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MODELING SOLAR IMPACTS ON HYDROGEN PRODUCTION FROM ELECTROLYSIS

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ABSTRACT

A model is presented to simulate the energy production from a solar photovoltaic (PV) array in Southern Nevada and its energy produced for hydrogen production at a hydrogen filling station. A solar PV array composed of four single axis tracking units provides power to a Proton Exchange Membrane (PEM) electrolyzer, which produces hydrogen that is stored on site for use in hydrogen converted vehicles. The model provides the ability to predict possible hydrogen production at the site, as well as the amount of hydrogen required to sustain a prescribed level of vehicle usage. Together, these results made it possible to determine the energy required to produce sufficient hydrogen to sustain the vehicles, and the percentage of that energy generated by the solar PV array. For an average year in Las Vegas and a travel requirement of 57 miles/day, this percentage was found to be 33 percent. This simulation has the potential to be modified for different locations, array size, amount of storage, or usage requirement.

INTRODUCTION

Producing hydrogen from renewable energy sources provides a sustainable way to power vehicles or hydrogen systems. One method of generating hydrogen is electrolysis, a process that uses electricity to separate water into hydrogen and oxygen. In this way energy can be stored in a tank in the form of hydrogen gas that can be used as fuel for a fuel cell or internal combustion (IC) engine. Renewable energy sources, including solar energy, provide an excellent source for the electricity required to perform electrolysis, because they produce no emissions and require little maintenance during operation [1]. A solar powered Hydrogen Filling Station (HFS) has been constructed in Las Vegas, Nevada for the purpose of investigating the performance of such a system. The station was built on the property of the Las Vegas Valley Water District (LVVWD) to provide fuel for a several vehicles that were converted to operate with hydrogen [2, 3]. A data acquisition system collects information related to all equipment power usage, solar power production, weather conditions, and eventually will collect total hydrogen production. In addition to monitoring the performance of this station, it is advantageous to predict the station's performance in order to determine how to modify its design or how a certain level of usage affects its operation. Therefore, a computer model has been created to simulate the energy production and use at the station, as well as how vehicle usage affects the energy and hydrogen balance at the station. Detailed reviews of modeling related to the renewably powered hydrogen systems are discussed elsewhere [4,5]. Previous models of the performance of this and another photovoltaic/hydrogen installation in the Las Vegas region have been performed [6,7].

The specifications of the solar PV array and the hydrogen production, storage, and dispensing system are given in the first section. Next, the hydrogen and electricity flows through the system are shown to describe the characteristics of the station's operation. Then the model of each part of the system is discussed, based on manufacturer's data as well as average monthly weather conditions. Finally, the results of the model show the total hydrogen produced at the station, the contribution of the solar PV array to the energy required to produce this hydrogen, and typical daily net power plots for the current station design.

HYDROGEN STATION DESCRIPTION

SOLAR PV ARRAY

The solar PV array shown in Figure 1, is rated at 16.8 kW DC (14 kW AC) and consists of 4 single axis tracking units installed by Arizona Public Service. The trackers are tilted at a 30º angle facing due south, and consist of 24 panels each rated at 175 Watts (Sharp NT-175U1 Panels). The single-axis trackers follow the sun throughout the day which allows a 27.5 percent increase in power output over fixed photovoltaic panels with the same tilt angle. The size and design of the array was chosen based on the available space at the station, the cost of the system, and the fact that earlier phases of this project required approximately 8-9 kW during operation [5]. The system is connected to the grid through a net metering agreement with Nevada Power Company that allows excess energy to go to the grid when the system is not generating hydrogen. Similarly, the system can draw power from the grid when the required power for generating and storing hydrogen is greater than the photovoltaic system output.

FIGURE 1: SOLAR PV ARRAY AT THE HYDROGEN FILLING STATION.

HYDROGEN GENERATION AND STORAGE SYSTEM

The HFS shown in Figure 2 generates hydrogen with a Proton Energy Systems FUELGEN 12 ® [8] PEM Electrolyzer (Unit 1) which has a 12.9 kg per day production capacity. A chiller (Unit 1a) is used to maintain the operating temperature of the PEM electrolyzer stack during hydrogen production. Unit 2 is an Air Products Series 100E dispenser that includes a compressor and storage tanks. The capacity of storage tanks is 6.5 kg of hydrogen at 6250 psig (430.9 bar).

