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News and Views

The homemaker's hydrogen generator: A report for IAHE student hydrogen design competition 2010

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ABSTRACT

As a highly reactive gas, hydrogen presents significant challenges for its acquisition and safe storage. Consequently, the viability of a sustainable hydrogen economy greatly depends on the development of an efficient, cost-effective method of hydrogen production. One model for addressing this challenge is to deploy portable hydrogen generators for the home. The Princeton University Chapter of the International Association for Hydrogen Energy (IAHE-PU) has designed and created a generator that produces hydrogen through water electrolysis and optimizes cost effectiveness and portability while maximizing hydrogen output.

For our proof-of-concept, the system utilizes simple household items with a Sharp ND130UJF 130W solar panel. In our design, Ni electrodes submerged in 8 M KOH solution in six glass containers were utilized to power an external circuit. Over 1 h, our system produced 8.61 L of hydrogen gas at an estimated cost of $8.58 per kilogram of hydrogen gas over the 25-year lifetime of the solar panel.

1. Introduction

Hydrogen gas, unlike other common sources of energy, cannot be mined like coal or pumped from the depths of the earth like petroleum or natural gas. Because of its high reactivity, hydrogen does not exist in its pure form on earth, presenting significant challenges in the acquisition and safe storage of the highly explosive gas. Furthermore, since the molecular weight of hydrogen gas is low, hydrogen can readily overcome earth's gravity and escape the atmosphere, accounting for the relative scarcity of hydrogen in the air. As such, the viability of a sustainable hydrogen economy greatly depends on the development of an efficient, cost-effective method of hydrogen production.

Our project designed and built a model solar-powered hydrogen generator, and investigated its energy conversion efficiency as well as economic feasibility of supplying power for home use applications.

2. Method and material selection

Various methods of hydrogen production exist, the most commercially widespread of which involves the breakdown of hydrocarbons, specifically of methane, by the steam reforming process. However, such reactions prolong our dependence on the earth's depleting supply of nonrenewable resources. In addition, they result in the emission of carbon compounds,

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such as CO and CO2, which pose environmental risks if released into the atmosphere. Electrolysis, which splits the water molecule into oxygen and hydrogen by means of an electric current, is a cleaner option. Not only are there zero carbon emissions involved, but no fossil fuels, such as methane, are required.

Our initial survey of potential methods to design a portable solar hydrogen generator led us to two viable options: biological and photovoltaic-electrolysis. At first, we were intrigued by the opportunities to exploit large colonies of bacteria, and considered mechanisms such as photolysis, photo-fermentation, water-gas shift, and dark-fermentation [1]. Our first consideration, the water-gas shift reaction, generates substantial amounts of hydrogen by converting CO and H_2O to H_2 and CO_2; one of the bacteria, *Rx. gelatinosus*, has close to perfect efficiency [1]. Yet we discovered that the bacteria's efficiency decreases significantly when operated in the presence of the air [2,6].

The remaining biological hydrogen production methods rely on direct photolysis and indirect photolysis. Comparing the predicted rates of hydrogen production for biological photolysis and photovoltaic-electrolysis systems, they are roughly on the same order of magnitude for an experiment of our scale. [3,4] However, because the biological approach also has many design and portability challenges relating to the growth and sustenance of the bacteria, we decided to focus on the more established path of hydrogen generation, photovoltaic (PV) electrolysis.

The chemical equations describing the basic electrolysis reaction are [5]:

$$\text{Net Reaction}: \; 2H_2O\,(l) \rightarrow 2H_2\,(g) + O_2\,(g)$$

$$\text{Cathode (reduction)}: \; 2H_2O\,(l) + 2e^- \rightarrow H_2\,(g) + 2OH^-\,(aq)$$

$$\text{Anode (oxidation)}: \; 2H_2O\,(l) \rightarrow O_2\,(g) + 4\,H^+\,(aq) + 4e^-$$

