STAND-ALONE RENEWABLE ENERGY SYSTEM BASED ON HYDROGEN PRODUCTION

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1. PROJECT GOALS

Energy storage can play an important role in the development and operation of environmentally friendly renewable energy (RE) systems. The integrated wind and solar energy system, based on long-term seasonal storage of electrolytic hydrogen (H_2), is considered as a promising solution to overcome the limitations associated with the intermittency of the RE sources. In comparison to commonly used battery storage, H_2 is well suited for seasonal storage, because of its inherent high mass energy density and longevity of energy storage (compared to batteries).

A stand-alone RE system based on hydrogen production from wind and solar energy has been developed and installed at the Hydrogen Research Institute (HRI). It includes a fuel cell and both short-term and long-term energy storage devices. It is the goal of this project to demonstrate that an autonomous renewable energy system may be realized with long-term energy storage in the form of hydrogen, and that the operation of such a system is safe and reliable. The major objectives are:

- Assessment of the hydrogen production sub-assembly undergoing intermittent operation
- Assessment of the fuel cell performance for matching residential electric and heat load profiles
- Integrating the various sub-assemblies via hardware/software control systems
- Overall assessment of the technology for residential use in remote areas

2. GENERAL DESCRIPTION OF PROJECT

In order to demonstrate a variety of possible configurations, the RE stand-alone system at HRI is operating with two different types of primary renewable energy sources. It includes a wind energy converter as well as a photovoltaic array. In addition, as in any typical self-sufficient RE system, facilities for short-term and long-term energy storage must also be provided. A battery bank is used for short-term energy storage because it has a high charging-discharging efficiency and can be used to lessen the effects caused by instantaneous load ripples, spikes, electrolyser transients and wind energy peaks. However, batteries alone are not appropriate for long-term storage because of their low energy density, self-discharge and leakage. The combination of a battery bank with long-term energy storage in the form of hydrogen can significantly improve the performance of stand-alone RE systems. In such a RE system, electricity production in excess of demand is converted to hydrogen, using an electrolyser, and electricity requirement in excess of production is met by converting the stored hydrogen back to electricity using a fuel cell.

The overall RE system performance is very sensitive to local weather conditions. To achieve an adequate performance from such a system requires appropriate components and a well-designed control system. The design and implementation of a control system for proper energy management in a stand-alone RE plant is challenging. We have designed and developed a control system with power conditioning devices to integrate the different components of the RE system and to manage the energy flow in the system to assure a continuous supply of electricity to meet the load demand. Each component of the renewable energy system has been studied for long-term operation by using this control algorithm. The system parameters are monitored continuously for real time operation and control. The system operation has been tested for autonomous operation and technical feasibility of the stand-alone RE system based on hydrogen production. Our integrated RE system has been in operation since May 2001.
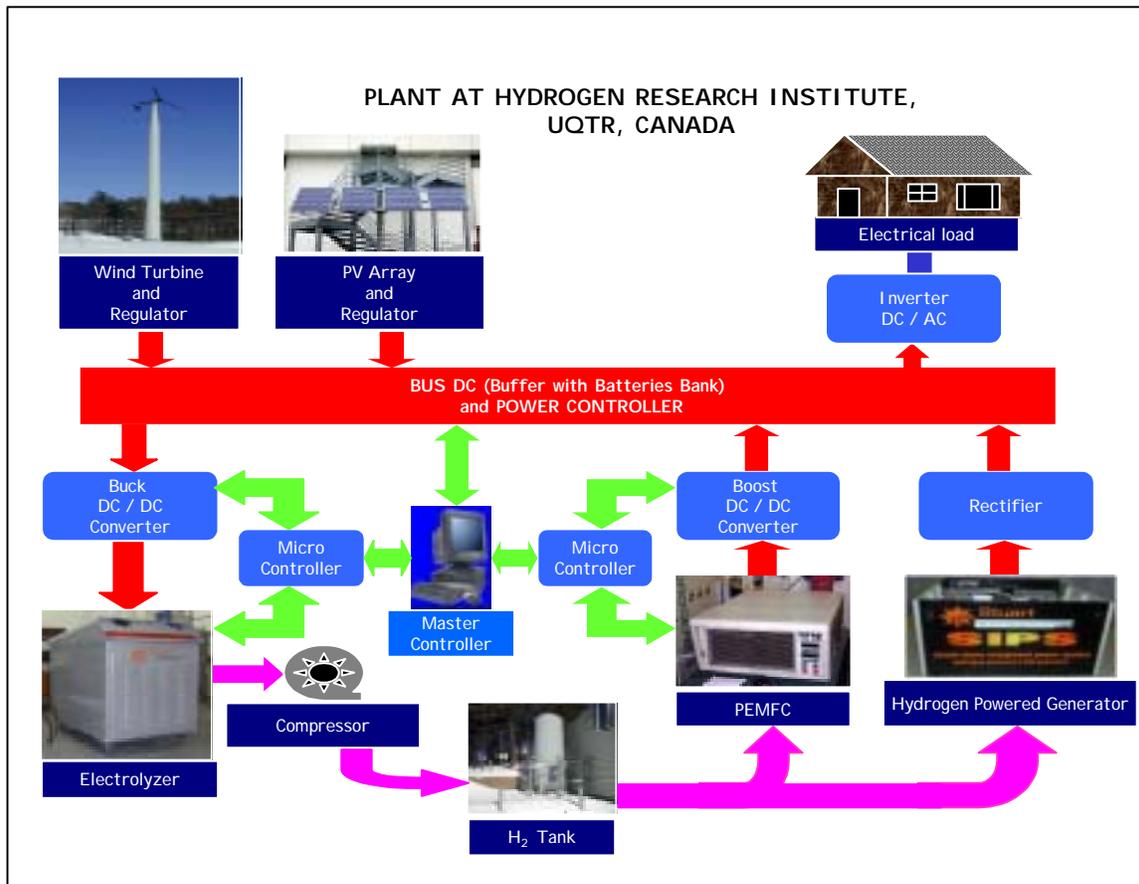

