Case Study: The Hawaii Hydrogen Power Park Demonstration at Kahua Ranch
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Introduction

The Hawaiian Islands import over 90% of their energy. 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 reduce dependence on imported fuels. Evolving towards a hydrogen economy is one of the potential paths to achieving that goal. Arguably, Hawaii has, of all the states in the US, the nearest-term potential to evolve towards a renewable hydrogen economy. The Hawaii Hydrogen Power Park (HPP) [1] program funded by the US Department of Energy (DOE) 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.

This case study resulted from a collaboration between Sandia National Laboratories and the Hawaii Natural Energy Institute (HNEI) over several years. Sandia staff performed analysis using models built under support from the DOE Hydrogen Program funding for Technology Validation. HNEI staff planned, developed, and operated the facility, and generously provided data and assistance in applying it for comparison to the model. Previous reports from the HNEI staff have the described the Kahua Ranch system and its development [2,3,4].

Project Scope

The Hawaii Hydrogen Power Park program was developed as a test bed for the integration and validation of hydrogen generation, storage, and use in a real world environment. In addition to technology validation, the project was developed to provide education and outreach opportunities to the inhabitants of Big Island, Hawaii. The project goals are defined as follows.

- Develop and operate a test bed to validate and characterize hydrogen technologies in a real world setting
- Integrate a renewable energy source with an electrolyzer, hydrogen storage and fuel cell
- Collect real-world cost and engineering data for the hydrogen infrastructure elements
- Conduct outreach to local authorities and the general public regarding hydrogen infrastructure
Background

The DOE vision for the transition to a hydrogen infrastructure begins with small-scale Distributed Generation (DG) systems fueled by hydrogen. In addition to providing stationary power, these systems may also have the capability of dispensing hydrogen for hydrogen-fueled vehicles. The DOE has named these hydrogen DG and transportation fueling systems "Hydrogen Power Parks". The hydrogen supply for hydrogen power parks can be produced by a variety of locally available energy sources including electrolyzers powered by electricity generated from renewable energy sources such as hydro, wind, geothermal, solar, biomass, or reformation of bio-fuels.

In October 2002, Hawaii's Department of Business, Economic Development & Tourism (DBEDT) was awarded a U.S. DOE contract to develop a hydrogen power park project in Hawaii. DBEDT in turn contracted the University of Hawaii's Hawaii Natural Energy Institute (HNEI) to implement the project. The Hawaii Power Park provides the opportunity of operating an integrated hydrogen energy system, measuring operational results, and evaluating technical and economic performances in a real-world environment. The results of these evaluations are being used to identify areas that require further research, development and validation. The Hawaii Power Park also increases public awareness of the potential of hydrogen for the generation of electricity and for transportation applications. Testing of various full scale and subscale components has been completed.

Project Description

Project dates and Duration

The project was designed and implemented in three phases,

Phase 1: Integrated electrolyzer-storage-fuel cell system operated at HFCTF (2002-2005)

The project proposed 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 system components including a 12 kg/day Stuart TTR225 electrolyzer, and a 5 kW GenCore Plug Power fuel cell power system [5] 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 [6]. This system, which uses a smaller electrolyzer from Electric Hydrogen (EH!) [7], is capable of remote operation with data acquisition and control over the internet.

Under Phase 3, which was scheduled to begin late in 2008, the DOE and the State of Hawaii have committed $2.4 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. The Hawaii Volcanoes National Park (HAVO) is acquiring from 2 to 5 fuel cell hybrid 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 work is not discussed further in this case study, but will be considered in future studies.

The map in Figure 1 shows the locations of the sites on the Big Island of Hawaii.

2. Hawaii Volcanoes National Park (HAVO)

Figure 1: Map of Hydrogen Demonstration Sites on the Big Island, HI
Participants & Partners

Participants and partners in this project are listed specific to the project phase.

Kahua Ranch (Phase 1 and 2)
- Partners include Kahua Ranch, PICHTR, Plug Power, and EH!
- One-to-one cost share by partners including DBEDT, PGV, Hydrogenics, HECO, HELCO, Gas Company

HAVO (Phase 3)
- HNEI has received recent funding of $1.2 million, from US DOE and $1.2 million from the State of Hawaii Hydrogen Investment Capital Special Fund, to build a hydrogen fueling station for HAVO.

