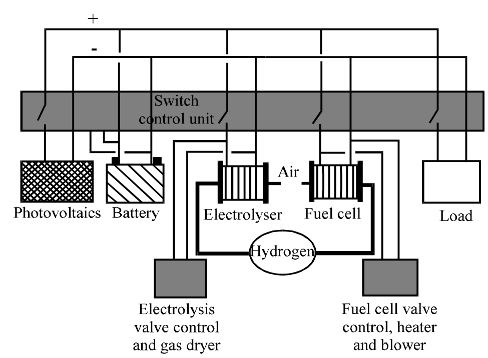

Fig. 3: University of Helsinki hydrogen energy test facility schematic

The test-bed initiated in 1989 consisted of a 1.3 kW PV array, a 12 kWh lead acid battery 20 bank, an 800 W alkaline electrolyser, a 500 W phosphoric acid fuel cell and a variable 500 W load, outlined in Fig. 3. The electrolyser is referred to as a pressurized type and no additional compression capabilities are mentioned. Conventional compressed hydrogen storage is assumed. A notable feature of this test-bed is the absence of power electronics to interface the components to the DC bus. The component characteristics were carefully matched allowing direct connection to the DC bus, thus eliminating the need for power conditioning converters. Furthermore, the load is a simple DC resistive type so, the typical inversion step is forgone. The power flow between system elements is directly linked to the state of charge of

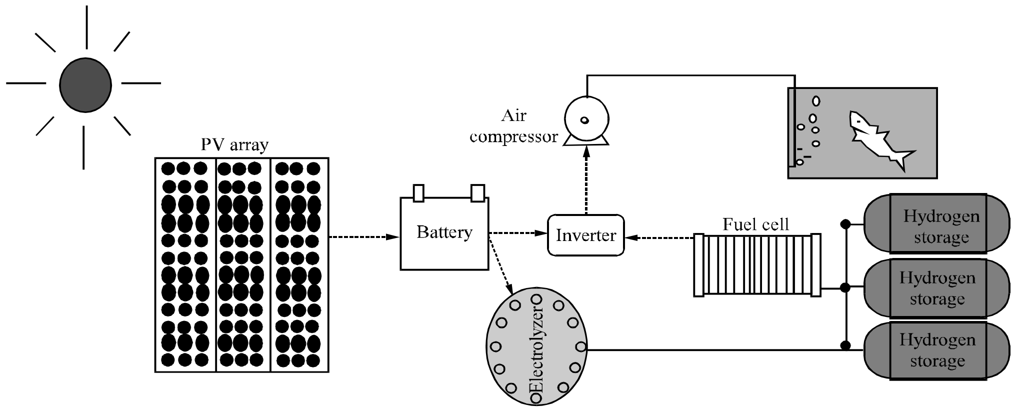

Fig. 4: Schatz Solar Hydrogen Project schematic

the batteries which determines the bus voltage. The experimental flexibility of the system is therefore, restricted to a limited operating envelope.

The system was designed with the belief that the round-trip efficiency of the hydrogen storage loop would be too low for daily use and applicable only to seasonal storage. Adequate short-term battery storage was therefore a necessity. Numerical models for the system components were developed and evaluated against experimental data. Simulation results showed good agreement with test data and a round-trip efficiency of 25% for the hydrogen storage system was demonstrated. Details regarding the fuel cell performance are omitted from the publications. A conclusion drawn from the research was that a PV array has to supply approximately three times the load energy for 100% self-sufficiency when operating in Helisinki's climate using the technology of the day. However, given the relatively large battery storage capacity, idealized load and lack of power conversion devices (i.e., low parasitic loses), this result many not be applicable to practical size systems. It would be interesting to know the ratio for a fully integrated renewable energy system using present day components.

