Task 1 Report

Production of Hydrogen by Photovoltaic-Powered Electrolysis

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PREFACE

This report describes the Sustainable Hydrogen Production research conducted at the Florida Solar Energy Center (FSEC) for the past year. The report presents the work done on the following four tasks:

- Task 1. Production of Hydrogen by Photovoltaic-Powered Electrolysis - This task represents the final effort of a cooperative project between the U.S. Department of Energy, NASA/Kennedy Space Center, FSEC and the Florida Energy Office. The activities covered five years of effort at a total funding of \$216,809. These results represent a successful coordination of two state agencies and two federal agencies.
- Task 2. Solar Photocatalytic Hydrogen Production from Water Using a Dual-Bed Photosystem - This task established the basis of the dual-bed concept by selectively evolving hydrogen or oxygen. A number of redox mediators were found to facilitate hydrogen production.
- Task 3. Development of Solid Electrolytes for Water Electrolysis at Intermediate Temperatures - Several ionomers were synthesized and fabricated into proton exchange membranes. Laboratory testing in an electrolysis cell gave comparable performance to the commercial product.
- Task 4. Production of Hydrogen by Thermocatalytic Cracking of Natural Gas - The experimental unit was constructed and a number of catalysts for methane cracking reactions were tested. Laboratory experiments established catalyst activity and identified stability problems.

This report was prepared by the Florida Solar Energy Center/University of Central Florida as an account of work sponsored by the U.S. Department of Energy (Contract #DE-FG04-94AL85802)). The work reported in this document does not imply endorsement by U.S. Department of Energy.

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PRODUCTION OF HYDROGEN BY PHOTOVOLTAIC-POWERED ELECTROLYSIS

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1.0 SUMMARY

The report presents results of a cooperative effort among the Florida Energy Office, NASA/Kennedy Space Center, the U.S. Department of Energy and the Florida Solar Energy Center (FSEC). It reports on a task to evaluate hydrogen production from photovoltaic (PV)-powered electrolysis. The resulting activities covered five years of effort funded at a total of \$216,809. The results represent a successful, coordinated effort among two state agencies and two federal agencies.

Results are reported on two separate investigations:

- 1) The first investigation looked at the use of line focus concentrating photovoltaics coupled with single-cell electrolyzers to produce gaseous hydrogen. The concept, and its design, construction and operation, are presented. The objectives of the line focusing PV system are to reduce overall system cost under the assumptions that lenses and mirrors are cheaper to deploy than are PV cells, and that low-voltage, high-current dc electricity can efficiently power a single-cell electrolyzer to produce hydrogen.
- 2) The second investigation evaluated a base case cost of PV electrolysis hydrogen production based on present-day PV and electrolyzer costs and efficiencies. A second step analyzed the hydrogen costs based on a "best" prediction of where PV costs and efficiencies will be in 10 years. These results set the minimum cost standards that other renewable production technologies must meet or better.

Line Focus Concentrating PV Electrolysis Hydrogen Production

The basic idea of the concentrating PV electrolysis concept is to combine the least-cost concentrator technology with high-efficiency photovoltaic cells and to use low-voltage, high-current power produced by the PV for water electrolysis using a single-cell electrolyzer. An assessment of water electrolysis as a matched load to concentrating PV systems looks very good. Electrolysis requires high-amperage, low-voltage dc electricity, and its load profile is very similar to charging lead-acid batteries. Ideally, the water electrolysis unit can be direct-coupled to the PV system without significant mismatch losses in efficiency and reliability-robbing electronics. Acknowledgment for development of this concept is given to Dr. Kirk Collier, a former FSEC employee.

The major components of the hydrogen production system that was installed at FSEC are a parabolic trough concentrator, a photovoltaic receiver assembly, a cooling system and electrolyzer cells. The parabolic trough concentrator was purchased from Industrial Solar Technology, Denver, Colorado, at a cost of approximately \$100/m² and consists of four 20-foot-long collectors, each 7.5 feet wide. The nominal focal width is 2 inches, which yields a geometric concentration of 56:1. The reflector material chosen for the FSEC installation was 3M aluminized film. The electrolyzer cells were supplied by The Electrolyzer Corporation Ltd., Toronto, Canada. The cells are alkaline cells of unipolar design, each rated at 250 amps and between 1.8 and 2 volts. Water from an above-ground swimming pool is used to cool the PV cells. Bonding and electrically connecting the PV cells proved to be a difficult and time-consuming task during construction, and failure of cooling of the system was a problem.

The system was continuously operated over the five-month period of July to December 1993; data were segregated between the summer (July-September) and fall (October-December) seasons. The most important measured parameter is the amount of hydrogen produced from a given amount of solar energy. Due to the complexity of accurately measuring gaseous quantities of hydrogen, the amount of current passing through the electrolyzer was used as the measure of the quantity of hydrogen produced. The trend of the electrical current supplied to the electrolyzer as a function of the direct normal solar flux at solar noon was reasonably linear for both summer and fall seasons. Of particular interest, however, is the performance at high values of solar radiation, approximately 800 W/m², where the current

deviates significantly from the linear behavior. This deviation is thought to be caused by mismatch between the PV output and the electrolyzer load.

The PV cells had a poor conversion efficiency -- less than 6% under concentration. Plots show the system conversion efficiency as a function of solar time for a typical summer and fall day. The system conversion efficiency is defined as the higher heating value of the hydrogen produced (assuming a coulombic efficiency of 100%) divided by the available solar energy. The overall system efficiency for the time period July through December was 2.8% based on total direct-normal radiation, and 1.8% based on total global radiation. Although these efficiencies seem extremely low at first glance, they do show that the mismatch losses between the PV cells and array and the electrolyzer are very low when compared to the PV and electrolyzer losses. The best instantaneous efficiency achieved was about 3.8% (based on direct-normal radiation).

