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Development of a dynamic regenerative fuel cell system

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Abstract

The development of a regenerative Integrated Renewable Energy Experiment (IRENE) is presented. IRENE is a laboratory-scale distributed energy system with a modular structure which can be re-configured to test newly developed components for generic regenerative systems integrating renewable energy, electrolysis, hydrogen and electricity storage and fuel cells. A special design feature of this test bed is the ability to accept transient inputs from and provide transient loads to real devices as well as from simulated energy sources/sinks. The findings of this study should be of interest to developers of small-scale renewable-regenerative systems intended to displace fossil fuel systems.

Developing an IRENE-like system with commercial products currently available is a challenging integration task. Various strategies for assimilating the components are discussed and the necessary modifications presented. Virtually all of the major components have required modification to achieve a cohesive and functional system. The integration issues considered fall into three general categories: power conditioning, control/communication compatibility and component reliability. An example of a generalized load/resource profile illustrating a variety of dynamic operation regimes is presented.

Keywords: Electrolyzer; Fuel cell; Hydrogen; Renewable energy

1. Introduction

Anthropogenic climate change has raised interest in the generation of power from renewable sources [1]. However, due to the sporadic and cyclical nature of many of the renewable power sources, particularly wind and solar, fluctuating demand and source availability are not necessarily in phase. The difference between the renewable power availability and load can be separated by minutes, hours or even days. Developing an integrated renewable energy system which can cope with this phase mismatch presents a significant challenge [2]. To overcome this phase mismatch, a method to store and buffer the energy generated needs to be considered. The stored energy can be used to meet loads which do not occur simultaneously with the renewable resource, and if necessary, can augment the power available if it is insufficient to meet the load.

This paper discusses the development of an Integrated Renewable Energy Experiment (IRENE) and is primarily concerned with renewable energy systems that employ energy conversion devices that export the renewable resource in the currency of electricity. The common conversion devices are photovoltaic panels which convert solar radiation into direct electrical current, and turbo machinery coupled to generators which convert wind, falling water and steam from either geothermal or bio-mass combustion into alternating or direct current.

1.1. Energy storage

Electricity once generated is difficult to store for extended periods of time. Batteries, magnetic fields and super-capacitors are the only direct means for storing electricity. Of these, batteries are the only practical commercial devices but they also suffer from self-discharge and are thus relatively short-term storage devices. Long-term energy storage can only be achieved with a time-independent media such as compressed air, pumped hydro, or chemical compounds.

Water electrolysis is a convenient method for converting electrical energy into a chemical form. Hydrogen can be stored as a gas, a cryogenic liquid, or as a metal hydride and can be

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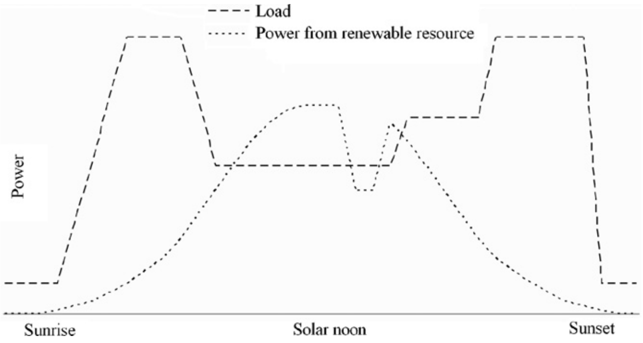

Fig. 1. Example load/input experiment.

converted back into electricity using a fuel cell or an internal combustion engine coupled to a generator. Daily and even seasonal time scales can be accommodated with appropriately sized hydrogen storage systems.

A regenerative power system that is not grid connected needs to provide for loads at all times of the day and must be able to compensate for fluctuations in the load and renewable power source. The system must also be able to store excess energy if the renewable power exceeds the load. Fig. 1 details a simplified experiment using a solar power source to meet the load of a generalized residential building. When no solar energy is available, such as during the night, the entire building load needs to be met using the energy stored in the regenerative power system. Beginning at sunrise the available solar power increases in intensity, peaks at solar noon, and then decreases until sunset. Fluctuations in the available power can take place from events such as clouds passing overhead, as depicted by the sudden drop in the solar resource curve. Even when available, the renewable energy source may not necessarily meet the demands of the building at all times during the day as seen when the load curve exceeds the input power curve. During these times, the solar power is augmented by using the system energy reserves so that the load is met. IRENE uses an electrolyzer for hydrogen production from excess available energy and a hydrogen fuel cell for electricity production when there is a deficit in available renewable energy. When completed, IRENE can be configured to simulate virtually any dynamic renewable source and load.