Figure 3 shows the manner in which water and hydrogen flow through the HFS. Water enters the electrolyzer, which outputs hydrogen into the buffer tank, and stores hydrogen at 435.1 psig (30 barg). The buffer tank decouples the operation of Unit 1 and Unit 2. As hydrogen is dispensed from Unit 2 to fill a vehicle, the compressor begins to draw hydrogen from the buffer tank. When the buffer tank drops to a pressure of 406 psig (28 barg), the electrolyzer senses a low product pressure and generates hydrogen until the buffer tank is full.

FIGURE 2: HFS GENERATION AND STORAGE EQUIPMENT.

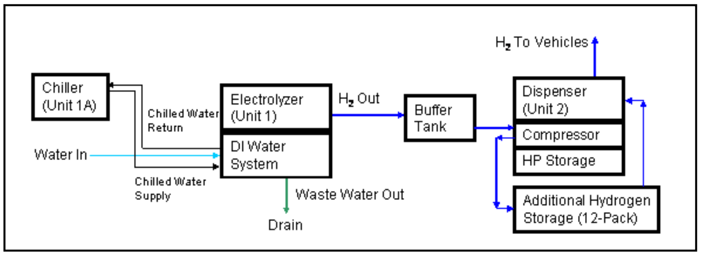

FIGURE 3: WATER AND HYDROGEN FLOW THROUGH THE STATION

Table 1 shows power and pressure specifications for the equipment involved in the generation and storage of hydrogen at the station. In the future, the station will be upgraded with an extra storage module, which will increase the total station storage capacity to 21 kg.

TABLE 1: HFS EQUIPMENT

	Hydrogen Pressure (barg/psig)	**Stored Hydrogen (kg)**	**AC Voltage (VAC)**	**FLA (A)**
Unit # 1	15/435	~ 0	240&480	28&112
Unit # 1a	N/A	0	480	28
Unit # 2	431/6250	~6.6	240	23
Buffer Tank	30&435	~0.702	480	N/A

Electricity flow through the system is shown in Figure 4. The electricity to the HFS equipment can be provided by either the solar PV array or the grid or both.

HYDROGEN VEHICLES

In addition to two small vehicle conversions that use the HFS, the hydrogen will mainly be used by the converted Ford F-150 pickup truck shown in Figure 5 [3]. The truck has five 90 L tanks on board, and is capable of holding 11.2 kg of hydrogen at 5076 psig (350 barg). The truck is powered by an 8 cylinder engine that formerly operated with compressed natural gas (CNG) at 3000 psig (207 barg), in which the timing and piping have been modified to accommodate high pressure hydrogen injection directly into the cylinders.

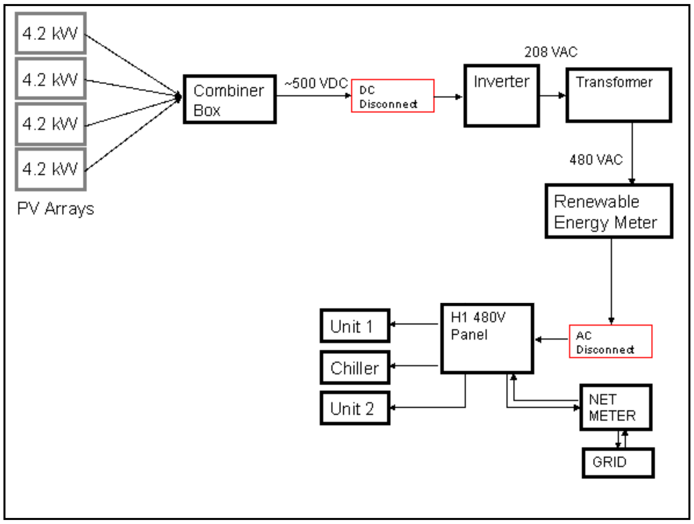

FIGURE 4: ELECTRICAL FLOW IN THE SYSTEM

Daily usage of the truck will be 57 miles/day, based on data provided by the LVVWD. Since performance data from this truck have yet to be obtained, an estimated value of 16 mi/kgH_2 was used, based on similar vehicle conversions [9].

FIGURE 5: REAR VIEW OF CONVERTED PICKUP TRUCK

HYDROGEN STATION SIMULATION

SOLAR PV ARRAY PERFORMANCE

The performance of the solar PV array is predicted based on TMY2 weather data for the Las Vegas region, including the beam, diffuse, and reflected solar radiation [10]. Energy received by the single axis trackers are calculated using the relations from [11]. The Perez model is used to calculate the amount of diffuse radiation on the tracker [12].

