Active Learning of Chemical Engineering Principles Using a Solar Panel / Water Electrolyzer / Fuel Cell System

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Abstract

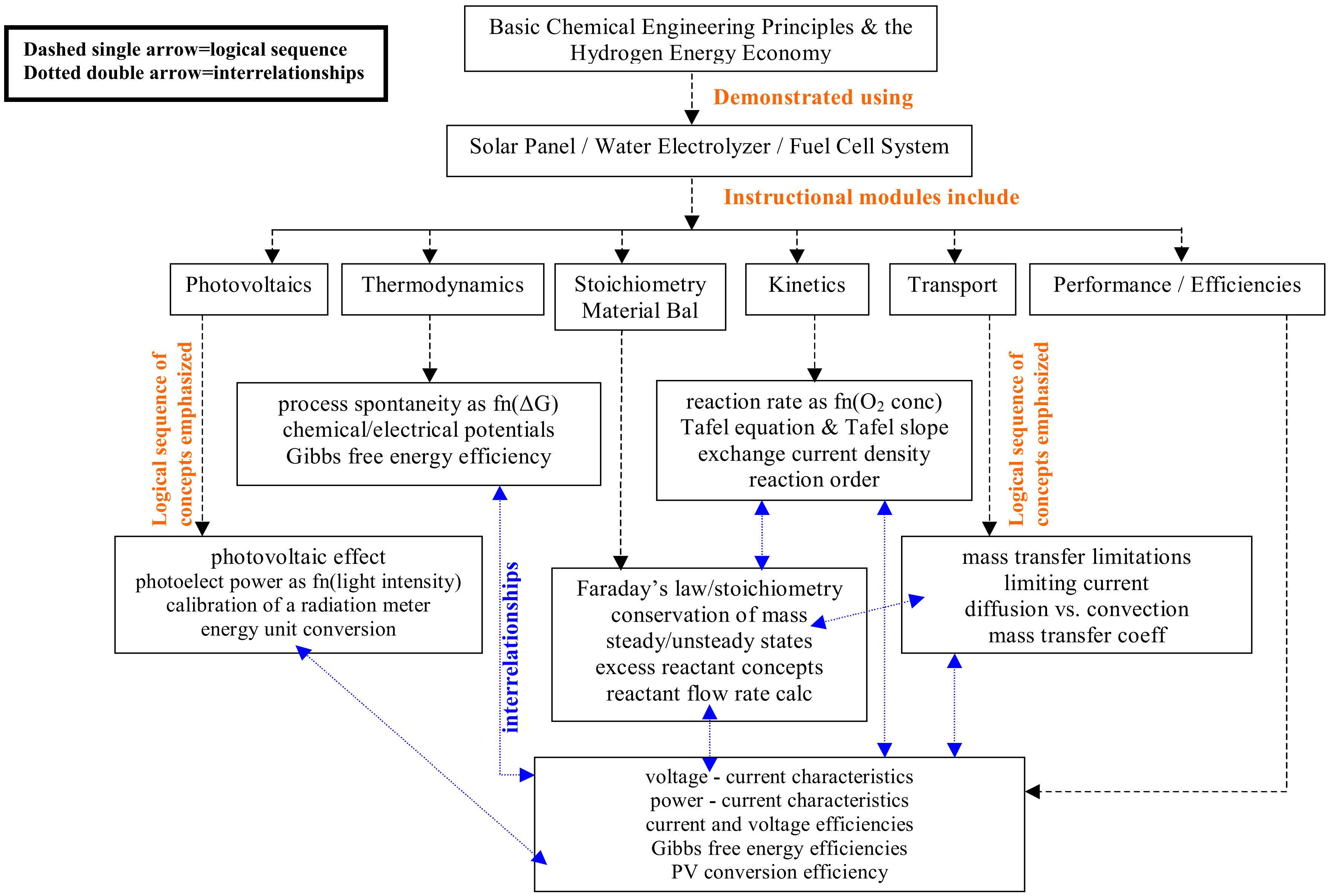
Modules are described that provide experimental/analytical investigation of traditional chemical engineering concepts within the framework of a solar/hydrogen renewable energy cycle. Module lessons cover photovoltaics, thermodynamics, stoichiometry, characteristic current-voltage curves/efficiency, kinetics and transport. A self-contained solar panel / electrolyzer / gas storage containers / polymer electrolyte fuel cell (PEFC) device along with separately purchased (or borrowed) spotlight, power supply, multimeters, and decade resistors are used for all experiments. The experiments are of short duration (15-50 minutes), simple, and produce data that can be analyzed by/used to verify traditional chemical engineering relations (given a few supplemental electrochemical engineering equations). The equipment used in the modules is inexpensive, simple to operate, safe, portable and commercially available. Ideally, this will permit multiple "systems" to be purchased and used simultaneously by students, providing a truly hands-on small group experience.

