PHOTOVOLTAIC HYDROGEN PRODUCTION PROTOTYPE: SUSTAINABLE ENERGY FOR RESIDENCES[1]

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ABSTRACT

Residential use of hydrogen (H_2), for utility or personal transportation, is currently limited by economic effectiveness, lack of residential sources, and need for engineering improvements. A modular photovoltaic hydrogen production prototype (PHPP) was constructed to produce three liters of hydrogen per day at standard temperature and pressure with maximum energy and Faraday efficiencies of 75% and 89%, respectively. Producing 3 liters of H_2 with the PHPP required 2.4 milliliters of distilled H_2O and 26 kJ of solar energy and eliminated 1.5 liters of byproduct CO_2 relative to steam reforming of methane to generate H_2. A capital investment of $5,651 to produce 30 liters per day using additional PHPP modules gave a return on investment of 4.2% and a payback period of 7.5 years. Interdisciplinary teams of university and high school students constructed the PHPP and were familiarized with key aspects of sustainable use of hydrogen as an energy carrier. Language and geographical barriers to effective communication and teamwork among the students were met by organizing teams to meet student needs, providing instruction and hands-on training in teamwork and facilitating web-based and in-class interactions. Quantitative ethnographic observation of student interactions showed involving students in lectures and extracurricular presentations and enhancing communication and teamwork with constructive responses to student feedback increased student satisfaction with the experience.

KEY WORDS

photovoltaic hydrogen, electrolysis, Photovoltaic Hydrogen Production Prototype (PHPP)

INTRODUCTION

Conventional sources of energy derived from fossil fuels do not meet increasing global requirements for nonpolluting, sustainable development. Sustainable development employs renewable natural resources equitably distributed with a level of economic well-being that can be perpetuated without compromising the ability of future generations to meet their own needs.[1] Fossil fuels are finite, nonrenewable resources with limited availability. Global demand for fossil fuels is anticipated to outstrip production capacity within a decade.[2] Fossil-fuel derived energy sources emit particulates, volatile organic compounds, SO_x, NO_x, CO and CO_2.[3] Worldwide, ten million tons of sulfur and lesser quantities of NO_x are emitted. With only 5% of the world's population, the United States produces 26% of the five billion tons of global carbon emissions per year and imports 55% of the oil it consumes domestically.

Hydrogen (H_2) represents a potential local source of sustainable zero-emission energy for point-of-use in electric utility in commercial/residential buildings, transportation or industrial applications (hydrogen sustainability). Implementation of photovoltaic hydrogen for residential usage, over the past 40 years, has evolved from converting home appliances to run on hydrogen gas[4] to entirely supplying a resident's home and automobile energy demands via fuel cells.[5] But as an energy carrier hydrogen is currently not cost-competitive with oil or natural gas due in part to limited infrastructure, idealistic economics and need for engineering improvements. Yet creating an economical production of hydrogen presents desirable outcomes that would eliminate atmospheric pollutants, preserve fossil fuel resources for future generations, and allow grass roots and local use of H_2 in developed and developing nations by eliminating infrastructure requirements.

Photovoltaic electrolysis of water to produce three liters of H_2 per day was selected to demonstrate the sustainability of H_2 as well as provide hands-on instruction of renewable energy to students. Photo-

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voltaic generation and subsequent consumption of H_2 is a sustainable process in which solar energy is absorbed to cycle hydrogen in water from a liquid molecule component to a gaseous energy carrier. An interdisciplinary group of university and high school students was organized to construct a scalable, energy-efficient photovoltaic hydrogen production prototype using commercially available components, comparing the costs of raw materials, capital, operation, and maintenance. The economical and environmental benefits arising from photovoltaic generation of H_2 were examined and results were publicly disseminated.

