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OPERATING EXPERIENCE WITH A PHOTOVOLTAIC-HYDROGEN ENERGY SYSTEM

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Abstract

We report on the performance, safety, and maintenance issues of a photovoltaic (PV) power plant which uses hydrogen energy storage and fuel cell regenerative technology. The facility, located at the Humboldt State University (HSU) Telonicher Marine Laboratory, has operated intermittently since June 1991, and in August 1993 went into full-time, automatic operation. After more than 3900 hours, the system has an excellent safety and performance record with an overall electrolyzer efficiency of 76.7%, a PV efficiency of 8.1%, and a hydrogen production efficiency of 6.2%.

1. INTRODUCTION AND SYSTEM DESCRIPTION

The Schatz Solar Hydrogen Project began in the fall of 1989. It is an automatically controlled PV electric power plant which uses hydrogen as the energy storage medium and a fuel cell as the regeneration technology. The intent is to demonstrate that hydrogen is a practical energy storage medium for solar energy and that solar hydrogen is a safe and reliable energy source for society.

The system (Figure 1) is located at the HSU Telonicher Marine Laboratory in Trinidad, CA (124.15°W, 41.06°N) and is designed to supply uninterruptible power to the air compressor (load) which aerates the Lab's aquaria. When possible, PV power from the array is delivered directly to the load. Any excess power is shunted to the electrolyzer to produce hydrogen for storage. If power is unavailable from the array, atmospheric air and the stored hydrogen are delivered to the fuel cell to continue generating electricity for the load.

The 9.2 kW PV array consists of 192 Arco M75 modules electrically connected into 12 independent subarrays. Each subarray is composed of 16 modules, wired in 8 series pairs to operate nominally at 24 VDC.

The electrolyzer is a medium pressure, bipolar, alkaline unit manufactured by Teledyne Brown Engineering. It consists of a 12 cell electrolysis module designed to deliver 20 SLM of H_2 gas at a current of 240 amps at 24 VDC. The H_2 gas exits at 790 kPa and is stored in three steel tanks with a total capacity of 5.7 m^3. This provides approximately 133 kWh of storage at the higher heating value (HHV) for H_2. This will operate the load (600 W) for approximately 110 hours assuming a practical fuel cell efficiency of 50% (HHV).

The system was originally designed around an H_2-O_2 proton exchange membrane (PEM) fuel cell contracted from a commercial manufacturer [1,2,3]. However, after more than two years they were unable to provide a working unit. As a result, in the fall of 1992, The Schatz Fuel Cell Laboratory was formed and began a collaborative effort with Texas A&M University to design and construct a 1.5 kW PEM cell using air as the oxidant. At present a preliminary four cell stack has been constructed and is performing successfully at a stack efficiency of 50%. The expected installation date for the full forty cell stack is the summer of 1994. For further details regarding the fuel cell, please refer to the companion paper in these conference proceedings [4].

2. OPERATION AND PERFORMANCE

Operating Hours

Since August 5, 1993 the Schatz Solar Hydrogen System has operated in a fully automatic mode twenty four hours a day, seven days a week. Over the four month period from August 5, 1993 to November 30, 1993, the system has operated for more than 2,600 hours with 104,000 amp-hours going to the electrolyzer to produce 530 normal cubic meters (Nm^3) of hydrogen. By comparison, the totals for the first seven months of the year are 1,300 hours of operation, 52,000 amp hours, and 267 Nm^3. These results are summarized in Tables I and II.

Efficiencies

Cumulative average efficiencies for 1993 are included in Table I, and a brief explanation of how they are calculated is found in Table III. These efficiencies represent updates from those reported previously [5]. They more accurately reflect performance for two reasons: First, new current shunts were installed in the spring of 1992. Second, and more importantly, present results are based upon nearly 4,000 hours of operation while those previously reported were specific to only two full days of operation. In general, these efficiencies are very encouraging and compare well with those reported by other sources [6, 7].