Figure 1: Stand-alone Renewable Energy System at the Hydrogen Research Institute

3. DESCRIPTION OF COMPONENTS

The stand-alone RE system based on hydrogen production was successfully tested at the HRI. The system consists of a 10 kW wind turbine generator (WTG) and a 1 kW (peak) solar photovoltaic (PV) array as primary energy sources. The renewable electricity that is produced in excess of the load demand is stored as hydrogen, produced using a 5 kW electrolyser. The hydrogen is stored and later used to produce electricity using a 5 kW fuel cell system for the times when there is not sufficient wind and solar energy to meet the demand requirement. The

RE system components have substantially different voltage-current characteristics and are integrated through the developed power conditioning devices on a 48V DC bus, which allows power to be managed between input power, energy storage and load. The DC-DC converters are used as power conditioning devices to connect the fuel cell and the electrolyser on the DC bus, which have different voltage ratings. Also the DC-DC converters give high flexibility to control power flow and operation of the electrolyser and the fuel cell. Compared to the DC bus voltage, the fuel cell output voltage is low and hence the DC-DC boost converter is used to transfer the power effectively to the DC bus. Similarly, the DC-DC buck converter has been used between the electrolyser and the DC bus to transfer the excess power effectively to the electrolyser. In addition, the system is equipped with AC and DC programmable loads and with a 10 kW programmable power source. The schematic of the RE system is shown in Figure 1 and the system components' specifications are given in Table 1.

Table 1: Specifications of the renewable energy system components

Component	Specifications
Wind Turbine Generator	10 kW, 3ϕ permanent magnet alternator, VCS-10 - 48 V DC, Bergey– BWC Excel
Photovoltaic Array	1 kW (peak) PV array, Golden Genesis GP 64 PV Modules (4S*4P) with Charge Controller
Electrolyser	5 kW, alkaline electrolyser with compressor, Stuart Energy System
Buck Converter	5 kW, multiphase PWM, 36-48 Volt, HRI System
Fuel Cell System	5 kW, proton exchange membrane fuel cell stack (MK5-E), 19-35 Volt, Ballard Power System
Boost Converter	5 kW, multiphase PWM, 24-48 Volt, HRI System
Controller	energy management control system, HRI System
DC Load	12 kW (programmable), water cooled, Dynaload
AC Load	3 kW (programmable), California Instruments
Inverter	5 kW, Trace Engineering
Battery	42.240 kWh
Power Source	10 kW (programmable), Elgar
H2 Storage	10 bar, 3.8 m^3 represents 125 kWh of stored energy

Current from the DC bus bar keeps batteries (short-term energy storage) charged, feeds power to the load bank via an inverter and also supplies power to electrolyser via the power-conditioning device. To simulate any type of electrical load profile, we used DC and AC programmable loads. Our RE system also has a programmable power source at DC bus and can be used to test the system, when there is no power available from wind and solar energy system. The programmable power source can simulate any type of intermittent power output.