Although the PV cells used in this system were of low efficiency, the data taken verified the design goals of the project. The system demonstrated that a relatively inexpensive concentrator system can be successfully employed in a direct-coupled PV-electrolysis system with minimal losses. Both mismatch losses between PV cells and between PV and electrolyzer were minimal, and the system operated relatively well under totally unattended operation.

To achieve acceptable conversion efficiencies, much higher efficiency PV cells must be used. Also, higher electrolyzer efficiencies are possible using alkaline technology if the cell temperatures are kept significantly above ambient temperature. The use of the cooling water from the concentrating PV would be an excellent candidate to increase the temperature and, thus, efficiency of the electrolyzer.

Photovoltaic-Electrolysis-Produced Hydrogen Costs

The efficiencies, costs and resulting performance of PV and electrolyzer systems for the present and for 10 years in the future were carefully evaluated in this investigation. Values of photovoltaic modules costs and efficiencies for the present and for the future were established using the DOE Five-Year Research Plan for Photovoltaics, with modifications

based on FSEC experience and other published data. These values were also examined with respect to present materials, process costs, and achieved efficiency results.

FSEC contacted major PV manufacturers and determined a quoted price of \$4 per peak watt of power as the present cost for large-scale PV. The calculations assumed a cost of \$400/m² and a 12% efficiency. The PV systems considered were flat plate, flat-plate tracking, and concentrating, rather than cells, in terms of materials or technology.

To predict performance of a PV system, specific sites must be selected to establish input values for solar insolation. Twenty regionally representative cities were selected, and Typical Meteorological Year (TMY) data for these cities were used to establish the site-specific insolation values. For each of these 20 sites, insolation enhancement factors for latitude tilt, tracking and direct-normal PV arrays were calculated. To produce representative insolation values for fixed, tracking and concentrating arrays, data from the 20 cities were averaged to represent four U.S. regions -- southwest, south, middle and north.

PV power was calculated for each of the four regions using site insolation times PV efficiencies. The PV life-cycle cost calculations were then made for the lifetimes of the equipment by equating the present value of the PV equipment (module cost plus balance-of-system cost) and operating cost (discounted to present value) to the power produced times the cost of power (inflated at the energy escalation rate). As an example, this calculation gives a dc life-cycle cost of \$0.15/kWh for a present-day flat-plate system located in the Southwest.

Results of the PV electricity cost calculations for dc electricity show that present PV-produced dc electricity costs \$0.14 to \$0.36/kWh, and that costs of \$0.06 to \$0.09/kWh are achievable in 10 years. PV system costs are \$500 to \$800/m² (\$46 to \$74/ft²) for the present, and \$325 to \$565/m² (\$30 to \$53/ft²) in a 10-year period. The variance between types of PV systems is slight, with flat-plate tracking producing slightly lower values.

A present-day ac electrolyzer was taken to have a conversion efficiency of 60% and an initial cost of \$780 per gaseous hydrogen (H₂) production unit of 1000 Nm³/year. The elimination of the need for ac-to-dc conversion equipment reduced the initial electrolyzer cost by 30%, giving a cost of \$550 for 1000 Nm³/year. In 10 years, the electrolyzer efficiencies were assumed to increase to 70%, with the initial costs remaining the same as at present.

Calculations of gaseous hydrogen production by PV electrolysis were performed, assuming that a constant value of 1000 Nm³/year of H₂ would be produced. These calculations used the PV-produced dc electricity cost results.

The results for the cost of gaseous H₂ show present-day prices of \$76 to \$99/MMBtu for the desert Southwest, and prices of \$127 to \$185/MMBtu for the northern U.S. The cost of hydrogen from conventional \$0.05/kWh electricity is \$34/MMBTU. Thus, present PV-produced hydrogen costs for the desert Southwest are approximately 2.5 times those of hydrogen produced with conventional electricity. Gaseous hydrogen for future PV costs were \$34 to \$46/MMBtu for the desert Southwest, and \$55 to \$82/MMBtu for the northern U.S. These results show that PV-produced hydrogen costs in 10 years may be as little as 20% higher than the cost of hydrogen produced with conventional electricity at \$0.05/kWh. All calculations show flat-plate tracking to be the minimum cost option. The calculations also show that the electrolysis equipment cost makes up 11% of the total H₂ cost.

2.0 INTRODUCTION

The project presented in this report is a cooperative effort among the Florida Energy Office, NASA/Kennedy Space Center, the U.S. Department of Energy and the Florida Solar Energy Center (FSEC). The report presents results of a task to evaluate hydrogen production from photovoltaic (PV)-powered electrolysis. PV-powered electrolysis is important in advancement of renewable hydrogen production, as it is the most straightforward of the renewable production technologies, and it sets the minimum cost standards that other renewable production technologies must meet or better.

The Florida Energy Office initiated this project in 1990 when it provided a \$94,921 contract to FSEC to design, construct and operate a photovoltaic-powered electrolyzer system for the production of gaseous hydrogen. The design and construction of a line focus concentrating photovoltaic and single-cell electrolyzer unit was completed in 1991. This system operated for two days in December 1991, after which the PV cells were destroyed by overheating caused by failure of the cooling system. The system design, construction and operation were reported to the Florida Energy Office in Reference 1; system details are presented in the Results section of this report.

As part of the Florida Energy Office project, FSEC provided \$73,355 to redesign the PV and cooling system and to install new PV cells. The resulting system was operated from June to December 1993. These results are presented in the Results section and are also reported in Reference 2.

In December 1993, NASA/Kennedy Space Center funded a \$30,000 project to engineer a PV-electrolysis production unit for KSC to use in fueling its fleet vehicles. This project evaluated the line focus concentrating PV electrolysis system and KSC's method of producing gaseous hydrogen. Recommendations were made to NASA/Kennedy Space Center to install a PV-electrolysis system for their gaseous hydrogen needs, although no such system was constructed.

