Homebrew Fuel Cell & Hydrogen Electrolyzer

Larry Elliott

For the past several years, fuel cells and hydrogen have been very hot topics in the news. Unfortunately, unless you are a well-funded university or a large corporation, purchasing a fuel cell or hydrogen electrolyzer has been next to impossible.

I've studied and researched fuel cells and hydrogen for several years, and I find them fascinating and technically challenging. It was always frustrating to learn only from books, without any hands-on experience with real equipment. This lead me to create KATTEL (Klamath Advanced Transportation Technology and Energy Lab), a nonprofit organization dedicated to advancing renewable energy, with special emphasis on fuel cells and hydrogen. We offer all services free of charge.

Last winter, I was approached by a group of mechanical engineering students at the Oregon Institute of Technology (OIT). They asked me to help them design and build both a proton exchange membrane (PEM) fuel cell and an electrolyzer to produce hydrogen from water. It would be a senior project, which is required for graduation. Although I don't consider myself an expert on fuel cell design, I felt that I had done enough homework and study to give it a shot.

Recently, legislation was passed to establish the Oregon Renewable Energy Center on campus. This fall, OIT will offer bachelor's degrees in engineering with emphasis on PV, fuel cells, and other renewable technologies.

Design Goals

We decided early on that the size of the fuel cell and electrolyzer should be kept relatively small to keep costs down. Fortunately, I had previously designed a 90 watt PEM fuel cell, as well as a 400 watt PEM electrolyzer. Both were only on paper, and had yet to be proven. The designs seemed to be a good match for supplying adequate power and fuel to the remote-controlled model car the students wanted to power. The car is a small, 7.4 volt unit that weighs about 6 or 7 pounds (3 kg).

Materials

The heart of any PEM fuel cell or electrolyzer is the membrane. Although several companies are now offering various versions of these membranes, we decided to use Nafion, a proven material from DuPont. It is a perfluorinated polymer similar to Teflon, but is treated with sulfur, carbon, and other chemicals to establish an ion path that can conduct protons.

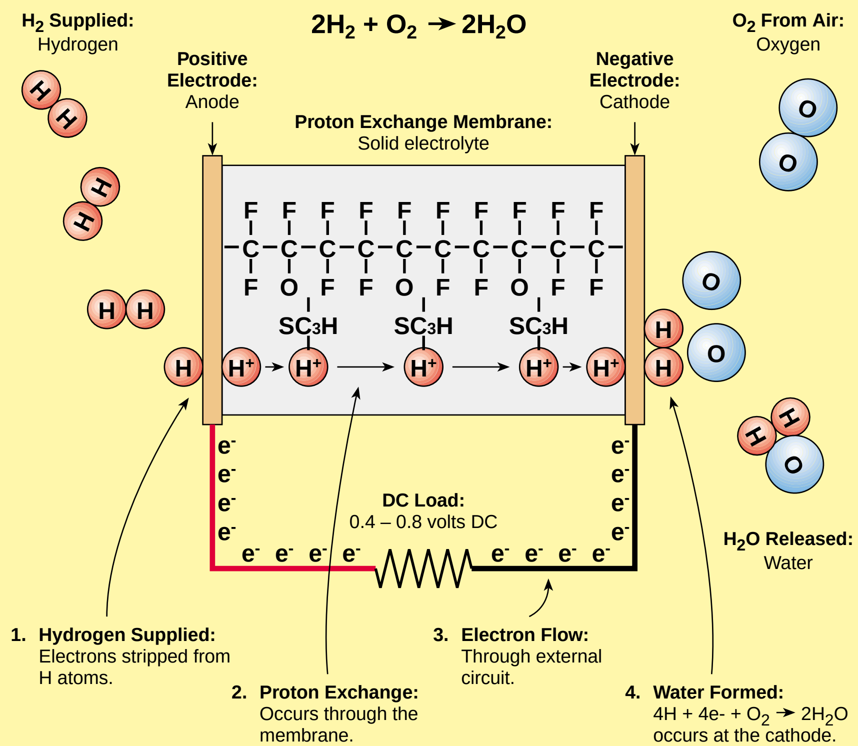
These membranes require that a layer of platinum (Pt) be bonded to the active surfaces. This provides the catalytic action necessary to help liberate electrons from the hydrogen (H_2), and supports a reaction of protons with oxygen (O_2). When processed, these membranes are called MEAs—membrane electrode assemblies. The amount of platinum is usually measured in tenths of a milligram per square centimeter.