The most common method to produce hydrogen using electrolysis is alkaline-based, but proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cells (SOEC) are slowly becoming practical alternatives [6]. Alkaline electrolyzers are usually composed of two electrodes separated by a thin membrane in an alkaline electrolyte, like KOH or NaOH. PEM electrolyzers are essentially PEM fuel cells run in reverse with a Nafion membrane as the separator but, compared to alkaline systems, require additional components like current collector plates, a water supply system, and a water circulation pump [7]. SOEC cells are theoretically the most efficient, but they face many problems, including corrosion and sealing [6]. While alkaline electrolyzers may be the least efficient of the three, they are the most established technology, developed, reliable, easiest to assemble, and lowest in cost [6]. Our decision to develop an alkaline-based electrolyzer stems from the fact that all of the components are readily available, the system is easy to assemble and deployable on a large scale, and the parts are cost-effective, fulfilling all of our objectives for the project.

2.1. *Challenges of PV-Electrolytic hydrogen generation*

In scaling up our system, the feasibility of mass-electrolysis depends on several factors, including high efficiency, low cost, intermittent operation, large range of operation, immediate response to control, and built-in safety precautions. It is also important to decide whether to enlarge the electrolysis unit or to build more small cells to maximize hydrogen production while minimizing cost [8]. We also need to consider the power source. Harnessing solar energy, as we did, is a clean method, but modern solar cells suffer from relatively low efficiency. Also they require reliable exposure to sunlight, which cannot be attained at night or during certain weather conditions. Advancement in solar panel technology could make solar energy a more viable option. Despite these challenges, modern commercial-sized alkaline electrolysis units exist but they contribute only a small fraction of the hydrogen produced industrially [9].

2.2. *Selection objectives*

In designing our laboratory-scaled photovoltaic-electrolytic hydrogen generator, we have taken considerations of factors such as scale-up economics and potential applications for home use. The selection of experimental setup and material was therefore based on three objectives: cost effectiveness, portability, and maximum hydrogen output.

2.2.1. *Cost effectiveness*

Our project had a limited budget of \$1500[1], so our setup had to be designed with cost in mind. We needed to account for the cost of experimental materials in our trials. Our initial prototype, consisting of a 2 L polycarbonate box, was custom made at the university for \$80. This would be not economical for scale-up. Eventually we were able to find necessary components for constructing the electrolysis cells from general household items. Please refer to the Appendix for a detailed list of material and cost. The Sharp ND130UJF 130W Solar Module Panel constituted the bulk of our expense. The external power source for indoor experiments, soap bubble meter, and lab equipment were borrowed from the Princeton University Department of Chemical & Biological Engineering at no additional cost.

Working within a budget is a challenge, but the feasibility of applying our model on large scale requires such monetary considerations. One of the biggest obstacles of reverting to a hydrogen energy economy is the lack of economic incentive to change the entire energy infrastructure from petroleum-based to hydrogen-based. It is essential to develop an economical method of hydrogen production to warrant such a change.

2.2.2. *Portability*

Just as money was limited, so also was space. Our prototype could have a maximum volume of 1 m cubed. In response to this constraint, we had to determine the most efficient setup that was within this size range. Although in reality there is no specific size restriction for hydrogen generators, researchers aim to keep methods of production as small and portable as possible. Large units are costlier to build and more cumbersome to maintain. We too, when designing our setup,

[1] From the Norman D. Kurtz '58 Fund for Innovation in Engineering Education, Princeton University.

considered size and portability. If our prototype were to be adapted on a large scale, the smaller our unit, the more economically attractive our method would be.

2.2.3. *Maximum hydrogen output*

Portability and size are important, but while keeping units small, hydrogen production must remain high. The most economically effective method is one that optimizes both portability and hydrogen generation. Our many trials were intended to use the least possible external power (the lowest possible voltage) that could produce the most hydrogen. Thereby we could find the minimum number of solar panels required for our prototype to work at maximum efficiency.

