COMPARATIVE PERFORMANCE OF ELECTROLYSIS CELL STACKS AT THE HUMBOLDT STATE UNIVERSITY HYDROGEN FUELING STATION

M. Harper[a], P. Lehman[a], G. Chapman[a], C. Capuano[b]

1. Introduction

At the 2009 National Hydrogen Association (NHA) annual conference, the Schatz Energy Research Center (SERC) reported on the initial performance of the newly installed hydrogen fueling station at Humboldt State University.[1] Afterwards, Proton Energy Systems approached SERC and suggested that we install and test one of their new Next Generation cell stacks that they are currently prototyping. The following describes the results from our comparative tests of the new cell stack's performance at the HSU Hydrogen Fueling Station.

Proton Energy System's Next Generation Cell Stack shows substantial potential for improvement upon their original line of commercial S40 cell stacks. In this study, we compared the performance of the original Proton HOGEN® S40 cell stack installed in our hydrogen station and a new Next Generation cell stack which Proton provided (Figure 1). Additionally, we measured the energy consumption of the two different cell stacks at two different temperatures. Efficiencies are reported for both the cell stack and entire electrolyzer system.

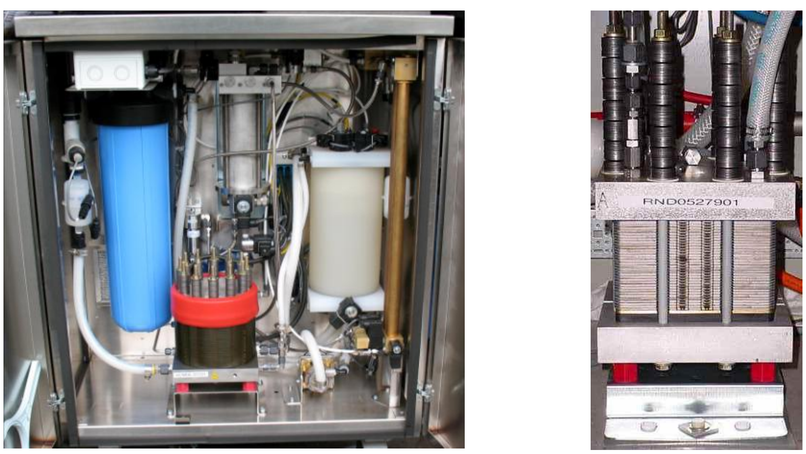

Figure 1. To the left is Proton's original S40 cell stack installed in the HOGEN® electrolyzer at the HSU station and to the right is Proton's Next Generation Cell Stack.

2. Station Overview

The HSU Hydrogen Fueling Station was originally inspired by a student entry in the NHA International Hydrogen Design Competition. Engineers from the Schatz Energy Research Center, in collaboration with HSU plant operations and additional project sponsors made this winning design a reality, officially opening the station in the fall of 2008. The station is the northernmost and only rural station on California's Hydrogen Highway. The station is located in the center of the HSU campus (Figure 2).