2. Prior research

A wide variety of theoretical models for hydrogen-based renewable energy systems are presented in the literature, including models for isolated renewable energy systems with hydrogen storage [3,4], methodologies for determining the performance of hybrid hydrogen systems [5], and energy-based simulation tools [6]. Sub-component models for hydrogen generation by electrolysis for renewable systems have been developed [7,8], and high-level models for stand alone and grid connected systems are reported [9,10]. While these studies provide insight on some of the system issues, they fail to address practical concerns that arise from the integration of real components.

Since the mid 1980s, a number of experimental renewable energy systems with hydrogen energy buffering have been developed. The first generation of these systems demonstrated that hydrogen could be generated from surplus renewable resource power through water electrolysis and stored for both short-term and seasonal energy buffering [11–13]. However, these systems also revealed that significant advances in electrolyzer, fuel cells, hydrogen storage and power conditioning technologies were required before reliable operation could be achieved. At the present time, most of the initial demonstration projects are no longer in operation.

Several second-generation residential scale systems have been developed using a combination of renewable input sources (solar and wind primarily), higher efficiency electrolyzers, and PEM fuel cells [14–17]. However, most existing systems lack sufficient hydrogen storage capacity for long-duration seasonal experiments. Research efforts with these test beds are focused primarily on developing control strategies.

Experimental results for small-scale renewable energy systems are not well documented in the literature. Where results are reported, they generally describe a "typical operational day" [11,12,18,19]. Actual operating efficiencies, round trip efficiencies and power at the fuel cell and electrolyzer can be found in the literature [20,21], but an experimental analysis detailing the energy balance within the system and quantifying the energy loss in various components has yet to be reported in a unified manner. Furthermore, the nature of the dynamic interactions between system components remains an area of research that is not well presented in the literature. The residential scale renewable energy test platform currently under development at the University of Victoria has been designed specifically to probe these research questions.

3. System design

IRENE is a flexible distributed, laboratory-scale energy system with a modular structure which is easily re-configured to test newly developed components for generic renewable-regenerative (electrolyzer/fuel cell) systems. A special design feature of this test bed is the ability to accept inputs from, and provide loads to real devices as well as from simulated energy sources/sinks.

The main components of IRENE are listed in Table 1 and consist of a controllable input power source, battery bank, power conversion elements, AC load devices, an electrolyzer/hydrogen storage/fuel cell loop and a central control/data collection system. The basic system schematic for the current IRENE configuration is illustrated in Fig. 2. Each component can have the voltage and current flow measured and read by the data acquisition system. This enables a total power/energy balance to be computed to ensure that all loads and losses can be determined.

3.1. IRENE power generation and utilization hardware

The primary DC input power to IRENE's 48 V bus is supplied via a Lambda EMI ESS 15 kW grid connected power supply. The supply output is adjustable from 0 to 60 VDC with adjustable current limiting to 250 A. Dynamic control of the voltage and

Table 1
Summary of primary system components

Component	Manufacturer/type	Current (A)	Potential (V)	Power (W)
Bus	n/a	>250	42–56, 48 nominal	n/a
Fuel cell	Ballard Nexa PEM	0–45	46 V at 0 A, 22 V at 45 A	1200
Electrolyzer	Stuart Energy SRA	107	42–56	6000
Battery	GNC Absolyte IIP deep cycle AGM	272 A h	42–56, 48 nominal	
DC power supply	Lambda EMI ESS	250	0–60	15,000
Load	NHR model 4600	27	110 VAC	3000
Inverter	Xantrex SW4840	180 peak for short duration	44–62, 48 nominal	4000

current set points enables direct simulation of the power output profiles from a variety of renewable energy conversion devices (without the limitation of being tied to any one particular device). Local insolation and wind resources will be measured with a Shell 100 W 24 VDC solar module and an AIR 403–48,400 W wind generator. Appropriate transfer functions will be developed to scale the solar and wind inputs and control the ESS power supply. Experimental simulation with other energy fluxes such as micro hydro, tidal or conversion devices (i.e. a large wind farm or hybrid system) will be possible by processing representative time series data from other sites with suitable transfer functions. The ability to drive IRENE from a variety of virtual input sources will allow for greater flexibility in range of experiments that can be investigated with the system and for accelerated testing of long-duration events.

