DESCRIPTION AND FIRST RESULTS OF A WIND-PV HYDROGEN SYSTEM AT KAHUA RANCH, ON THE BIG ISLAND OF HAWAII

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1. Introduction

With over 90% of its energy system fueled by imported fossil fuels, isolated by over 2,400 miles of ocean from the nearest land mass, and with the highest energy costs in the nation, there is compelling motivation for Hawaii to harness its diverse renewable energy resources to achieve energy self-sufficiency. Evolving towards a hydrogen economy is one of the potential paths to achieving that goal. Arguably, Hawaii has, of all the states, the nearest-term potential to evolve towards a renewable hydrogen economy. The Hawaii Hydrogen Power Park (HPP) program funded by the US Department of Energy (USDOE) is a critical component in advancing this vision. Hawaii's political leadership is critically concerned with Hawaii's energy situation and has developed supportive policies, backed by funding, to advance a hydrogen economy. The initial focus of this effort is the Big Island which has significant wind, solar and geothermal resources.

The Hawaii Hydrogen Power Park was established in 2002 in support of USDOE's Technology Validation Program, to conduct engineering and economic validation of pre-commercial hydrogen technologies. Power Park is funded by the USDOE through Hawaii's Department of Business, Economic Development and Tourism's Strategic Industries Division (DBEDT) under the State Energy Partnership program. The Hawaii Natural Energy Institute (HNEI), a research unit in the School of Ocean and Earth Science and Technology at the University of Hawaii, serves as the implementing partner and manages development and operation of Power Park activities.

Power Park proposes to use renewable sources for the production of hydrogen for a range of stationary and transportation applications. Under Phase 1 (2002-2005) HNEI conducted testing of major system components including a 12kg/da Stuart TTR225 electrolyzer, and a 5 kW GenCore Plug Power fuel cell power system at its Hawaii Fuel Cell Test Facility (HFCTF) in Honolulu. Under Phase 2 (2005 - 2007) HNEI developed and has initiated operation of an integrated wind-photovoltaic-electrolysis-hydrogen-fuel cell system at Kahua Ranch on the Big Island. This system, which uses a smaller electrolyzer from Electric Hydrogen, is capable of remote operation with data acquisition and control over the internet.

Under Phase 3, scheduled to begin later this year, USDOE and the State of Hawaii have committed $1.6 million for development of hydrogen fueling infrastructure on the Big Island. This effort includes hydrogen production utilizing renewable electricity, compression, storage, delivery, and dispensing to hydrogen vehicles.

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The Hawaii Volcanoes National Park (HAVO) is acquiring from 2 to 5 battery-dominant fuel cell hybrid plug-in shuttle buses. These vehicles are expected to reduce congestion at the park and to provide a better (quieter and cleaner) visitor experience. The Hawaii Center for Advanced Transportation Technologies (HCATT), which currently manages a hydrogen fueling station for the US Air Force at Hickam Air Force Base on Oahu, has converted several vehicles for fuel cell use and has been identified by HAVO to manage the vehicle conversions. The hydrogen infrastructure developed under Phase 3 Power Park will be used to support HAVO's hydrogen fueling requirements.

This article describes Phase 2 Power Park installation at Kahua Ranch from its design to its first experimental results and conclusions.

2. Kahua Ranch Installation

Kahua Ranch [1] has a long history of involvement in the development of renewable energy (RE) in the Big Island. In 1985, it hosted the first Big Island wind farm supplying the grid with 2.3 MW. In 1996, Kahua Ranch was supplied by a wind-solar-battery-diesel system developed by our partner Pacific International Center for High Technology Research (PICHTR, [2]). This village power system has been modified under this project to include a hydrogen storage system (HSS).

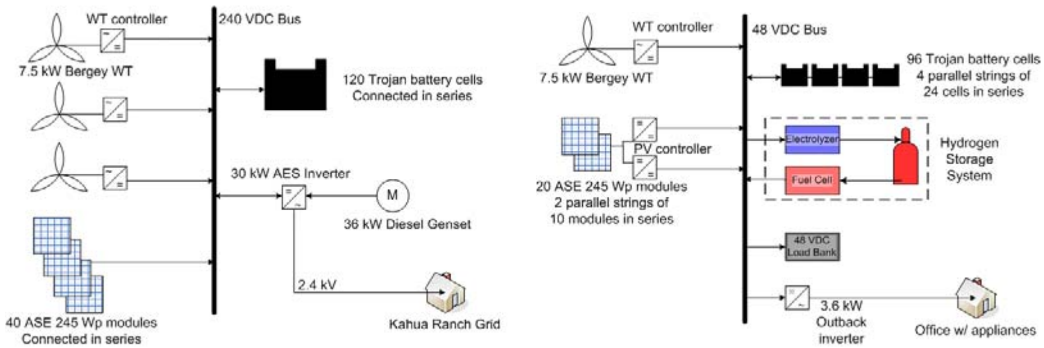
2.1. Kahua Village Power System

Completed in 1996, PICHTR has developed a Renewable-Hybrid-Village-Power demonstration plant including three 7.5 kW wind turbines (WT), a 10 kW photovoltaic (PV) array, and a 30 kW diesel generator in conjunction with a battery bank and pumped hydro system to supply power to a greenhouse, 11 homes and shops on the ranch [3]. The 360 kWh/day system was a prototype for a larger version built in Fiji in 1998.

Figure 1.a shows a schematic of the Kahua village power system. The three Bergey WT generators produced an unregulated AC electricity that was transmitted to the electrical room through a 500 m long buried power cable. Each unit had a rectifier/controller such that wind energy is made available as DC current at the battery voltage. The PV array consisted of 40 ASE Americas GP-8 modules rated at 245 W_{peak} at standard conditions. The DC electricity from the PV was also transmitted via 60 m buried cable to the electrical room. The RE generators (PV and WT) were connected to a 240 VDC flooded lead acid Trojan battery system with a storage capacity of 428 kWh. A single point watering system by Watermaster was used to water the battery system with distilled water. In addition, the system had a diesel generator and a rectifier/inverter/controller from Advanced Energy System supplying the village load using renewable resources, battery or diesel generator.

From 1996 to 2006, the Kahua Ranch village was supplied by the village power system allowing renewable energy to be accounted for 80% of annual electricity production. Essential information on these systems including operation and maintenance cost was recorded [4].

In March 2006 during the design of the new HNEI installation, two of the three WT malfunctioned requiring important repairs. Kahua Ranch decided to switch to Hawaii Electricity Light Company (HELCO) services. The reminder of the original power system was then converted into 48 VDC output for exclusive use in the HNEI power park project.



(1.a) (1.b)

Figure 1. Design of the Installations at Kahua Ranch – (1.a): Village Power System; (1.b): Present RE-Hydrogen Power System.