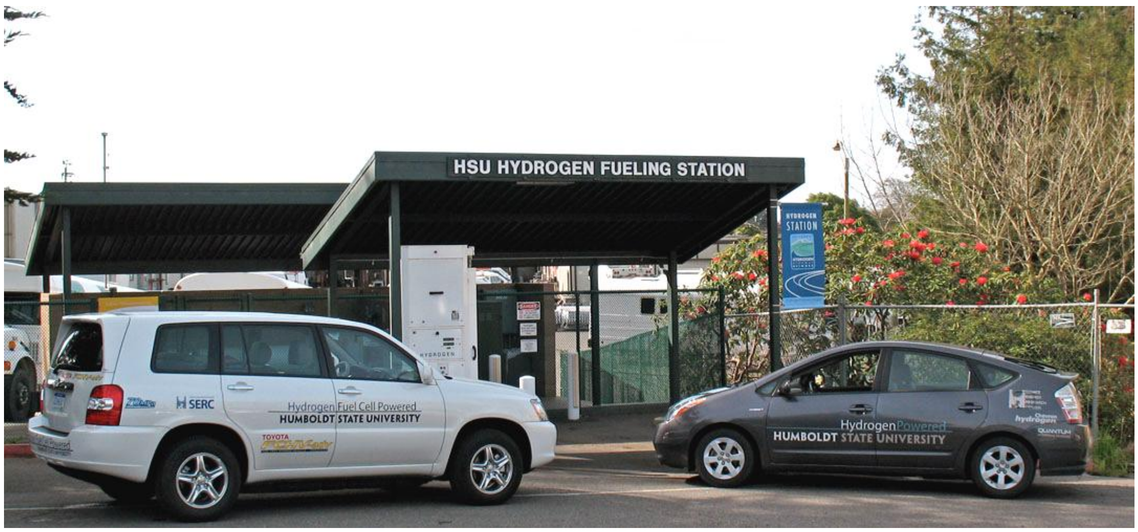

Figure 2. The Toyota FCHV-adv and hydrogen-fueled Toyota Prius parked in front of the HSU hydrogen fueling station.

The station currently serves a fleet of two vehicles; a Toyota Prius converted to run on Hydrogen by Quantum Technologies and a Fuel Cell Hybrid-Advanced vehicle (FCHV-adv), based on the chassis of the Toyota Highlander. Both vehicles are treated as experimental vehicles and driven regularly to test both the vehicles and the operation of the fueling station.

The station generates hydrogen with a Proton HOGEN® S40 electrolyzer, compresses it to 420 bar storage with a PDC compressor, and dispenses it to vehicles at 350 bar with an FTI dispenser. The station can produce approximately 2.3 kg of hydrogen a day, which has been tested to be extremely pure and suitable for use in fuel cell vehicles.[1] To fulfill the education and outreach mission of the station, interpretive signage, brochures and tours are offered at the station to describe the hydrogen generation process to visitors (Figure 3).

[1] Testing performed in 2009 by Atlantic Analytical Lab; the hydrogen was found to be 99.9995% pure with no detectible impurities.

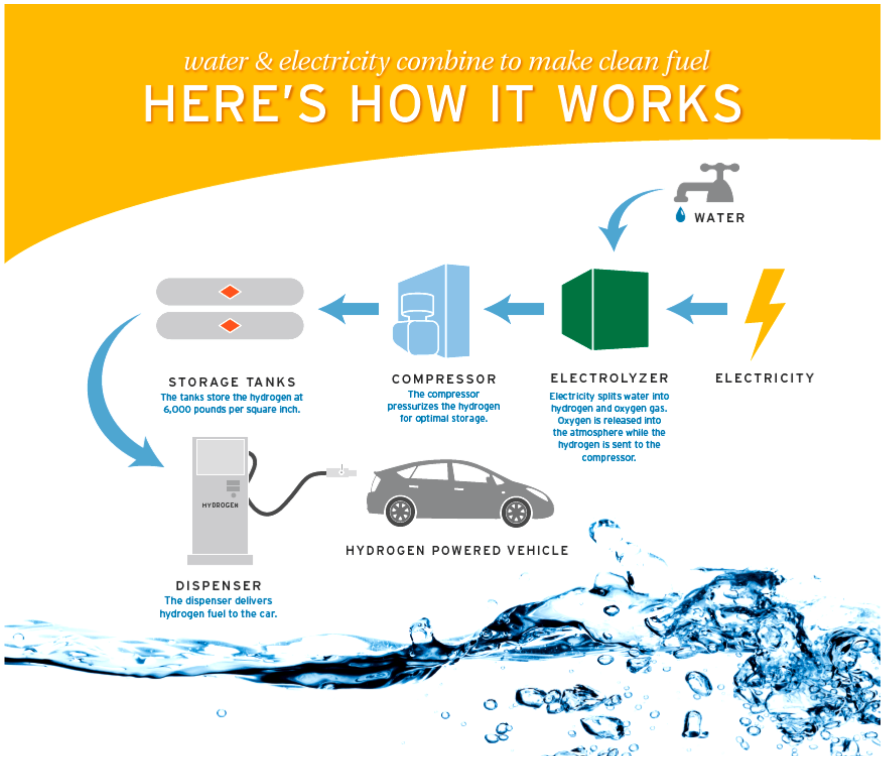

Figure 3. An interpretive sign at the HSU Hydrogen Fueling Station that describes the hydrogen generation process to visitors.