The battery storage bank consists of 24 GNC Absolyte IIP deep cycle AGM cells arranged in series for a nominal bus voltage of 48 VDC. The batteries are rated for 1200 cycles to 80% depth of discharge (DOD) with an 8 h discharge rating of 272 A h. Working voltage at 80% DOD is approximately 46.5 VDC. The batteries are considered fully discharged at 42 VDC. The maximum charge rate is 60 A and the maximum charge voltage is 56 VDC. Optimum float life occurs at 54 VDC. The battery bank is relatively small and is not sized for primary energy storage, but rather provides bus stability for high-speed transients. The batteries also act as the primary voltage reference for the bus, thus the charge state is an important parameter as it directly affects the working voltage of components attached to the bus (a 42–56 V window).

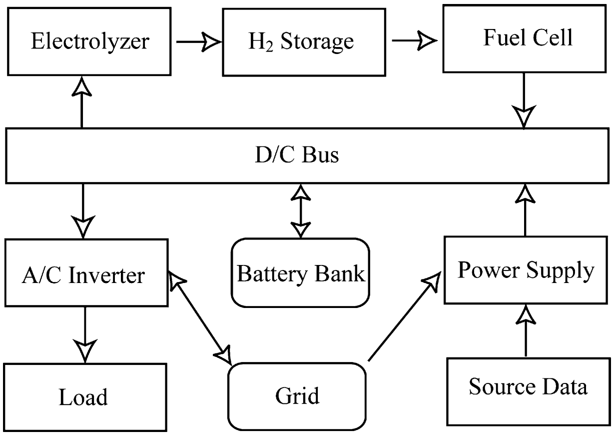

Fig. 2. IRENE test platform schematic.

Two Xantrex SW4840 4 kW 110 V AC output stackable power inverters handle the main DC/AC conversion. These units are designed for nominal 48 VDC systems and operate on input ranges from 44 to 62 VDC. The design point is 50.4 VDC at 100 A, but peak draw can be in excess of 180 A. The inverters have connection points for grid and generator inputs and defaults to these AC sources when present. If the load exceeds the capability of a connected AC source (i.e. supplying the inrush current to start an electric motor from a small generator) the inverters automatically transfer power from the DC input to make up the shortfall. The inverters also have the capability of diverting DC power back to the grid. When connected to an AC source, the inverters can function as battery chargers with a maximum charge rate of 60 A DC. The inverters are equipped with a manual interface for adjusting the parameter settings. In the initial system configuration the two inverters will operate independently to service individual AC loads (i.e. one can be configured to act as a small AC generator attached to the second inverter which in turn supplies the main AC load).

The primary AC load is a NHR model 4600 3 kW fully programmable load bank that can simulate reactive loads. Additional 110 V loads may be serviced via four standard AC receptacles equipped with electrical contactors to allow for computer control over the total AC load. Direct simulation of a variety of loads (typical of residential scale) will be possible by utilizing a combination of fixed base loads and the dynamic capabilities of the programmable load. A series of purely resistive loads is currently being integrated to reduce bus voltage/current fluctuations and noise picked up by the data acquisition system.

A Ballard Nexa 1.2 kW fuel cell is employed as the regenerative component. Hydrogen consumption at the peak rated output of 26 VDC at 46 A is 1100 L h^{-1}. The output is unregulated 46–22 VDC depending on the demand current. A power conditioning system is used to filter and transfer the Nexa's output power to the main DC bus.

Excess system power is used to generate hydrogen via a Stuart Energy SRA 6 kW electrolyzer. The cell stack is a low-pressure design with a maximum 900 L h^{-1} H_2 production under optimal conditions. The electrolyzer control system will allow the stack to operate provided the input voltage range falls between 42 and 56 VDC. H_2 production is roughly linear with respect to input power. The electrolyzer is equipped with a gas purification stage and a small piston compressor to raise outlet pressure to a maximum of 17 bar. The oxygen generated by the electrolysis process is vented to atmosphere.

3.2. Hydrogen storage

IRENE is equipped with both compressed and metal hydride hydrogen storage systems. Three Dynetek composite 150 L (water volume) storage tanks are dedicated to low-pressure storage operating at the electrolyzer output pressure. Excess hydrogen is compressed (maximum 200 bar) via a PDC 3–6000 diaphragm compressor and stored in a fourth Dynetek tank. A metal hydride storage system operating in parallel to the compressed gas storage system is under development. The initial configuration will utilize Ovonics 58250 and Palcan 300 canisters. Other metal hydride compounds will be implemented in subsequent stages to allow for a broader range of comparisons in storage media efficiencies.