2.2. Renewable Hydrogen System (RE-H_2 System)

Figure 1.b shows a schematic of the HNEI power system. In this new system, the diesel generator is not used. Instead, a second hydrogen based energy storage system (HSS) was added comprising of an electrolyzer, hydrogen gas storage cylinders, and a fuel cell. Although less efficient than the battery storage, the HSS has other advantages such as a long term energy storage capacity, an independent energy/power relationship, a possibility for cogeneration of electricity and heat, and a capability to supply hydrogen to other applications such as transportation applications. A 48 VDC configuration was selected because this voltage is widely used in renewable energy and hydrogen technologies. The decision was largely influenced by the possibility to use the 48 VDC fuel cell system, tested during phase 1 of the HPP.

The main tasks of HNEI were the selection of the components available for this application and the development of the interface between all components allowing safe and stand-alone operation of the overall installation. The selection of the components was based on the availability, the capacity of configuring into 48VDC bus, the efficiency and the investment cost. The interface was designed to be expandable, easily movable and visible/controllable from everywhere via internet.

2.2.1. Initial System Modification

The wind turbine system was modified by installing an additional transformer to step wild 300 VAC voltage down to 48 VAC. A Bergey controller VCS-10 was also added to convert the 48 VAC into controlled 48 VDC. The VCS-10 controller can also be used to disconnect the source to avoid overcharge of the batteries. Part of the PV array was rewired into 2 arrays of 10 modules in series.

Each of the resulting 2.45 kW arrays were connected in parallel with two 3 kW Outback Power Systems MX60 PV Maximum Power Point Tracker (MPPT) controllers allowing maximum use of solar energy and customized battery recharging including absorbing charge and floating control based on battery voltage. The 2 MPPT controllers have difficulty running in parallel (see 2.3. Experimental Results) reducing the available PV power. The battery bank was rewired into a 48 VDC configuration using the best 96 cells. The overall battery storage is therefore a 10 year-old battery storage of 343 kWh.

2.2.2. Hydrogen Storage System (HSS)

A HSS is now in place at the Kahua Ranch. Figure 2 shows the hydrogen room where most of the equipment is installed. Figure 3 shows the equipment including safety equipment, placed outside in the gas storage area. The HSS includes an electrolyzer (EL) splitting deionized water into hydrogen and oxygen, a hydrogen tank, a fuel cell (FC) system, and a deionized water supply tank. The HSS was built and tested at the HFCTF in Honolulu (Figure 4), then shipped to the Big Island by barge.

Figure 2. Hydrogen Room at Kahua Ranch

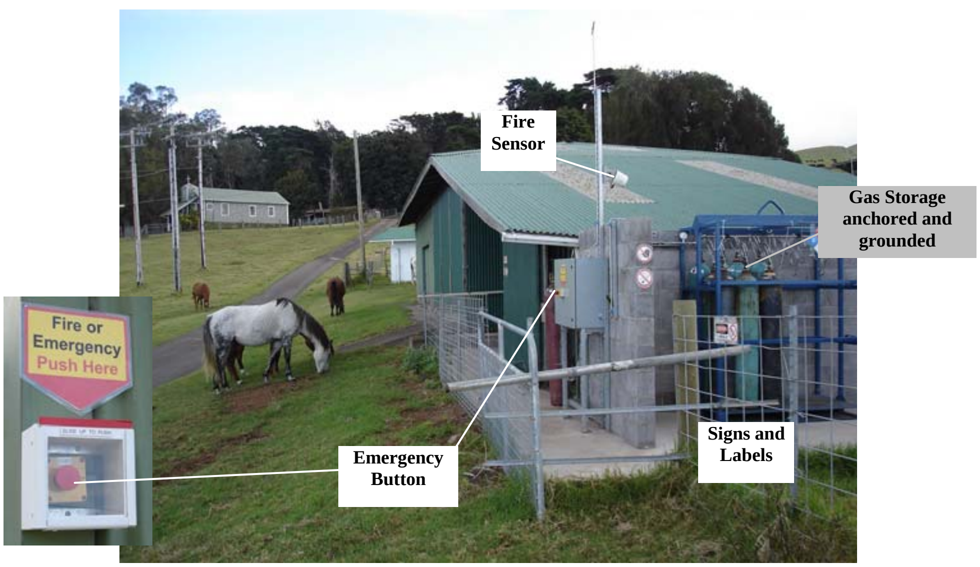


Figure 3. Kahua Ranch Gas Storage – Safety Equipment

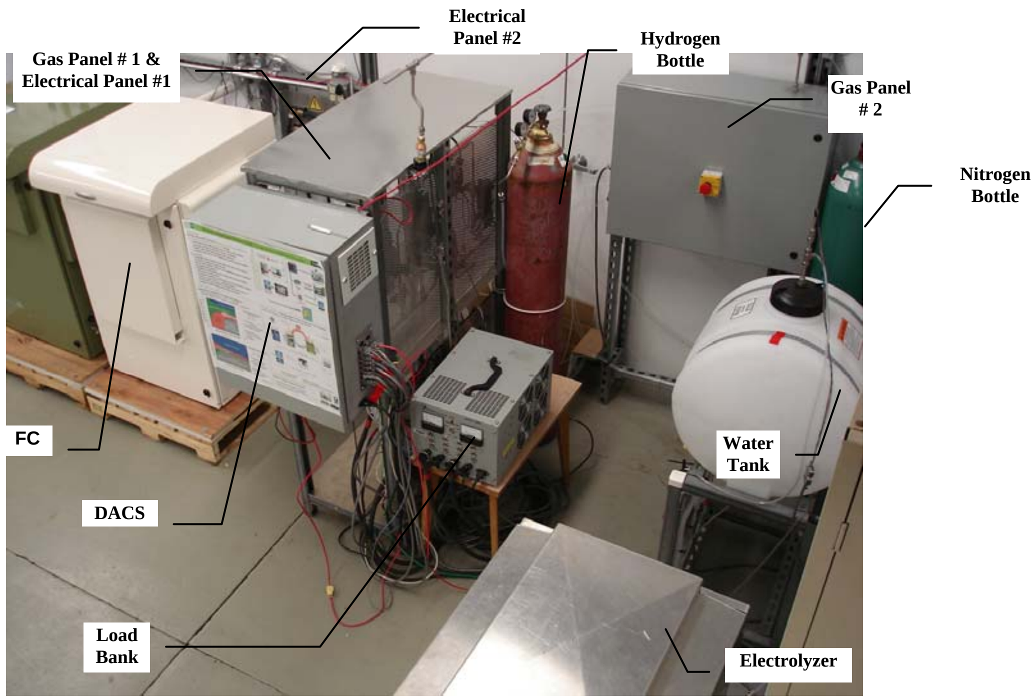


Figure 4. View of the Installation in Test at the HFCTF in Honolulu

The Proton Exchange Membrane (PEM) electrolyzer supplier is Electric Hydrogen, Eh! [5], a new Canadian company that was selected as having a good background in PEM electrolyzers and proposing a 48 VDC unit with high efficiency that would be designed for our application. Also, the small size of the unit is rare on the market and was available at a relatively low price. The EL specifications are a hydrogen production rate of 0.2 Nm^3/h (7 scf/h) at 12 bar gage (175 psig). The electrical input specifications are: 25 A at 48 VDC with an allowable range from 46 V to 58 V. The hydrogen generator consumes deionized water (ASTM Type I) supplied at a pressure between 3 and 20 psig. The maximum efficiency was specified to be 74% based on high heating value (HHV) – 63% based on low heating value (LHV). The analysis approach used for the electrochemical components will be detailed in an upcoming publication [6].