We studied the electrolyser and the fuel cell polarization characteristics, which depend mainly on voltage, current and temperature. Sensors were used to record real-time voltages and currents of WTG, PV array, DC bus / battery, electrolyser, fuel cell, load, hydrogen detectors, electrolytic hydrogen flow rate from the electrolyser, hydrogen consumption rate in the fuel cell, oxidant consumption rate in the fuel cell, hydrogen and oxidant pressure in the fuel cell, fuel cell stack temperature, electrolyser cell temperature, DC-DC converter (boost and buck) duty ratio. Additional sensors in the electrolyser and the fuel cell systems provide the secondary information.

4. RENEWABLE ENERGY SYSTEM OPERATION AND CONTROL

A control system is required for efficient energy management and autonomous operation of the RE plant. The control system is a challenge because the sensor data required for continuous real-time operation are fed to the same control algorithm that is used to send signals to the power conditioning devices on a real-time basis. The control system was developed to control the autonomous operation, even with intermittent RE sources. It was designed to maximize the direct energy flow from the RE sources to the electrolyser and the load in order to avoid losses in the batteries. The energy level at the DC bus plays an important role for the operation and control of the RE plant. It allows effective energy management among the primary power sources, the electrolyser input, the fuel cell output and the load. The control system consists of a master controller and two secondary micro controllers (Figure 1). The real-time data of RE system are recorded and used for decision-making in the control algorithm. With respect to energy level at DC bus and pre-defined limits of energy levels in the control algorithm, the master controller sends the conditioned signal (duty ratio) to the secondary controllers for on / off operation of the electrolyser and the fuel cell. The secondary micro controllers manage the power flow with respect to the energy availability at DC bus through the digitally controlled DC-DC converters. The DC-DC converters use multiphase technique to generate pulse width modulation signals to control the power flow. The limits of energy levels in the control algorithm are managed through double hysteresis strategy. The DC-DC (i.e. buck and boost) converters are important components in the system for effective operation and power flow control of the electrolyser and the fuel cell. The control algorithm was developed in such a way that the fuel cell and the electrolyser do not operate simultaneously. The limits of energy level in the control algorithm and the load profile were varied from time to time to check the reliability and the technical feasibility of the control system for autonomous operation. Although the major power components in the system are intermittent in nature, the integrated RE system has operated automatically and effectively by using the control algorithm and power conditioning devices.

The excess energy is stored as hydrogen, which is produced electrolytically using the hydrogen production system, consists of a 5 kW electrolyser with a control unit, a compressor, purification and drying process. The electrolyser input energy is controlled, with respect to energy available at DC bus, through the duty ratio of DC-DC converter. The H_2 produced by the electrolyser is temporarily stored in a water-sealed tank of the electrolyser system and when this tank is full, the electrolyser compressor starts automatically and sends the hydrogen, at high pressure, through the purification and drying process and to the main storage tank of 3.8 m^3 capacity. The time cycle period, which corresponds to the filling and compression of the hydrogen in the water-sealed tank, depends on the electrolyser input power. The stored hydrogen is utilized to produce electrical energy based on the load requirement through a 5 kW fuel cell. The fuel cell power output is managed based on the energy requirement via the DC-DC converter. The

electrolyser and fuel cell on / off operations are controlled automatically as a function of pre-defined limits of energy levels in the control algorithm.