Our membranes were ordered from Ion Power in Delaware, and have approximately 0.4 milligrams of platinum per square centimeter of surface, heat-bonded to the PEM electrode surface. The PEM active area is one mil thick, and is mounted in a Kapton frame. Moisture management of the PEM is important, so we went with a very thin membrane to help in this area.

PEM Fuel Cell Basics

Hydrogen is composed of one proton and one electron. As hydrogen enters the anode diffuser, it contacts the platinum catalyst layer on the membrane, and an electron is stripped off. The electron travels to the external load. The proton passes through the membrane and recombines, via another platinum catalyst at the cathode, with oxygen and the electron coming from the load. The byproduct is water, which is usually shuttled back to the anode* to keep the membrane hydrated. It also keeps the cathode from "drowning."

*Anode and cathode are defined by the direction of proton flow (from anode to cathode) rather than electron flow.



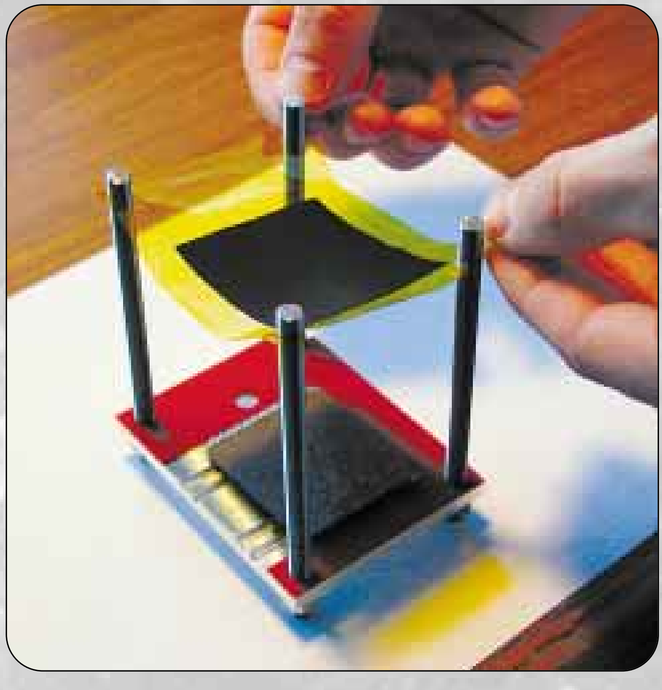
Because the PEM fuel cell and PEM electrolyzer are very similar in their operation, we decided to build both from the same basic materials. Most PEM fuel cells use machined graphite plates that serve as both gas diffuser and conducting electrode. Machining this graphite requires precision. It can also be quite dusty and dirty, and without use of a CNC (computer numerical control) milling machine, it can be very labor intensive.

As a compromise, we decided to use a very stable and cost-effective plastic known as Delrin, generically known as acetal plastic. This would be easy to machine, serve as a good insulator, resist moisture in the electrolyzer, and be nonreactive to hydrogen and oxygen. A combination of nickel wire mesh and Spectracarb carbon paper was selected to serve as our combination electrode/gas diffuser. Along with some silicon rubber for gaskets and stainless steel hardware, our materials were easy to obtain, and the costs were kept low.