Schatz Solar Hydrogen Project: Lehman *et al.* (1997) discussed the Schatz Solar Hydrogen Project initiated in 1989 at Humbolt State University. This project began with the goal of demonstrating that hydrogen was a practical storage media for solar energy. The system in its final form consisted of a 9.2 kW solar array, 5 kWh battery bank, 12 cell 6 kW bipolar alkaline electrolyser, 8 bar compressed hydrogen storage, a prototype 1.5 kW PEM fuel cell, DC-AC output inversion and a 600 watts aquarium air compressor load. A system schematic is shown in Fig. 4. System reliability was a key design parameter given that the load was a primary life support system for the aquarium. A fail-safe power transfer system was incorporated to return the air compressor to local grid power in the event of a failure in the hydrogen energy system. Although, the solar collectors, electrolyser, hydrogen storage and inverter worked reliably, problems with the fuel cell led to limited system utilization. The original commercial fuel cell manufacturer was unable to provide a working unit during the 1st 2 years of the experimental program. The poor fuel cell performance led to a university research initiative to develop fuel cell technologies. The system was not energy self-sufficient due to the control system and auxiliary components loads (electrolyser makeup water pump, cooling systems, safety monitors, etc.). As such, accurate figures on the overall system efficiencies are not available. However, an efficiency of 34% can be estimated based on the ratio of power to produce and subsequently recovered from a given volume of hydrogen. Other efficiencies are quoted for the electrolyser and fuel cell but are somewhat dubious, since they do not take into account the parasitic loads. This study reinforces the need for accurate accounting of all system loads when evaluating the real world efficiency and utility of an energy system. Another technical challenge identified was the difficulty in matching the electrolyser and PV array characteristics. The direct connection topology between the electrolyser and the DC bus introduced control issues during electrolyser start-up and illustrated the need for power conditioning between DC bus elements. Similar problems were not mentioned in the Helsinki test-bed but they had >15 times the relative battery capacity. This raises questions on the minimum short-term energy buffer requirements to maintain system stability.

Freiburg self-sufficient solar house: Goetzberger *et al.* (1993) outlines the renewable energy system of a self-sufficient solar house designed to use only solar radiation to supply heat and electricity for the inhabitants. The house located in Germany, incorporated many novel technologies including transparent insulation, solar space heating, advanced flat plate solar hot water heaters,4.2 kW solar array, 19 kWh battery storage, 2 kW alkaline high pressure electrolyser, compressed hydrogen and oxygen storage, a 500 watt alkaline fuel cell, power

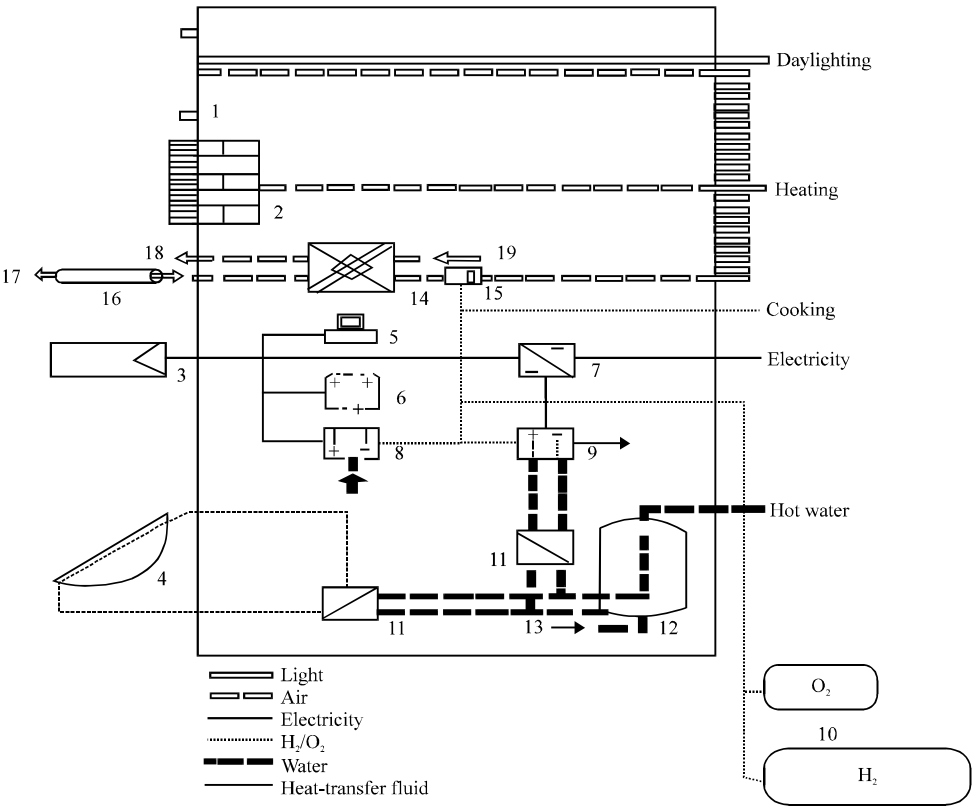

Fig. 5: Freilburg Self-Sufficient Solar House Energy System diagram; 1: windows, 2: TI wall, 3: PV generator, 4: aquisition, 6: battery, 7: inverter, 8: electrolyser, 9: fuel cell, 10: H_2 and O_2 storage tanks, 11: heat exchanger, 12: water storage, 13: mains water, 14: ventillation heat recovery, 15: heater, 16: earth heat exchanger, 17: fresh air, 18: exhaust air, 19: return air