The EL system consists of a gas generation unit, a gas/liquid management unit, and a cooling unit. The gas generation unit contains a stack of 10 PEM cells connected in series. The stack is mechanically connected on the cathode side to the gas/liquid separator and a pressure regulator, allowing hydrogen production upon reaching 12 bars. The anode side of the stack is connected to a gas/liquid tank for oxygen drying and for managing the water level in the stack. The product oxygen is vented to the atmosphere. A solenoid valve allows water to fill up the tank when it reaches a preset low water level. The cooling unit, part of the anode side, contains a water pump, and an air/liquid heat exchanger to regulate the stack temperature. Finally, the unit is protected by an outdoor cabinet that is vented in order to cool the unit and to avoid hydrogen accumulation. An integrated hydrogen sensor in the cabinet shuts down the unit if necessary.

The first prototype unit was commissioned on August 2007. With a design adapted to be integrated into a stand-alone power system, the unit started up as soon as it is connected to the DC bus bar and it reached its maximum performances in 5 minutes; 0.1 Nm^3/h at 8.6 bar consuming 20 A at 53.5 V, on the commissioning day. The 10 cells stack operated at 28 A at 33.1 V. The unit demonstrated an overall efficiency of 37% (HHV) but exhibited a good gas efficiency losing only 2% of the theoretical gas production. Loss in auxiliaries was 14%. The main problem on the unit was the stack showing 49% of the unit loss in heat. In addition, the stack experienced rapid degradation lowering the maximum operating point. A new stack was built by Eh! and integrated into the unit on December 2007. The unit met the specifications producing 0.2 Nm^3/h at 12 bars. The efficiency has been evaluated at 50.2%.

The 5 kW Plug Power Gencore FC system [7] requires pure hydrogen (99.95%, dry), access to ambient air (temperature between -40°C to 46°C and non-condensing relative humidity between 0% to 95%), and produces up to 5 kW electrical power on a regulated 48 VDC load. The outputs are oxygen-depleted humidified air and water.

The fuel cell system consists of a stack of 70 cells connected in series, air and hydrogen supply units, a cooling unit, a power converter, a battery pack wired in parallel with the FC system output, and a microprocessor for data acquisition and automatic operation. The hydrogen supply system includes an exhaust gas recirculation system for injecting non-consumed hydrogen and water vapor into the anode inlet stream. There is no active hydrogen flow controller; instead hydrogen automatically enters the system through a pressure regulator to maintain 0.07 bar (gauge) into the gas line. The air supply unit consists of a filter that removes hydrocarbons and other chemicals, an air blower with speed mapped to FC power demand, and a humidifier. The cooling unit has a single speed circulation pump and 2 coolant loops. One loop includes a heater used at start-up to heat the stack to the operating temperature of approximately 55°C. The second loop is used for cooling the stack by passing the coolant through a radiator, which has a fan with speed mapped to FC power demand. The batteries are used at start-up to supply auxiliary power. However, as soon as the FC is connected to the DC bus, the stack supplies power to the parasitic loads. The FC power converter uses either the stack power or the battery power to support the load with regulated voltage between 46V and 56V. The FC unit has an operation mode called Low Bus Operation. When selected, the internal controller starts the unit to maintain the output voltage in a settable range. This operation mode is appropriate for operation in the Kahua Ranch installation because the FC unit can automatically start up when the battery voltage is low avoiding over-discharge of the batteries. In that way, the battery storage is used as the priority storage system and the HSS is the secondary storage.

During Phase 1 of the Hawaii Power Park, the fuel cell system was evaluated in steady state operation [6]. This study showed the system has good reliability and an efficiency above 35% (HHV) from 10% to 100% of the maximum power with a peak at 42% around 2 kW output. At maximum power, loss is mainly due to heat (52%), while gas loss is 6% and 4% is used to supply the auxiliaries. During this testing period, in consultation with Plug Power, the inlet pressure specified at 5.5 bar (80 psig), was reduced to 2 bar (30 psig) without operational degradation. This test was conducted to increase the usability of the low pressure hydrogen gas storage system in the final stationary application.

Several options were studied for the hydrogen gas storage during the design process. Compression was quickly abandoned as it is a big energy consumer and the ranch has the real estate for a large low pressure storage system. In the final design, the maximum storage pressure is then the maximum pressure of the electrolyzer (12 bars). The hydrogen gas storage was intended to be a 7.6 m^3 (2,000 gallons) low pressure propane tank. For safety reasons, the supplier decided to supply a tank specially designed for hydrogen. This would have caused a significant delay in the project and it was decided to use 9 hydrogen cylinders of 50 liters each connected into an 18 cylinder bottle rack. The full storage is then equivalent to 5.4 Nm^3 or 452 g (17.8 kWh, HHV). It is acknowledged that this storage capacity is too small for optimal operation but it is easily expandable later. The project goal was to demonstrate the potential to use pre-commercial components, to evaluate present technologies, to complete an expandable test bench, to develop the data acquisition and control system, and to improve knowledge on such applications.

The water storage system is comprised of a 113 liter (30 gallons) applicator tank from American Tank Company. The tank is made of a linear, high-density polyethylene resin. The lid has been modified as shown in Figure 2 in order to add 4 water-level switches and to pressurize the water to 0.5 bar (6 psig) as required by the electrolyzer. The pressure is supplied by pressure regulated nitrogen supplied from a high pressure nitrogen cylinder.

2.2.3. Additional Equipment

One high pressure nitrogen cylinder is connected to the gas lines for purging before hydrogen use, and for supplying pressure to the pneumatic system and the water tank. In operation, the nitrogen consumption should be virtually nil. Nitrogen is used only for start-up/shut down periods or if hydrogen tanks needs to be purged.

An Avtron K492 7.8 kW resistive DC load bank is used to simulate resistive load profiles. The load bank is connected to the 48 VDC bus.

An additional Outback Power Systems GVFX 3648 3.6 kW inverter was installed in December 2007 in the electrical room on the 48 VDC bus, supplying electricity to the office equipped with small home appliances. This inverter could be used to supply the grid for grid-connected experimental purposes.