5. RENEWABLE ENERGY SYSTEM PERFORMANCE

The performance of RE system is shown in Figures 2 through 7 for a typical day and for long-term operation. The energy available from the WTG and the PV array for a typical day (in this case, 10 December 2001) is shown in Figure 2. On this day of operation, the control algorithm was set to start the electrolyser at 99% of energy level at DC bus and to stop the electrolyser at 84%. The fuel cell on and off set points were 83% and 85%, respectively. During this operation, the RE source power, the load profile, the electrolyser input power, the hydrogen flow rate, the fuel cell output power, and the hydrogen consumption rate were recorded and are shown in Figure 3. The ripples and peaks in the electrolyser power are due to the cyclic operation of the compressor. The hydrogen flow rate is measured as it is sent to the main storage tank. The power flow of batteries (i.e. charging / discharging) is also carefully monitored. The power supplied to the electrolyser is mainly from the short-term energy storage (i.e. batteries) when insufficient energy was available from the RE sources. The electrolyser and the fuel cell were started and stopped automatically as per pre-defined energy levels in the control algorithm. In the control algorithm, the proper selection of energy levels is required for the most effective operation of the electrolyser and the fuel cell. However, the choice is a complicated problem and was determined only by trial and error. The energy levels are chosen in such a way so as to keep the batteries at a near-full charge, only allowing them to be discharged for a short period and then recharged. This allows the batteries to act as a buffer for the RE system, when components such as electrolyser or load bank are suddenly turned on. The performance of the electrolyser and fuel cell were judged by different efficiencies. The electrolyser utilization factor (i.e. current efficiency) was about 85%; the energy efficiency with the compressor running was about 60% and without the compressor running it was 65%. The fuel cell utilization factor was about 90% and the energy efficiency was more than 45%.

The RE system performance was recorded for long-term operation from 3 December 2001 to 17 April 2002 for daily operation of six hours. Frequently, no energy was available from the RE sources at our location because of climatic conditions. Therefore, a 10 kW programmable power source was used to simulate the typical RE patterns for those days when no RE power was available. During this period, the power available from primary energy sources is shown in Figure 4. The electrolyser input power, the fuel cell output power, the batteries charging / discharging power at the DC bus, and the load profile are shown in Figures 5 and 6. The electrolyser input energy and the corresponding hydrogen flow rate are shown in Figure 7. The electrolyser, the fuel cell operation and power flow were automatically managed through the digitally controlled DC-DC converters. The master controller used information obtained through the sensors to make the required decisions and control the entire operation. The load profile, the programmed output energy pattern of the DC power source and the energy levels in the control algorithm were changed from time to time to check the reliability of the system and the validity of the developed control algorithm. The performance analysis shows that an autonomous RE system based on electrolytic hydrogen is safe and reliable.
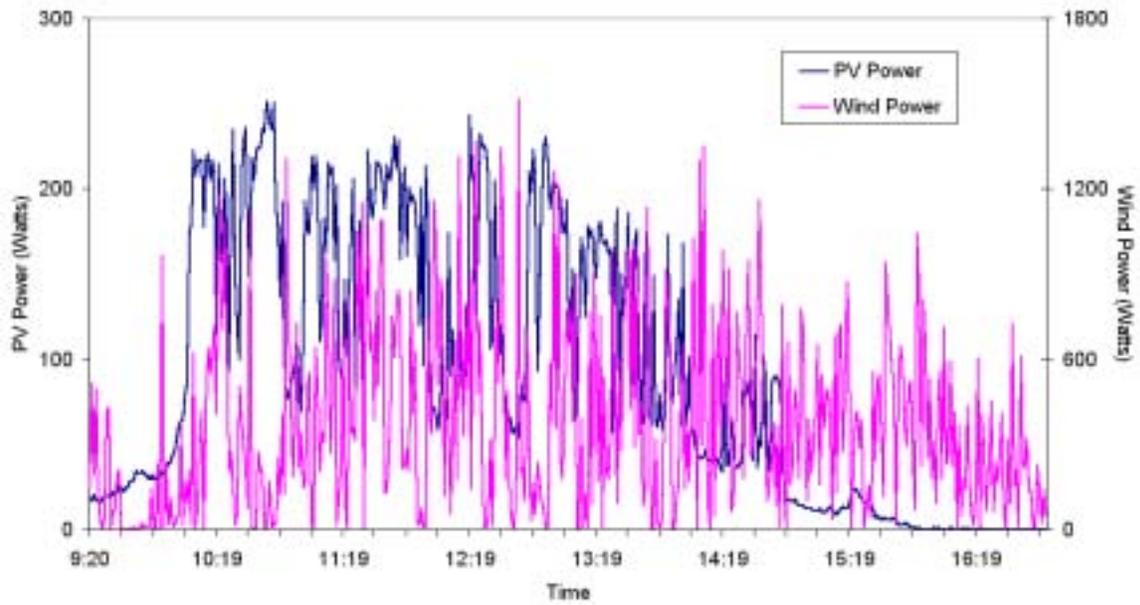
Figure 2: Power available from wind turbine generator and PV array on Dec 10, 2001
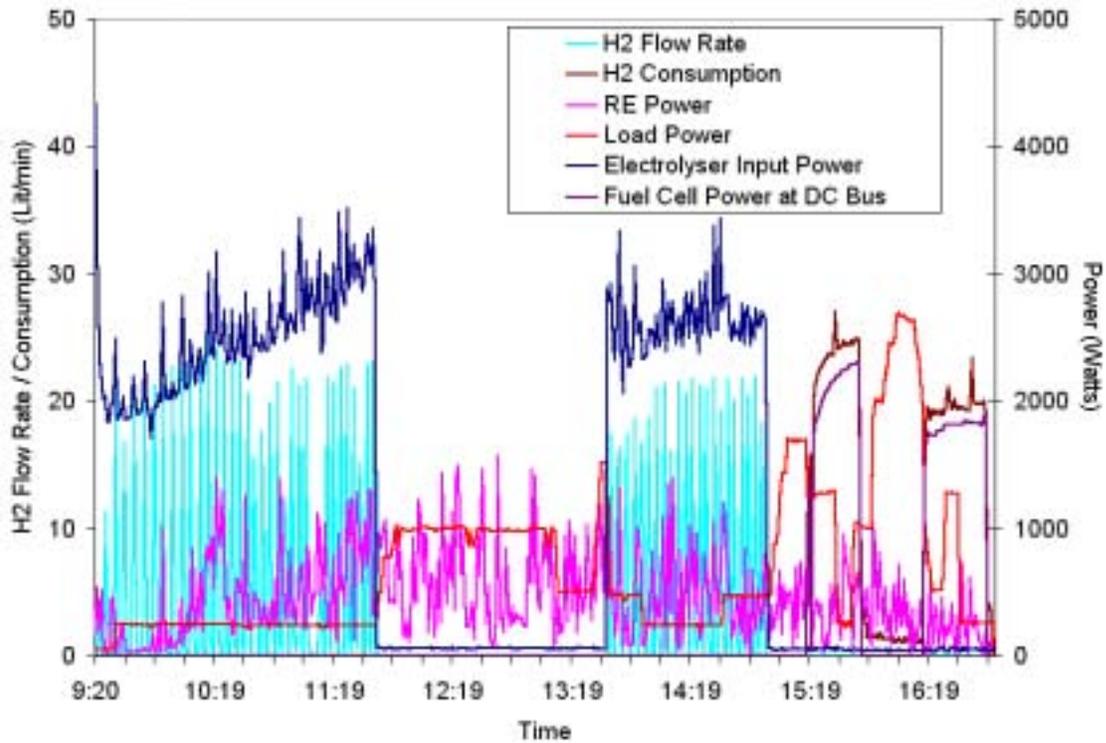