Modules can be used at all levels of the undergraduate curriculum (freshman through senior) and can be used in multiple classes (Freshman Engineering, Intro to Chemical Engineering, Thermodynamics, Kinetics, Transport, Laboratory Practice, and Electives) to illustrate appropriate material. Figure 1 contains a concept map linking modules to concepts within the curricula that are addressed in this paper. Use of the modules can be preceded by classroom discussions of the hydrogen economy, its projected political, social, and environmental impacts (both locally and globally) and/or the challenges associated with converting to such an economy. The modules can also be modified for use at the pre-college level for a wide variety of projects and/or simple in-class or public demonstrations.

Motivation

There are several motives behind this work. The primary motive is to provide instructors with "active learning" modules that can be easily imported into traditional lecture courses to enhance student retention of basic principles in multiple subject areas of chemical engineering. The exercises have been designed to be "instructor friendly", i.e. they are simple and can be performed during a normal 50 minute lecture. The equipment used in these experiments is relatively inexpensive compared to pilot scale equipment of similar nature, thus multiple set-ups can be purchased for use in a single class. An excellent instruction manual is provided by the manufacturers of the solar panel / electrolyzer / fuel cell system and many of the experiments described here are adaptations of experiments described in the manual[1].

Figure 1. Concept Map Linking Modules with Chemical Engineering Principles



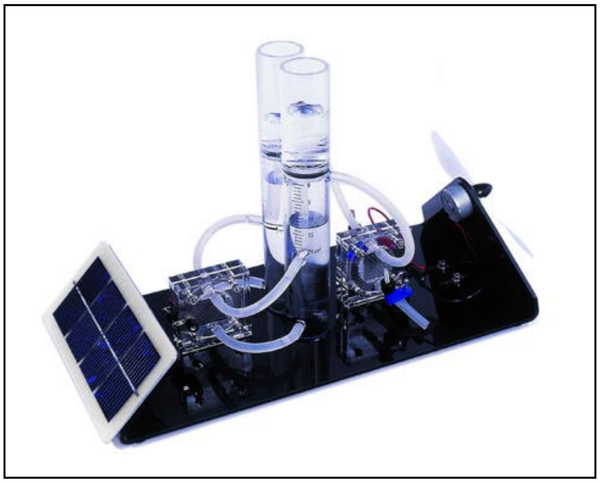
The second is to raise awareness of the future advantages and challenges of an H_2 economy. There are tremendous political, social, and environmental advantages of switching our nation's primary energy supply from a non-renewable, "dirty", and/or difficult to dispose of sources to a renewable, clean, safe hydrogen source that can be produced locally. Classroom discussions (topics and references provided below) of the hydrogen economy and its projected impacts can precede the experiments. In this way instructors can address ABET criterion 3 items (h) understanding the impact of engineering solution in a global and societal context and (j) knowledge of contemporary issues within their core chemical engineering courses.

The final motive is to stimulate interest in the area of fuel cells and associated technologies, helping to establish an infrastructure to meet future hydrogen economy work force needs in CT and nationally. The equipment used in these modules provides a concrete demonstration of the possibility of providing renewable energy. The modules can be adapted to emphasize the advantages of a hydrogen economy to pre-college and public audiences.