High school students were selected through a partnership created through the Lowell Bennion Community Service Center (Bennion Center) between University of Utah and the Academy for Math, Engineering and Science (AMES). AMES is a public charter high school in Salt Lake City that provides a pre-engineering curriculum to traditionally underserved students including a significant percentage of ethnic minorities (38%) and first-generation college bound students (31%). The Bennion Center is a university center that fosters lifelong service and civic participation by engaging university students, faculty and staff with the greater community in projects, shared curricula and learning activities. University of Utah students were drawn from departments in Engineering, Architecture, Biology, Economics, Communication and Political Science to provide an interdisciplinary context for hydrogen sustainability. Seminar curricula were designed and administered by professors from University of Utah departments of Architecture, Biology, Communication, Economics, Engineering and Political Science, administrators from the Bennion Center and educators from AMES. Organizational communication specialists from the Center for Leadership in Engineering and Research (CLEAR) at the University of Utah provided instruction and hands-on training in teamwork.

EXPERIMENTAL METHODS AND COMPONENTS

Photovoltaic Hydrogen Production Prototype

The layout and orientation of the PHPP is illustrated in Figure 1. The semiconductor photovoltaic panel (at six o'clock position) consisted of four amorphous silicon p-n junction semiconductor cells soldered in series at a cost of $400.[6,7] Continuing clockwise in Fig 1, modular electrolyzer cells were machined at the University of Utah Machine shop. The initial unit cell consisted of a pair of opposing distributors and two endcaps and cost $687. Additional distributor pair units cost $200 each. High-grade nickel mesh screens with 1 1 µΩ-cm resistivity at 20°C, were used as electrodes to contact the Nafion(polymer electrolyte membrane, which cost $90 per cell (Nafion 112; DuPont 2003, 51 microns thick, 100 g/m^2; Ion Power, Bedford, MA). The system for hydrogen purification and storage cost $2,444. It consisted of (1) a distilled H_2O scrubber or "bubbler" in a Pyrex column (Cole Parmer Instrument Company) at ten o'clock in Fig 1; (2) C-type coalescers (P/N S1M-2C10-025; Parker Filtration, Oxford MI) to remove water vapor from gaseous scrubber effluent and from recombiner effluent at twelve o'clock and four o'clock in Fig 1.; (3) a catalytic recombiner (Model RCP-10-2000-4SS; Resource Systems, Inc., East Hanover, NJ) to remove residual O_2 from H_2 at three o'clock in Fig 1; (4) flashback arrestors (Model FA-1; Western Enterprises, Westlake OH) before and after the recombiner in Fig 1. containing an integral check valve to prevent H_2 backflow and a silica screen to quench any flame front; (5) a check valve to provide pressure relief for pressures in excess of 58 psig; and (6) a flexible hydrogen containment bladder (P/N D1075006-10; Cole Parmer Instrument Company, Vernon Hills, IL) not shown attached to the terminal flashback arrestor in Fig 1.

Economic Measures

Ten year straight-line depreciation (D) was used and tax rate (t) was assumed to be 37%. Return on investment (ROI) and payback period (PBP) were calculated as:[6]

$$ROI = \frac{(1-t)(S-C)}{TCI} \quad (1)$$

$$PBP = \frac{TDC}{(1-t)(S-C)+D} \quad (2)$$

Measures of PHP Efficiency

Energy efficiency, η_{energy}, of the electrolyzer was determined by dividing the energy released by burning the measured volume of hydrogen evolved, V_{H2}, by the electrical energy, the product of amps, volts and time, I*V*t, used to release V_{H2}:[8]

$$\eta_{energy} = \left(V_{H2} * 286{,}000 \frac{J}{moleH_2} \frac{1}{24{,}000} \frac{moleH_2}{cm^3} \right) \bigg/ \left(V * I \frac{coulombs}{sec} * t \, sec \right) \tag{3}$$

Faraday efficiency, $\eta_{Faraday}$, of the electrolyzer was determined by dividing the measured volume of hydrogen evolved, V_{H2}, in time t at current I by the theoretical volume evolved:[9]

$$\eta_{Faraday} = V_{H2} \bigg/ \left(24{,}000 \frac{cm^3}{moleH_2} * I \frac{coulombs}{sec} * t \, sec * \frac{1}{2} \frac{moleH_2}{e^- - mole} * \frac{1}{96{,}500} \frac{e^- - mole}{coulombs} \right) \tag{4}$$