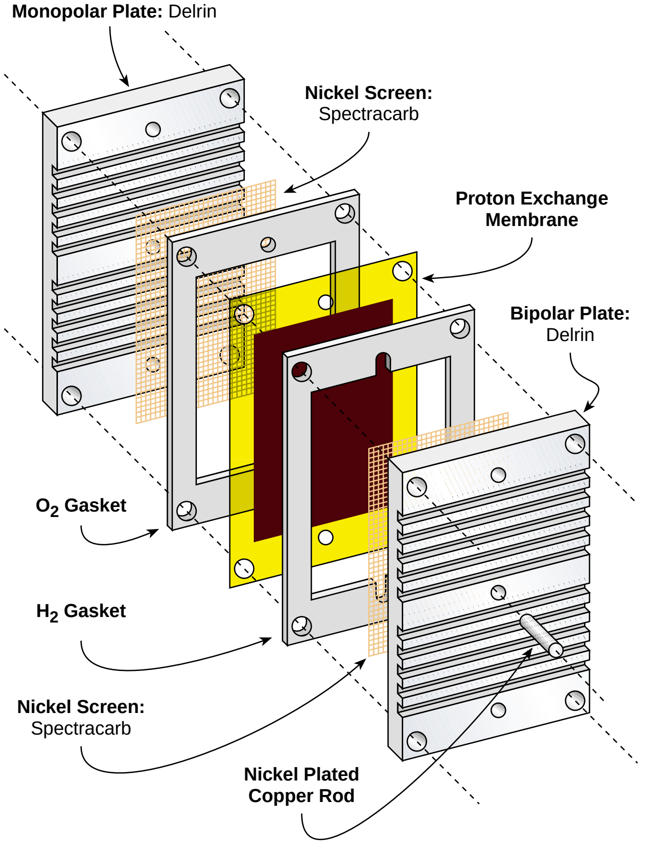
Designing for Power Input & Output

An individual solar-electric cell has a fixed voltage of approximately 0.5 volts. The current output is primarily a function of the surface area exposed and the intensity of the sun. A fuel cell is very similar in its operation. A typical cell voltage is in the range of 0.4 to 0.8 volts, and the current output is a function of surface area exposed to hydrogen and oxygen flow. Real world performance is determined by temperature, gas diffusion rate, internal resistance, and other variables far too extensive to cover in this short article. We had to use many of the same techniques in sizing our fuel cell stack and electrolyzer that are used in sizing solar arrays.

A proton exchange membrane being assembled into the stack of a fuel cell.



Stacking of One Proton Exchange Fuel Cell



Using published performance data for prototype and commercial fuel cells, we based our power output on a current density of 400 milliamps per square centimeter of active membrane surface and 0.6 volts per cell. We decided to build two separate cell stacks of twelve cells each, with each cell having an active area of 3.5 square inches (22.5 cm^2).

We would have twelve cells in series, giving an expected 7.2 volts, and two stacks in parallel to provide an expected 9 amps each. This would give a power output of 130 watts (7.2 volts x 9 amps x 2 = 130 watts).

For our electrolyzer design, we knew from published figures that 1.23 volts was the theoretical voltage needed to separate the hydrogen/oxygen bond. We wanted to be able to run the electrolyzer from a 12 volt nominal solar-electric panel. After taking voltage readings from my three, 1980s vintage General Electric PEM electrolyzers, we selected 2 volts per cell as the design voltage. This would mean that our eight-cell stack would operate at close to the maximum power point of most 12 volt silicon solar cell modules. We expected to limit the current to no more than 20 amps.

Design Details

A fuel cell is very similar to a battery except for the fact that it is continuously charged by the flow of hydrogen and oxygen. It has a cathode or negative pole where oxygen reacts, and an anode or positive pole where the hydrogen reacts. The trick in a fuel cell is to get the hydrogen to flow on one side of the membrane and the oxygen on the other. In a single cell, this is not too difficult. When cells are stacked, the mechanics of getting proper gas flow and air flow to each cell is harder.