3.3. Data acquisition and control

IRENE is fully instrumented to measure energy and mass flows between system elements. A National Instruments SCXI 1000 collects and multiplexes the respective signals and feeds them into the PC responsible for overall system control. The SCXI is equipped for both analog and digital input/output. Control of the individual components is achieved through the use of RS232 communication ports. The entire system is monitored and controlled by an integrated LabVIEW data acquisition system. A master control virtual instrument (VI) under development supervises the high-level control and data monitoring activities. Under this umbrella, individual sub VIs communicate with and ensure the proper operation of each device. An analog measurement system monitors the power flow between system components and provides feedback to the main controller. Appropriate parameters that characterize the system response are logged for post experiment analysis.

4. Component integration

Developing an IRENE-like system based on commercially available components is a challenging integration task. All of the major components were originally designed for other applications and were modified for use in IRENE. The components were far from “plug and play”. Integration issues encountered during development fall into three general categories: power conditioning, control/communication compatibility and component reliability.

4.1. Power conditioning

IRENE is fundamentally a large power conditioning circuit interconnected via a floating DC bus. Problems arise when two or more components compete for control of the bus. System devices must tolerate both the floating nature of the bus and instantaneous ripple noise imposed on the bus. The ripple is due to the fact that the input sources and output demands on the system are not inherently smooth.

The DC/AC inversion process imposes a time varying current draw on the bus inherent in generating an AC output wave form. The AC load characteristics are reflected back to the DC side, but the current demand is amplified by (at minimum) the ratio of the AC to DC working voltages (i.e. to maintain net power transfer, higher currents are imposed on the lower voltage side). A purely resistive AC load reflects a relatively smooth sinusoid at 120 Hz. However, real loads (particularly those with switching elements) impose significant high frequency, large amplitude current demands on the DC bus. If the system is to provide an uninterrupted output, energy storage elements with sufficient capacity and response time must be included on the DC side to service the anticipated transients.

In traditional stand-alone renewable energy systems, the battery bank is sized to fulfill transient source/sink requirements. IRENE was however intentionally constructed with a small battery bank since the basic premise of the project is to utilize hydrogen as the energy buffer media, not batteries. As a result, the DC bus can be readily pushed around by the sources and sinks. Future improvements to IRENE may include ultracapacitors as a means to stabilize the bus voltage.

4.1.1. Electrolyzer control

One method for improving bus regulation is through active control of a secondary energy sink which, in this case, is the electrolyzer. While the electrolyzer cannot source current to service a transient demand of the inverters, the power diverted to the electrolyzer can momentarily be reduced to lessen the total load on the bus, if required. Likewise, power diverted to the electrolyzer can be ramped up during periods of high resource input and low demand output from the inverters. Although this mimics the basic control concept for IRENE (to make hay while the sun shines or, in our case, hydrogen) the time scale is shifted from the averaged values of supply and demand on an hourly or sub-hourly basis to the millisecond level.

Custom power conditioning electronics are required to attain active control over the electrolyzer power flow. The electrolyzer, as delivered from the manufacturer, has no power conditioning and operates strictly in a binary on/off mode with the load demand set by the basic voltage/current characteristics of the electrolyzer cell stack. The voltage window of the bus and electrolyzer are similar, so the power converter would require both step-up and step-down capabilities. A commercial product with the correct voltage range, current capability and efficiency is not readily available. However, a bank of high current diodes has been installed as a means to limit the voltage seen by the electrolyzer. Each diode is individually shunted and can be controlled by a LabVIEW umbrella program. The diode bank is a simple solution which allows us to limit the proportion of the renewable resource directed to hydrogen production.

The electrolyzer creates a large draw on the DC bus and rapidly discharges the batteries in cases with low to moderate levels of renewable input power. As a result, large fluctuations in the DC level of the bus occur. This condition is far from optimal since it creates many scenarios where the system is potentially unable to service a load. For example, if the batteries are depleted and a sudden loss in the input power (i.e. a lull in the wind or cloud passing over a PV array for a wind or PV powered system) occurs at the same instant as a large output demand side event.

Hydrogen production from the electrolyzer is also dependent upon the stack temperature. If the stack is allowed to cool down below optimal operating temperatures, hydrogen production is reduced. Ideally, the stack should be maintained at design conditions and methods to maintain temperature between operations are being considered.