PV cell performance can be predicted by the single diode model [11]. I-V characteristics of the PV cells as a function of incident irradiation and cell temperature can be predicted using

$$I = I_L - I_O \left[\exp \left[\frac{V + I \cdot R_S}{a} \right] - 1 \right] - \frac{V + V \cdot R_S}{R_{sh}} \tag{1}$$

Where light current I_L, diode reverse saturation current I_O, series resistance R_s, shunt resistance R_{sh} and modified ideality factor (a=nkTN/q eV, with Boltzmann's constant k (1.381×10^{-23} J/K), electronic charge q (1.609×10^{-19} As), number of cells in series N, cell temperature T) are the five parameters needed for predicting the current and voltage of the PV cell. The model uses the data provided by the manufacturer (short circuit current (I_{sc}), open circuit voltage (V_{oc}), current and voltage at maximum power point (I_{mp}, V_{mp} respectively)) at the standard conditions to calculate the five parameters at reference conditions. These parameters are further used to calculate the performance of the PV panel at any other conditions.

HFS EQUIPMENT PERFORMANCE

Hydrogen demand of the pickup truck is calculated based on the daily distance traveled and the expected performance of the truck in terms of miles per kgH_2. Assuming the daily travel of 57 miles and 16 miles per kgH_2, the daily usage of hydrogen was found to be 3.56 kg. Assuming that the truck would be fuelled two times a day at 8 AM and noon for an 8 hour shift, the amount of hydrogen required per fill was found to be 1.78 kg.

Hydrogen generation, storage and utilization were modeled to predict the performance of the HFS. The simulations were performed on a minute-by-minute basis to accurately describe the transient behavior. The gas levels of the storage tanks and flow rates were considered on mass flow basis to eliminate the effects on sudden pressure changes throughout the system.

Simulations were performed for each month in order to predict the performance and ensure that the HFS meets the hydrogen demand of the vehicle. At the beginning of each month both the buffer tank and dispenser storage tanks are assumed to be 100% full. The compressor starts only if the hydrogen level inside the dispenser falls below 90% and the hydrogen level inside the buffer tank is greater than 40 %. From experimental data, the compressor operates at 2 kW and draws hydrogen from the buffer tank at 0.045 kgH_2 per minute. The electrolyzer starts producing hydrogen when the hydrogen level inside the buffer tank falls below 93 %.

Based on manufacturer's and observed experimental data, the performance of the electrolyzer can be estimated by a fairly simple conversion for this analysis. It has been shown that the FuelGen 12 ® uses approximately 39 kW during hydrogen production, which agrees with published data regarding electrolyzer operation [13]. The production rate at this level of power use is 0.009 kgH_2 per minute. During electrolyzer operation the coolant used to maintain the PEM cell stack temperature begins to heat up, and triggers the auxiliary chiller to operate. From experimentally collected data at the station, the chiller draws between 1 and 7 kW during operation. Additionally, the chiller tends to run more in the summer months when ambient temperatures are high. Therefore, the chiller was modeled to run simultaneously with the electrolyzer, at a fraction of its rated power depending on the average temperature of the month. Figure 6 shows a flow chart for the simulation.