Figure 3: Power, H$_2$ flow rate and consumption rate in RE system on Dec 10, 2001
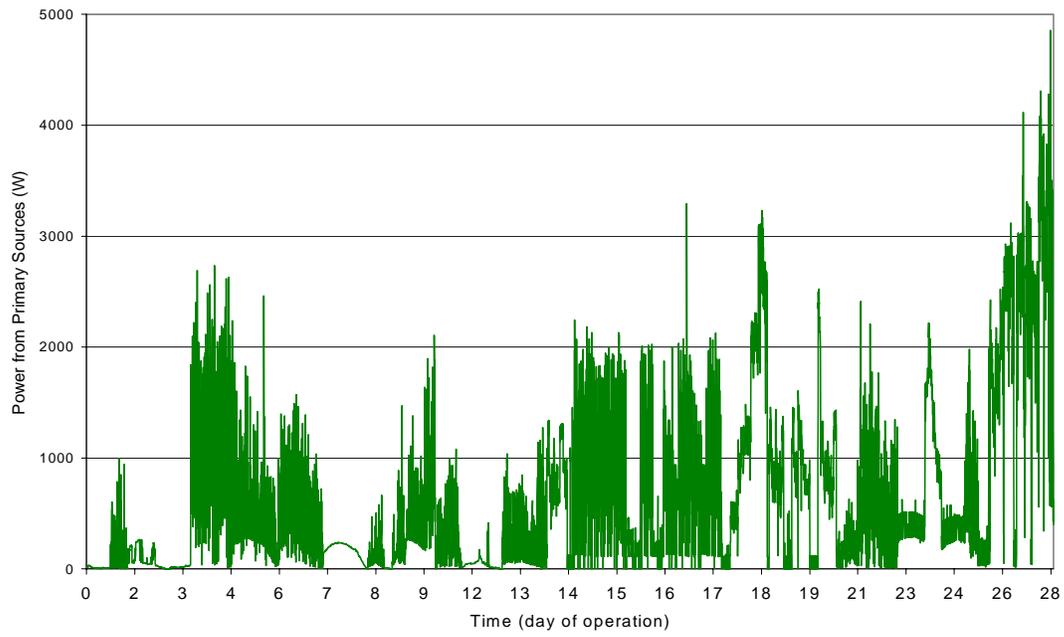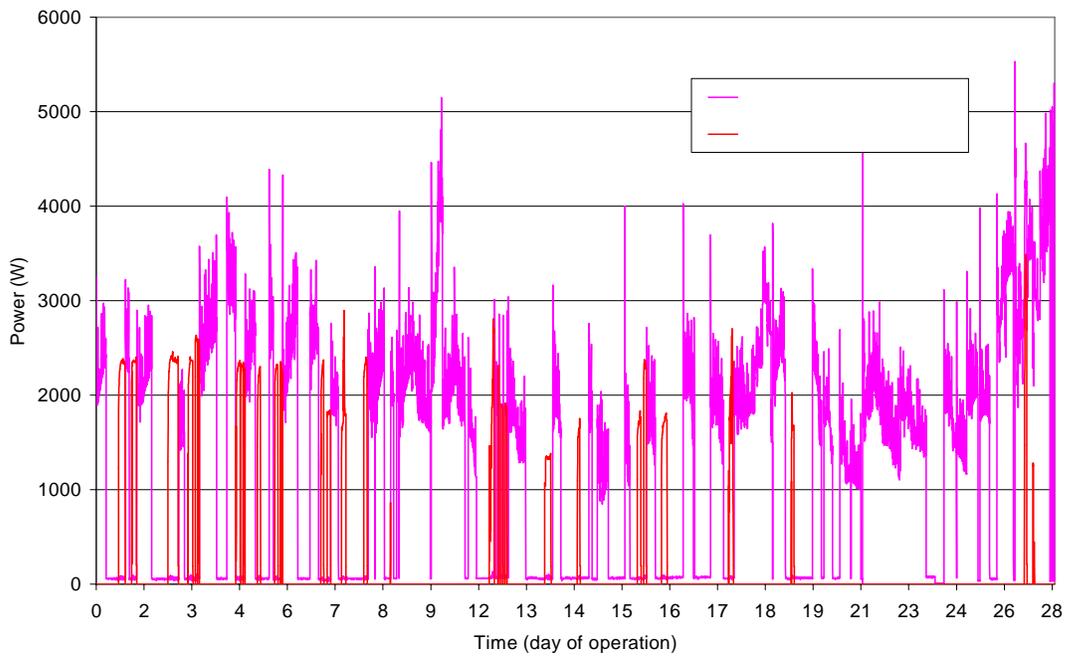
Figure 4: Power available from primary energy sources