inverters and energy efficient hydrogen powered appliances. A brief description of the energy systems utilized in the house is shown in Fig. 5. The primary design focus was on the thermal aspects considering that 80% of the energy demand of a conventional German residence is for space heating. Seasonal thermal self-sufficiency was achieved but the electrical demand was under estimated. The installed PV capacity was insufficient to supply the electrical load under real operating conditions. Fuel cell reliability proved to be a serious issue for completing the project. A stack life time of <100 h was obtained leading to very short demonstrations of house in self-sustained operation. Initial publications indicate that a replacement fuel cell was planned for the future but follow up reports detailing performance improvements of the house were not found. This research demonstrated that the photovoltaic system must supply much more energy than required for the basic household electrical appliances alone. For example, the energy requirements of the control, conversion and emergency systems for the hydrogen related equipment was equivalent to the electrical energy demand of all the common household appliances.

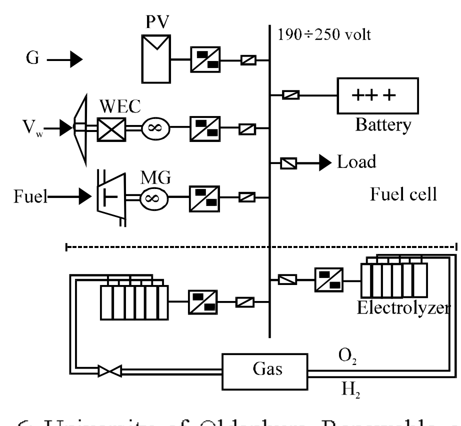

Fig. 6: University of Oldenburg Renewable energy test facility

Considerable thought must be given to the design and integration of the hydrogen buffers peripheral support systems.

University of Oldenburg Renewable Energy Project: Limited information on the University of Oldenburg experimental system is available. A brief overview of the

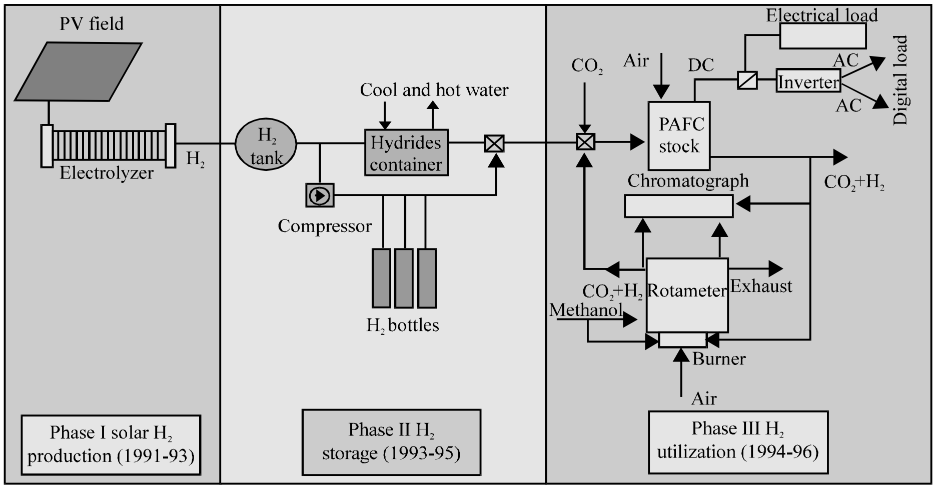

Fig. 7: INTA solar hydrogen energy test facility block diagram

system is given by Snyder (2000) who reports that the system began operation in 1990 and included both wind and solar power generation components (Fig. 6). The system employed a 6.2 kW PV array and a 5 kW wind turbine, a battery bank of unspecified size, an 800 W electrolyser, compressed hydrogen storage, a 600 W fuel cell and an undefined load. It is noted that the system was designed for seasonal energy storage inferring that significant hydrogen storage capacity was implemented. This is the first experimental renewable energy test-bed reported to have both wind and solar input sources. However, it is likely to have encountered fuel cell reliability issues that plagued other experimental studies conducted at that time period.