3. Testing Design and Methods

After first collecting data on the original S40 cell stack, we installed the new Next Generation cell stack at the station (Figure 4). The new stack is a developmental model with a bipolar plate design, which integrates the frame, flow-field and separator plate into a single embodiment. This design reduces both the number of parts by 70% and the interfacial contact resistances within the stack.

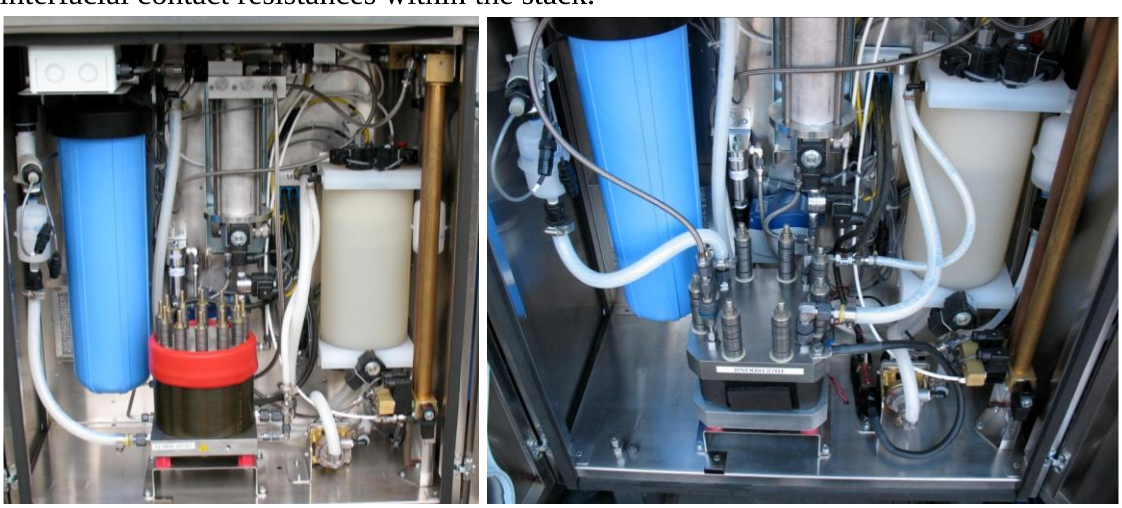

Figure 4. The HOGEN® electrolyzer with the original cell stack (L) and the Next Generation cell stack (R) installed

To determine the efficiency of each cell stack, as well as the efficiency of the overall electrolyzer system with each cell stack installed, measurements of the current and voltage across each cell stack were collected during approximately hour-long test periods. Additionally, during the test periods, the power consumption and hydrogen production of the electrolyzer system were recorded. Each cell stack was tested at two different operating temperatures to assess the performance of the cell stacks at elevated operating temperatures.

The station is equipped with a computerized data acquisition system that, among other parameters, records the power consumed by the electrolyzer and the mass flow of hydrogen. Additionally, for the cell stack testing, we installed a current shunt and manually monitored the current and voltage across the fuel cell stack during the test periods. Temperature readings from the unit's thermistor were used to determine the cell stack temperature. Specification and tolerances of the measurement equipment are listed in Table 1.

Table 1. Equipment specifications

Measurement	**Equipment Make and Model**	**Specifications**
Shunt voltage (current shunt calibration is 6A = 1 mV)	Fluke 73 III multimeter	Range: ±600 V Accuracy: 0.3% Resolution: 0.1 mV
Stack voltage	Fluke 45 Dual Display multimeter	Range: ±1000V Accuracy: 0.025% Resolution: 1 μV
Stack temperature	Thermistor internal to HOGEN® electrolyzer water system	Max temp: 60˚C Resolution: ± 1˚C
Electrolyzer Power	Flex Core current transformer Model 189-050	Current Ratio: 50A-5A ANSI Accuracy: 0.6
	Flex Core single phase power transducer Model AGW-002B	0 – 1000 W = 0 - 1 mA Accuracy: 0.2%
Electrolyzer Hydrogen Flow	Hastings Mass Flow Meter Model 201	Range: 0 - 100.0 slm

In order to test the cell stacks at both ambient and elevated operating temperatures, we installed a heat exchanger bypass unit at the back of the electrolyzer (Figure 5). The two adjustable valves allow water to partially bypass the heat exchanger, making it possible to control the operating temperature of the cell stack. Due to limitations of other components within the electrolyzer, the system can only run at temperatures up to 60˚C. We took measurements at 34˚C, a normal operating temperature with the heat exchanger bypass valve closed, and 56˚C, an elevated operating temperature.