Kahua Ranch Hydrogen Demonstration

Kahua Ranch has excellent wind and solar resources and is being used to test wind-to-hydrogen and solar-to-hydrogen generation systems. This site originally hosted a renewable energy power system that was installed by the Pacific International Center for High Technology Research (PICHTR). The objective of the PICHTR project was to demonstrate the use of wind and solar resources to power small villages as found in many parts of the Pacific. In the original configuration, the energy from wind turbines and photovoltaic arrays was stored in a large industrial battery. The battery then supplied AC power via a converter to power the ranch.

In the present Kahua Hydrogen demonstration, the electricity generated by the wind turbine and solar array is used to power an electrolyzer and make hydrogen. The hydrogen is stored without further compression at low pressure. When electricity is needed, the hydrogen is supplied to a fuel cell to produce electrical power.

All components are connected to a 48 V DC Bus Bar via DC/DC or AC/DC converters (Figure 2). The Bergey wind turbine, initially designed for 240 V DC supply, has been modified to produce 48 V DC. The hydrogen storage system uses an Electric Hydrogen (EH!) [7] electrolyzer (48 V DC unit producing 0.2 Nm3/h of hydrogen delivered at 12 Bar), a low pressure hydrogen storage tank, and a Plug Power Gencore 48 VDC Fuel Cell system [5]. Gas and electrical management panels were constructed. Sensors, contactors and valves are connected to a Data Acquisition and Control System (DACS), described later.
Figure 2 shows a schematic of the Kahua village power system. The Bergey wind turbine produces an unregulated AC electricity that is transmitted to the electrical room through a 500 m long buried power cable. A rectifier/controller provides DC current at the battery voltage. The PV array consists of 40 ASE Americas GP-8 modules rated at 245 W peak at standard conditions. The DC electricity from the PV is also transmitted via 60 m buried cable to the electrical room. The renewable generators (PV and wind) are connected to a 48 V DC flooded lead acid Trojan battery system with a storage capacity of 343kWh.

The hydrogen storage system (HSS) consists of an electrolyzer, hydrogen gas storage cylinders, and a fuel cell. Although less efficient than battery storage, the HSS has advantages for long term energy storage capacity. A 48 V DC configuration was selected because this voltage is widely used in renewable energy and hydrogen technologies. The decision was largely influenced by coupling to the 48 V DC fuel cell system, tested during phase 1 of the project.

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 48 V DC bus, the efficiency and the investment cost. The interface was designed to be expandable, easily movable and accessible/controllable via internet.

**Hydrogen Storage System (HSS)**

Figure 3 shows the hydrogen storage tanks and safety equipment placed outside in the gas storage area. The HSS includes an electrolyzer splitting deionized water into hydrogen and oxygen, a hydrogen tank, a fuel cell system, and a deionized water supply tank. The HSS was built and tested at the HFCTF in Honolulu, then shipped to the Big Island by barge.
The Proton Exchange Membrane (PEM) electrolyzer supplier is the Canadian company Electric Hydrogen, Eh! [7]. The small size of the unit is rare on the market and was available at a relatively low price. The specifications are a hydrogen production rate of 0.2 Nm3/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 to 58 V. The hydrogen generator consumes de-ionized water (ASTM Type I) supplied at a pressure between 3 and 20 psig. The maximum efficiency was specified to be 63% based on the lower heating value (LHV) of hydrogen.

The electrolyzer system includes 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 at 12 bar. 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 a 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. 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 Nm3/h at 8.6 bar consuming 20 A at 53.5 V, on the commissioning day. The 10-cell stack operated at 28 A at 33.1 V. The unit demonstrated an overall efficiency of 31% (LHV), 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 over time, 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 Nm3/h at 12 bars. The efficiency was evaluated at 42% (LHV).
Gas Storage

Several options were studied for the hydrogen gas storage during the design process. Compression was abandoned, as it is a big energy consumer and the ranch has adequate space for a large low pressure storage system. In the final design, the maximum storage pressure is the maximum pressure of the electrolyzer (12 bars). The hydrogen gas storage was intended to be a 7.6 m³ (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; it was decided to use 18 hydrogen cylinders of 50 liters each. The full storage is then equivalent to approximately 1 kg hydrogen (33 kWh, LHV). This storage capacity is too small for optimal operation, but it is easily expandable.