INTA Solar Hydrogen Project: Schucan (2000) summarizes a demonstration project for non-centralized electric generation using hydrogen and fuel cells conducted at the Instituto Nacional de Tecnica Aeroespacial (INTA) in Huelva, Spain. Work on the project occurred primarily between 1990 and 1994. Detailed experimental results are not reported in the literature. The basic system outlined in Fig. 7 consists of an 8.5 kW photovoltaic field, a 5.2 kW alkaline electrolyser, metal hydride and compressed hydrogen gas storage, a 10 kW phosphoric acid fuel cell and an AC inverter tied to a local grid load. A methanol reformer was included as a secondary hydrogen source to improve the overall flexibility of the experimental system. Alternate system architecture was employed where the renewable input was tied directly to hydrogen generation. Short-term battery storage of PV power was not included. The number of functional electrolyser cells could be varied based on the available solar power. During periods with high solar radiation 24 cells were used to draw 90-120 A from the PV array. By adding more cells in series, the effective electrolyser load decreases for a given PV array voltage. The current draw for 25 and 26 cells was 60-90 and 30-60 A, respectively. This simple control method dispensed with the need for a DC-DC matching converter to maximize power transfer from the PV array. The system was in operation for 3 years and worked satisfactorily in direct connected operational mode. Integration issues typically encountered in systems employing a common DC bus were avoided by fully decoupling production and utilization using hydrogen buffering. However, the global efficiency of this system architecture was shown to be <3%. This research illustrates that the hydrogen system architecture can have a significant impact on performance and that direct comparisons between various configurations would be valuable.

Friedli residential solar hydrogen: Hollmuller *et al.* (2000) outlines a photovoltaic hydrogen production and storage installation in a private residence in Switzerland that began operation in 1991. This system is unique in the sense that it was built by the owner Markus Friedli for domestic use without major support from public funds. It was constructed primarily from commercial components and operates without an elaborate control scheme. The system consists of a 4.5 kW photovoltaic array, a 38 kWh lead acid battery bank, a 10 kW alkaline electrolyser and a metal hydride hydrogen storage system (Fig. 8). Domestic AC power is supplied exclusively from the battery bank via DC-AC inversion. An option to export AC power to the grid exists. A converter for battery charging and electrolyser operation from the grid is included for backup. Grid power is also used for the electrical control circuits. Hydrogen is consumed in several household appliances as well as a converted mini bus with a separate metal hydride storage system. Gas purification and storage system were the reported weak

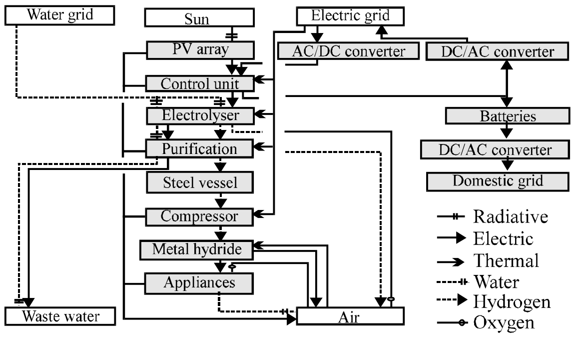

Fig. 8: Friedli Residential Solar Hydrogen House Energy System block diagram

points in the system implementation. The hydrogen purification unit consists of a water bath, condenser and dryer. The condenser filled with noble metals catalytically removes oxygen but required regeneration by heating and reverse flow consuming up to 8% of the hydrogen produced. An intermediate compressor increased the hydrogen pressure to 29 bar required by the metal hydride storage system. The regeneration and compression processes were power intensive and as such utilize the grid. The storage capacity of the hydride system was compromised by the hydrogen purity and failure to use a thermalizing circuit. In the original configuration, the system did not contain sufficient hydrogen storage for seasonal sustainability. A ten fold increase in capacity would be required given the reported consumption levels. Several peripheral issues that arose given the residential nature of the project were the high water consumption (in excess of 40 L h^{-1}) required primarily for electrolyser cooling and the lack of an automated control system to select the storage mode (batteries/hydrogen/grid). For safety reasons, the system was only operated when the inhabitants were at home leading to low overall efficiency. Although, this project did not include a regenerative fuel cell, the work is relevant to the current research, since it demonstrates a real world implementation of a residential scale renewable energy system. It illustrates that individuals are seeking alternative solutions for powering their households. However, also reveals how difficult it is to implement hydrogen based solution without the grid for backup or partial assistance. The fact that the project was completed without the resources and assistance of a research organization specializing in hydrogen system development is impressive. The only reported interaction was system characterization and performance studies conducted after the installation was complete.