In our design (see the diagram at left), small grooves (1/16 inch; 3 mm) are cut into the cathode face of each Delrin bipolar plate. This allows air flow across the entire cathode surface. The nickel mesh and carbon paper (Spectracarb) are set between the membrane surface and the Delrin. These are the electrodes that contact the platinum surface of the membrane. The Spectracarb is a good conductor and gas diffuser, and helps manage the moisture generated on the cathode side of the membrane.

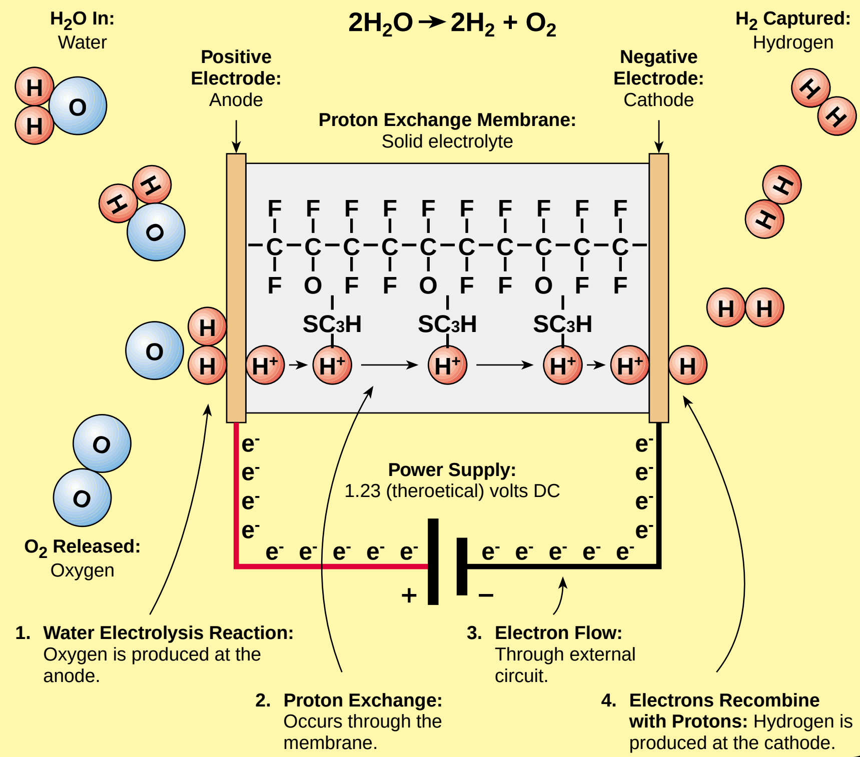
The anode and cathode electrodes are connected in series by a small, nickel-plated, copper rod that runs through the Delrin plate. Hydrogen gas flow is directed to the anodes by way of a series of holes and gas channels machined into the bipolar plates and gaskets. A small (1/16 inch; 3 mm) hole is machined at the opposite end of each anode. It allows the hydrogen to flow up and across the nickel mesh screen and Spectracarb, allowing good diffusion of the hydrogen across the entire membrane.

Two fuel cell stacks in parallel, 7.2 volts each at 18 amps for a total of 130 watts. The fan forces air through the stacks, providing oxygen for the reaction.

PEM Electrolyzer Basics

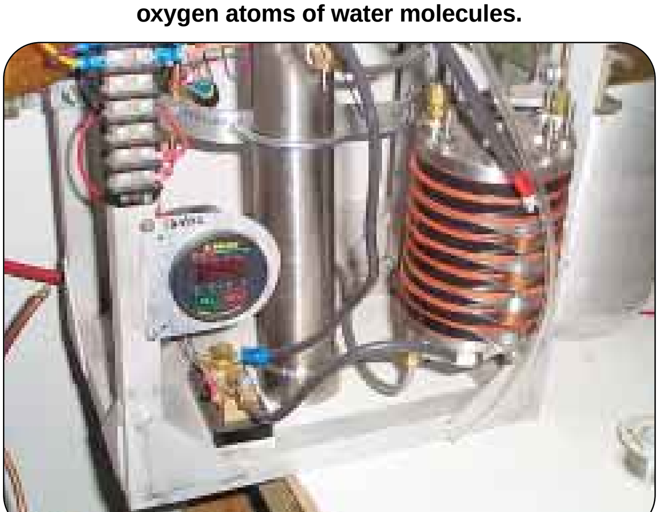
In the electrolyzer process, water is distributed to the anode side of the membrane. With sufficient voltage, the bonds between the hydrogen and oxygen in the H_2O are broken by electromotive force (EMF) and the catalytic action of the platinum. The membrane segregates the H_2 from the O_2. The proton migrates through the membrane and recombines with the returning electron. We then have one proton and one electron on the cathode* side becoming H_2.