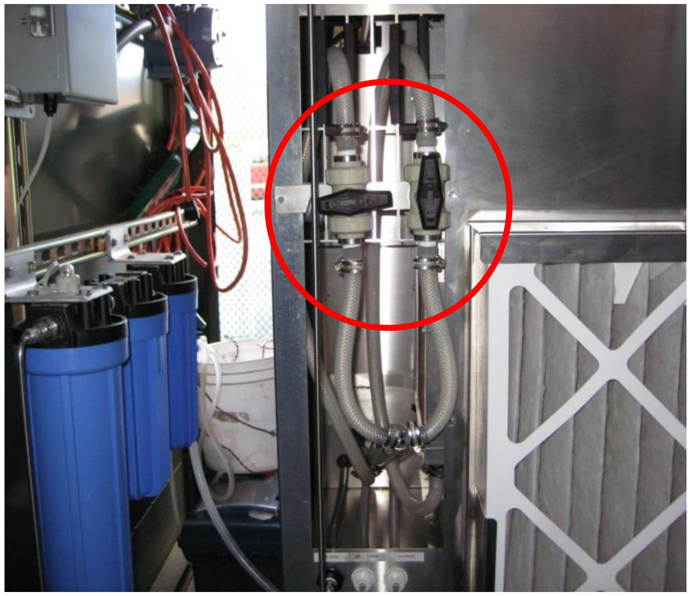

Figure 5. Heat exchanger outlet and bypass valves installed at back of electrolyzer unit

4. Performance Metrics

For each cell stack, the voltage efficiency, specific energy consumption and the hydrogen conversion efficiency were calculated. Additionally, we report the specific energy consumption and hydrogen conversion efficiency of the entire electrolyzer system with each cell stack installed.[2]

The voltage efficiency of the cell stack is defined as the ratio of the measured electrolyzer cell voltage and the ideal, or thermoneutral, electrolyzer cell voltage, as shown in Equation 1. [2] The thermoneutral voltage of a hydrogen electrolyzer cell is 1.482 V.

$$\eta_{voltage} = \frac{V_{TN}}{V_{cell\ stack}} \qquad \textbf{(1)}$$

where:

$\eta_{voltage}$ = voltage efficiency of the cell stack
V_{TN} = thermoneutral voltage (for 20 cells = 29.64 V)
$V_{cell\ stack}$ = measured cell stack voltage (V)

The specific energy consumption of the cell stack is defined as the ratio between the energy consumed by the cell stack and the mass of hydrogen produced. The hydrogen output of the cell stack cannot be measured directly as the gas must be dried and pass through the rest of the electrolyzer system before reaching the mass flow meter. The mass of hydrogen produced during the test periods was determined using the

[2] The electrolyzer system refers to the HOGEN® S40 unit. Calculations do not consider energy input or hydrogen losses during compression, storage or dispensing. Data from the first year of operation showed the specific energy consumption of the station's compressor to be approximately 12 kWh/kg H_2. [2]

stoichiometric relationship between the measured current and hydrogen flow. At STP, each Ampere of current will produce 0.00696 slm of hydrogen per cell.

The hydrogen conversion efficiency of the cell stack is defined as the ratio between the energy in the hydrogen produced and the energy consumed by the cell stack, as shown in Equation 2. The hydrogen conversion efficiency was calculated using the lower heating value (LHV) of hydrogen. [3]

$$\eta_{cell\ stack} = \frac{E_{hydrogen}}{E_{cell\ stack}} \qquad (2)$$

where:

$\eta_{cell\ stack}$ = hydrogen conversion efficiency
$E_{hydrogen}$ = energy contained in the hydrogen produced (kWh)
$E_{cell\ stack}$ = energy used by cell stack (kWh)