2.2.4. System Control

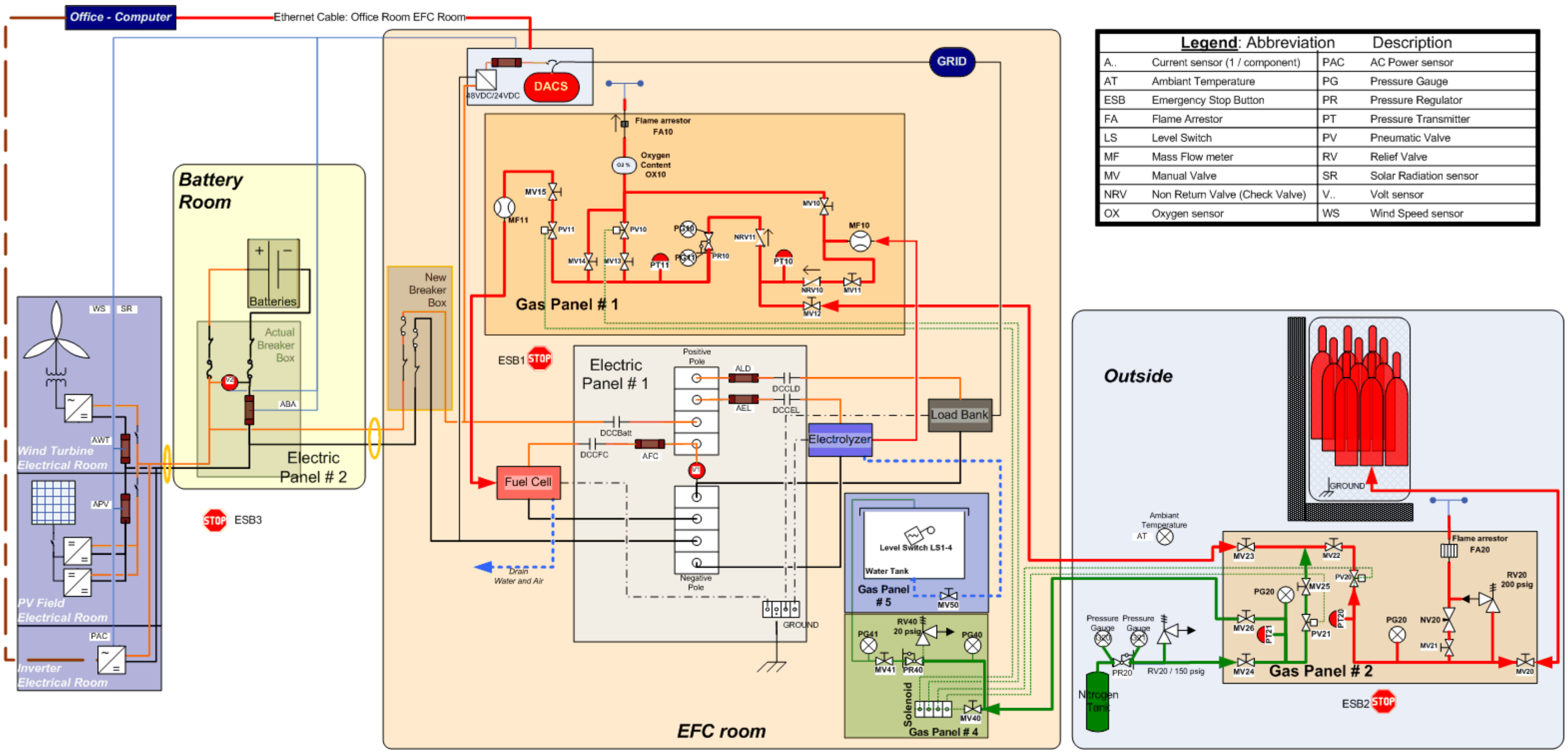
All of the components described above require an interface to operate together. The interface developed by HNEI connects all components electrically, electronically, and mechanically into an integrated system. It includes sensors, valves, and relays connected to the Data Acquisition and Control System (DACS) for system control and data recording. A safety analysis in the design process resulted in the development of a fail-safe system. Because the main components have their own controllers to run safely and automatically, the HNEI DACS controls the overall system especially the shut-down procedures in case of emergency such as fire, earthquake or instrumentation failure. It also optimizes the energy management of the system. In addition, it has been designed to be expandable, easily movable, and visible/controllable utilizing the internet.

Guaranteeing safety in a demonstration hydrogen project is essential for their sustainability and public acceptance. Therefore, the overall design criteria for the installation design was based on the safety requirements listed in the following codes and standards publications:

- ✓ NFPA 55: Standard for Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks
- ✓ NFPA 583: Installation of Stationary Fuel Cell Power Systems
- ✓ ASME B31.3: Process Piping
- ✓ CGA G-5.4: Standard for Hydrogen Piping
- ✓ CGA-5.5: Hydrogen Vent Systems

Safety control components were included in the installation including a hydrogen fire sensor, a hydrogen sensor, and an oxygen concentration sensor for controlling hydrogen purity. Three (3) emergency stop buttons identified by large signs are situated at different locations on the site. Many essential measurement sensors were duplicated in order to insure that gas leaks or component failure would be detected. A brick firewall was built surrounding the hydrogen storage. Warning signs identify restricted areas including the hydrogen storage area and the hydrogen room. Some of these safety measures and equipment are shown in Figure 3.

Other essential safety features included in the design are intended to address unattended events such as losing system control due to a DACS power shortage or a depressurization of the pneumatic line. In order to avoid hazardous situations, the interface was designed as a fail-safe system meaning that in such unattended events, the system stops safely: 1) all components are disconnected, 2) the gas storage is isolated, and 3) the gas lines are depressurized. The design was subjected to a safety analysis based on Fault Tree Analysis methodology. Up to now, the system has been operating as planned. Long-term operations are essential to validate and improve system safety design for unattended autonomous operations.



Legend: Abbreviation		Description	
A..	Current sensor (1 / component)	PAC	AC Power sensor
AT	Ambiant Temperature	PG	Pressure Gauge
ESB	Emergency Stop Button	PR	Pressure Regulator
FA	Flame Arrestor	PT	Pressure Transmitter
LS	Level Switch	PV	Pneumatic Valve
MF	Mass Flow meter	RV	Relief Valve
MV	Manual Valve	SR	Solar Radiation sensor
NRV	Non Return Valve (Check Valve)	V..	Volt sensor
OX	Oxygen sensor	WS	Wind Speed sensor