5 kW PEM Fuel Cell System

The Plug Power Gencore 5 kW fuel cell system [5] requires pure hydrogen (99.95%, dry) and access to ambient air (temperature between -40°C to 46°C and relative humidity between 0% to 95%). It produces regulated 48 VDC electrical power. The output flows are oxygen-depleted humidified air and liquid water. The system consists of a stack of cells connected in series, air and hydrogen supply units, a cooling unit, a power converter, a battery pack wired in parallel with the fuel cell 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, an air blower with speed mapped to fuel cell 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 fuel cell power demand. The batteries are used at start-up to supply auxiliary power; however, as soon as the fuel cell is connected to the DC bus, the stack supplies power to the parasitic loads. The power converters use either the stack power or the battery power to support the load with regulated voltage adjustable between 46 V and 56 V.

System Integration and Control

The multiple-site design includes a data acquisition and control system (DACS). The function of the DACS is to ensure that all components are connected electrically and mechanically. This also controls the overall system operation and shut-down procedures in case of emergency. The energy management is optimized and the system is accessible over internet.

The control system design includes sensors, valves and relays connected to the DACS for system control and data recording. A safety analysis was conducted and found this to be a “fail-safe” system. Data visualization and remote control uses the Labview interface (Figure 5).

The control of the overall installation is implemented into the DACS controller using Labview software program. Different operational modes have been programmed. The system can operate
in “Manual Mode”, where each component can be controlled individually, and “Automatic Mode”, where the power system runs stand-alone. 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.

Analysis

Modeling and simulation of the Kahua Ranch facility began before the facility was constructed, as part of the collaboration between Sandia and HNEI. Interim analysis of possible designs was presented to the DOE Hydrogen Program Annual Merit Review [8]. Analysis of the facility as now operating is presented in this section, with a combination of data analysis and comparison to the simulations.

Wind Turbine

The wind turbine model uses correlations for the turbine power output versus the wind speed, the so-called power map. The power map uses as input the wind speed, typically averaged over some timescale for which data is available. The wind speed at Kahua Ranch provided by HNEI [9] is shown in Figure 5 for a December day. The average speed is typically higher in December (22 mph) than in summer months (~15 mph in July). The comparison of the potential wind power to the actual turbine power output is shown in Figure 6. The potential power is computed from the kinetic energy of the wind passing through the area swept by the blades.

\[ \dot{W}_P = \frac{1}{2} \rho A V^3 \]

The efficiency of the turbine is defined by the ratio of the actual power to the potential.
\[ \eta = \frac{\dot{W}_A}{\dot{W}_p} \]

The wind potential in Figure 6 shows large variations about the average. The actual turbine power does not vary nearly as much, suggesting that the turbine inertia moderates the wind variations. Consequently, the temporal view of turbine efficiency should consider the wind potential averaged over some period (as a rolling average). Computing the efficiency using the averages over the day for the power and wind potential gives an average turbine efficiency of 23%. The average turbine power for the day was 4.9 kW, with a total power output for the day of 117 kWh.

Figure 7 compares the wind turbine data to the manufacturer’s turbine map: power versus wind speed. In this plot, the disparity between the relatively moderate changes in turbine power and the much wider variation in the wind speeds noted above for Figure 6 appears to make the data not fit the turbine map. The average wind speed and power are shown by the larger blue circles, in bins of width 2 m/s in velocity. The error bars show one standard deviation above and below the average turbine power. The black curve shows the power map provided by Bergey [10] for the 7.5 kW turbine. Despite the variation in the data, the average power points do seem to approximate the expected performance, with the exception of the data at the highest wind speeds, where the power appears to be dropping at a lower wind speed than expected.