Electrolysis requires an electric current, since the formation of hydrogen is not a spontaneous process. As a result, the choice of how much power to apply to the unit and the source of that power are very important to consider. As required, we decided to harness our energy from the sun, via photovoltaic cells. However, nonrenewable sources of energy are often used to power electrolysis units because they are more efficient. The use of renewable energy sources, specifically that of solar energy, is unlikely unless we make advancements in solar cell technology. Modern cells have poor efficiency and are ineffective at night or during bad weather. We must realize, however, that in the long term, hydrogen production powered by renewable energy sources is worthwhile, environmentally and sustainability-wise.

3. Experiment and analysis

Our team chose to focus on the method of solar-powered alkaline electrolysis as a means of hydrogen production. We decided to keep our experimental setup simple, with the main objective being optimization of a small-scale electrolysis unit. The components of our system included various metal electrodes and electrolyte solutions. For our preliminary experiments, we tested two alkaline electrolytes, NaOH and KOH, in different molar concentrations. We likewise experimented with a selection of metal electrodes, including Ni, Al, and NiO. Our goal was to test all these variables to find the most effective setup that produced the most hydrogen gas.

3.1. *Design and construction*

We custom-designed and built our initial electrolysis setup, creating a polycarbonate box sealed with silicone, with openings on top for the electrodes. However, when working with highly concentrated electrolyte solution, we found that silicone was not an effective seal. Instead, we decided to continue our trials using common household items, such as durable *Tupperware*® and *Glasslock*™ containers, to house our electrolysis experiments. They provided an airtight cell from which the hydrogen produced could successfully be measured through a small opening using a soap bubble meter with negligible leaking.

Our final system (Fig. 1 a, b, c) utilizes *Glasslock*™ containers with a small outlet on one side of the lid for the gas collection tube and two tiny holes for wires to connect the electrodes which are immersed in 8 M KOH solution to the external circuit powered by a *Sharp*® *ND130UJF* 130W Solar Module Panel. We decided to use 8 M KOH solution since that allows "close to maximum conductivity" for KOH dissolved in water [10]. We settled on Ni electrodes for both the anode and cathode because of its chemical stability in the presence of concentrated KOH solution and relatively inexpensive cost [11]. We tried to separate the two electrodes with a very thin membrane so that hydrogen gas and oxygen gas would not mix, but we did not achieve complete separation. We also had to rely on caulk to effectively seal the interface between the electrolysis box and the gas collection tube so the gas could be measured by the soap bubble meter.