The cumulative distributions of the daily average efficiencies also appear encouraging. Figure 2 shows the distribution of the electrolyzer efficiencies for 1993, which represents a wide range of operating conditions, with current densities ranging from 15 mA/cm^2 to more than 400 mA/cm^2 and electrolyzer temperatures extending from 10°C to 70°C. For example, even though the Faraday efficiencies lie between 44% to 99%, more than 70% of these efficiencies exceed 93%. Although the Faraday efficiency is helpful in assessing electrolyzer performance, the best overall performance indicator is the electrolyzer efficiency. As seen in Figure 2 more than 70% of these daily averages exceed a value of 75%.

Figure 3 shows the cumulative distributions of the of the daily PV and hydrogen production efficiencies. The hydrogen production efficiencies range from 2.8% to 7.2%, with more than 70% of these daily averages at or above 6.0%. Similarly, the PV efficiencies are equally dispersed, with more than 70% of the values exceeding 7.8%.

An example of a single day of operation is displayed in Figure 4. As can be seen from the insolation curve, the day was bright and clear. Also displayed are Faraday and electrolyzer efficiencies. Early and late in the day, when insolation is low, there is some switching between the load, and the electrolyzer as evidenced by the oscillatory nature of the efficiencies. Between these times the system operates smoothly.

As can be seen in Figure 4 the efficiencies vary throughout the day. Most of this variation can be accounted for by considering the conditions under which the system operated. When the insolation is low, the electrolyzer runs at low current densities and the parasitic currents are higher both actually and proportionally [8]. As a result the Faraday efficiency is lowest at the beginning and end of the day. Conversely, higher current densities increase the voltage necessary for electrolysis. This has a large negative effect upon the electrolyzer efficiency. For example, at 12:32 PM, when Faraday efficiency is at its maximum (99.2%), electrolyzer efficiency is 75.5%, current density is 407 mA/cm^2, and the electrolyzer is operating at 1.94 V/cell. At 17:10 PM Faraday efficiency declines to 92.9% while electrolyzer efficiency reaches its maximum (85.8%). At this time the current density is only 77 mA/cm^2 and the electrolyzer voltage has dropped to 1.60 V/cell.

Auxiliary Energy Consumption

This system has a number of auxiliary power requirements which are not considered in our efficiency calculations. The electrolyzer requires a small pump to add makeup water, a cooling fan, and an electronic controller. Automatic control of the remaining system is performed by two Macintosh SE computers and various digital control hardware, which has been previously described

[3]. In addition, there are several safety monitors, and a small ventilation fan in operation. These loads require approximately 1000 watts of power which is 150% of the power required for the air compressor. While these parasitic loads exceed the system's power capacity, the purpose of our efficiency calculations is to assess the performance of the photovoltaic-hydrogen fuel-cell power cycle. In a larger system these parasitic loads would be proportionally much smaller.

System Stability

May 20, 1993 provided radically different operating conditions from those of August 25 as can be readily seen from Figure 5. The weather was intermittently cloudy with short periods of bright sunlight. Over a good portion of the day the insolation levels were well in excess of 1000 W/m^2 with the peak value just below 1200 W/m^2. Note that these are two minute averages and that instantaneous values can be considerably higher. The magnitude of these values can be attributed to cloud focused light which is common during such rapidly changing weather. These conditions present a severe test to the automatic control system. Nevertheless, as Figure 5 clearly shows, the control system functions extremely well and the power to the load remains very stable throughout the entire run.

System Reliability

System reliability has been excellent since full time, unattended operation began in August. With the exception of one PV module failure due to a loose connection in its junction box, there have been no component failures thus far. Because our PV array is electrically divided into 12 subarrays, we disabled the affected subarray from the system and performed repairs without any loss of operating time; this is an example of the benefit of having modularity in the system. However, several utility power outages have occurred which shut down our system, causing the loss of several days of operation. Additionally, in the middle of November we went off-line for seven days to perform semi-annual maintenance and minor modifications of the computer system. In the future, we intend to perform such routines at night so as to minimize downtime and increase the reliability of the system.