*Anode and cathode are defined by the direction of proton flow (from anode to cathode) rather than electron flow.

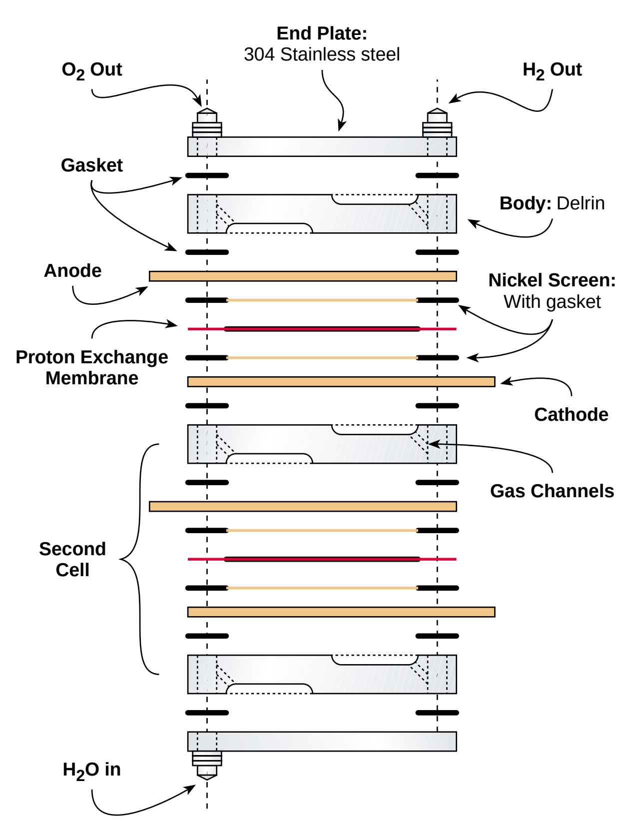


Because the contact pressure in the junction between the membrane and the electrode is critical in keeping resistance and voltage drop to a minimum, a machined and very flat aluminum plate is set at both ends of the stack. Using stainless steel rods passing through the stack at each corner, controlled pressure can be applied. A spring washer, known as a Bellville washer, is used under each bolt head to help control compression as the stack heats up and expands.

The PEM electrolyzer stack—eight cells operating at 2 VDC nominal per cell—separates the hydrogen and oxygen atoms of water molecules.



Electrolyzer Stack Showing Two Complete Cells



Membrane and nickel electrode screens for the PEM electrolyzer.

The homebrew fuel cell on the test bench.

Assembly & Test

Careful assembly of a cell stack is critical to good operation. With concerns for gas flows, conductivity, and proper contact pressures, assembly becomes very labor intensive. Even with the best commercial designs, the labor cost component is high. Proper design and automation can address most of this at the commercial level.

We did many calculations of performance based on variables such as gas flow, temperature, and pressures. It was the real world testing that proved to be the most rewarding as a learning experience. We used a fairly sophisticated test setup. It included a digital mass flow meter calibrated for H_2, a velocity meter and manometer for air flows, a pressure gauge that accurately reads to 1/10 psi, and several very precise pressure regulators and needle valves. Most of this equipment was purchased as surplus from a local supplier. We acquired a fairly sophisticated lab on a bargain basement budget.