In 1994, \$18,533 of U.S. Department of Energy funds and the remaining NASA funds were allocated to be used to improve the efficiency of the PV cells and the PV electrolysis system by thermal management and to continue monitoring of the PV electrolysis system. The PV

system was operated until FSEC relocated to new facilities in Cocoa, Florida. Relocation required that operation be discontinued, and the system was dismantled. The system is now in storage at the FSEC Field Test Site and can be reconstructed should the need arise.

The major objective of this project was to evaluate the price of hydrogen from PV-powered electrolysis. A "best-effort" detailed analysis of the cost of hydrogen from PV-powered electrolysis was conducted to accomplish this objective. This analysis updated work originally done five years ago, as reported in Reference 3.

3.0 RESULTS

The results of this \$216,809 multi-agency project are presented in this section. These results can be grouped into two separate investigations, as follows:

- 1) The first investigation looked at the use of line focus concentrating photovoltaics coupled with single-cell electrolyzers to produce gaseous hydrogen. The concept, and its design, construction and operation, are presented. The objectives of the line focusing PV system are to reduce overall system cost under the assumptions that lenses and mirrors are cheaper to deploy than are PV cells, and that low-voltage, high-current dc electricity can efficiently power a single-cell electrolyzer to produce hydrogen.
- 2) The second investigation evaluated a base case cost of PV electrolysis hydrogen production based on present-day PV and electrolyzer costs and efficiencies. A second step analyzed the hydrogen costs based on a "best" prediction of where PV costs and efficiencies will be in 10 years. These results set the minimum cost standards that other renewable production technologies must meet or better.

3.1 Line Focus Concentrating PV Electrolysis Hydrogen Production

A hydrogen production facility utilizing a parabolic trough, concentrating-photovoltaic electrolysis system was designed, constructed and operated by FSEC. The project began in 1990, and the six-month operational period occurred in summer and fall of 1993. The initial project was funded by the Florida Energy Office and FSEC. Initial operation of the system took place over two days in December 1991 (reported in Reference 1). The limited operational

time was due to failure of the cooling system, which caused the PV cells to be destroyed by overheating. The PV cells were then reinstalled, and the system was made operational again in 1993.

The basic idea of the concentrating PV electrolysis concept is to combine the least-cost concentrator technology with high-efficiency photovoltaic cells and to use the resulting low-voltage, high-current power for water electrolysis using a single-cell electrolyzer. Acknowledgment for development of this concept is given to Dr. Kirk Collier, former FSEC employee [References 1 and 2]. The key to this concept is the use of low voltage and high current. Dr. Alexander Stuart of Electrolyzer Corporation supplied the single-cell electrolyzers to utilize the PV system's low voltage and high current. Dr. Stuart, in personal communication [Reference 4], indicated that there are three other similar applications of the concept, as follows:

1. A flat-plate PV-electrolyzer system of 3-4 kWp on the Electrolyzer Corporation roof in Toronto, Canada, that was installed five years ago and that has operated for four years.
2. A flat-plate PV-electrolysis system at the University of California, Riverside, that is still operational.
3. A PV electrolysis system at Xerox Corporation in Los Angeles that became operational in 1995.

On November 15, 1995, D. Block visited the University of California at Riverside and discussed the PV electrolysis system with Mr. James Heffel [5]. The description of the University of California site is as follows:

- Purpose - To demonstrate production, storage and utilization of hydrogen in one complete location. Refueling of vehicles is done as part of demonstration.
- Photovoltaics system array - Flat-plate Siemens modules of 3.5 kW size, wired to produce 24 volts.

- Electrolyzer - Twelve 7.3 kW electrolyzer cells from Electrolyzer Corporation which are wired in series to use the 24-volt PV power. Each individual electrolyzer looked exactly the same as the single cell used at FSEC.
- Other components - The produced hydrogen gas is compressed to 5000 psi and stored. The site has a refueling station for vehicles and has operated for approximately two years. The system is still in operation.
- Performance - A report from the University of California is near completion but has not yet been released.

Mr. Heffel [5] has described the PV electrolysis system at Xerox Corporation as follows:

- Purpose - To supply a refueling station for two pure hydrogen vehicles, with the hydrogen being supplied by PV electrolysis.
- Photovoltaics system - Concentrating PV using 11" x 11" Fresnel lenses and Siemens PV cells. The system size for 15" x 15" Fresnel lenses was to be 48 kW. With 11" x 11" lenses, the system is less than 48 kW (exact size not known). The author estimates the concentrator ratio of this system at 10 to 1. The array produces 24 volts and 300 amps.
- Electrolyzer - The electrolyzer is the same as used at the University of California at the Riverside site. Other details are not known.

Review of the PV electrolysis literature has shown that the other reported PV electrolysis systems all use the more conventional high-voltage PV and electrolyzers [6,7,8].

3.1.1 Concept Description

Concentrating PV has been demonstrated for a considerable period of time, with the majority of the applications in the area of utility power [9, 10, 11]. These applications of photovoltaics and parabolic trough technology have not been successful because of the concentrator's optical characteristics and the requirement of the electrical load for 120-240 volts. The 120-240

voltage requirement mandates that up to 300 individual PV cells must be wired in series, as a single PV cell provides approximately 1 volt, so cells must be added to reach the voltage requirement.

Because of the physics of a PV cell, the solar flux distribution at the focus of solar concentrators must be extremely uniform to maintain high system efficiency. Such solar flux uniformity is required so that the electrical current produced by the PV cell is proportional to the incident solar flux. If the solar flux doubles, then the current produced by the PV cell approximately doubles. The voltage characteristics are different. Output voltage remains almost constant with large changes in the incident solar flux.

The practical implications of this behavior are that PV cells are easy to voltage-match under varying solar flux levels, but will not current-match under these same conditions. This means that cells wired in series must be subjected to identical solar fluxes in order for their current outputs to be the same. If they are not the same, the low-current cells will behave like resistors to the high-current cells, and the efficiency of the string will decrease accordingly.

The solar flux distribution along the focal line of available parabolic trough concentrators is not uniform enough to maintain high efficiency for applications requiring the relatively high voltages needed for power production. However, for low-voltage applications, the situation is reversed. This is the concept proposed by this PV electrolysis system.