Similarly, the specific energy consumption of the electrolyzer system is defined as the ratio between the energy consumed by the electrolyzer and the mass of hydrogen produced, and the hydrogen conversion efficiency of the electrolyzer is defined as the ratio between the energy in the hydrogen produced and the energy consumed by the electrolyzer, as shown in Equation 3. Both metrics use the average value of hydrogen production measured to be 18.0 slm during the four test periods.[4] Again, the LHV of hydrogen is used to calculate hydrogen conversion efficiency of the system.

$$\eta_{electrolyzer} = \frac{E_{hydrogen}}{E_{electrolyzer}} \qquad (3)$$

where:

$\eta_{electrolyzer}$ = hydrogen conversion efficiency
$E_{hydrogen}$ = energy contained in the hydrogen produced (kWh)
$E_{electrolyzer}$ = energy used by electrolyzer (kWh)

5. Results of Performance Testing

The current and voltage measurements across each cell stack allowed us to calculate the power consumption of the cell stacks. By plotting the cell stack power versus temperature, the inverse dependence on temperature is displayed (Figure 6). As

[3] The LHV for hydrogen is 33.39 kWh/kg.

[4] During each test, we measured the hydrogen output of the electrolyzer system and found that at constant power, the hydrogen flow cycles between approximately 15 slm and 20 slm. These fluctuations are due to two processes within the electrolyzer system: the filling and emptying of the hydrogen water separator tank, and the use of product gas to regenerate the desiccant columns in the hydrogen gas dryer. Assuming that the hydrogen output of the cell stack was nearly constant between runs, to compensate for the fluctuations in hydrogen flow, the average value of all the test periods (18.0 slm) was used in the calculations of specific energy consumption and hydrogen conversion efficiency for the entire electrolyzer system.

operating temperature increases, the cell stack's power consumption decreases. Note neither the power nor the temperature axis starts at zero.