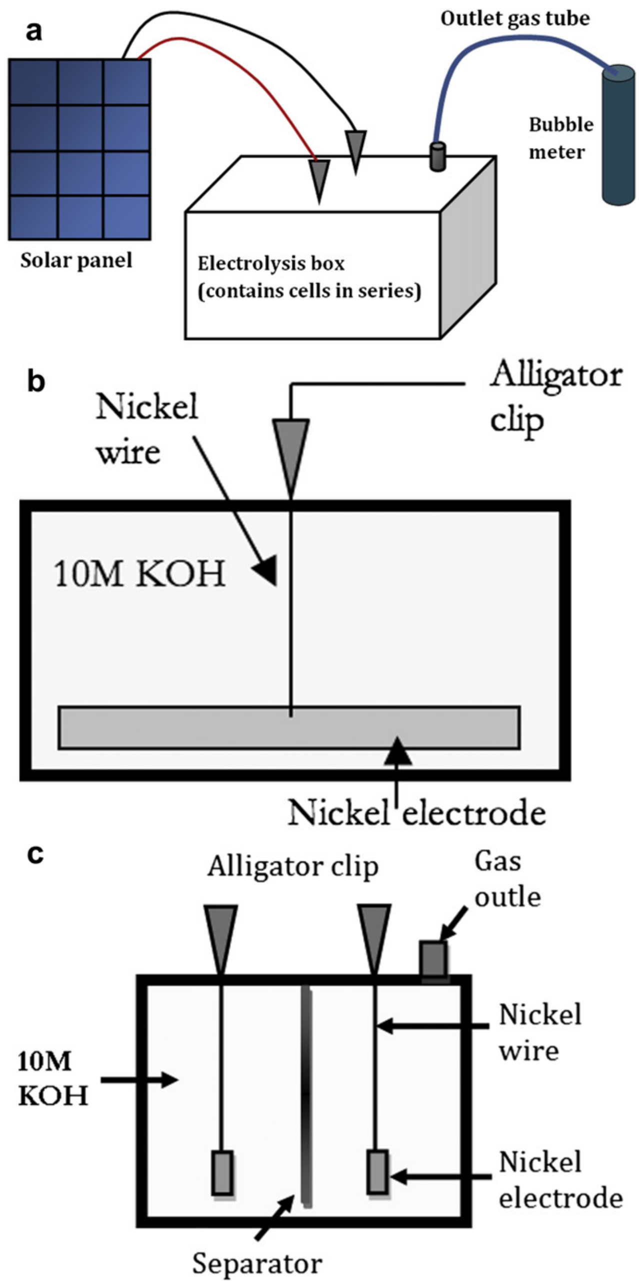

Fig. 1 – (a): Schematic of Setup, (b): Side View of a Single Cell, (c): End View of a Single Cell.

3.2. *Experiment*

For our trial tests, we started by using an electrical power source to power one of our electrolysis cells indoor, varying the voltage and recording the current produced and the rate of gas production using a soap bubble meter. By starting with an outside power source, we hoped to find the optimal voltage and setup for gas production, which would enable us to find an appropriate solar cell with a similar voltage rating. Based on our calculations (Section 4.1), we also determined the near-optimal number of electrolysis cells in series for maximum hydrogen production to be 6 which was then confirmed by experiment. Our final setup consists of six identical electrolysis cells placed in series with a solar cell though only one of them is connected to a soap bubble meter for measuring the volume flow rate of gas being produced.

For our generator, the major quantity being measured was the amount of gas produced. At constant pressure and temperature, volume and the amount of gas vary directly, and so for our purposes, instead of directly measuring the moles of hydrogen gas being produced, we measured the overall volume of gas produced. The volumetric rate was determined using a soap bubble meter. The meter is essentially a modified graduated cylinder with three openings: two at the ends and one extra arm near the bottom (Fig. 2). A rubber bulb containing a soap solution is attached to the bottom end, and a tube connected to the electrolysis cells is attached to the bottom arm. When the bulb is squeezed, some of the soap solution is pushed upward so that a film forms within the tube just above the side arm. As gas is produced and pushed into the meter, the film travels upward at a near-constant rate. Since the gas travels through a known, fixed volume, the volume of hydrogen produced can be determined by simply timing how long it takes for the film to travel up the column.

To determine the efficiency of our system, we used two multimeters (Radioshack 15 range digital multimeter and a BK Precision 2703) to determine the voltage drop of each electrolysis cell and the overall current. Since all of the cells were place in series, current is constant across all cells. The total voltage supplied by the solar panel could also be calculated since the effective resistance of each cell is approximately the same. Fig. 3 demonstrates how our system could be thought of as a simple series circuit. The solar panel is represented by a near-constant current source, and each cell can be modeled as a simple resistor. The placement of the multimeters in the circuit is also shown. The results of our experiment are presented and analyzed below.