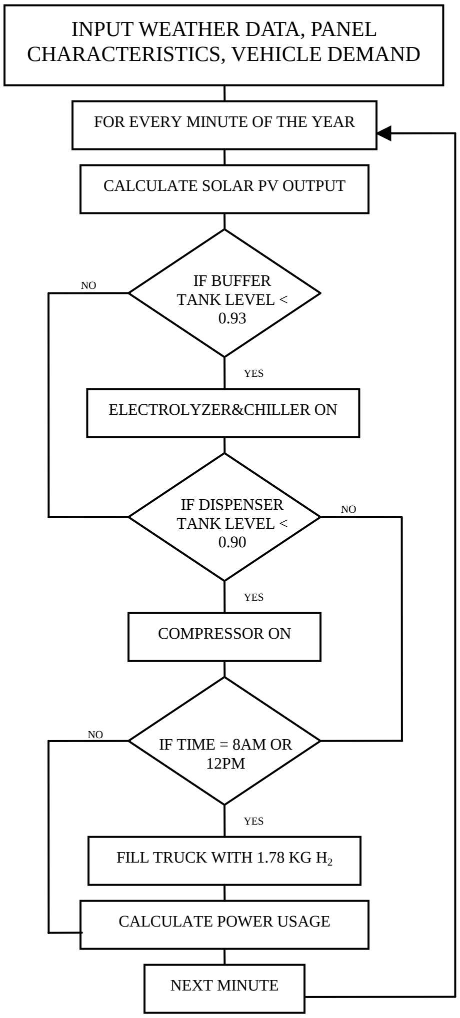

FIGURE 6: HFS SIMULATION FLOW CHART

RESULTS

Combined, the solar PV array and HFS simulations fully describe the energy use and hydrogen production at the station for each minute of one typical year. Based on current station characteristics, the monthly contribution of solar energy to the total energy use of the station is shown in Figure 7. The energy contribution of the solar PV array ranges between a low of 25.7% in December and a maximum of 40.8% in May. The station produces a total of 1292.1 kgH_2 in one year, of which almost 431 kg is produced by solar energy. The efficiency of the hydrogen generation and storage processes was found by dividing the energy required to produce and compress the hydrogen by the energy contained in that amount hydrogen, according to its higher heating value of 39.38 kWh/kg. Therefore, the efficiency of the station was dependent on the assumptions about energy usage from each piece of equipment, and in this case it was calculated to be 49.3%. Based on the expected fuel efficiency of the truck, the 14 kW AC solar PV array is capable of supporting 19 of the 57 miles per day required by the truck.

Table 2 shows overall performance data from the model. In order to fully supply the power required to produce the amount of hydrogen necessary to drive the truck 57 miles per day, the solar PV array would need to be increased to 50.4 kW. This could be accomplished with 8 additional single axis tracking units.

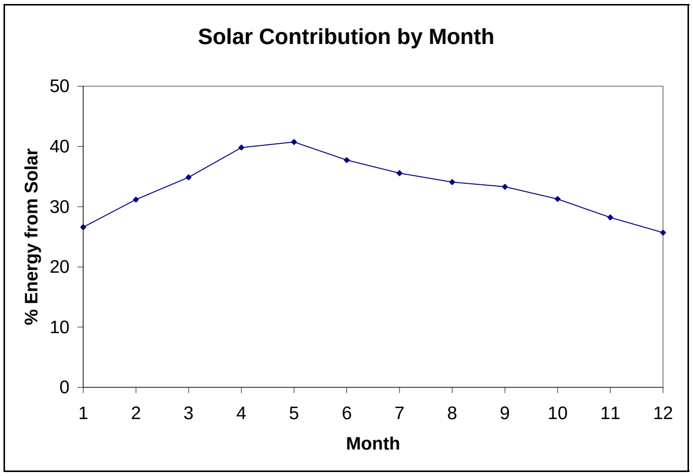

FIGURE 7: MONTHLY SOLAR CONTRIBUTION TO TOTAL ENERGY USE

TABLE 2: AVERAGE YEARLY STATION PERFORMANCE

Hydrogen Production	1292.1	kg
Solar Energy Production	34.39	MWh
Solar Contribution to Hydrogen Production	33.34	%
Hydrogen Produced from Solar Energy	430.87	kg
Hydrogen Generation/Compression Efficiency (HHV)	49.3	%

The hydrogen level in the dispenser is shown for a sample day in Figure 8. The minimum level of hydrogen in the dispenser is 63% of its capacity. This indicates that the station is capable of dispensing more hydrogen during each fill, which could potentially increase the range of the truck. If the truck was filled until the dispenser level reached 50%, its range would increase by over 80% to over 50 miles per fill (formerly 28.5 miles per fill). However, any extra mileage driven by the truck will require 100% grid energy.

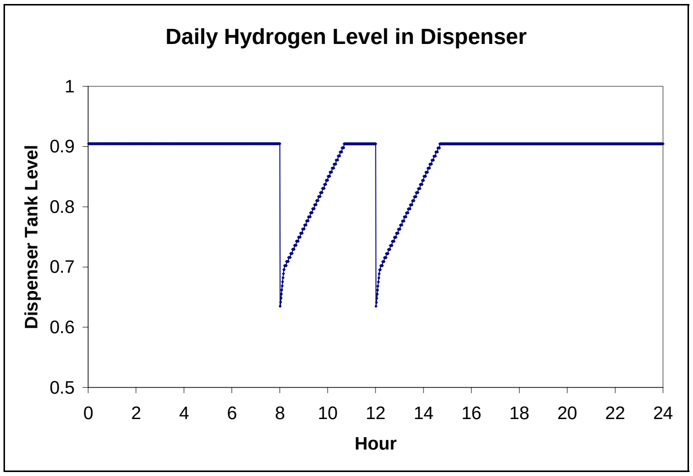

FIGURE 8: DAILY DISPENSER TANK LEVEL

Hydrogen level in the buffer tank is shown for a sample day in Figure 9. It is shown that the buffer tank level cycles up and down due to the hydrogen input from the electrolyzer and output into the dispenser. Again, it is noted that the minimum level of the tank only drops to 45%, indicating that more hydrogen could be drawn during each fill.