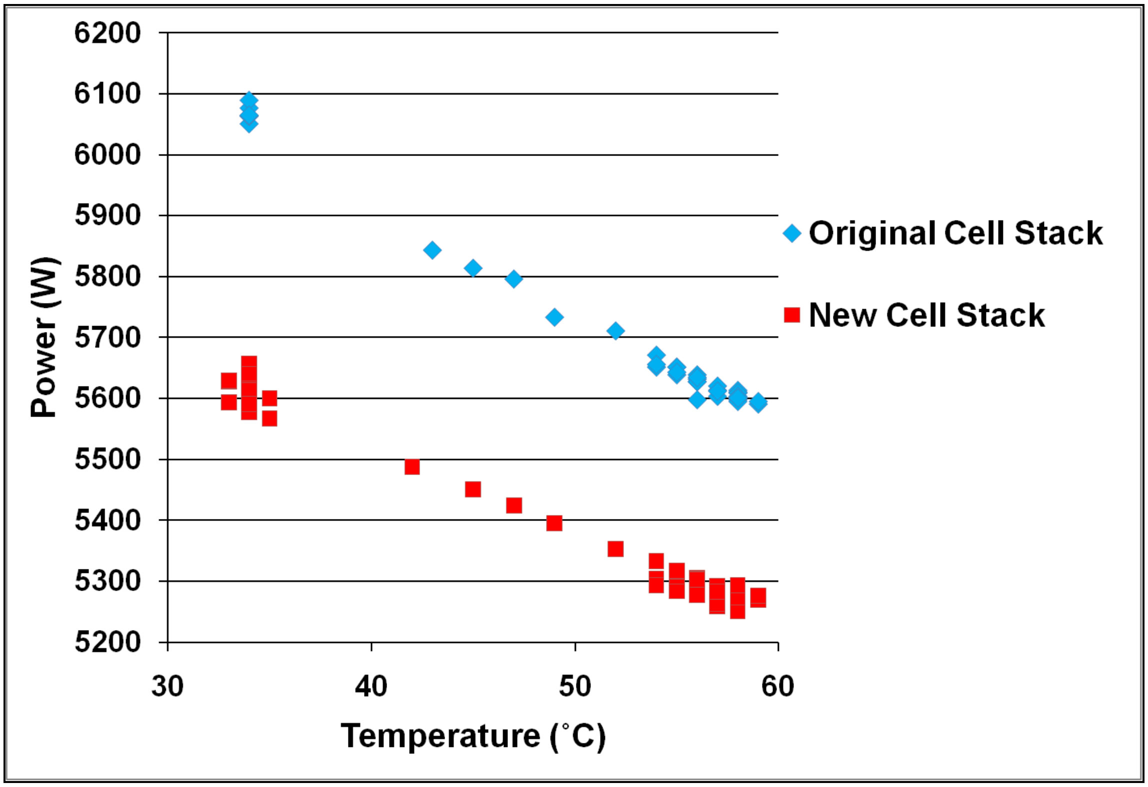

Figure 6. Relationship between cell stack power and temperature

The performance metrics of the cell stacks (Table 2 and Figure 7) show that the new cell stack is more efficient than the old cell stack at both ambient and elevated operating temperatures. At approximately 34˚C, the new cell stack's efficiency is 63.0%, which represents an 8.0% increase in efficiency. At elevated temperatures, this efficiency improves from 62.9% to approximately 66.9%, a 6.4% increase in efficiency. The narrow error bars in Figure 7 represent two standard deviations of the mean and imply that the observed improvements are significant. The current supplied to the cell stacks and the corresponding rate of hydrogen production remained nearly constant throughout the tests, suggesting that these efficiency gains are due to the lowered resistance of the Next Generation cell stack, which enabled it to operate at a lower voltage, require less power and therefore consume less energy to produce the same amount of hydrogen.

Table 2. Results of Cell Stack Performance Tests

Cell Stack	Temp. (˚C)	Stack Current (A)	Stack Voltage (V)	Voltage Efficiency	Power (W)	Theoretical Hydrogen Production (slm)	Specific Energy Consumption (kWh/kg H_2)	Cell Stack Hydrogen Conversion Efficiency (LHV)
Original	**34.0**	**141.2**	**42.98**	**68.9%**	**6067**	**19.7**	**57.2**	**58.3%**
New	**33.9**	**141.2**	**39.75**	**74.5%**	**5614**	**19.7**	**53.0**	**63.0%**
Original	**56.8**	**141.0**	**39.86**	**74.3%**	**5620**	**19.6**	**53.1**	**62.9%**
New	**56.6**	**141.2**	**37.46**	**79.0%**	**5288**	**19.7**	**49.9**	**66.9%**