Equipment

The experimental system, pictured in Figure 2, is a commercially available unit (Junior Basic by H-Tec, http://www.h-tec.com) comprising a 2V/ 350 mA solar panel, 1.0 W Proton Exchange Membrane (PEM) water electrolyzer, 20 cm^3 hydrogen and oxygen storage reservoirs, 500 mW PEM fuel cell and 10 mW electric load (fan) all mounted on a base plate. Additional equipment needed to run a full range of experiments are a spotlight (a desk lamp is adequate), a variable DC power supply (5V, 5A) or a 6V lantern battery in combination with a variable resistor, a handheld multimeter, connector cables and a variable resistor load box (Load Measurement Box item # 592708 at www.fuelcellstore.com). The Junior Basic set allows students to observe how solar (or lamp) energy is used to electrolyze water to produce hydrogen and oxygen. The gases generated by the electrolyzer are stored in cylinders and can be fed to the fuel cell which in turn powers the fan. The cost of the Junior Basic Set is $224 and it can be purchased in the U.S. at www.fuelcellstore.com. Accessory equipment can be borrowed (most electrical engineering departments have this equipment) or purchased for ~$200-300 per set. More sophisticated experiments are possible if a potentiostat is available or can be purchased ($1000-$10,000).

Figure 2. Photograph of H-Tec's Junior Basic System.



Global/Societal Impacts & Contemporary Issues

Following is a list of topics that can be discussed (or assigned as research/homework projects) in conjunction with the classroom experiments. The list is by no means exhaustive. This is also an excellent way to increase student interest in and retention of course material. Information regarding these topics can be found in references [1]-[8].

Are we too reliant on fossil fuels?
What are the environmental impacts of fossil fuels (vs other energy sources)?
Are oil and gas reserves in danger of running dry within the foreseeable future?
What are some alternative sources of energy and their advantages and disadvantages?
Is energy independence crucial to our economy and our country's security?
Why use hydrogen? Are there other fuels?
What are the environmental and economic advantages of hydrogen?
Is hydrogen safe?
How can we produce hydrogen?
How can hydrogen be stored?

An example of the type of information that is available for discussion is shown in Table 1 taken from [4].

Table 1. Environmental Damage Caused by Each of the Fossil Fuels

Type of Damage	**Environmental Damage 1998 $ per Giga Joule**		
	Coal	**Petroleum**	**Natural Gas**
Effect on Humans- Premature deaths Medical expenses, Loss of working efficiency	5.16	4.19	3.09
Effect on Animals- Loss of domestic live stock, Loss of wildlife	0.75	0.63	0.45
Effect on Plants and Forest- Crop yield reduction from ozone, Crop yield reduction from acid rains, effect on wild flora (plants), Forest decline (economic value), Forest decline (effect on biological diversity), Loss of recreational value	1.99	1.61	1.20
Effect on aquatic ecosystems- Oil spills, Underwater tanks, leakages, Liming lakes, Loss of fish population, Effect on biological diversity	0.26	1.55	0.16
Effect on man-made structures- Historical buildings and monument degradation, Detriment to building and houses, Steel construction corrosion, Soiling of clothing, cars, etc.	1.66	1.34	0.983
Other air pollution costs- Visibility reduction, Air pollution abatement costs	1.45	1.16	0.88
Effect of strip mining	0.73		
Effect of climactic changes- Heat waves, Droughts, Agricultural losses, Livestock losses, Forest losses Wild flora and fauna losses, Water shortage and power production problems, Floods, Storms, hurricanes, tornadoes	2.04	1.66	1.22
Effect of sea level rise	0.47	0.38	0.28
TOTALS	**14.51**	**12.52**	**8.26**

Background Information and Equations

This background can either be presented to students before running the experiments or an "inductive" approach could be used to identify these principles after the experiments have been run.