Although a fuel cell is similar to a battery in that they both produce DC power, the similarity ends there. In the fuel cell, gas flow and pressures, temperature, and loads all have to be adjusted and accurately balanced. When we did an open circuit test of a single cell, we were very pleased with the performance. We were not ready for some of the later surprises when testing the assembled stacks.

A fuel cell uses hydrogen as a fuel and the oxygen in the air as an oxidizer. This is much the same as an internal combustion engine, except for the fact that the fuel is not burned. The process is more like rusting than like fire or combustion. Just as an engine can be starved for air when choked out with a mixture too rich with gasoline, a fuel cell must also have a balanced fuel-to-air (or stoichiometric) ratio, so all hydrogen gets turned into power and H_2O.

The air in our fuel cell is forced into the cell stack and across the membranes using a small, 1 watt, brushless DC fan. To simplify the design, we decided to suck the air in, instead of blowing it in under pressure. We assumed it would make little difference. After failing to get the cell stack to deliver anywhere near full output, we realized that we needed to change the air flow direction. Careful observation of current and voltage levels relative to air and fuel flow lead us to this conclusion. Because air is composed of only 20 percent oxygen, any increase in pressure also increases oxygen density for a given volume flow rate. After a change of fans and manifold, our power output doubled.

The next problem was internal resistance causing excessive voltage drops and excessive heat under load. The problem proved to be a lack of contact pressure between the membrane and the electrodes. After carefully tightening the compression bolts, we increased our voltage by 2 volts at the same load

The completed hydrogen PEM fuel cell.

current. We originally designed the stack to operate with H_2 under a fixed pressure. After careful testing, we found that a small weep hole was needed to let a little of the hydrogen flow over the diffuser layer and exit at the top of the cell stack.

A Necessary Addition

Our remote control car has high and variable surge loads. Our fuel cell stack lacks a fuel-control management circuit, and has rather poor surge capacity. So a capacitor was placed in parallel with the load to aid in starting the motor. We managed to obtain capacitors with extremely high storage per unit weight. Maxwell Technologies manufactures a complete line of these ultra-large capacity, PowerCache capacitors rated at up to 2,500 farads.

Large size capacitors such as these are being added to hybrid and fuel cell autos for some of the same reasons. These capacitors are excellent choices for delivering large bursts of power, while batteries are better at delivering a lot of energy over time. We purchased ten PC10s. These capacitors, at ten farads, weigh just over 6 grams (0.2 oz.), and are smaller than a postage stamp. Yet they deliver more than 2.5 amps at 2.5 volts. They have proven to be indispensable in leveling out the surge loads placed on the fuel cell, and have increased overall system efficiency.

From H_2O to H_2 & Back Again

The device that made this project especially interesting was the PEM electrolyzer. It converts water into hydrogen and stores it at pressure. Later, we run the fuel cell from the same hydrogen, converting it back to water. This is nothing short of magic, with a technological twist. The sidebar on page 55 shows a schematic of the reactions taking place in the electrolyzer.

Unlike many designs, the PEM uses no acids or bases as electrolyte. The PEM membrane acts as the electrolyte and also serves to keep the oxygen and hydrogen separated. The beauty of this design is that the hydrogen creates its own pressure. It has no known upper limit except for the mechanical strength built into the cell design. It also produces 99.9 percent pure gas.

Using Delrin and nickel mesh and plate, an eight-cell stack was fabricated. The diagram on page 55 shows its assembly. The testing is where some interesting problems cropped up.

With raw Nafion in a single, clear Plexiglas cell, we could generate gases at a pretty good rate. Unfortunately, when we assembled our stack using this raw Nafion, it refused to electrolyze for long. It would gas for several minutes as the voltage dropped lower and lower. Finally it would just stop conducting. Disconnecting it for several hours seemed to restore conduction, but then it stopped again.