4.1.2. Fuel cell control

The power conditioning of the fuel cell output presents additional integration challenges. Direct connection of the Nexa to one of the Xantrex inverters is not possible due to the significant mismatch in the source/load characteristics. For example, the Nexa is unable to service a current ripple greater than 25% of the DC output current which is insufficient to support the ripple generated by the inverters. A second issue stems from the substantial voltage drop that occurs with increasing current output from the Nexa. Although the inverters accept a wide input voltage range, the variation in the Nexa's output is beyond the acceptable range.

Since direct inverter connection is not an option, the fuel cell power must be routed to the main DC bus. However, the bus voltage exceeds the Nexa's unregulated output voltage during all meaningful operating scenarios. The temporary solution for interfacing the fuel cell to the bus is to float the Nexa on an external current-limiting power supply. The power derived from the external supply is monitored and accounted for in the main LabVIEW control program.

A passive LC filter has been installed to limit the transient effects of the bus on the fuel cell. The filter is capable of making the bus appear smooth to the fuel cell. However, a custom hardware management system is required to monitor and minimize potential fly back effects from the filter and has been integrated into the fuel cell. This hardware disconnects the Nexa if the specified operating parameters are exceeded and hence prevents damage to the fuel cell. The LC filter/hardware management system is integrated directly on to the Nexa and is transparent to the operation of IRENE.

4.2. Control and communication compatibility

Numerous integration issues have stemmed from the different communication and control protocols used by the individual components. Ground plane issues abound due to the floating nature of the system. Extensive use of optical isolation was required to connect the devices to a single computer. Once a physical connection of the components and data acquisition hardware was made to the computer, a more difficult challenge arose in developing a unified control program. Each of the major devices functioned only with the OEM proprietary software. Significant reverse engineering of the communication data stream was required to develop LabVIEW interfaces with each of the devices. A primitive multi-window controller has been assembled to allow for initial operation of IRENE while further work on a fully integrated controller takes place.

Issues related to the communication rates of several of the devices have been identified. The standard RS232 communications protocol used by a number of the devices imposes limitations on data transfer rates and hence the response rate of the devices. Remote adjustment of the inverter control parameters is particularly slow. Experiments in which dynamic response of system elements will be mapped will require careful implementation of software control to avoid problems. In general, the lack of standards on the type of information shared between devices makes the integration of a complex system like IRENE a significant challenge.

4.3. Component reliability

The reliability of components used in the individual sub-systems has been disappointing. Each of the major pieces of equipment acquired for this project had manufacturing defects and/or significant functional omissions that required repair or custom upgrades before they could be implemented in IRENE. This is perhaps not surprising given the prototype nature of many of the components. The batteries have been the only components that worked as per specification "out of the box".

The details of individual problems are omitted but, in general, faulty electrical wiring, malfunctioning control hardware and component compatibility issues leading to premature failure have been recurring causes of reliability issues. For commercial success of an IRENE-like system to occur, the quality of the individual sub-systems would need to be substantially improved, especially in light of the costs.

4.4. Data acquisition

Operation of IRENE relies upon control of each of the components based on time-dependent conditions. The current and voltage levels at each component need to be known for this control to be possible. To acquire these data, the voltage across each component of IRENE is measured. The current at each device is also measured using resistive shunts. Mass flow measurements are made at various points throughout the system to determine hydrogen consumption and production.

Operation of many of the components creates electromagnetic noise which affects the acquired data. In addition, each measurement device supplies different voltages to the data acquisition system and hence different gains must be applied to each signal. To solve these problems, power conditioning electronics were developed to both filter noise and provide an appropriate gain to each signal. This also provided the benefit of increasing the maximum data acquisition rate. Physical shielding and mounting location of the signal conditioning devices have also been important factors for minimizing noise inherent in operation of IRENE.

5. Preliminary operation and characterization of components

The individual components of IRENE can be programmed to operate either dynamically or statically depending on the design of the experiment. For instance, any one of the individual components can be held at a constant output/input while other components can change to meet any load demands placed upon

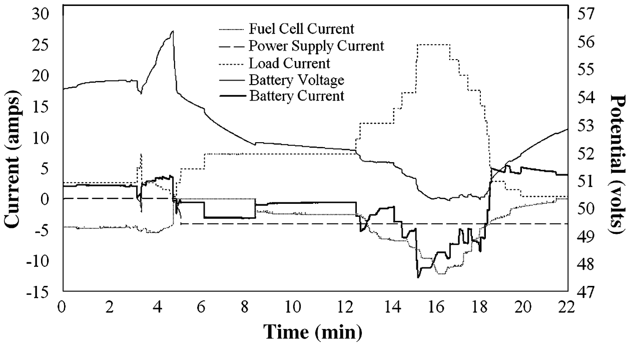

Fig. 3. System currents and bus voltage during test operation of IRENE.

the system. Fig. 3 shows a sample operation of IRENE. A negative current indicates the component is a source and a positive current indicates the component is a sink.