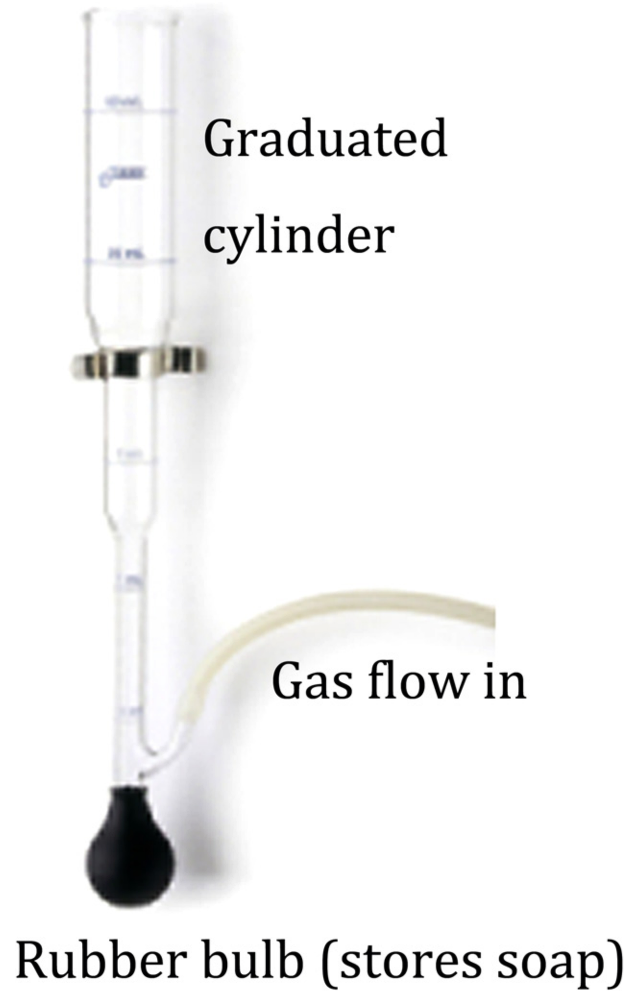

Fig. 2 – Soap Bubble Meter.

4. Result and discussion

4.1. *Overall generation of hydrogen*

Our analysis of data taken on a sunny spring day in Princeton, New Jersey, gave us an average rate of *0.399 mL* of hydrogen per second per electrolysis cell (Table 1). Assuming a constant rate of gas generation, our simple setup, which consists of 6 equivalent cells, will give a total hydrogen production of 8.61 L over an hour's operation.

Table 1 presents the data we obtained from running the experimental setup described earlier with our solar cell. The voltage, current, and rate of hydrogen gas production are recorded in Table 1. Our electrolysis energy conversion efficiency was estimated based on the electrical and gas flow rate data measured over a single electrolysis cell. The enthalpy of combustion of hydrogen at standard states of 298.15 K and 1 atm is 9.88 J/mL [13]. Assuming this value, the rate of chemical energy production from the hydrogen generated by a single cell is 3.94W $\pm$ 0.04W. From the direct measurement of current and voltage across the single operating cell, electrical power consumed is at 12.2W $\pm$ 1.1W. In summary, the conversion efficiency of from electrical to chemical energy is estimated at 32.59% $\pm$ 3.29%.

The radiation received by the solar panel is estimated to be 700W $\pm$ 100W at the time of our measurement, which led to 23.6W $\pm$ 0.2W of chemical energy production from total hydrogen generated by 6 equivalent electrolysis cells. The overall conversion rate from input solar energy to produced chemical energy is therefore at 3.38% $\pm$ 0.48%.

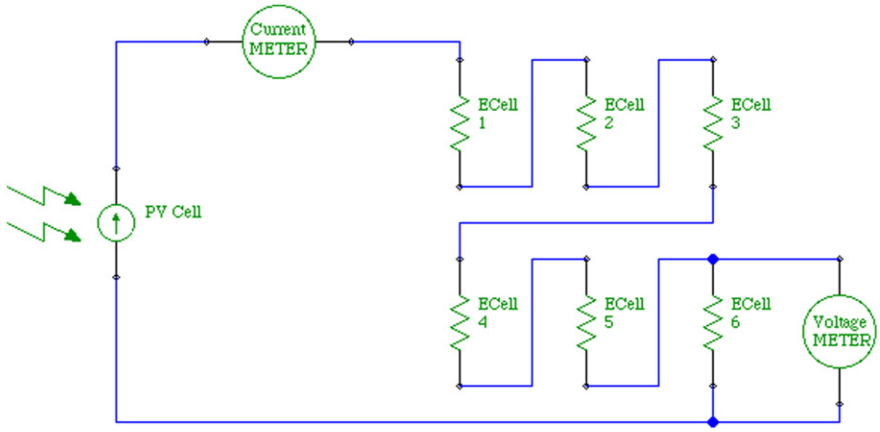

Fig. 3 – Generalized Circuit Diagram of Experimental Setup.