We needed a platinum layer on the anode side to help keep the process going. It was also discovered that the voltage across the PEM must be carefully regulated to maintain conduction. This conclusion was derived with a lot of blind testing. So far, we don't understand the relationships between voltage and generated pressures and what reactions are taking place within the membrane. We hope we can discover it on our own, so

Oregon Institute of Technology students Dan Hill and Jacob Pelzer.

OIT Fuel Cell and Hydrogen Electrolyzer Costs

Raw materials	*Cost (US$)*
24 membranes	$1,920
Raw Nafion 117, 0.41 x 0.41 m^2	310
Liquion compound, 0.125 litre	275
10 PC10 capacitors	100
1 gram 20% Pt on carbon	100
Carbon paper, 648 $inch^2$	95
Delrin sheets and rods	90
Silicon rubber gaskets, 9 sq ft x 1/8 inch	75
Misc. stainless steel fittings and valves	60
Fan and manifold	19
24 Bellville washers	16
Nickel grid (free samples)	0
Total	$3,060

we can build a more precisely regulated DC control circuit. Using a 20 percent platinum black-on-carbon compound and liquid Nafion (known as Liquion), we were able to heat-press a layer and reassemble the stack. Our design is, at best, 50 percent efficient now, but with further redesign, 85 percent may not be an unrealistic goal.

In our system, we stored the hydrogen at fairly low pressures of less than 100 psi, in a 2 cubic foot (0.06 m^3) aluminum gas cylinder. Since we are going from a dense liquid to a very light gas it stands to reason that the electrolyzer becomes self-pressurizing when the gases are contained within a closed vessel. One interesting discovery was the fact that the electrolyzer acted as a fuel cell once the power was disconnected. I think a practical, combination fuel cell/electrolyzer is quite possible, but it would require a fair amount of redesign. Additional detailed information on this process is available at Proton Energie's web site at: www.protonenergy.com or Stuart Energy at: www.stuartenergy.com.

Renewable Hydrogen

We pursued this method of hydrogen production in spite of criticism from those who felt it was wasteful to use renewable energy to power the less than 100 percent efficient electrolysis process. Few seem to consider the fact that extraction of fossil fuels, in many cases, uses enormous quantities of fuel just to get it to the end user. There are, in fact, many good arguments for the use of this PV, electrolyzer, hydrogen storage, fuel-cell process.

Electrolyzers that use renewable energy to convert water into hydrogen gas could expand the use of solar and wind power. Both of these sources of energy are highly variable. Sun is available less than half the day, and wind is highly erratic, even in good wind regions.

This means that we now use the grid, lead-acid batteries, or some other means to store this energy. In the case of the grid, it is not truly stored, and the true overall efficiency is rather poor. Lead-acid batteries can never serve as a practical storage medium if off-grid systems become ubiquitous.

I have yet to see a solar or wind system that lacks a voltage regulator. Most of these regulators dump excess energy when the battery is full. Would it not be more efficient to *use* the wasted energy to electrolyze water?

Water is available universally, worldwide. When 2.3 gallons (9 l) of water is turned to hydrogen, the energy equivalent of one gallon (3.785 l) of gasoline is liberated. Even the most advanced battery system could store only a fraction of this energy when weight and volume are taken into account. When consumed, hydrogen turns back to water, whether burned or run through a fuel cell.

With more research, electrolyzers can reach as high as 85 to 90 percent efficiency. Fuel cells have the potential to reach 75 or 80 percent efficiency. With combined cycle efficiencies of over 60 percent, we exceed the overall efficiency of most fossil fuel extraction and any form of grid power. All of this gives us good reasons to pursue and further promote the electrolysis process.

Our adventure into fuel cell and electrolyzer design and fabrication has been very rewarding. We were able to learn a lot about the electrochemistry involved, in a hands-on manner. It greatly increased our interest in promoting this technology as a practical and ultimately cost-effective addition to the ever-expanding renewable energy inventory. We hope to provide more detailed updates in future issues of *Home Power.*

Access

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