3. SAFETY AND MAINTENANCE

Safety has played an important role in the design, construction, and operating phases of our system. A methodological approach to planning has made it possible to conceive and evaluate fault and safety conditions arising from human or equipment failures, and natural catastrophes. Licensed authorities from private, local and state agencies have provided invaluable consultation and evaluation [9,10,11,12]. Finally we have been careful to observe all applicable codes as they pertain to the system [13,14,15].

Safety Strategy

We developed an extensive fault tree from which we tested human and system response to all fault and safety conditions [16]. For those fault tests which could not easily be simulated, we relied upon thought experiments and manufacturer's safety information to estimate the possible ramifications on the operation of the system and its equipment.

During June of 1993 we operated the system for a week under daytime supervision to evaluate system control. This resulted in extensive program debugging and minor hardware modifications. At the end of this period a battery of fault tests were performed to verify the effectiveness of the changes.

In addition, we prepared an emergency response plan and training procedure for laboratory personnel [16]. This document includes general information about the hazards associated with hydrogen gas as well as an outline of procedures to follow in any emergency situation. It defines procedures for situations including hydrogen fires, chemical spills involving KOH (used in the electrolyzer) or HCl , and earthquakes. As well, it clearly describes a number of ways that the solar hydrogen system can be safely shut down in the event of an emergency.

Automatic Safety Features

While most of these features have been previously reported [3], one important new system interlock has been added. A fail-safe power transfer system has been incorporated to return the load to the local power grid in the event that the solar hydrogen system cannot supply power. This allows the system to run automatically and ensures that the air compressor will run at all times without the need for human intervention. The marine laboratory has always had an auxiliary generator system in place.

Maintenance Schedule

To ensure safe and reliable operation of the system and related equipment, we developed a comprehensive maintenance schedule which includes regular weekly, monthly, biannual, and annual inspections [16]. While most of the review intervals follow manufacturer’s time tables, several have been made more frequent until greater operating experience and confidence are gained.

4. CONCLUSIONS

Based on the work performed over the past year and the data reported here, we draw the following conclusions:

- Numerous improvements have been made to the Schatz Solar Hydrogen Project over the past six months. At this point, the system is in full-time automatic operation and, with the exception of the fuel cell, the system is complete and functioning as designed.
- The electrolyzer functions extremely well with a PV generator. The average electrolysis efficiency of 76.7% and hydrogen production efficiency of 6.2% are excellent and higher than have been previously reported for a complete system.
- The maintenance and safety systems in place are effective and working well.

For the future, our plans include:

- Continuing to operate the system and record performance.
- Manufacturing and installing a fuel cell to complete the system.
- Developing a mathematical model to simulate the operating characteristics of the Altus 20 electrolyzer when powered by a PV array.

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TABLES

TABLE I: AVERAGE EFFICIENCIES (%), 1/1/93 - 11/30/93

Faraday	Electrolyzer	Voltage	PV	H_2 Production
94.2	76.7	83.9	8.1	6.2

TABLE II: CUMULATIVE TOTALS , 1/1/93 - 11/30/93

Hours System Was On	Electrolyzer Amp Hours	Hours Load Was Run By System	Hours PV Array Was Used	Hydrogen Gas Produced (Nm^3)
3,908	155,197	1176	1,449	797

TABLE III: EFFICIENCY DEFINITIONS

Electrolyzer	$\dfrac{\text{Rate of } H_2 \text{ production}}{\text{DC power supplied to the electrolyzer}}$
Faraday	$\dfrac{\text{Actual amount of } H_2 \text{ produced}}{\text{Theoretical amount of } H_2 \text{ for current used}}$
Voltage	$\dfrac{(1.482 \text{ V})}{\text{Actual operating voltage per cell}}$
PV	$\dfrac{\text{PV power used by the system}}{\text{Solar power incident on the array}}$
H_2 Production	PV Efficiency x Electrolyzer Efficiency