However, it is important to note that the efficiency of the Sharp ND130UJF 130W Solar Module Panel is limited to 13%. From our electrical measurements over a single cell, our operation of the solar panel achieved a solar to electrical conversion efficiency of 10.4% ± 1.5% out of 13%. While our setup design and experimental work were mainly responsible for the electrochemical cells' efficiency, the performance of solar panel therefore turned out to be a primary limiting factor on the overall efficiency of the solar hydrogen generator.

4.2. *Electrical efficiency*

We aimed to maximize the total efficiency of our photovoltaic-electrolytic system by optimizing electrical coupling; in other words, by ensuring that the source solar panel is well-matched to the load chemical cell. Electrical power is the product of panel voltage and current, which are determined by the electrochemical cell load. Our panel's rating of 130W is a maximum value that can change drastically with load resistance, even when solar power is constant. Fig. 4(a) shows the current vs. voltage (I–V) curve of our solar panel at 700W/m^2, our estimate of solar insolation during the test. The power vs. voltage curve is also shown, and the corresponding maximum power point is marked. To maximize coupling efficiency, our task is to present a load that operates at this optimal current and voltage.

A model for our electrolytic cell's I–V curve is shown superimposed on that of the PV panel in Fig. 4(b). The intersection of the curves determines the system operating point. For a single cell connected directly, the operating power is a tiny fraction of maximum potential power. Some solar systems solve this problem with a charge controller that presents an appropriate load to the solar panel; however, this approach wastes the power used by the controller.

We decided to solve this problem by modifying the I–V characteristic of the load. By putting identical electrochemical cells in series, we can do just that, as shown in Fig. 4(c). In this way, we calculated the number of electrochemical cells that would present a load nearest to ideal for the PV panel, which is why we used six cells. In our experiment, the efficiency of the solar panel directly influences our calculated cost of electrolysis. This consideration will transit our discussion into the economics analysis of hydrogen production from our setup, which we believe to be a more meaningful way of interpreting our data.

Table 1 – Solar, electrical and chemical energy conversion efficiency analysis. Calculations were made based on the measurements from a single electrolysis cell. "Total" indicates data which reflects our setup of 6 identical electrolysis cells in series. Assumes solar radiation power of 700 ± 100 W.

Trial	V (V)	I (A)	Electrical Power (W)	Rate of H_2 (mL/s)	Chemical Power [12] (W)	EC Efficiency (%)	Total Solar Efficiency (%)	Overall Total Efficiency
1	3.36	3.29	11.1	0.403	3.981	36.012	9.475	3.412
2	3.75	3.55	13.3	0.397	3.922	29.459	11.411	3.361
3	3.5	3.46	12.1	0.396	3.912	32.302	10.380	3.353
Mean	3.54	3.43	12.2	0.399	3.938	32.591	10.422	3.376
StDev	0.20	0.13	1.1	0.004	0.037	3.286	0.968	0.032
						32.59 ± 3.29%	10.42 ± 1.49%	3.38 ± 0.48%