Photovoltaic Energy Conversion System (PECS): Hollenberg *et al*. (1995) describes a small photovoltaic energy conversion system constructed at The Cooper Union Engineering School in 1992. This system consisted of a 150 W solar array, a 95 W electrolyser, metal hydride hydrogen storage and a PEM fuel cell showed in Fig. 9. A significant portion of the research centered on the development of a load matching device between the PV array and the electrolyser. Once this was constructed, experiments were conducted that studied the effect of unsteady insolation on hydrogen production. They concluded that the hydrogen generation did not exhibit the same unsteady behaviour as the insolation and that significant smoothing in hydrogen production occurred. Detailed results for the fuel cell and combined system operation are not reported hinting that the test capabilities were never fully developed. The reported electrolyser operating behaviour is desirable from a system implementation perspective but the experiments were conducted using low power devices. Duplicating these results with larger system components is required to validate that the smoothing effect is scale independent.

PHOtovoltaik, Elektrolyseur, Brennstoffzelle Und Ststemtechnik (PHOEBUS): The German PHOEBUS plant located at central library in Forshungszentrum was a large, high visibility demonstration project for solar hydrogen energy buffering. Ghosh *et al*. (2003) summarizes the equipment used and operating experience gained though this 10 years project. The equipment included 4 photovoltaic arrays totalling 312 m^2 with combined output of 43 kW, DC-DC matching converters, 303 kWh of lead acid battery storage, a low-pressure 5-26 kW 35 V alkaline electrolyser, high-pressure hydrogen and oxygen storage, several different fuel cells and a 15 kW inverter feeding a local grid (Fig. 10). The system was built around a high voltage bus (200-260 V) in an effort to reduce system ohmic losses.

At the start of the project pneumatic driven piston compressors were used but reliability issues and the high input energy required to compress the hydrogen and oxygen to 120 and 70 bar, respectively (>100% of the energy stored in the gas) led to replacement with high efficiency metal membrane compressors. Problems encountered with the original compressors also led to the development of a smaller 5 kW high-pressure (120 bar) electrolyser and a two stage solar thermal metal-hydride compressor. During the course of the project both of these units were tested and integrated into the system. However, the original electrolyser remained the main hydrogen generator for the system.

A 6.5 kW Siemens alkaline fuel cell was used in the first phase of the project but was found to be too unreliable. Efforts were made to develop two replacement