Photovoltaics

A photovoltaic device (generally called a solar cell) converts photons to electricity. The device consists of layers of semiconductor materials with positive and negative electronic properties. An electric field (called a junction) is created at the interface between positive and negative layers. When light hits the solar cell, some of the photons are absorbed in the region of the junction, freeing electrons to move through the silicon and into an external circuit. A more detailed description of photovoltaics is provided in references [9] and [12]. Some chemical engineering phenomena associated with photovoltaic devices, including material science and production aspects, cannot be investigated with the Jr. Basic device. However, the concepts of steady state flux through a varying cross-sectional area, unit conversion, calibration, characteristic curves, and efficiency can be illustrated. Light intensity, defined as power (energy/time in W) per unit area (m^2), describes the flux of energy. Artificial light sources produce energy that travels radially outward from the source (sunlight also travels radially, but the rays reaching the earth after several million kilometers have all been sent out in nearly the same direction). Cross-sectional area of illumination increases with distance from the source and consequently, flux decreases. The power produced by the solar cell (current/area × voltage) is related to the input light intensity (power/area) through the efficiency. Thus, by measuring short circuit current (and/or no-load voltage) one can study light intensity (flux) as a function of distance from the source and can calibrate the solar cell as a "light intensity" meter. Information on characteristic curves, efficiency and details regarding experiments are provided in the following sections. Note also that the "distance between solar panel and artificial light source" and the angle of incidence must be kept constant in later experiments where constant power input to the electrolyzer is required.

Thermodynamics

In an electrolytic process, chemical change is achieved by passing electrical energy through a device. It is a non-spontaneous process; in other words, energy must be provided for the electrochemical reaction to proceed. An example of such a process is water electrolysis. In water electrolysis, the anode, cathode, and overall reactions are:

anode: $H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$ $\quad E_a^o = 1.229$ V wrt SHE (Eqn 1)

cathode: $2H^+ + 2e^- \rightarrow H_2$ $\quad E_c^o = 0$ V wrt SHE (Eqn 2)

overall: $H_2O \rightarrow \frac{1}{2} O_2 + H_2$ $\quad E^o_{cell} = E^o_c - E^o_a = 0 - 1.229 \text{ V} = -1.229 \text{ V}$ (Eqn 3)

$$\Delta G^o_{cell} = -nFE^o_{cell} \quad \text{(Eqn 4)}$$

$$= -(2 \text{ equiv/mol})(96{,}485 \text{ coulombs/equiv})(-1.229 \text{ J/coulomb})$$

$$= 237{,}200 \text{ J/mol} \qquad \text{reaction not favored}$$

Note: 1V = 1 J/C

In these equations, 1.229 and 0 represent the potential of the anode and cathode reactions with respect to the standard hydrogen electrode (SHE), E^o_{cell} is the standard potential of the overall reaction, ΔG^{o}_{cell} is the change in Gibbs free energy where n is the number of electrons participating in the reaction (units of equivalents/mol) and F is Faraday's constant (96,485 coulombs/equivalent). The superscript o indicates standard conditions: 25°C and unit activity for the species. A positive change in Gibbs free energy means the reaction is not thermodynamically favored to proceed in the direction indicated, i.e. toward the products.

In a galvanic process, electrical energy is produced by chemical change. It is a spontaneous process. Batteries and fuel cells are examples of galvanic processes. The electrochemical reactions in a hydrogen/oxygen fuel cell are given below:

anode: $H_2 \rightarrow 2H^+ + 2e^-$ $\quad E_a^o = 0$ V wrt SHE (Eqn 5)
cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$ $\quad E_c^o = 1.229$ V wrt SHE (Eqn 6)
overall: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ $\quad E^o_{cell} = E^o_c - E^o_a = 1.229 - 0\text{ V} = 1.229\text{ V}$ (Eqn 7)
$\Delta G^o_{cell} = -nFE^o_{cell}$
$= -237{,}200$ J/mol reaction favored

Although a reaction may be thermodynamically favored, it may not proceed at a significant rate (kinetic, ohmic and/or transport limited). Clearly, the role of free energy in determining spontaneity can be demonstrated along with its physical significance i.e. one must impart energy to electrolyze water (consuming energy) vs. the fuel cell which produces energy.

The maximum available voltage from a galvanic process or the minimum decomposition voltage in electrolysis involves thermodynamic evaluation of energy differences between the initial state of reactant and the final state (reversible potential or E). Maximum available or minimum decomposition voltage is useful for calculating efficiencies and for determining upper (or lower) limits of performance. Thermodynamic equations relate reversible potential to state variables. Sample calculations taken from reference [10] show how potential varies with temperature for the H_2/O_2 fuel cell reaction at unit activity for the gaseous reactants and liquid water product.