The Simulink model captures the wind turbine output, as shown in Figure 8, using the power-speed map and the wind data from Kahua Ranch. In the simulation, the average turbine power is 5.3 kW and the total electricity produced for the day is 126 kWh; these model values are some 8% higher than the observed averages, due to the approximation of the power map to the data in Figure 7. Nevertheless, the simulation can reflect the performance of the wind turbine to sufficient accuracy for estimating the potential hydrogen production.
Figure 5. Wind speed measured on 2-minute intervals at Kahua Ranch for a December day.

Figure 6. Potential wind power at Kahua Ranch compared to the actual turbine power.
Figure 7. Wind turbine power versus wind speed. Red dots are data from Kahua Ranch for the December day of Figures 5 and 6; blue circles are binned averages of the data with error bars showing one standard deviation from the average; black curve is the power map provided by Bergey for the 7.5 kW turbine.

Figure 8. Wind turbine power simulation using the wind input for the December Kahua Ranch wind data. The axes on this Simulink window display power in Watts and time in seconds.
**Photovoltaic Panels**

Data from the Kahua Ranch photovoltaic (PV) panels are shown in Figures 9 through 11. The orange symbols in Figures 9 and 10 show the incident radiation as measured by a radiometer at the site for the equivalent area of the panels. The black symbols in Figures 9 and 10 show the power produced by the panels over the same day in December as Figures 5 through 7.

Defining the efficiency of the solar panels as the power output divided by the incident radiation, the daily variation in efficiency is shown in Figure 11. The average efficiency for the day was 9.6%. The efficiency is slightly lower at mid-day, most likely due to the panels heating up, which causes lower power output as more energy is dissipated to the surroundings. The higher efficiencies at low radiation levels early and late in the day are consistent with the temperature effect.

Figure 10 shows the model approximation applied to photovoltaic panels. Rather than use radiation data, which are often not available for a given site, the existing model uses an algebraic formulation to approximate the incident radiation based on the longitude, latitude, altitude, and angle of elevation for the panels [11]. The comparison of the radiation data (orange symbols) to the dashed curve in Figure 10 shows that the prediction of the incident radiation is about 25% low. In addition, the shape of the radiation profile during the day is shifted slightly towards the morning. This is evident in the comparison of the simulated solar power (solid curve), where the model underestimates the power in the late afternoon. Consequently, setting the photo-electric efficiency in the model to 10%—based on the data—gives approximate collection for the day that is about 25% low at the peak: 2.6 kW in the simulation versus the peak of 3.4 kW observed. Integrated over the day, the total power observed was 0.91 kW.

The mechanism of using the model is shown in Figure 11, which contains a screen-shot of the Simulink blocks and a "scope", which is the interactive graphic provided by the software. The blocks are assembled as a diagram from a palette of tools in the H2Lib developed by Sandia. The clock icon and the constant block that initiates the day-of-year for this simulation are shown; the yellow radiation model block points to a function that computes the incident radiation, while the gray PV block applies a specified efficiency.
Figure 9. Solar photovoltaic power (black symbols) during the December day at Kahua Ranch. Orange symbols are incident radiation measured at the site.

Figure 10. Model approximation of photovoltaic power during the December day at Kahua Ranch. Symbols are same as Figure 9; green dashed curve is model radiation, red curve is simulated solar power.
Figure 11. Computed efficiency of photovoltaic panels during the December day at Kahua Ranch.

Figure 12. Simulink screen-shot of the block diagram for the solar model and sample PV power output “scope” over a day.
**Electrolyzer Operation**

Sample operation data for the electrolyzer at Kahua Ranch are shown in Figure 13(a) for a period of the December day considered for the turbine and PV data above. The electrolyzer ran at a nearly steady state for approximately 8 hours, with an efficiency of 41 to 45% (based on lower heating value of the hydrogen produced). Note that the seemingly spurious efficiency values after the 18-th hour are not realistic, as the system has been shut down.

The production of hydrogen from the electrolyzer is shown in Figure 13(c) as the green dashed line. On this day of testing, the wind power was relatively strong, so it provided more than enough power to the bus bar to enable the electrolyzer to be producing renewable hydrogen.