Figure 5. Process Instrumentation Diagram

Table 1. List of Inputs at Kahua Ranch Hydrogen Installation

Name	Name	Description	Unit
H2 Pressure (FC Side)	PT11	Pressure on the FC side line after Pressure Regulator PR 10 (30 psig)	psig
H2 Flow FC	MF11	Flow of hydrogen produced by electrolyzer	slm
H2 Flow EL	MF10	Flow of hydrogen consumed by Fuel Cell	slm
O2 content in Vent	OX10	Oxygen content into vent	%
Wind Speed	WS	wind speed sensor located on the roof of the office	mph
H2 Pressure GP1	PT10	Pressure of gas storage located on gas panel # 1	psig
Amb Temp	AT	Ambient temperature	Celsius
Solar Radiation	SR	Solar radiation sensor located on the roof of the office	Wpm2
PV Current	APV	Shunt measurement	A
WT Current	AWT	Shunt measurement	A
DCBus Volt (Batt)	V2	Voltage measurement on DC Bus in Electric panel # 2	V
DCBus Volt (EFC)	V1	Voltage measurement on DC Bus in Electric panel # 1	V
Shunt EL	AEL	Shunt measurement	A
Shunt LD	ALD	Shunt measurement	A
Shunt Batt	ABA	Shunt measurement	A
Shunt FC	AFC	Shunt measurement	A
N2 Pressure	PT21	Pressure on nitrogen line (75 psig)	psig
H2 ST Pressure	PT20	Pressure of gas storage located on gas panel # 2	psig
FC Alarm	FCES	Send Boolean signal to stop the FC system	0 or 1
ESB3	ESB4	Emergency Stop Button # 3 – Outside the battery room	0 or 1
Batt Signal DCC	DCCBatt	Contactor signal between initial system and HSS	0 or 1
EL Signal DCC	DCCEL	Contactor signal for electrolyzer	0 or 1
FC Signal DCC	DCCFC	Contactor signal for FC system	0 or 1
LD Signal DCC	DCCLD	Contactor signal for load bank	0 or 1
WLS High	LS51	Water tank level switch # 1	0 or 1
WLS MidHigh	LS52	Water tank level switch # 2	0 or 1
WLS MidLow	LS53	Water tank level switch # 3	0 or 1
WLS Low	LS54	Water tank level switch # 4	0 or 1
ESB1	ESB1	Emergency stop button # 1 – On the main interface unit	0 or 1
ESB2	ESB2	Emergency sStop button # 2 – On the gas panel	0 or 1
Fire Sens	FS	Fire sensor	0 or 1
H2 Sens	HS	Hydrogen sensor on the ceiling of the hydrogen room	0 or 1
Earthquake Sens	EQS	Vibration sensor located in the DACS box	0 or 1
AC Supply	Auto	Signal if DACS is supplied with grid or power system	0 or 1

Table 2. Digital Outputs of the Kahua Ranch Installation

FC Estop	ESFC	Send boolean signal to emergency stop the FC system	0 or 1
Batt DCC	DCCBatt	Contactor between the initial system and the HSS	0 or 1
EL DCC	DCCEL	Contactor for the electrolyzer	0 or 1
FC DCC	DCCFC	Contactor for the FC system	0 or 1
LD DCC	DCCLD	Contactor for the load bank	0 or 1
EV_Vent	PV10	Electrovalve allowing Pneumatic Valve de/pressurisation – Vent	0 or 1
EV_ST	PV20	Electrovalve allowing Pneumatic Valve de/pressurisation – Storage	0 or 1
EV_FC	PV11	Electrovalve allowing Pneumatic Valve de/pressurisation – FC supply	0 or 1
EV_PV	PV21	Electrovalve allowing Pneumatic Valve de/pressurisation – N_2 supply	0 or 1
Grid Supply	Relay	Contactor for either grid or 48 VDC supply	0 or 1

Figure 5 shows the Process Instrumentation Diagram (PID) of the installation showing all sensors for pressure, flow, current and voltage measurements as well as the valves and the contactors. All elements are connected to the DACS. The interface is split into 4 main assemblies to allow easy transport of the system:

1. The main assembly is in the hydrogen room (Figure 2) including gas panel # 1, electrical panel # 1, and the DACS box.
2. In the gas storage area, a cabinet contains gas panel # 2 (Figure 3).
3. The structure under the water tank holds gas panel # 4 (Figure 2).
4. Finally, electrical panel # 2 is situated adjacent to the batteries.

The Data Acquisition and Control System (DACS) located in a vented cabinet includes:

- ✓ A Fieldpoint (FP-2000) microprocessor controller from National Instruments programmed using Labview software.
- ✓ Analog/digital input/output modules. The input data is listed in Table 1 and the output data is in Table 2.
- ✓ Power supply hardware to supply the control unit using either the 48 VDC power system itself or the grid.
- ✓ A communication unit allowing data transfer between the host computer and the DACS, the electrolyzer, and the FC via service interfaces.

The program in the microprocessor assures safe stand-alone operation taking into account the requirement for operation via the HNEI service interface or via the emergency stop buttons. Figure 6 shows a simple diagram of the repeating sequence running every 250 ms in the controller. This frequency has been considered high enough to assure quick emergency responses if necessary. Based on the data and control configuration files, sensor measurements are analyzed and sent to the host computer for data acquisition and visualization. Analyzed data is used by the program to determine the present state of the system as well as the next state according to the external control from the host computer or the automatic operation. The updated system state induces new values for the output modules. The configuration files allow changing the scaling of analog data and the parameters of the control without stopping the system.

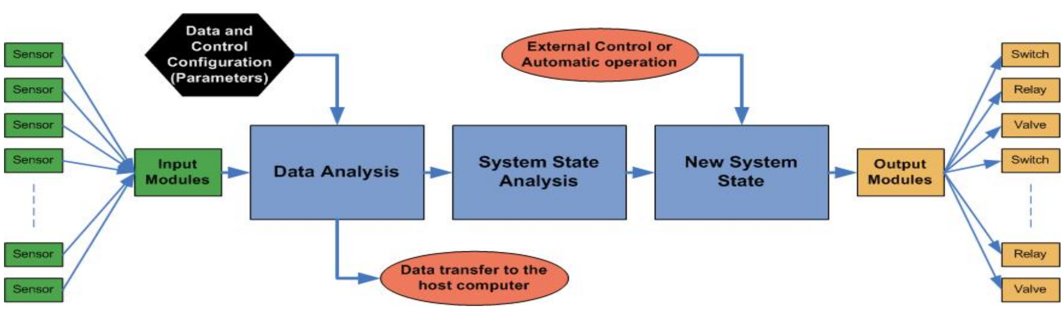


Figure 6. Repeating Sequence in the Control Program (every 250 ms)

The microprocessor is completely stand-alone meaning that if the host computer or internet connection has a problem, the power system is still controlled and may be stopped in case of hazardous situation or on-site using emergency stop buttons.