When PV cells are wired in parallel, the output currents of individual cells simply add to one another. They do not need to be matched to maintain efficiency. This means that parallel configurations of PV cells will maintain high efficiency in conditions of non-uniform solar fluxes.

This situation offers benefits when applied to water electrolysis. Water electrolysis requires only 1.5 to 2.0 volts dc to operate. For this application, only three to four parallel PV "strings" need to be operated in series rather than the 200-300 needed for utility-grid applications. Because the PV output is dc, the costs and inefficiencies of electrical inverters are also eliminated.

3.1.2 System and Design Considerations

Electrolysis provides a near-perfect electrical load for a line focus concentrating PV system, since most single electrolysis cells require hundreds of amps at between 1.5 and 2.0 volts. For a parabolic trough concentrator and available PV cells, a receiver length of about 30 to 45 cm should provide 200 amps of current. To create the 1.5 to 2.0 volts necessary, three to four strings of parallel cells must be connected in series. The optical requirements of solar uniformity are now much less stringent. The average solar flux over the total 30 to 45 cm length now must match over the 5 cm series connection length. Present parabolic trough systems can accomplish this quite well.

A first-cut assessment of water electrolysis as a matched load to concentrating PV systems looked very good. Electrolysis requires high-amperage, low-voltage dc electricity, and its load profile is very similar to charging lead-acid batteries. Ideally, the water electrolysis unit can be direct-coupled to the PV system without significant mismatch losses in efficiency and reliability-robbing electronics.

The major components of the hydrogen production system are the parabolic trough concentrator, the photovoltaic receiver assembly, the cooling system and the electrolyzer cells. These components are shown schematically in Figure 1.

The parabolic trough concentrator was purchased from Industrial Solar Technology (IST), Denver, Colorado, at a cost of approximately \$100/m². The IST concentrator system, as shown in Figure 2, consists of four 20-foot-long collectors that are each 7.5 feet wide. The nominal focal width is 2 inches, which yields a geometric concentration of 56:1. The construction of the IST concentrator is an inherently low-cost design, since it incorporates lightweight aluminum with maximum structural rigidity. The reflector material chosen for the FSEC installation was 3M aluminized film. Although the reflectivity of this film is lower relative to silver film (84% vs. 93%), the manufacturer recommended aluminum film for environmental reliability in Florida's climate.

A cross-section of the PV installation on the focal receiver assembly is shown in Figure 3. The PV cells are mounted in a single plane and are water cooled via jet-impingement on the back side of the mounting surface. Specially manufactured single-crystal silicon concentrator

PV cells was obtained from AstroPower Inc., Newark, DE. The nominal size of the cells was 10 x 5 cm. The PV cells are bonded to a square (3.8 cm x 3.8 cm) aluminum tube with a thermally conductive (relative to air) glass-filled epoxy adhesive (.2 mm thick).

Not shown in Figure 3 is the protective covering. First, the face of the cells is covered with optically clear silicone RTV potting compound; then the entire assembly is placed inside a heat-shrinkable Teflon tube.

Electrical connections from the cells to the copper bus bars are made with solder-coated copper ribbon (0.125 mm thick) soldered to the cell edges and the copper bus bars. Electrical isolation among components is achieved through the use of glass-filled epoxy adhesive.

Electrically, seven cells are connected in parallel, and four seven-cell strings are connected in series for a total of 28 cells. Because each cell is only 9.5 cm long, each parallel string is approximately 66.5 cm long. Series connections are created by reversing the polarity of the cells relative to the bus bars. Bonding and electrically connecting the PV cells proved to be a difficult, time-consuming task during construction of the receiver system.

Finally, a ½ inch (U.S. pipe size) PVC pipe is inserted inside the square aluminum tube for receiver cooling. Cooling water enters the PVC pipe and exits through a small hole opposite the back of the PV cell. The water then exits the aluminum tube at the other end of the receiver assembly. This design improves the convective heat transfer at the area of contact with the PV cells.

The system is designed such that a flow rate of 6 gallons per minute would yield a maximum cell temperature that is approximately 13°C above the water coolant temperature. The water used to cool the PV cells is itself cooled by an above-ground swimming pool. Aeration and passive evaporation/convection are the available cooling mechanisms. An emergency cooling system was also incorporated into the system design in case of power failure while the receiver is in focus. The back-up system is accomplished with a normally closed electromagnetic valve separating the city water supply and the PV cooling system. If electric power fails, this valve opens, allowing city water to circulate through the receiver tube for cooling.

The electrolyzer cells, shown in Figure 4, were supplied by The Electrolyzer Corporation Ltd., Toronto, Canada. These alkaline cells of unipolar design are rated at 250 amps and between 1.8 and 2 volts. Unipolar cell design was chosen as such cells are considered to perform better under transient electrical input than are bipolar cells. Make-up water for the electrolysis cells was obtained from a solar still and was processed by water treatment hardware shown in Figure 5.

The hydrogen and oxygen gases produced in the electrolyzer are transported to a water seal via 1.5" black iron pipe. The water seal allows adjustment of back pressure on the electrolyzer while ensuring that no outside air enters the system during times of non-production, such as at night.

Data acquisition for the system consisted of a Campbell 21X system with the ability to record direct-normal insolation, 28.5° tilt insolation, water temperature in and out of the receivers, temperature of the PV cells, pool temperature, electrolyzer temperatures, current and voltage output of the PV array, current and voltage across the electrolyzer, and hydrogen output. The data acquisition system was designed to test six different receiver designs at a time. All weather conditions are also available from the on-site FSEC weather station (e.g., temperature, wind speed and direction, relative humidity, etc.).

3.1.3. Hydrogen Production Results

The system was continuously operated over the five-month period of July to December 1993, and data were segregated between the summer (July-September) and fall (October-December) seasons. Occasional system shutdowns occurred when the cooling water flow rate sensor became inoperable due to debris in the line. The system controller was programmed to monitor cooling water flow rate. The controller required a flow of 2 liters/minute or it would shut the system down to avoid overheating the receiver.