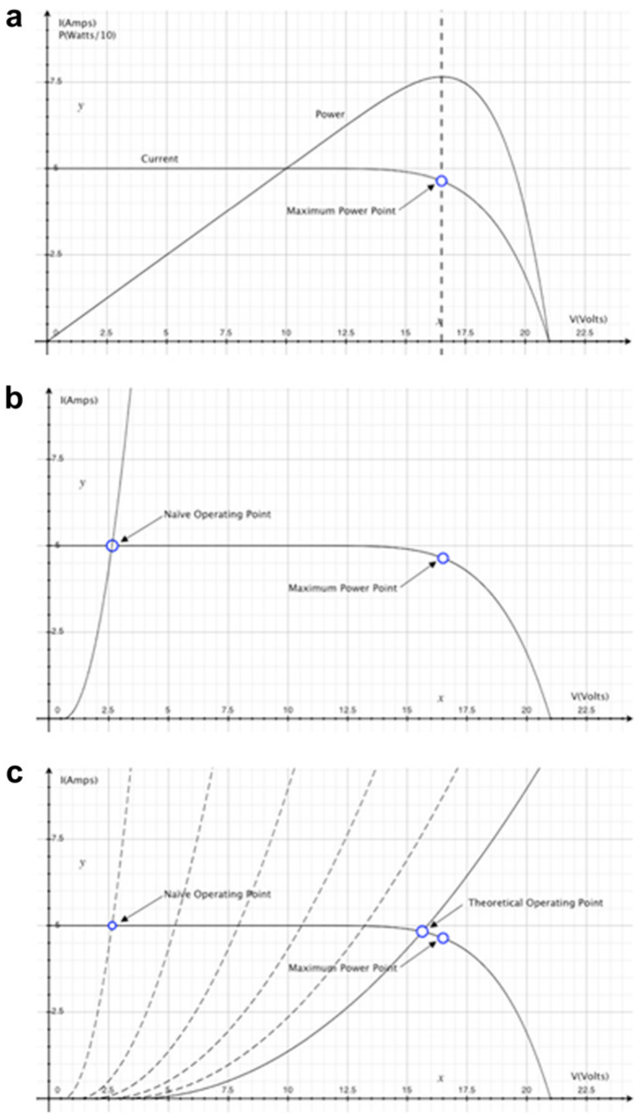

Fig. 4 – Electrical Efficiency Analysis.

4.3. *Production economics analysis*

To determine cost per kilogram of hydrogen produced, we made the following assumptions:

1. The lifetime of the solar panel (Sharp ND130UJF 130W Solar Module Panel) is 25 years – the length of its warranty.
2. There would be no need to replace any KOH during the lifetime of the solar panel.
3. The price of water is $1.50 per thousand gallons of water.
4. The electrodes would not corrode for the lifetime of the panel.
5. The price of the assembly construction materials (caulk, etc.) is fixed at $10.
6. The system would run for 12 h per day, every day of the year. Of course, the amount of useable sunlight varies between season and between days. However, we will assume an average amount of daily sunlight throughout the year to be 12. This may be slightly optimistic.

Given these assumptions, we can extrapolate the total amount of hydrogen gas produced (measured at 298.15 K and 1 atm) to be about 75.542 kg over 25 years. Thus, the total cost per kg of hydrogen gas produced is about $8.58.

5. Discussion: Comparison to current industrial hydrogen production

To give an idea of how our system compares with the cost of hydrogen produced industrially, we will use the linear relationship between the cost of hydrogen production per kilogram and the cost of electricity derived in Levene et. al. [14]. Since grid electrical power is priced differently for industrial use, we consulted the records kept by Ted Borer, the energy plant manager for Princeton University's co-generation power plant. Princeton University generates its own electricity and hot water when electricity prices are at peak demand and then switches to grid power when demand is at its lowest and price is cheapest (at night, for example). To do this, the plant monitors the price of electricity in real time at all times. For our purposes, we will use the price of grid electricity averaged between August 1st, 2006 and December 30th, 2008 at 1 h intervals: 7.2 cents per kilowatt-hour. Assuming that this is a feasible price of electricity for an industrial company producing hydrogen gas and only grid power is used, the average cost per kilogram of hydrogen is about $6.92 (adjusted for inflation) at the industry technology level in 2004 [15]. If the cost of electricity were zero, or in other words, a company uses a renewable source and ignores capital costs, the cost of hydrogen per kg is about $2.01 (adjusted for inflation).