Educational Methods

Students were organized into five teams containing two high school and two university students. The student group included ten women, two Hispanics, one black, one Polynesian, and one Armenian. Student teams participated in a one-credit-hour Hydrogen Sustainability service-learning seminar (ChFEN 4975) co-sponsored by the Bennion Center and the Department of Chemical Engineering at the University of Utah; meeting two hours every other week in the first semester and two hours every week in the second semester. CLEAR specialists monitored seminar instruction and activities, assessing team-member interactions and attitudes towards the K-12/university interdisciplinary service-learning seminar and facilitated ongoing feedback.[9]

Lecturers introduced sustainability concepts during the 1st hour and mentored project development by student teams in the 2nd hour. Representatives from non-profit local civic organizations invested in sustainability, including Envision Utah, Clean Cities USA and the Salt Lake Valley Airshed Project, presented guest lectures and led student discussions. Lectures were structured to encourage students to actively engage in the thinking process, participate in group discussions, contribute as a team member, and increase student's awareness of sustainable energy developments.

RESULTS AND DISCUSSION

Photovoltaic Hydrogen Production Prototype (PHPP)

The layout and orientation of the PHPP is illustrated in Figure 1. P-n semiconductor photovoltaic cells soldered in series on a panel capture incident

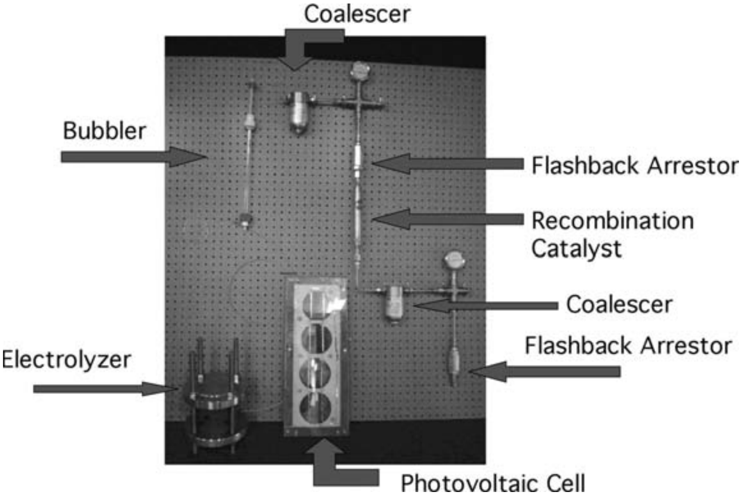


FIGURE 1. Photovoltaic hydrogen production prototype (PHPP) including PV panel, electrolyzer and H_2 purification system. Individual components are described in the accompanying text.

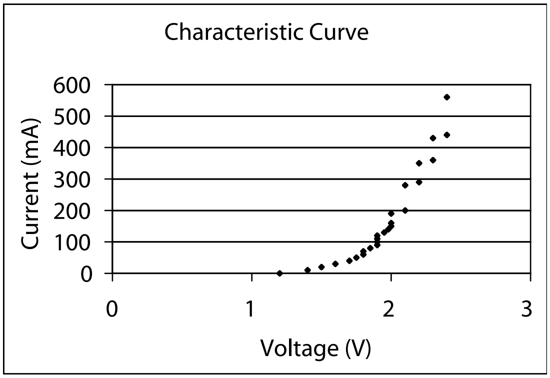
solar radiation at bandgap energy levels corresponding to the decomposition voltage of water. A platinum-catalyst coated polymer electrolyte membrane (PEM) separates H^+ from O^- split from H_2O. Oxidation of oxygen and reduction of hydrogen occurs at nickel anode and cathode, respectively, adjacent to the PEM. Hydrogen is purified from particulates and residual oxygen and stored for use in an adjoining hydrogen fuel cell (not shown).