The most important parameter to be measured is the amount of hydrogen produced from a given amount of solar energy. Due to the complexity of accurately measuring gaseous quantities of hydrogen, the amount of current passing through the electrolyzer was used as the measure of hydrogen production.

Figure 6 shows the electrical current supplied to the electrolyzer as a function of the direct-normal solar flux at solar noon for both summer and fall conditions. The trend of the data for both seasons appears reasonably linear. Of particular interest, however, is the performance at high values of solar radiation. It appears that at around 800 W/m^2 , the current deviates significantly from linear behavior. A possible reason for this deviation may be mismatch between the output of the PV system and the electrolyzer load.

Figure 6 also shows that the current output of the electrolyzer is slightly lower during fall than in summer. A possible reason for this deviation may be the lower electrolyzer efficiency caused by lower electrolyzer operating temperatures in the cooler fall season. These two situations will be further discussed in this section.

Further examination of Figure 6 shows that the maximum current supplied by the PV system during summer would be about 140 amps without load mismatch. This corresponds to about 20 amps per PV cell. Figure 7 shows the current/voltage (IV) curve for an individual AstroPower PV cell as measured by Sandia National Laboratories, Albuquerque, New Mexico. At an irradiance of 33 suns, the maximum current is 22 amps. Measurements with a reference cell showed the optical concentration ratio to be approximately 39:1 at solar noon. The geometric concentration ratio for the IST system is 56:1, which yields a system optical efficiency of approximately 70%. A direct-normal radiation of 800 W/m^2 will correspond to approximately 31 suns at the receiver. Thus, the system of 28 PV cells is responding very closely to the sum of the individual cells.

Further examination of Figure 7 also shows how poorly these cells perform. With a PV cell conversion efficiency of less than 6% under concentration, the total system performance cannot be expected to be exemplary. Figures 8 and 9 bear this out. These plots show the system conversion efficiency as a function of the solar time for a typical summer and fall day. The system conversion efficiency is defined as the higher heating value of the hydrogen produced (assuming a coulombic efficiency of 100%) divided by the available solar energy. The available solar energy is defined as the direct-normal pyreheliometer measurement corrected by projection into the plane of the local meridian. This is the component of the direct-normal radiation that a single-axis, north-south tracking system can use.

The overall system efficiency for July through December was 2.8% based on total direct-normal radiation and 1.8% based on total global radiation. Although these efficiencies seem extremely low at first glance, they do show that the mismatch losses between the PV cells, the PV array and the electrolyzer are very low when compared to the PV system and electrolyzer losses. The best instantaneous efficiency achieved was about 3.8% (based on direct-normal radiation).

Of particular interest is the system's behavior during fall, as shown in Figure 9, where efficiency decreases symmetrically about solar noon. A possible explanation for this behavior may be the mismatch between the PV system and the electrolyzer, and the fact the electrolyzer operating temperatures are much lower in fall than in summer. For higher values of solar flux, the IV curve of the PV cell is higher, requiring higher voltages to power the electrolyzer. The colder the electrolyzer, the higher this voltage requirement becomes. Figure 10 shows the electrolyzer temperature as a function of solar time for summer and fall conditions. As one would expect, the electrolyzer temperature is higher for a longer portion of the day in summer than in fall.

Figure 11 shows the electrolyzer efficiency as a function of current. For these calculations, Gibbs Free Energy, rather than the more common Helmholtz Energy, is used as the baseline. Gibbs uses the higher heating value of hydrogen based on 1.24 volts rather than 1.43 volts. If the higher Helmholtz voltage were used, overall system efficiency (solar to hydrogen) results could be misleading, since an efficiency of greater than 100% would be possible.

Although the PV cells used in this system were of low efficiency, the data taken have verified the design goals of the project. The system has shown that a relatively inexpensive concentrator system can be successfully employed in a direct-coupled PV electrolysis system with minimal losses. Both mismatch losses between PV cells and between the PV system and the electrolyzer were minimal, and the system operated relatively well under totally unattended operation.

To achieve acceptable conversion efficiencies, much higher efficiency PV cells must be used. Also, much higher electrolyzer efficiencies are possible using alkaline technology, if the cell temperatures are kept significantly above ambient temperature. The heated cooling water

from the concentrating PV system would be an excellent candidate for increasing the efficiency of the electrolyzer.

3.2 Cost of Hydrogen Produced from Photovoltaic Electrolysis

The efficiencies, costs and resulting performance of PV and electrolyzer systems for the present and for 10 years in the future were carefully evaluated in this task. The process updated work originally performed approximately five years ago and reported in Reference 3.

3.2.1 Photovoltaic Efficiencies, Power Output and Costs

The first step in evaluating photovoltaics output is to establish the cost and efficiencies of present and future photovoltaic modules. These PV costs and efficiencies were initially established using those published in the DOE Five-Year Research Plan for Photovoltaics [12]. These values were then modified by FSEC experience and other published data. They were also examined with respect to present materials and process costs, and achieved PV cell efficiency results. FSEC contacted major PV manufacturers and determined a quoted price of \$4 per peak watt for the present cost of large-scale PV. For a module with an efficiency of 12%, a balance-of-system efficiency of 90% and a power efficiency of 95%, the ratio of the area to peak watts is $9.75 \text{ m}^2/\text{kW}_p$. Using $\$4/\text{W}_p$ as the module cost, the PV cost per m^2 is \$410. The calculations assumed a cost of $\$400/\text{m}^2$.

Table I presents the efficiencies and costs that were selected for the calculations herein. The PV systems in Table I are presented as flat plate, flat-plate tracking, and concentrating, rather than in terms of cell materials or technology.

The 10-year future costs were also based on the DOE Research Plans for PV [12, 13] and on FSEC experience. These future values appear to be realistic. The following points were considered when establishing the values:

- Efficiencies greater than the module values assumed have already been achieved in laboratory cells [13]. Experience has shown that the timing between laboratory cell achievements and production cells realization lags by approximately 10 years.