The control of the overall installation is implemented into the DACS controller using LabVIEW software program. Different operational modes have been programmed:
In "Manual Mode", each component can be connected individually, the gas lines can be purged, and the complete installation can be stopped. The operation called "Automatic Mode" is used for the power system to run stand-alone. It induces a purge of the gas lines before use of hydrogen and connection of all components. In this operation mode, the components are automatically connected/disconnected for safe operation and optimized energy management. The automatic mode control has been designed to harvest the maximum amount of available renewable resources, using the battery storage as primary storage due to its high efficiency compared to the HSS. It utilizes bus voltage and hydrogen storage pressure as its primary system sensors. It controls by connecting and disconnecting the load bank and the electrolyzer because the generators of the installation (WT, PV and FC) have their own regulators. The implemented automatic control has been designed to be as simple as possible. A more sophisticated control could also be tested by reprogramming the controller program.

Main Control: In all operation modes, the controller always checks to see if there are any warnings or alarms. Warnings or alarms can be generated by analog sensors that show signals out of their allowable ranges. Ranges are defined in the configuration files. Alarms may also be linked to the safety equipment such as the fire, hydrogen or earthquake sensors, or the emergency stop buttons. Alarms or long warnings (occurring for 5 seconds) automatically trigger a complete shut down of the installation: 1) all components are disconnected from the bus, 2) the gas storage is isolated and 3) the gas lines are purged and depressurized. Once such emergency stops occur, an operator is required to restart the installation.

Voltage Control: Battery voltage has been selected to control the system. Although the state of charge (SOC) is more accurate to evaluate the available energy stored into the battery, it is also very difficult to measure. Moreover, the regulators integrated into the generators of the installation already use the battery voltage to operate. Indeed, the PV and wind generators reduce the available renewable power to avoid overcharge of the batteries. The regulation starts when the battery voltage reaches 56.8 V for the WT and 58 V for the PV. Figure 7 illustrates the voltage control of the whole installation showing the operating voltage range of each component. The FC system has been set in order to operate to avoid battery deep discharge. It starts up when the battery voltage reaches 47 V and maintains it between 47 V and 47.7 V. It automatically stops when the voltage gets higher than 47.7 V. The load bank, priority load, is always connected when the battery voltage is between 46.8 V and 60 V. It may be disconnected when the FC runs and the hydrogen storage is empty. In such a case, both of the storage systems are considered empty and the load is reduced to allow the recharge of the storage systems. The electrolyzer supply is allowed when there are 1) an excess of renewable resources, 2) the batteries are charged, and 3) the hydrogen storage system is not full. Therefore, the electrolyzer voltage range has been set between 49 V and 60 V. The EL unit starts up when the battery voltage reaches 54 V and the battery current is above 20 A. It is disconnected when the battery current is less than 0 A. A two minutes average on the battery current is used in order to avoid short-term operation of the electrolyzer. When the low voltage limit is reached (49 V), the electrolyzer is turned on again only if the batteries are recharged and their voltage is 54 V or above.

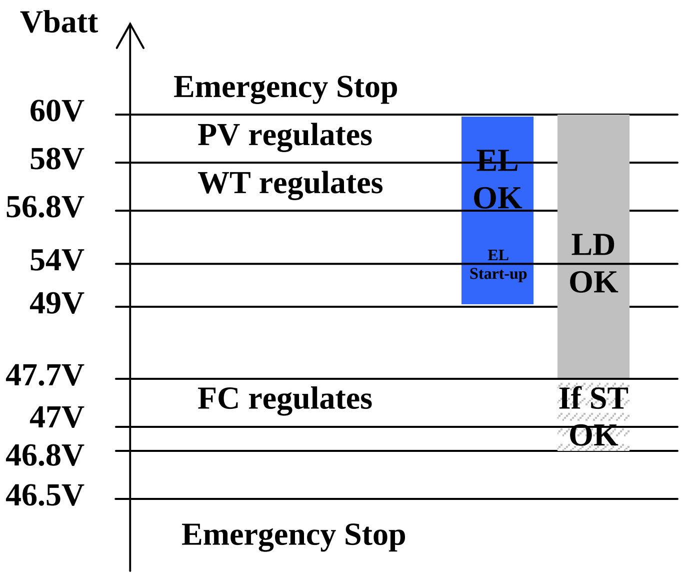


Figure 7. Voltage Control in the Overall Installation – Operating Voltage Range of the Components

Pressure Control: Control based on the hydrogen storage pressure avoids starting the electrolyzer when the gas storage is full in order to avoid idle consumption by the unit. As mentioned earlier, when the gas storage is empty, the end-user load is disconnected because the FC system cannot help in matching the demand without a risk of running out of gas.

All the voltage and pressure set points can be simply modified using the service interfaces or the configuration files. For most of these set points, hysteresis are used in order to avoid short-term operation of the components.

A LabVIEW program runs in the host computer for data visualization and remote control. Data sent via Ethernet by the DACS are recorded directly or after averaging. It is also displayed into a graphic service interface. Data recorded every 250 ms is used for trouble shooting the installation. Figure 8 shows the program used on the host computer for this purpose. Fast measurements are also helpful to evaluate the transient behavior of the whole installation. Averaged data is more convenient when evaluating the overall energy flow in the power system during one day or longer period of time.

Figure 8. Trouble Shooting Windows

Figure 9 shows the service interface allowing data visualization and system control. Data shown on the visualization screen consists of all the measurements or controls detailed in Table 1 and Table 2. A graph allows visualizing the time evolution of the recorded data. Finally, the interface displays information on the system state (mode of operation, gas line status), and on the status of the control program itself. The picture on the right of Figure 9 is the control service interface which allows changes in the operation mode, connecting and disconnecting components, and control parameters. Although the visualization screen is available to anyone on the project web site, the control program is only accessible to authorized users.

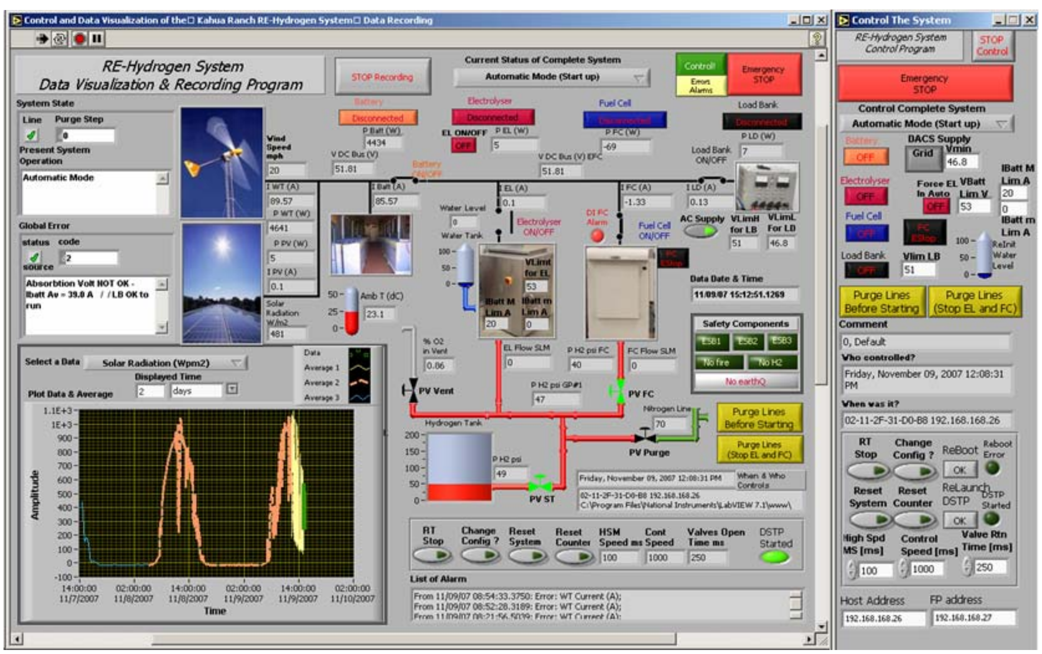


Figure 9. Data Visualization of the Kahua Ranch Installation (left) Available on a Web Site and Control Interface (right) only Accessible to Authorized Users.