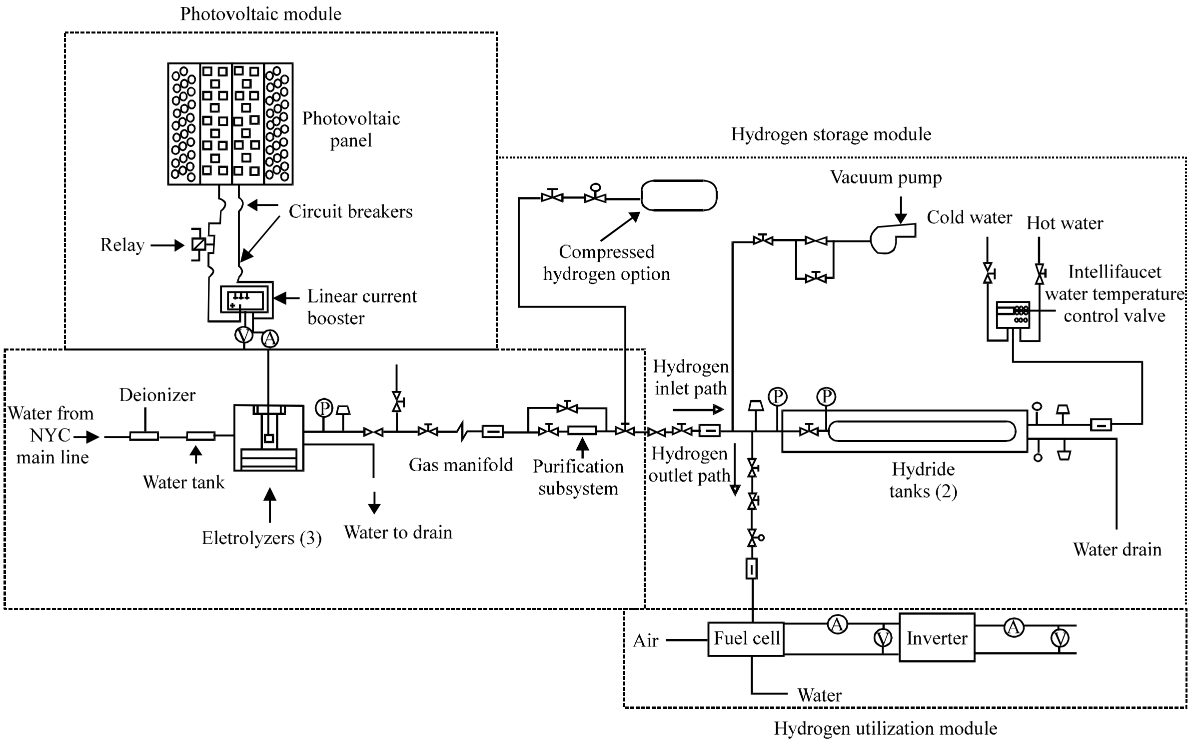

Fig. 9: The copper union hydrogen energy test facility schematic

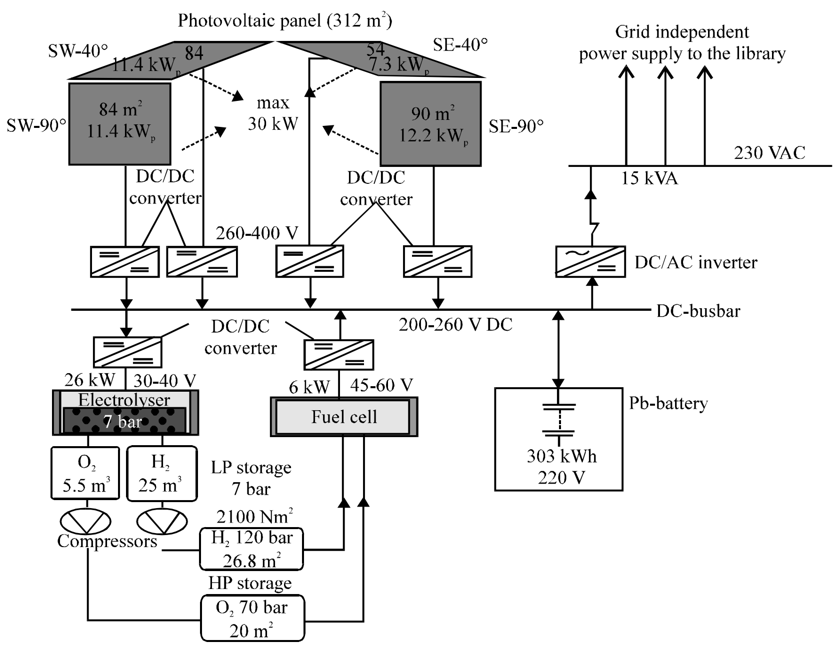

Fig. 10: PHEOBUS block diagram

2.5 kW PEM fuel cells. These first PEM fuel cells were also plagued with operational problems and finally in 1999, a reliable 5 kW unit was installed which functioned until the end of the project. An AC-DC converter fuel cell simulator was extensively used as a proxy to allow continued operation of the system during periods where the fuel cell power was unavailable. One of the main goals behind PHOEBUS was to show that a high level of energetic reliability could be achieved in a renewable energy system with very low battery capacity. Although, the battery bank consisting of 110 lead acid 1380 Ahr cells appears large, it could only fulfil the energy demand of the system for 3 days. Operational results indicated that the hydrogen system could store sufficient energy to offset seasonal fluctuations in solar input. A sensitivity analysis of photovoltaic array position to the long-term system energy balance was conducted. Average efficiency associated with the hydrogen buffer loop was calculated at only 22%.

In the original plant design, the electrolyser and the photovoltaic array output were of equivalent power ratings. During the course of operating, it was determined that sufficient hydrogen for long-term storage could be produced with a smaller electrolyser without sacrificing the energetic reliability of the system. However, a reduction factor is not specified. Additional research is required to determine the relative scaling factors between system components. Energy management schemes based on the battery state of charge were conceived during this project that warrant further development.

CONCLUSION

Although, a significant amount of research has been conducted in the development of renewable regenerative systems but the detailed experimental results of the operating characteristics of these systems such as hydrogen fuel cells are not well documented in the literature. If results are published, they are typically for short durations (i.e., a single operational day) and report the average operating efficiencies. Experimental results detailing the energy balance within the system and quantifying the energy loss in various system components has yet to be reported in a unified manner. Furthermore, experimental evaluation of the dynamic interactions between system components remains an area of research that has received little attention.

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