**Fuel Cell Operation**

Sample operation data for the fuel cell stack is shown in Figure 13(b). The fuel cell ran for a couple hours of the evening to provide power to the office building. The efficiency appears quite high upon start-up of the stack, then levels out at about 50% in steady operation. The abnormally high efficiency (~70%) computed for the warm-up period is artificial, because the battery is providing part of the power from the system until the stack is sufficiently warm and operating in a steady mode. Note that the hydrogen flow to the fuel cell, shown as the solid curve in Figure 13(c), is lower during the start-up period than it is later on in steady operation.

An example of nearly steady-state operation of the fuel cell system at Kahua Ranch is shown in Figure 14. The fuel cell runs at two different load points before and after time 4.5 hours. At about 15% of maximum load (~0.75 kW), the efficiency hovers about 25%, while at nearly 20% of load (~1 kW) the efficiency is just below 40%. The change in efficiency with load occurs because the stack is operating at low-load, where activization losses are significant; these losses decrease relative to the power output as the load increases.

These two load conditions, along with others gathered from sample data at Kahua Ranch are shown in Figure 15 along with testing of this Plug Power stack performed at the HNEI Fuel Cell Test Facility at the University of Hawaii. In addition, Figure 15 includes other data collected by DOE demonstration systems on similar Plug Power units operated by two utilities: DTE Energy in Michigan and Arizona Public Service. The Kahua Ranch data in red are shown with error bars to indicate some variation in real world operation. There is remarkable consistency between the data from the four different sources.

A curve fit to this collection of data provides a “power map” for the fuel cell system that can be used directly in simple fuel cell models. The map can also be useful for validating more detailed models of the fuel cell that start from a voltage-current relationship and predict the power output for specified hydrogen inflow.
Figure 13. Sample data for a day of electrolyzer and fuel cell operation at Kahua Ranch.
Figure 14. Fuel cell efficiency for steady-state operation at Kahua Ranch.

Figure 15. Fuel cell efficiency for Plug-Power 5 kW units versus normalized load. Red circles are data collected at Kahua Ranch. Green squares are data collected at HNEI’s Fuel Cell Test Facility. Other (gray) symbols are data from similar units at other DOE demonstration facilities.
The map collected here shows that the electrical efficiency is a maximum of 50%, beginning at about 1/4 load. The efficiency remains near the maximum as load increases, only decaying slightly at full load. As expected, the efficiency is low at low load. Rather than operate at less than 1/4 power, in systems like Kahua Ranch that provide battery storage, it is better to operate the system at higher load and store electricity in the battery.

**Operation of the complete system**

Sample power flow of the electrochemical components in operation in the complete installation are presented in Figure 16 for the December day used as a sample in Figures 5 though 13. The load is constant during the early morning hours. Initially, the battery provides most of the load, until the wind turbine starts proving roughly 7 kW. During daylight hours, the renewable components (turbine and PV) provide power for the electrolyzer and recharging the batteries. During a couple evening hours, the fuel cell system follows the load. The wind turbine continues to provide power for the electrolyzer and batteries to midnight.

![Figure 16. Power flow for operation of the Kahua Ranch facility. Positive values represent power to the bus bar; negative values represent power drawn from it.](image)

A simulation of the net system power using the Simulink model assembled for the Kahua Ranch of the system is shown in Figure 17 for the data in Figure 15. The wind data and approximate hours of operation of the electrolyzer and fuel cell provide input to the model. In addition, the efficiencies of the wind turbine, PV array, electrolyzer, and fuel cell are validated by the operational data. However, the logic of the power flow between the bus bar, load, and battery is
not replicated in the model. Instead, Figure 17 shows a model scope of the net power available from the components in the model.

The fluctuating power from the wind turbine overlays the contributions of the components throughout the day. During morning hours, the wind turbine alone provides power. The PV array adds power during the day, as depicted by the parabolic rise in power. The electrolyzer draws power from the system during the next period. Power is returned by the fuel cell stack later in the day.

![Figure 17. Power (in Watts) to the bus bar in the simulation of the Kahua Ranch system for the sample December day examined in Figure 16.](image)

**Kahua Ranch observations:**

The operational data for the system and individual components are useful for analysis and validation of models. The PEM electrolyzer has efficiency limited to 40 to 45% (LHV) in steady operation. The fuel cell system operation in the field is consistent with laboratory tests at various loads; the electrical efficiency is 50% (LHV) over a range from 1/4 to nearly full load.