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(a)

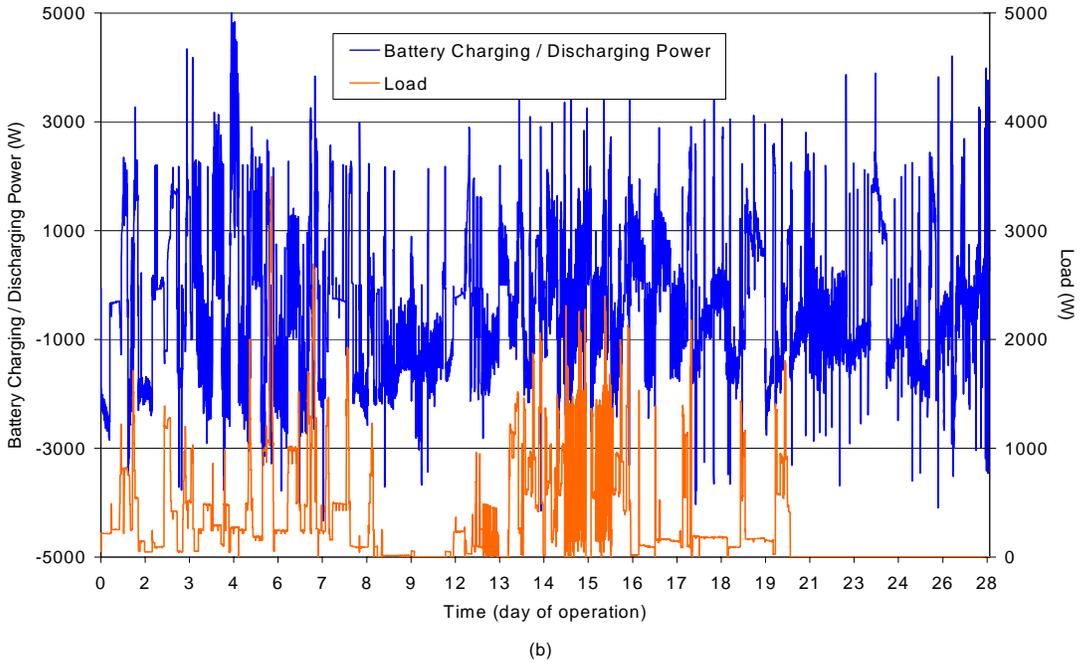**Figure 5: Electrolyser input and fuel cell output**