Semiconductor Photovoltaic Panel

Amorphous silicon p-n junction semiconductors were used in place of $GaInP_2/GaAs$ semiconductors[10] because they were less expensive and readily available. Reported efficiencies of Gallium semiconductors are 30.5% (V_{mp} = 2.64 V and J_{mp} = 4.05 A/cm^2) at 350 suns (37.2 W/cm^2) (Spectrolab; 191-µm thick triple-junction concentrator cell on a Ge substrate). Also considered were $CuIn_{1-x}\ Ga_x\ Se_x$ (CIGS) and $CuIn_{1-x}\ Ga_x\ S_2$ (CIGS2) thin film photovoltaic cells, which proved to be costlier and more difficult to procure. Due to reported corrosion of photoelectrochemical cells in electrolyte media,[11] photovoltaic cells were not contacted directly with the electrolytic cell. The four cells in the photovoltaic (PV) panel were soldered in series to supply 2 A at 2 V based on early estimates of PHPP energy efficiency. At optimum orientation in full sunlight the completed panel supplied 2.2 A at about 2.3 V, as shown by the characteristic curve in Figure 2. A single unit cell consumed between 0.5 and 0.7 A at 2 V. An imbalanced load resulted from connecting the PV panel to a single electrolytic cell, but adding more unit cells in series would balance the load.

Adequate power to produce 3 liters H_2 per day was dependent on the available power per unit area, at the PHPP location. Energy from incident radiation required to split one mole of water is 2.229 eV. At standard conditions this is equivalent to 118.6 kJ per 1 mole of H_2O or 22.42 liters of H_2. Producing three liters H_2 per day thus requires 15.9 kJ per day. According to the National Solar Radiation Database (http://rredc.nrel.gov/solar/old_data/nsrdb/), the lowest incident light in Salt Lake City occurs in December and results in ~11,507 kJ/day per m^2. Thus the minimum required surface area is 13.8 cm^2 for 3 liters of H_2 per day, divided by the solar-to-hydrogen efficiency.

FIGURE 2. Characteristic curve of the PHPP showing and overpotential of 0.17 volts.



Electrodes

High-grade nickel (Ni) screen electrodes with 11 µΩ-cm resistivity at 20°C contributed to a measured overpotential of 170 mV in the system as shown in Figure 2. Overpotential is the difference between the experimental decomposition voltage (minimum voltage needed to split water) and the cell voltage of the $H_2/H_2O/O_2$ galvanic cell under standard conditions, 1.23 V. Overpotentials of 0.3–0.5 V are common in low-temperature $H_2/H_2O/O_2$ cells. The magnitude of the overpotential depends on electrode material, electrode surface texture, electrolyte type and concentration, current density and temperature.

Polymer Electrolyte Membrane (PEM)

The Nafion® PEM membrane consists of a polytetrafluoroethylene backbone derivatized with perfluorinated vinyl polyether with terminal sulfonic acid groups to exchange the protons. Long-term instability of the PEM and decreased proton flux at temperature (T) > 100°C, at T < 95% limit current application of hydrogen fuel cell technology in transportation. Polyfuel, Inc. introduced a new membrane[12] reported to provide 10–15% more power output at low relative humidity (~35%) and an operating temperature of 95°C; unfortunately the product was unavailable at the time of the PHPP assembly.

Electrolyzer cell

Novel, scaleable electrolyzer cells were designed consisting of opposing circular Teflon endcap distributors. In each cell, the distributors sandwiched nickel screen anode, Pt-coated PEM and nickel screen cathode, respectively, between rubber gaskets. Distilled H_2O was gravity fed from 6 symmetric inlets into the periphery of the anodic endcap via a semicircular groove and flowed radially inward toward a single exit port at the center of the anode. Hydrogen gas produced at the cathode exited the cells through 6 radially symmetric channels into the H_2 purification system. This design eliminated mechanical pumping of H_2O into the cell. Stacking each electrolyzer cell end-to-end with an adjacent electrolyzer cell provided ease of scaleability.

Solar Distillation

A solar still (not shown) was customized to heat and distill water for H_2 generation by the PHPP up to 3 liters per minute (LPM) to eliminate a projected electrical requirement of 2750 kW ($110.08 per day) at 3 LPM. At production rates of 3 liters of H_2 per day (2.4 milliliters of H_2O), however, it was more cost-effective to gravity feed 18 MΩ distilled deionized water (Millipore Corp., Bedford, MA) into the cells.