2.2.5. Economic Data

Figure 10 summarizes the budget analysis for the Kahua Ranch Hydrogen Storage System including the interface and the HSS components. It only takes into account the material cost. The overall cost was $80k with 60% allocated to the electrochemical components. The next two important costs were the gas connection materials and DACS. Other expenses included the shipping cost ($1.2k for inter-island freight) and the cost for the initial system modification ($20k).

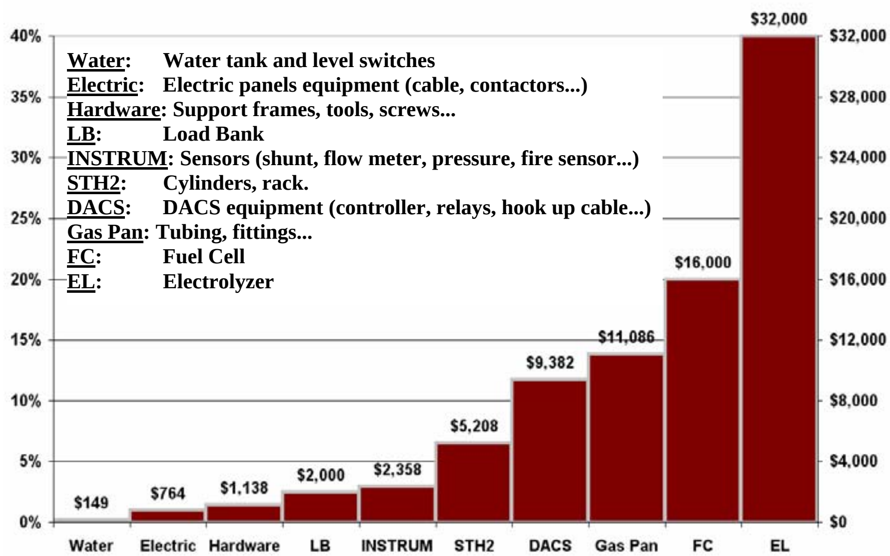


Figure 10. Budget Analysis for the Kahua Ranch Installation

2.3. Experimental Results

After installing the hardware, each component was connected individually. During the first operating phase, the scaling of all analog electrical data was checked using a digital multimeter and a current clamp-on meter. Then, the emergency procedures were verified. When the electrolyzer was connected, the oxygen sensor showed that the product hydrogen did not contain oxygen. However, a peak level of oxygen was observed after a long stand-by period of the electrolyzer. This issue was resolved by replacing the PFA (Perfluoroalkoxy) tubing by stainless steel tubing. A special procedure might be necessary in order to regularly test the hydrogen purity particularly after a long standby period of the electrolyzer. Finally, the general control of the installation was improved and the control parameters were tuned in order to reach a reliable, safe and stand-alone operation of the overall installation.

The initial experiments were conducted with the PV as the only renewable generator. The wind turbine was connected on November 9th 2007. Figure 11 and Figure 12 show the system performance recorded on October 5th, 2007. In Figure 11, the sun started rising at 7 am and reached a peak power output of 1,200 W/m^2. The solar radiation reached zero at 6 pm. After sunrise, the PV array supplied current to charge the batteries whose voltage (Figure 12) reached 54 V just after 8:30 am. This signaled the electrolyzer to start. The current of the electrolyzer unit (prototype # 1) reached an average current of 7.2 A in 5 minutes (min) and the hydrogen production started 3 min later. The current increased to 10 A after 2.5 hours of operation. Similarly, as shown in Figure 12, the hydrogen flow meter measures an average flow of 0.63 SLM and 0.97 SLM during these intervals. The EL efficiency is evaluated at 35% and 36% (HHV) for these two operating points. The hydrogen storage pressure increased continuously during the electrolyzer operation reaching 125 psi just after 2 pm, causing the electrolyzer to be disconnected by HNEI’s controller because it reached the maximum storage pressure set at 125 psi. The storage volume during this day was 130 Liters.

After 10 am, the PV/Battery also supplied power to the load bank. Although the load bank is priority, the electrolyzer was not shut down because the average battery current staid higher than -20 A (battery discharge of 20 A), one of the electrolyzer’s control parameters. This parameter was set at this low value to increase the use of the electrolyzer. It is now set at 0 A to avoid discharge of the batteries to produce hydrogen.

At time 2:15 pm, the required load bank current increased to 130 A inducing a drop of the bus voltage below 47 V. The FC system started up automatically to maintain the voltage between 47 V and 47.7 V. The FC current followed the large variation of the PV current. This variation was actually due to a conflict between the 2 MPPT operating in parallel. One of the MPPT was shut down at 2:35 pm removing the conflict as shown in the figures. The average efficiency of the FC unit during this operation is calculated at 34.3%. The maximum FC current demand was 43 A, 40% of its maximum power output. The FC unit might be oversized for the selected system configuration. Further experiments will be focused on this issue.

At time 3:30 pm, the load bank was shut down by the main controller because the hydrogen storage is considered empty (low pressure set point is 40 psi). It induced an automatic stop of the FC unit as the battery voltage increased without the load demand. Then the load bank demand was reduced to 0 A and the available excess energy allowed the electrolyzer to run again.