- Future costs for modules (the largest cost factor) of thin-film cells are given as \$51.45/m² [14] and as \$26.31/m² [15]. These two values are both lower than the \$250/m² number assumed for the 10-year cost.
- All cell materials are common and are in plentiful supply. No problems of availability or escalating prices are anticipated [15].
- Balance-of-system and power conditioning efficiencies are already at the values expected in the late 1990s, and future expectations are excellent.

To predict performance of a PV system, specific sites must be designated to establish input values for solar insolation. This analysis required three insolation values: global at latitude tilt (fixed flat-plate), global normal (two-axis flat-plate tracking) and direct normal (concentrating two-axis tracking). Twenty regionally representative cities were selected, and Typical Meteorological Year (TMY) data for these cities were used to establish the site-specific insolation values [16]. TMY data represent the long-term climatic mean for a particular location.

For each of these 20 sites, insolation enhancement factors for latitude tilt, tracking and direct-normal PV arrays were calculated using the method developed by Liu and Jordan [17]. To produce representative insolation values, data from the 20 cities were then averaged to determine values for four U.S. regions -- southwest, south, middle and north. Table II presents the horizontal insolation data and the enhancement factors for the cities and for the four regional averages.

PV electricity costs were next computed using the efficiencies, cost values and lifetimes of Table I and the average insolation data of Table II. The economic assumptions made in the calculations were a discount rate of 6% and an energy escalation rate of 4%. Yearly PV operation and maintenance costs were taken for the present as \$3/m² per year. This value corresponds to a reported value of approximately \$0.01/kWh. Ten-year O&M values were based on the future DOE values [12].

The PV life-cycle costs were made by first calculating the PV power produced at a specific location (insolation times efficiencies). For example, the present-day flat-plate case fixed at

latitude for the desert Southwest will produce $252.8 \text{ kWh/m}^2 \cdot \text{year}$, calculated by multiplying $5.83 \text{ kWh/m}^2 \cdot \text{day} \times 0.12 \times 0.90 \times 1.10 \times 365 \text{ days/year}$. The life-cycle cost calculations for the equipment were made by equating the present value of the PV equipment (module cost plus balance-of-system cost) and operating cost (discounted to present value) to the power produced times the cost of power (inflated at the energy escalation rate). This calculation gives a dc life-cycle cost of $\$0.15/\text{kWh}$ for the present-day flat-plate Southwest example.

Results of the PV electricity cost calculations for dc electricity are presented in Table III. These results show that present PV-produced dc electricity costs $\$0.14$ to $\$0.36/\text{kWh}$, and that $\$0.06$ to $\$0.09/\text{kWh}$ is achievable in 10 years. PV system costs are $\$500$ to $\$800/\text{m}^2$ ($\$46$ to $\$74/\text{ft}^2$) for the present, and $\$325$ to $\$565/\text{m}^2$ ($\$30$ to $\$53/\text{ft}^2$) in a 10-year period. The variance between types of PV systems is slight, with flat-plate tracking producing slightly lower values.

Although not presented, the cost of PV-produced ac electricity (which requires use of an inverter) increased the dc electricity cost by $\$0.01$ to $0.015/\text{kWh}$ for the present day, and $\$0.003$ to $0.007/\text{kWh}$ for the 10-year case. Thus, power conditioning costs are minimal.

3.2.2 Electrolyzer Performance and Gaseous Hydrogen Production

Calculating representative present and future values for the efficiencies and costs of an electrolyzer was the next objective of this analysis. Personal communication [18] indicated that present-day ac electrolyzers have a conversion efficiency of 60% and that a commercial unit's initial cost is $\$780$ per gaseous hydrogen (H_2) production unit of $1000 \text{ Nm}^3/\text{year}$. It was assumed that the elimination of the need for ac-to-dc conversion equipment in the electrolyzer would reduce the initial cost by 30%. The resulting cost would be $\$550$ for $1000 \text{ Nm}^3/\text{year}$. In 10 years, the electrolyzer efficiencies were assumed to increase to 70%, with the initial costs remaining the same as present values.

Calculations of gaseous hydrogen production by PV electrolysis were performed by assuming that a constant value of $1000 \text{ Nm}^3/\text{year}$ of H_2 would be produced. These calculations used the PV-produced dc electricity cost results. The other electrolyzer parameters used were lifetimes of 20 and 25 years, and yearly operation and maintenance costs of 10% and 7.5% of the initial cost. These electrolyzer values are presented in the bottom of Table I.

Table IV shows the flat-plate PV array area necessary to produce 1000 Nm³/year. As expected, the desert Southwest requires the smallest PV array. Note that the reductions in size from the present to the 10-year values are due to increases in system efficiencies. PV array sizes for other H₂ production rates may be scaled linearly from Table IV.

The main parameter of interest is the cost of gaseous H₂. These costs were calculated in terms of \$/MMBtu, and the results are presented in Table V. The values of Table V are obtained by calculating the cost per year to produce the specified amount of hydrogen from the PV electricity costs of Table III plus the yearly cost of the electrolyzer equipment using a 6% discount rate and the electrolyzer lifetimes.

For clarity, an example calculation for the present-day flat-plate desert Southwest case follows. The cost of gaseous H₂ is the electricity (kWh) needed to produce the H₂ times the dc electricity price of Table III, with the result converted to MMBtu, or

$$H_2 (\$/MMBtu) = 1 \times 10^6 / 0.60 \times kWh / 3413 \text{ Btu} \times \$0.155 / kWh = \$76 / MMBtu \quad (1)$$

The annualized equipment cost is the initial cost annualized over the lifetime plus the yearly operation and maintenance cost. The initial cost of the electrolyzer for a 1000 Nm³/year production is \$565. For a 20-year lifetime at a 6% discount rate, the annual cost of the electrolyzer is \$56. The operation and maintenance cost is 10% of initial cost, or \$56. The total equipment cost is then \$112 for a 1000 Nm³/year production, which is \$9.10/MMBtu.