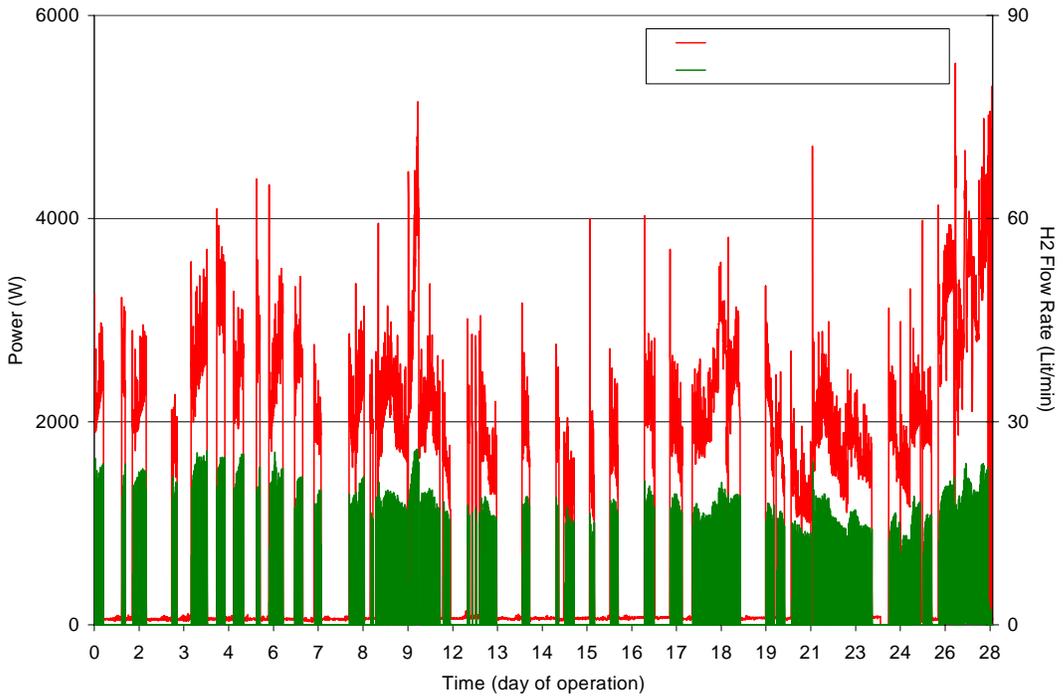**Figure 6: Battery charging /discharging and load power**

Figure 7: Electrolyser input power and H$_2$ flow rate

6. CONCLUSIONS

The successful long-term autonomous operation and performance of a stand-alone RE system based on hydrogen production has been demonstrated using a control system and power conditioning devices. The components of the RE system, which have substantially different voltage-current characteristics, were integrated using power conditioning devices on the DC bus for effective operation. The system was tested successfully for autonomous operation. The sensors collected real-time data and utilized this information in the control algorithm for effective energy management in the system. The buffer energy storage provided by batteries managed the load transients, electrolyser ripples and the intermittent power peaks from the RE sources efficiently. The developed control system and power conditioning devices were tested for different load profiles and for various intermittent input power patterns, which were also generated through the programmable DC power source.

We also used a programmable power source as input to our RE system, which can simulate any type of intermittent power output by using the wind or solar energy profile of any region. The different load profiles were generated using a programmable load to test the system operation and performance. The stand-alone RE system developed at the HRI can thus be utilized to test the operation and performance of any stand-alone RE system based on electrolytic hydrogen.

7. CONTACT INFORMATION

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