Hydrogen Purification & Storage

The purification system consisted of a bubbler and catalytic recombiner with associated coalescers, flame arrestors, check valves and a pressure relief valve set at 58 psig. Thirty liters H_2 per day could be purified by the system at pressures up to 58 psig. All reported data were obtained at 647 mm Hg, the ambient pressure in Salt Lake City. H_2 gas from the electrolyzer is scrubbed with distilled H_2O in a Pyrex column to remove particulates that might include flakes of Pt black from the PEM. Water vapor from the electrolyzer and scrubber coalesces in a C-type coalescer. To achieve a 99% purity specification for compressed hydrogen that arises from a 6.4% the upper flammability limit of O_2 in H_2, a catalytic recombiner was installed to combine residual O_2 with H_2 prior to storage. The recombiner consisted of 0.5% Pt coating 1/8-inch alumina pellets in a stainless steel tube. Pre- and post-combiner flashback arrestors contained integral check valves to prevent H_2 backflow and silica screens to quench any flame front. Flexible bags allowed low-pressure (Orientation of the Semiconductor Photovoltaic panel

Optimum orientation and angle of photovoltaic cells in the panel was determined by examining 30-year averages of incident sunlight for each month in Salt Lake City obtained from the National Solar Radiation Database; maintained by the Renewable Resources Database Center, RReDC, a division of the Department of Energy. Panels were oriented southward at an angle of 55°, based on the latitude of Salt Lake City (40°) plus an additional 15° to maximize incident solar light collected during winter months.

PHPP Efficiency Relative to Photovoltaic Area Requirement

Figure 3 shows, η_{Energy} of the PHPP, calculated using Eqn 3, decreased from 0.67 to 0.61 (blue diamonds) as voltage increased from 2.1 to 3 V. By increasing the contact area between the Ni electrode and the PEM, measured energy efficiency at 2.3 V increased from 0.66 to 0.75. Figure 4 shows Faraday efficiency, η_{Faraday}, of the PHPP, calculated using Eqn 4, increased from 0.62 to 0.81 as voltage increased from 2 to 2.5 V. Values near unity indicate that secondary reactions such as corrosion are not occurring. By increasing the contact area between the Ni electrode and the PEM, measured Faraday efficiency at 2.3 V increased from 0.78 to 0.89.

Streamlined Life Cycle Costing and Analysis

Total capital investment (TCI) for the modular PHPP system scaled to produce up to 30 liters H_2

FIGURE 3. PHPP Energy Efficiency as a function of voltage. Lower (diamond) and higher (square) contact surface area of nickel electrode with PEM.

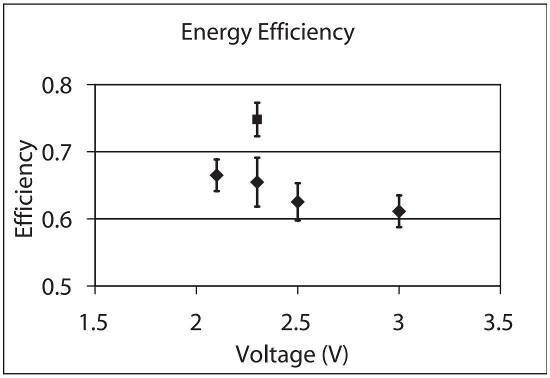
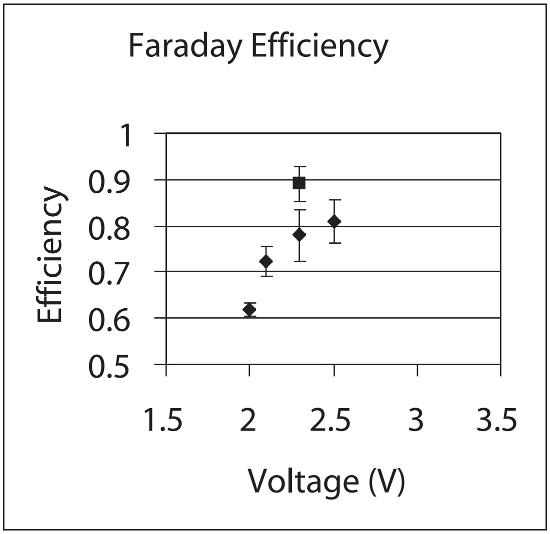


FIGURE 4. PHPP Faraday Efficiency as a function of voltage. Lower (diamond) and higher (square) contact surface area of nickel electrode with PEM.