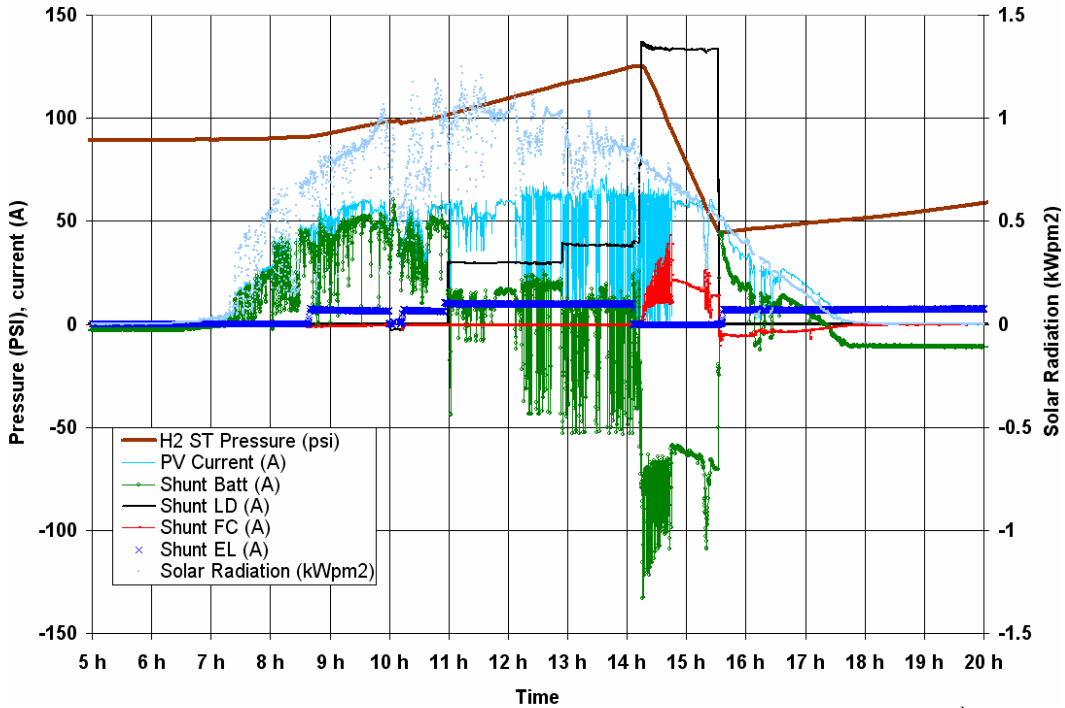


Figure 11. Evolution of Main Data during a Day of Operation – October 5th, 2007

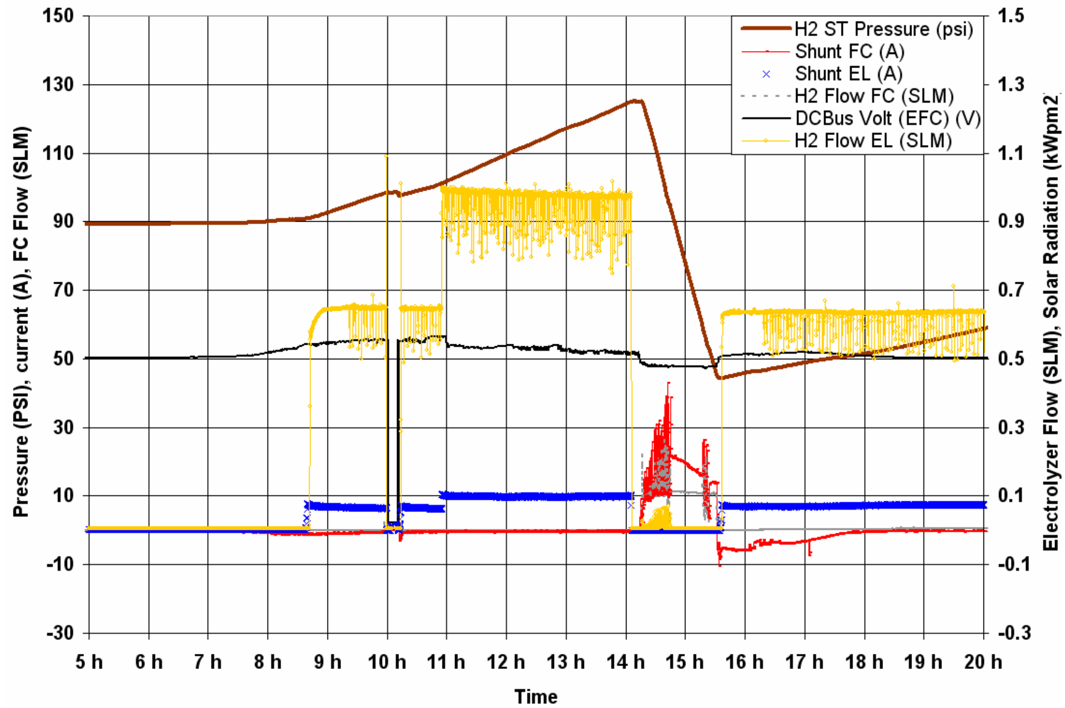


Figure 12. Evolution of the Hydrogen Storage System Data during a Day of Operation – October 5th, 2007

3. Conclusions

The renewable hydrogen stand-alone power system has been successfully designed, installed and tested at Kahua Ranch on the Big Island. It demonstrates the integration and operation of renewable energy and commercial hydrogen technologies.

The interface to control the overall system has been carefully designed to safely operate a stand-alone power system. Experiments show that the interface is reliable and easy to use, allows remote control and can be easily modified. This interface has been designed to be able to expand the size of the system components and accommodate higher current, higher pressure and/or higher flow rates.

The RE-H_2 power system offers opportunities for a wide range of experiments. It is equipped with different types of loads (DC, AC and grid-connected). The two storage units, the battery storage and HSS, can be reduced or expanded allowing experiments with different component size as well as testing other hydrogen technologies such as hydrogen compressors or internal combustion engine. Finally, the availability of the data on a web server will be useful for education purposes.

Experimental results presented in this paper illustrate the control of the complete installation in stand alone operation. The primary conclusions on the component operation are:

- ✓ The two MPPT planned for using the 4.9 kW connected PV modules show a parallel operation conflict introducing harshly variable PV power. Only one MPPT unit will be used while solving this issue.
- ✓ The electrolyzer shows an adapted design for its integration to the stand-alone power system. Indeed, it starts up as soon as connected to the 48 VDC bus, the warm up period is short (5 min) and the unit delivers hydrogen only 3 min after connection. The unit is presently 36% efficient but the next stack will increase the efficiency, the hydrogen production rate, and the delivery pressure.
- ✓ The FC unit low bus operation mode looks adequate for complete system integration avoiding over discharge of the battery storage. Nevertheless, the unit might be oversized compared to the available battery capacity. The efficiency during the described experiments is 34.3%.

The system has been tested in stand-alone operation for 2 months. The experimental results will be detailed in further publications showing the efficiency of each component and of the whole system.

New sets of experiments should lead to optimization of the control parameters as well as validating or improving the safety of the RE-H_2 power system. Other experiments should be realized by changing the size of the components especially by using only a quarter of the battery storage capacity. These results will help to understand the relationship between component size and system capacity. Collected data may be used to develop or validate simulation models of the components or of the complete installation. The availability of data every 250 ms can provide answers on transient behavior of the components and of the system. Faster measurement speed could be added to increase the precision.

4. Acknowledgements

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