The renewable components of the system operated as expected. The wind turbine efficiency range varies from 10 to 35%; the data varies about the manufacturer’s turbine map, but the map provides a good representation of the average performance. The average efficiency of the PV arrays was 10%, with slightly higher efficiency early and late in the day when the incident radiation is lower, presumably because the panels are cooler then.
Environmental Aspects and Safety Issues

Permitting and Safety

Figure 18 depicts the layout of the Kahua Ranch facility installation. Concrete pads were poured in the hydrogen room and the gas tank location, and a fire wall surrounds the hydrogen storage tank which acts as a heat shield between the hydrogen storage tank and the facility. Fences also protect the area to keep out ranch livestock.

Figure 18: Kahua Ranch Layout

Licenses and Regulations

HNEI states that guaranteeing safety in a demonstration hydrogen project is essential for their sustainability and public acceptance. 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.

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.

**Economic considerations**

Figure 19, taken from reference [2], summarizes the analysis for the Kahua Ranch Hydrogen Storage System including the interface and the HSS components. It takes into account the material cost only. The overall cost was $80K with 60% allocated to the electrochemical components (electrolyzer and fuel cell). The next two significant 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).

Due to the small size of the electrolyzer at the facility, analysis of the levelized cost of hydrogen produced does not provide meaningful representation of any real cost of renewable hydrogen.
Conclusions and Recommendations Including Lessons Learned

The analysis of this site showed that it is difficult to justify economically and technically the use of hydrogen from water electrolysis to store electricity. Important improvements are necessary to reach better efficiency and relatively low cost. The advantages of the hydrogen storage system are important and unique, as follows.

Environmentally friendly energy carrier

When using hydrogen produced by an electrolyzer the only by-product of a fuel is water that returns to nature’s cycle and can be split again into hydrogen. Using electrochemical components also decreases noise.

High range of operation

Long term storage: storing hydrogen gas allows long term storage with almost no loss over time. The first experiments on renewable hydrogen systems in the 1990’s proved the possibility of using hydrogen to store energy from summer to winter.

Storage of a transportable fuel: Stored hydrogen can be used to supply transportation applications.

Production of heat and electricity: As identified by the experimental result analysis, electrolyzers and fuel cells should have a design allowing use of waste heat. In addition to much higher system efficiency, heat is an important by-product in some market niches especially when supplying homes in remote areas.

Highly adaptable storage

Hydrogen storage allows perfect sizing as energy and power are completely independent contrary to the batteries other than the flow batteries. Each part of the HSS is independent of the others. Therefore, the electrolyzer is sized to match the available excess of energy or with the required flow. The FC power is selected to match the load or the maximum required power demand. In addition, electrolyzers and fuel cells have a very wide range of power. Finally, the gas volume depends on the needs of the stored energy and on the efficiency of the FC unit, the ICE or any other components converting hydrogen to the end-users.

High potential storage

In addition to these advantages, the HSS has potentially other essential characteristics such as long life time (already proven for alkaline technologies), low maintenance requirement, low disposal and recycling concerns. Contrary to the old and mature storage technologies, the HSS has a high potential for improvements in these fields.
Future Plans for the Project

Kahua Ranch Future Uses

The Kahua Ranch facility remains operational, with electricity from the wind turbine and PV array continuing to power the small office building. The hydrogen storage system (electrolyzer and fuel cell) are not in continuous operation, due to lack of funding and the requirement of routine maintenance to oversee operation. However, the hydrogen system is operated periodically for maintenance, tours and special events. The limited data from the limited operation may prove useful for evaluating the reliability and durability of the equipment. The facility remains a focal point for renewable energy outreach and education at HNEI and on the Big Island.

Hawaii Volcanoes National Park Hydrogen Fueling Station

The next phase of the effort to establish hydrogen applications on the Big Island is the refueling station that will be constructed at the Hawaii Volcanoes National Park. This facility will be considered for evaluation in future studies.

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References