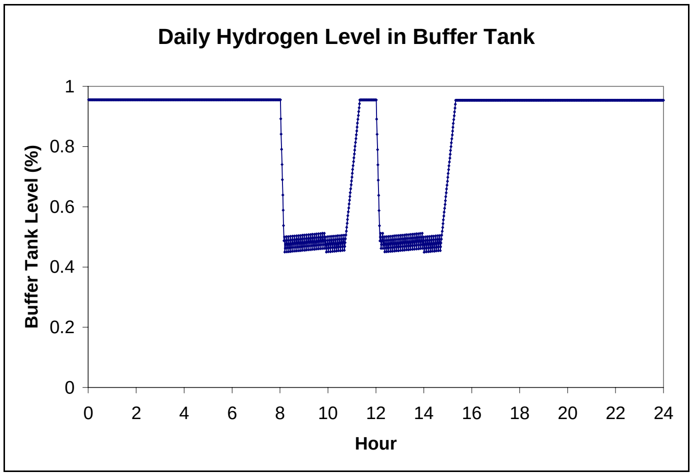

FIGURE 9: DAILY BUFFER TANK LEVEL

Typical daily net power curves vary based on the solar production at the station. Two different sample days are shown in Figure 10, for opposite times (summer (a) and winter (b)) of the year. It is noted that although the hydrogen deficiency at 8 AM and noon results in the same drop in net power to the grid, the amount of solar power drastically increases for the month of June.

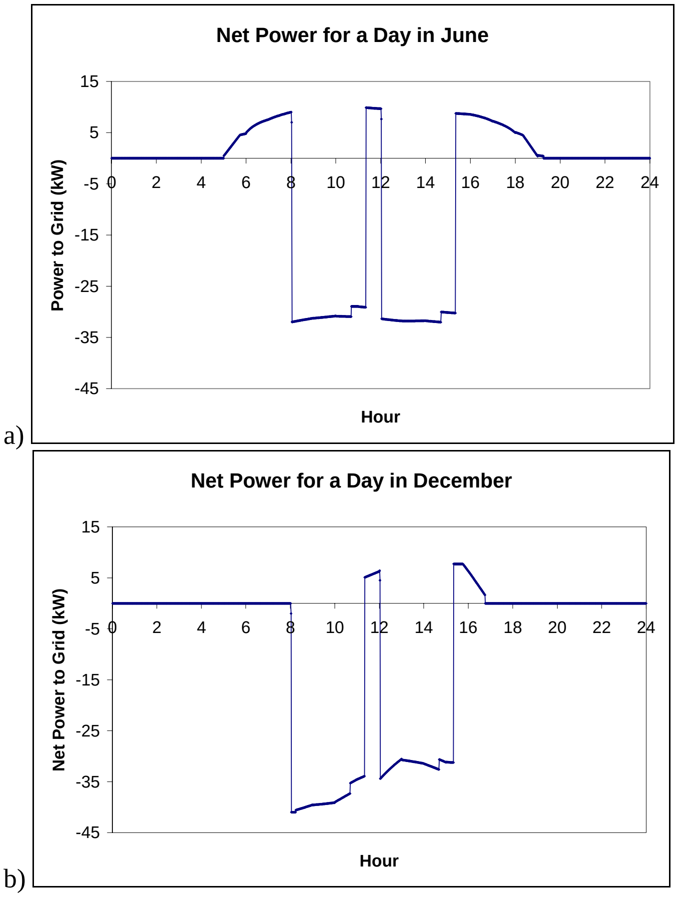

FIGURE 10: NET POWER FOR TYPICAL (A) JUNE AND (B) DECEMBER DAYS

CONCLUSION

This paper provides insight about the performance of a HFS powered with grid connected solar PV array. The station is an example of a way that solar energy can be used to generate hydrogen for transportation. In its current configuration, 33.34 % of the hydrogen produced was obtained from solar energy, which amounted to 430.87 kgH_2 for a typical year of operation. It was found that 8 additional trackers are required to supply enough energy to produce 1292.1 kgH_2 in one year.

Data related to power usage and tank levels are important parameters to include during system design. Because this station was originally configured to power a PEM electrolyzer that produced 2.2 kgH_2 per day at 8 kW, the extra energy required to operate the upgraded equipment now at the station exceeds the available solar energy. Additionally, extra storage at the HFS is necessary to provide enough hydrogen to completely fill the converted pickup truck, although current storage levels are sufficient to meet the demands of the pickup truck. With further improvement in the performance of hydrogen IC vehicles, the HFS will be able to support a higher level of hydrogen demand.

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