per day from 24 milliliters of H_2O using 260 kJ of solar energy and 10 electrolyzer cells per stack was \$5,651. Replacing PHPP electrical duty for pumping and heating by gravity and solar energy reduced annual utility costs (C) for operation to a negligible amount for H_2O (<\$0.01 for 24 milliliters). Negligible costs for startup, land, royalties and working capital resulted in total depreciable capital (TDC) equal to TCI. Annual sales (S) of H_2 would be \$378 using a price of \$0.0345/liter for 99.9% purity, which is 50% greater than current market price. Energy tax credits available for adopting solar-derived H_2 and public demand for non-polluting, renewable sources of energy are anticipated to support a price 50% greater than the current market price. Using 10-yr straight-line depreciation (D) with an estimated salvage value of \$500, return on investment (ROI) is 4.2% with a payback period (PBP) of 7.5 years using the expressions in Equations 1 and 2. The cost and durability of the PEM are crucial: annual replacement gives maintenance costs (C) of \$720.

The PHPP provides sustainable energy at a positive initial cash flow, but the low return and long payback period are marginal and highly sensitive to PEM replacement costs. Design refinements and system optimization to increase productivity threefold and reduce TCI to one-third the value of the first unit could accommodate annual PEM replacement and provide better values of ROI = 13.8% and PBP = 4.7 years.

Environmental Benefits of PHPP

Every 3 liters of H_2 produced by modular PHPP eliminates 1.5 liters of byproduct CO_2 relative to steam reforming of methane to generate H_2. Three liters of H_2 per day requires 2.4 milliliters of H_2O and 26 kJ of solar energy at 60% energy efficiency. At this rate, nonpolluting, sustainable H_2 energy equivalent to 1 liter of gasoline is produced from 339 milliliters of water in 140 weeks, using a solar photovoltaic area of 13.8 cm^2 oriented southward at 55°, divided by the solar-to-energy efficiency. The design of the PHPP eliminates electrical requirements for pumping and distillation/heating using gravity and solar energy, respectively.

Obstacles of Conventional Photovoltaic Hydrogen Production

Economic limitations are ultimately due to technology barriers and costly materials; namely solar panel efficiency and electrolyzer components. For photovoltaic hydrogen to become a feasible energy alternative it will essentially require a more competitive production, delivery, and storage than established energy approaches.[13] Recently researchers at MIT reported significant advancements in solar panel technology. Ordinary glass is coated with two or more layers of light-capturing dyes collecting and channeling sunlight to solar cells “generating at least ten times more power.” This breakthrough technique provides and efficient affordable process with an estimation of three years until it becomes commercially available.[14]

University and High-School Student Teams

Teams were organized with attention to language barriers, learning styles, and mentoring roles. For example, a non-native English-speaking high-school student was paired with two university students and an advisor who were conversant in that student’s native language. In the first semester, student teams designed and specified complementary elements of the PHPP. Team 1 designed a solar still and an H_2O supply system. Team 2 identified coalescers for dehumidification and flashback arrestors to contain H_2-O_2 recombination. Team 3 applied energy balances to eliminate H_2 compression. Team 4 designed the electrolyzer cell using Nafion" PEM. Team 5 specified and constructed the photovoltaic solar panel. In the second semester, student teams that were reorganized based on student input and participation style created a Hydrogen Sustainability website. The teams evaluated and built web pages discussing (1) current U.S. energy stocks, sources and sinks; (2) impacts of current U.S. energy policy; (3) application of hydrogen technology; (4) the solar hydrogen economy; and (5) global hydrogen sustainability, respectively.

Assessment of Students' Experiences in Service Learning and Engineering Design

Quantitative and qualitative ethnographic observation of students' classroom experiences was performed by CLEAR consultants. Pre- and post-semester tests were administered to the students to assess cognitive learning using twenty-five questions contributed by faculty instructors to analyze understanding of basic terms and concepts regarding technical, environmental and economic aspects of hydrogen sustainability. A separate evaluation was administered to assess students' experiences, perspectives and attitudes toward service learning, K-12 classroom integration, teamwork, engineering design and other aspects of the course. Increasing student participation in lectures and extracurricular presentations and enhancing communication and teamwork increased student satisfaction in the program.[15]

Methods for Instruction and Dissemination of Results

Student feedback in the first semester indicated the five miles separating university students on the University of Utah campus in northeast Salt Lake City from high school students on the AMES campus in Cottonwood prevented personal interaction between university and high-school students outside class time, which decreased effective communication and teamwork. Instructors responded by increasing time available in-class and by implementing internet-accessible web pages to prepare and submit homework assignments, create chat rooms, received course updates, post supplemental material, and post grades. Students were granted access and trained to use the WebCT system. Consequently student groups communicated about the various projects that were assigned on group chat rooms.