The total H₂ cost is \$76 for electricity plus \$9.10 for equipment or \$85/MMBtu. This calculation shows that the electrolysis equipment cost is 11% of the total H₂ cost. The last line of Table V presents the H₂ cost using conventionally produced electricity at \$0.05/kWh and the present-day electrolyzer initial cost of \$780/1000 Nm³/year.

The results for the cost of gaseous H₂ show present day prices of \$76 to \$99/MMBtu for the desert Southwest and prices of \$127 to \$185/MMBtu for the northern U.S. The cost of hydrogen for conventional \$0.05/kWh electricity is \$34/MMBTU. Thus, present PV-produced hydrogen costs for the desert Southwest are approximately 2.5 times those of hydrogen produced with conventional electricity. Gaseous hydrogen for future PV costs were \$34 to \$46/MMBtu for the desert Southwest and \$55 to \$82/MMBtu for the northern U.S. These

results show that PV-produced hydrogen costs in 10 years can be as little as 20% more than the cost of hydrogen produced with conventional electricity at \$0.05/kWh. All calculations show flat-plate tracking to be the minimum cost option.

4.0 CONCLUSIONS

This project has demonstrated the ability to coordinate the efforts of two state agencies and two federal funding agencies and to produce successful results.

A hydrogen production facility utilizing a parabolic trough, concentrating-photovoltaic electrolysis system was designed, constructed and operated by the Florida Solar Energy Center. The project began in 1990, and the six-month operational period occurred in summer and fall of 1993. The data have been segregated between the summer (July-September) and fall (October-December) seasons. The major components of the hydrogen production system are the parabolic trough concentrator, the photovoltaic receiver assembly, the cooling system and the electrolyzer cells.

The overall system efficiency for the time period of July through December was 2.8% based on total direct-normal radiation and 1.8% based on total global radiation. Although these efficiencies seem extremely low at first glance, they do show that the mismatch losses between the PV cells, the PV array and the electrolyzer are very low when compared to PV system and electrolyzer losses. The best instantaneous efficiency achieved was about 3.8% (based on direct-normal radiation).

The data taken have verified the design goals of the project, and the system has shown that a relatively inexpensive concentrator system can be successfully employed in a direct-coupled PV-electrolysis system with minimal losses. Both mismatch losses between PV cells and between PV and electrolyzer were minimal, and the system operated relatively well under totally unattended operation.

To achieve acceptable conversion efficiencies, much higher efficiency PV cells must be used. Also, much higher electrolyzer efficiencies are possible using alkaline cell technology if the cell temperatures are kept significantly above ambient temperature. Water heated by cooling

of the concentrating PV would be an excellent candidate to increase the efficiency of the electrolyzer.

The costs of gaseous hydrogen from PV electrolyzer systems for the present and for 10 years in the future were carefully evaluated in the second investigation. Results of the PV electricity cost calculations for dc electricity show that present PV-produced dc electricity costs \$0.14 to \$0.36/kWh, depending upon the U.S. location, and that \$0.06 to \$0.09/kWh is achievable in 10 years. PV system costs are \$500 to \$800/m² (\$46 to \$74/ft²) for the present, and \$325 to \$565/m² (\$30 to \$53/ft²) in a 10-year period. The variance between types of PV systems is slight, with flat-plate tracking producing slightly lower values.

The costs of PV-produced hydrogen for the present day vary between \$76 to \$185/MMBtu. For the desert Southwest, these costs are approximately 2.5 times those of hydrogen produced with conventional electricity at \$0.05/kWh. Results also show that PV-produced hydrogen costs in 10 years can be as little as 20% more than the cost of hydrogen produced with conventional electricity at \$0.05/kWh.

5.0 ACKNOWLEDGMENTS

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**TABLE I: PHOTOVOLTAIC EFFICIENCIES
AND COSTS USED IN THE SYSTEMS ANALYSIS**

PV Systems	Present Day	Ten Years
A. <u>Flat Plate</u>		
Module efficiency	12%	15%
Balance-of-system efficiency	90%	91%
Power conditioner efficiency	95%	96%
Module cost	\$400/m ²	\$250/m ²
Balance-of-system cost	\$100/m ²	\$ 75/m ²
Power-related cost	\$400/kW	\$250/kW
Operation and maintenance cost/yr.	\$3/m ²	\$2/m ²
Lifetime (years)	20	25
B. <u>Flat-Plate Tracking</u>		
Module efficiency	}	All values are the same as flat plate values.
Balance-of-system efficiency		
Power conditioner efficiency		
Module cost		
Balance-of-system cost		
Power-related cost		
Tracking cost	\$100/m ²	\$75/m ²
Operation and maintenance cost/yr.	\$3.75/m ²	\$2.50/m ²
Lifetime (years)	20	25
C. <u>Concentrators</u>		
Module efficiency	18%	21%
Balance-of-system efficiency	90%	91%
Power conditioner efficiency	95%	96%
Optical efficiency of concentrator	90%	90%
Concentrator module cost	\$600/m ²	\$400/m ²
Balance-of-system cost	\$100/m ²	\$ 90/m ²
Power-related cost	\$400/kW	\$250/kW
Tracking cost	\$100/m ²	\$ 75/m ²
Operation and maintenance cost/yr.	\$3.75/m ²	\$2.50/m ²
Lifetime (years)	15	20
D. <u>Electrolyzer</u>		
Efficiency	60%	70%
O&M cost as percent of initial cost	10%	7.5%
Lifetime (years)	20	25