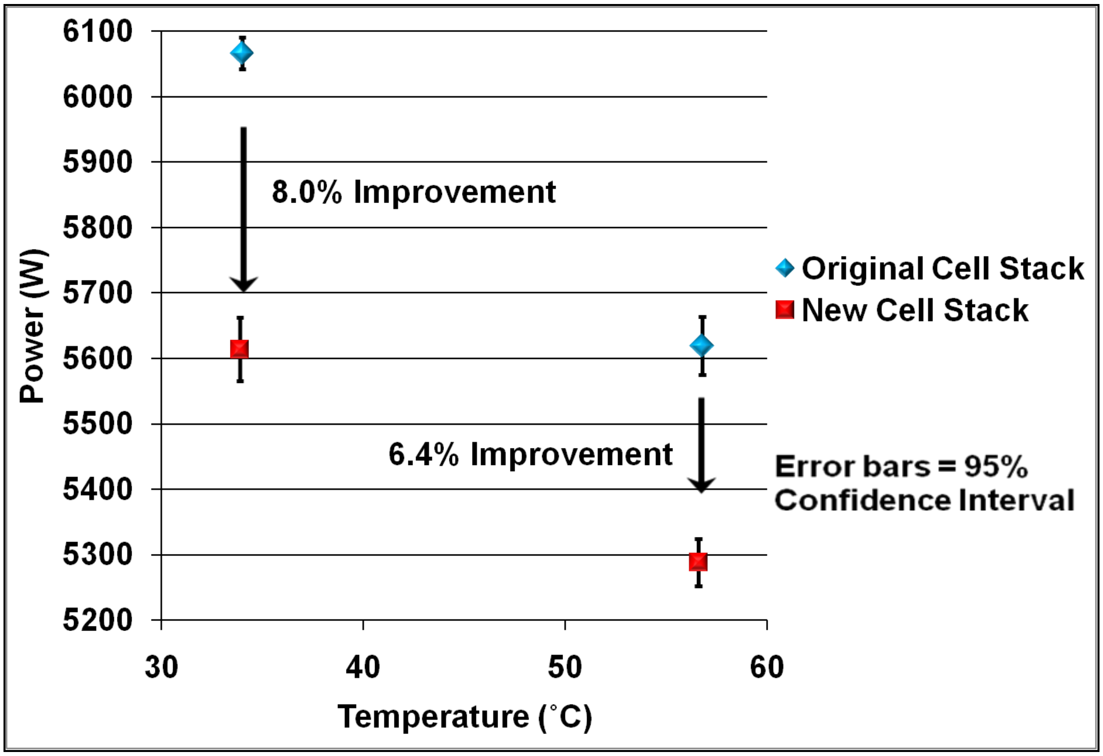

Figure 7. Power consumption of cell stacks at 34˚C and 56˚C

Using the measurements of power consumption and hydrogen flow from our data acquisition system, we calculated the total energy consumption of the entire electrolyzer system, including the power supplies and auxiliary loads, at normal and elevated temperatures for each cell stack (Table 3). At low temperatures, the electrolyzer with the original cell stack required 78 kWh/kg hydrogen, which is the same average energy consumption recorded at the station during its first year of operation. [1]

The energy consumption of the electrolyzer using the new cell stack at elevated temperatures is significantly reduced to 70 kWh/kg. This improved value is less than the average electrolyzer energy consumption of 73 kWh/kg as reported by NREL for the DOE Technology Validation Project [3]; and also lower than the value reported on specification sheets from Proton Energy Systems, which indicate that the HOGEN® S40 electrolyzer requires 74.5 kWh/kgH_2.[5] [4]

Table 3. Overall Electrolyzer Performance Results

Cell Stack	Temp. (˚C)	Electrolyzer Power (W)	Electrolyzer Specific Energy Consumption (kWh/kg H_2)	Electrolyzer Hydrogen Conversion Efficiency (LHV)
Original	**34.0**	**7601**	**78.3**	**42.6%**
New	**33.9**	**7091**	**73.0**	**45.7%**
Original	**56.8**	**7143**	**73.6**	**45.4%**
New	**56.6**	**6783**	**69.9**	**47.8%**

Additionally, though the new cell stack significantly increased the efficiency of the system, a specific energy consumption of 70 kWh/kg still represents substantial efficiency losses in the electrolyzer system. The low system efficiency highlights the need to incorporate efficiency improvements into the balance of plant, such as increased dryer efficiency and power conversion, when considering hydrogen production for fueling applications.

6. Conclusion

The new Next Generation cell stack is more efficient than the original S40 cell stack, improving efficiencies by approximately 8.0% at low temperatures and by 6.4% at high temperatures. By replacing the cell stack and raising the operating temperature, the overall electrolyzer efficiency improved by approximately 10%. Additionally, the new stack has been installed and working well for over three months. At the station's current generation rate of approximately 110 kg/year, these efficiency improvements would save approximately $100/year in electricity costs. At a constant generation rate, producing 876 kg/year, these improvements would save approximately $800 in electricity costs. At a larger station these savings would be more substantial, making improvements in efficiency of both the cell stack and the overall electrolyzer system more valuable.

[5] The Proton Energy Systems specification sheet states that the energy consumed per volume of gas produced is 17.6 kWh/100ft^3, which converts to 74.5 kWh/kg.

7. References

1. Allen, A., Lehman, P., Chapman, G. and C. Chamberlin. “Costs and Operational Data for the Humboldt State University Hydrogen Fueling Station,” presented at the National Hydrogen Association conference, Columbia, South Carolina, April 2, 2009.

2. Johnstone, P. “Performance trends and control strategies for the Schatz solar hydrogen project,” Thesis for Master of Science degree in Environmental Systems: Environmental Resources Engineering Option at Humboldt State University, December, 2009.

3. Wipke, K. National Renewable Energy Laboratory, "On-Site Hydrogen Production Efficiencies," DOE Hydrogen Technology Validation Program, personal communication, April 6, 2009.

4. Proton Energy Systems. “Technical Specifications: S-Series Hydrogen Generators,” available on company website: http://www.protonenergy.com/tools_commercial.php, retrieved April 2010.