To enhance communication and team interactions in the second semester, classrooms were scheduled weekly, alternating between AMES high school and the University of Utah. This gave twice as much time for student team interaction, provided more equal footing for interactions between high school and university students, and allowed student access to unique AMES resources for web design and development.

Students responded positively in the first semester to opportunities to report on PHPP developments. In second semester, arrangements were made for students to present a discussion of "Photovoltaic Hydrogen Production Prototype" to an audience of students, educators and press.[16] Participants in the Hydrogen Sustainability Seminar were recognized by local media[17] and university organizations[18] as well as national sponsors. Two undergraduate researchers presented a description of the PHPP to Utah State Legislators.[19] One student presented a summary of the PHPP at the departmental undergraduate seminar.[20] Three students in Public Relations Cases and Campaigns (COMM 5580) collaborated with the Hydrogen Sustainability Seminar to prepare a public relations media kit to demonstrate the PHPP on in the National Mall in Washington, D.C. The kit contained press releases, brochures, newsletters, feature stories and an in-depth backgrounder on the history and future of hydrogen sustainability. All students participated in a hands-on demonstration in Washington D.C., which was attended by members of the National Academy of Engineering, the Environmental Protection Agency, and President Michael Young from the University of Utah. Two AMES high school participants were selected to present results of the project at a high school student research symposium.[21]

CONCLUSIONS AND RECOMMENDATIONS

Five teams of university and high school students collaborated effectively to engineer and construct a modular photovoltaic hydrogen production prototype (PHPP) that produced 3 liters of H_2 per day, to build a website discussing key aspects of Hydrogen Sustainability and to publicly disseminate their results in a variety of local, regional and national venues. Producing 3 liters of H_2 per day required 2.4 milliliters of distilled H_2O and 26 kJ of solar energy and eliminated 1.5 liters of byproduct CO_2 relative to steam reforming of methane to generate H_2. The PHPP could produce nonpolluting, sustainable H_2 energy equivalent to 1 liter of gasoline from 339 milliliters of water in 140 weeks, using a solar photovoltaic area of 13.8 cm^2 oriented southward at 55^o divided by the solar-to-energy efficiency. Energy efficiency and Faraday efficiency in the PHPP increased from 66 to 75% and 78 to 89%, respectively, after contact between a nickel anode and the Pt-coated polymer electrolyte membrane was increased. The modular design allowed easy scale-ability to produce 30 liters H_2 per day with a total capital investment (TCI) of $5,651. This resulted in a return on investment (ROI) of 4.2% and a payback period (PBP) of 7.5 years.

Geographical, language and educational challenges were effectively met to create experiences for university and high school students as mentors, leaders and team members that were both productive and individually satisfying. Quantitative ethnographic observation of students' participation in a Hydrogen Sustainability Seminar identified two ways to enhance students' experience: increased student participation in lectures and extracurricular presentations and facilitating communication and teamwork by increasing in-class interaction time at both the university and high school and by adopting internet-accessible web pages that facilitated dialogue via chat rooms and e-mail.

Coupling the PHPP to a fuel cell would provide a point-of-use source of on-demand, sustainable energy. Further efficiency increases could be obtained by increasing catalytic efficiency at the anode and improving vapor-liquid mass transport at the catalytic surface. Implementation of photovoltaic hydrogen as a mainstream energy provider, as a fuel and electric utility, continues to depend on engineering improvements to increase system efficiency and economic demand to decrease material costs. Students participating were introduced firsthand to prevalent issues and dynamic challenges often encountered by engineers: cost, efficiency, time usage, demand, assembly, and teamwork. Throughout the experience students positively responded and solved challenges presented.

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