TABLE II: SITE INSOLATION DATA AND AVERAGE VALUES

Cities	Daily Horizontal Insolation kWh/m ² (Btu/ft ²)	Latitude (Degrees)	Global Cloudiness Index KT	Insolation Enhancement* for Fixed at Latitude Tilt and South Facing	Insolation Enhancement* for Two-Axis Tracking	Insolation Enhancement* for Two-Axis Direct Normal Tracking
Albuquerque, NM	5.80 (1840)	35.10	0.70	1.12	1.51	1.33
Daggett, CA	5.82 (1846)	34.87	0.70	1.09	1.47	1.30
Las Vegas, NV	5.93 (1882)	36.10	0.73	1.12	1.53	1.36
Phoenix, AZ	5.90 (1873)	33.40	0.70	1.09	1.46	1.28
Prescott, AZ	5.72 (1816)	34.65	0.69	1.10	1.52	1.33
DESERT SOUTHWEST AVERAGE:	5.83 (1851)	34.83	0.70	1.10	1.50	1.32
Dallas, TX	4.64 (1472)	32.83	0.55	1.08	1.39	1.14
Honolulu, HI	5.18 (1643)	21.30	0.56	1.02	1.25	0.96
Miami, FL	4.72 (1498)	25.80	0.52	1.05	1.29	0.98
Orlando, FL	4.66 (1477)	28.50	0.53	1.05	1.30	0.98
San Diego, CA	5.02 (1593)	32.40	0.59	1.09	1.36	1.12
SOUTHERN U.S. AVERAGE:	4.85 (1537)	28.17	0.55	1.06	1.32	1.04
Atlanta, GA	4.30 (1363)	33.70	0.51	1.07	1.35	1.06
Baltimore, MD	3.89 (1235)	39.20	0.49	1.09	1.38	1.08
Charleston, WV	3.55 (1126)	38.37	0.45	1.06	1.30	0.96
St. Louis, MO	4.21 (1335)	38.70	0.53	1.09	1.41	1.14
Washington, DC	3.83 (1215)	38.90	0.48	1.09	1.38	1.08
MIDDLE U.S. AVERAGE:	3.95 (1254)	37.77	0.49	1.08	1.36	1.06
Boston, MA	3.47 (1101)	42.40	0.46	1.09	1.42	1.13
Chicago, IL	3.83 (1215)	41.78	0.49	1.10	1.42	1.14
Minneapolis, MN	3.69 (1170)	44.90	0.51	1.13	1.48	1.21
Portland, OR	3.40 (1078)	45.60	0.47	1.05	1.36	1.05
Seattle, WA	3.25 (1032)	47.50	0.46	1.06	1.39	1.09
NORTHERN U.S. AVERAGE:	3.53 (1119)	44.44	0.48	1.09	1.41	1.12

*All insolation enhancement values are with respect to the horizontal insolation.

TABLE III: PHOTOVOLTAIC DC SYSTEM AND ELECTRICITY COSTS

PV Systems	Present	Ten Years
A. <u>Flat Plate</u>		
System Cost		
\$/m ² (\$/ft ²)	500 (46)	325 (30)
\$/kW _p	4870	2480
Electricity Cost		
Desert Southwest	\$ 0.15/kWh	\$ 0.07/kWh
Southern U.S.	0.19	0.09
Middle U.S.	0.23	0.11
Northern U.S.	0.26	0.12
B. <u>Flat-Plate Tracking</u>		
System Cost		
\$/m ² (\$/ft ²)	600 (56)	400 (37)
\$/kW _p	5850	3050
Electricity Cost		
Desert Southwest	\$ 0.14/kWh	\$ 0.06/kWh
Southern U.S.	0.19	0.09
Middle U.S.	0.22	0.10
Northern U.S.	0.24	0.11
C. <u>Concentrating</u>		
System Cost		
\$/m ² (\$/ft ²)	800 (74)	565 (53)
\$/kW _p	5776	3422
Electricity Cost		
Desert Southwest	\$ 0.18/kWh	\$ 0.09/kWh
Southern U.S.	0.28	0.14
Middle U.S.	0.34	0.17
Northern U.S.	0.36	0.18

TABLE IV: FLAT-PLATE NONTRACKING PV ARRAY SIZE TO PRODUCE 1000 Nm³/YEAR

Location	Present	Ten Years
Desert Southwest	2.23 kW _p	1.93 kW _p
Southern U.S.	2.80	2.43
Middle U.S.	3.36	2.91
Northern U.S.	3.74	3.24

TABLE V: COST OF GASEOUS HYDROGEN USING PV-ELECTROLYSIS

PV Systems	Present	Ten Years
A. <u>Flat Plate</u>		
System Cost - \$/m ² (\$/ft ²)	500(46)	325 (30)
H ₂ Cost (\$/MMBtu)		
Desert Southwest	85	37
Southern U.S.	104	45
Middle U.S.	123	52
Northern U.S.	136	57
B. <u>Flat-Plate Tracking</u>		
System Cost - \$/m ² (\$/ft ²)	600 (56)	400(37)
H ₂ Cost (\$/MMBtu)		
Desert Southwest	76	34
Southern U.S.	101	44
Middle U.S.	118	51
Northern U.S.	127	55
C. <u>Concentrating</u>		
System Cost - \$/m ² (\$/ft ²)	800 (74)	565 (53)
H ₂ Cost (\$/MMBtu)		
Desert Southwest	99	46
Southern U.S.	147	66
Middle U.S.	174	78
Northern U.S.	185	82
D. <u>Electricity at \$0.05/kWh</u>		
H ₂ Cost (\$/MMBtu)	34	29

Solar Concentrator

Fig. 1. PV-electrolyzer system.

Fig. 2. IST collector system.

Fig. 3. Collector receiver assembly cross-section.

Fig. 4. Single-cell electrolyzer manufactured by The Electrolyzer Corp., Ltd.

Fig. 5. Make-up water treatment hardware.

Fig. 6. Seasonal system performance.

Fig. 7. Electrical characteristics of AstroPower cell.

Fig. 8. Conversion efficiency for typical summer day.

Fig. 9. Conversion efficiency for typical fall day.

Fig. 10. Electrolyzer temperature vs. time of day.

Fig. 11. Electrolyzer efficiency.