Given these two measures, our system appears to produce hydrogen more expensively with a cost difference of about $1.50 per kilogram. However, it is difficult to compare small-scale production against industrial manufacturing using only these raw figures. There would undoubtedly be additional costs if industrially produced hydrogen needed to be transported and shipped for commercial and consumer use. Specifically, compression of produced hydrogen is a major cost-intensive and energy-intensive factor that would make small-scale, on-site production of hydrogen more attractive. Furthermore, grid electricity is a volatile commodity whose market price can see large fluctuations throughout the day [16]. Our use of a time-averaged price does not take into account what temporal requirements are needed in industrial production – whether a plant must produce a certain volume of hydrogen at certain times of the day. A plant may be able to buy grid power when the price is lowest, or it may be forced to purchase power at peak hours for immediate use (which more than often may be the case).

Overall, because we used easily obtainable parts and could produce hydrogen at a cost that could compete with industrially produced hydrogen, our system demonstrates that a portable electrolysis hydrogen generator can become a viable source of energy, with applications in both residential and small commercial settings.

6. Conclusion

We have constructed a portable hydrogen generator that can be easily replicated using readily-available household materials. Our setup consists of a solar panel, purchased from amazon.com, and 6 identical electrolysis cells, which are contained in airtight glass food containers and consist of basic nickel electrodes and potassium hydroxide electrolyte. Our design is straightforward enough for almost anyone to construct and understand, making it an appealing choice for general public use. Despite the simplicity of our setup, the performance of our hydrogen generator is extremely respectable, approaching industrial standards for cost and efficiency. Our system was tested on a late March afternoon in New Jersey, and in 1 h, we produced 8.38 L of hydrogen gas at an estimated cost of $8.58 per kilogram of hydrogen gas (assuming a 25-year lifetime). These preliminary results suggest that a hydrogen generator such as ours is indeed an option that is worthy of more attention and research. In the future, we hope to further improve our hydrogen production rate by experimenting with different electrodes, electrolyte concentrations, cell connection configurations, and other variables that may be adjusted to optimize our system. We would like to thank Professor Jay Benziger for overseeing and advising our work and the High Meadows Foundation for funding this undertaking.

Probably the greatest obstacle to the widespread implementation of electrolysis is not science-related, but has to do with economics. The world's energy system is petroleum based, and every industry and every person is affected by and dependent upon such energy. Reverting to a hydrogen-based economy has numerous benefits: it would relieve nations dependent on foreign sources of energy; it would dramatically reduce the levels of carbon emitted into atmosphere; it would be a reliable, sustainable source of energy for the future. However, such a change would require massive, expensive alterations to our current energy infrastructure. So far, we have not been willing to start the transition.

Acknowledgment

The Princeton IAHE Team owes its deepest thanks to Professor Jay Benziger, whose guidance and support has enabled the team to accomplish this project. The team thanks the Princeton University Department of Chemical & Biological Engineering and the Princeton Institute for the Science & Technology of Materials (PRISM) for offering the laboratory space and essential equipment. The team would like to thank many individuals at Princeton University for their kind support to this project: Mr. James Boehlert, of Princeton Environment Health and Safety; Mr. Ted Borer, Manager of Princeton University Mechanical Systems; Professor Nan Yao and Ms. Mary Monahan, both of PRISM; and Mr. Glenn Northey and Mr. Don Schoorman, both of the Princeton School of Engineering & Applied Sciences.

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Appendix List of material and budget summary

Table A-1 – Budget summary

Component	Supplier	Quantity	Unit Price ($)	Cost ($)
Nickel Strips	*Science Co.*	12	4.50	54.00
KOH	*Utah Biodiesel*	2.672 (lb)	12.50	33.40
Sharp® ND130UJF 130W Solar Module Panel	*Amazon*	1	509.15	509.15
Glasslock™ Containers	*Ebay*	6	8.30	49.80
Construction Material	*McMaster Carr*			5.00
				651.35

A.2 Material summary:

1) Nickel electrode (Dimensions: 3.4" × 5" × 0.1"; 12 strips).
2) Glasslock™ Containers (Dimensions: 3.5" × 5.5" × 1.5"; 6 boxes).
3) KOH (2.672 b).
4) Sharp® ND130UJF 130W Solar Module Panel (1 Panel).

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