- For the first 4 min, the simulated renewable source (Power Supply) produced little or no power while a relatively constant load is met primarily by the fuel cell. An adjustment to the load bank created the spike near the 4 min point.
- At approximately 5 min, the simulated renewable started to produce power which decreased the load on the fuel cell.
- From 5 min to the end of the experiment, several conditions were tested with different responses from each of the individual components observed.

Fig. 3 shows everything from "simple" charging of the battery, to the battery, fuel cell and renewable all being used simultaneously to meet the desired load condition. The battery bank has been intentionally kept small as the fuel cell is meant to be the primary source of power when no renewable power source is present. This allows the individual components to radically change the voltage of the bus as seen in the figure (battery voltage).

Hydrogen production volumes of the electrolyzer are currently being measured at various voltage, current and temperature conditions. Since fluctuations in power occur throughout all of IRENE's components, having the ability to throttle the power supplied to the electrolyzer is critical to ensure that the primary load can be met. To determine what level of control is necessary, characterization of the electrolyzer is essential. A series of these measurements have been performed and are currently being assessed. Preliminary results show that at the electrolyzer's maximum allowable input power, auxiliary thermal management becomes necessary as temperature limits are exceeded and internal protection devices shut off the unit.

6. General design considerations

Many of the challenges confronted while assembling IRENE result from integrating hardware components. While the details are important to the inner workings of IRENE, they are of little consequence to the development of other renewable energy systems. There are however issues which arose during this work that are more generic in nature and applicable to a broad range of small-scale energy systems.

The number of conversion steps must be held to a minimum to attain a functional system. This design principle is motivated not only by the obvious degradation in performance due to compounding efficiency losses, but also by the increased likelihood of inducing problematic dynamic interactions between conversion processes. This is particularly relevant when multiple input sources feed a common bus as with IRENE. Careful design and integration of the power conditioning electronics are required to avoid system oscillations which can degrade performance or damage equipment.

Transient load demands must be considered when selecting components for a renewable energy system. The majority of the simulation models reviewed during IRENE development were limited to steady state operating conditions which compute the average power transferred between system elements. These results underestimate the instantaneous power transfer required to service real loads. Transients one order of magnitude larger than the average values have been observed during operation of IRENE. System components must be sized to handle these transients if real devices are to be powered from a renewable energy system.

System architectures with direct source to load structure obtain much higher transfer efficiencies than designs which rely on energy buffering. In a residential scale system, for every 6 kW of power diverted to the electrolyzer, only 1 kW (maximum) can be returned to the system by the fuel cell based on the current hydrogen production/consumption levels. Inefficiencies in the electrolyzer, fuel cell, and power conditioning circuits along with parasitic loads all contribute to the power losses observed. The efficiency is further reduced if additional compression work is required to store the hydrogen at higher system pressures.

On an industry basis, standards for the working ranges, communication protocols and interfaces are required for the manufacture of components for renewable energy systems to reduce complexity of system level integration. Components currently offered by manufacturers may work well independently, but are not designed to work together. This poses a significant barrier to the widespread adoption of small-scale regenerative fuel cell systems.

7. Conclusion

A small-scale renewable energy test bed with hydrogen energy buffering has been constructed using commercial and pre-commercial components. The facility is designed to be readily re-configurable to enable testing of new system components as they become available. The test bed is fully instrumented to log not only the long-term average system parameters (energy flows, hydrogen production rates, etc.), but also to capture the high-speed transient interactions which occur between system components.

The integration challenges that arose during construction of this facility and which are generally applicable to the development other of renewable energy systems have been discussed. Ideally, system components should be chosen so that they are comparable in power requirements and operating voltages. The large electrical input and output differences between IRENE components only exacerbated the difficulty of system integration. Poor performance of the individual components has also created problems in construction of IRENE. Novel devices have been developed to overcome many of the integration issues encountered. Many of the components also need major reconstruction to make up for design shortcomings.

Future work will involve performing detailed energy balances for a variety of resource/load scenarios to obtain the actual operating efficiencies. The performance of alternative system configurations will be assessed experimentally and compared with results obtained from energy systems modeling software. The technical feasibility, practicality, and economic viability of various system designs will be probed.

Acknowledgements

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