Sample Calculations – Reversible Potential at varying Temperatures

For P=1 atm, **25°C**, 1 mole of H_2 reacting
$\Delta G = \Delta H - T\Delta S$
= -285,840 J/mol - (298 K)(-163.2 J/mol K)
= -237,210 J/mol
$\Delta E = -\Delta G / nF$

$$\Delta E = -\frac{(-237{,}210\text{ J/mol})}{2\text{ equiv/mol x }96{,}485\text{ C/equiv}}$$

= 1.23 J/C = 1.23 V

For P=1 atm**, 80°C**, 1 mole of H_2 reacting
The values of ΔH & ΔS change only slightly compared to T.
ΔG is approximated as
ΔG = -285,840 J/mol - (353 K)(-163.2 J/mol K)
= -228,230 J/mol

$$\Delta E = -\frac{(-228{,}230\text{ J/mol})}{2\text{ equiv/mol x }96{,}485\text{ C/equiv}}$$

= 1.18 V

The Nernst Equation can be used to calculate reversible potential at "non-standard" concentrations and a given temperature. Equation 8 is the Nernst Equation specifically written for the H_2/O_2 reactions given in Equations 5, 6, and 7.

$$E = E^{o} + \left(\frac{RT}{nF}\right) \ln \frac{[P_{H_2}][P_{O_2}]^{1/2}}{[P_{H_2O}]} \qquad \text{(Eqn 8)}$$

where R = gas constant (8.314 Joule/mol ^{o}K), E^{o} = Reversible Potential at standard concentrations and temperature T, E = Reversible Potential at non-standard concentrations and temperature T, and P_{H2}, $P_{O2,}$ P_{H2O} = partial pressures of H_2, $O_{2,}$ and H_2O respectively (atm) which are approximating the activities of $H_2(g)$, $O_2(g)$ and $H_2O(l)$.

Stoichiometry / Material Balance

There is a direct relationship between the charge passed (current consumed or produced) and the amount of product formed or reactant consumed in electrochemical reactions. The relationship is described by Faraday's Law:

$$I = \frac{m\,n\,F}{s\,M\,t}\,\text{(Amp)} \quad \text{or rearranged} \quad \frac{m}{M \cdot t} = \frac{I}{n \cdot F}\ \text{(mol/time)} \qquad \text{(Eqn 9)}$$

where I (A) is the current, m (g) is the mass of product formed (or reactant consumed), n and F are defined above, s is the stoichiometric coefficient of either the product or reactant species, M (g/mol) is the atomic or molecular mass of the product (or reactant) species, and t(s) is the time elapsed. Equation 9 is valid for a constant current process. In the hydrolysis of H_2O, the current consumed by the hydrolyzer is directly proportional to the volume of H_2 and O_2 generated (observable and quantifiable using the Jr. Basic). Similarly, in the H_2/O_2 fuel cell, the current generated is directly related to the hydrogen and oxygen consumed. An example of fuel cell feed flowrate calculation involving Faraday's Law, the Ideal Gas Law, and the concept of "excess feed" is shown below.

Sample Flow Rate Calculation [11]

Faraday's Law: $\frac{m}{M \cdot t} = \frac{I \cdot s}{n \cdot F}$ mol/time

Hydrogen consumption in fuel cell = I /(2F) mol/time
Oxygen consumption in fuel cell = I/(4F) mol/time
To produce a current of I=1 Amp, H_2 consumption is:
= I /(2F) = 1 / (2 x 96485) = 5.18 $*10^{-6}$ mol/s
= 3.11 $* 10^{-4}$ mol/min

According to the gas law: PV = NRT
At 80C and 1 atm, V/N = RT/P = 0.082*(273.15+80)/1 = 29 L/mol
So H_2 consumption is: V_{H2} = 9.0 ml/min @ 1 Amp current
O_2 consumption is: V_{O2} = 4.5 ml/min @ 1 Amp current
Corresponding Vair = 4.5 / 0.21 = 21.4 ml/min @ 1 Amp current

For desired 45% H_2 utilization at 1 Amp current
Utilization = moles consumed/moles fed = 0.45
H_2 feed flow rate is: V_{H2} = 9.0/0.45 = 20 ml/min @ 1 Amp

Current-Voltage Characteristics, Power, and Efficiency

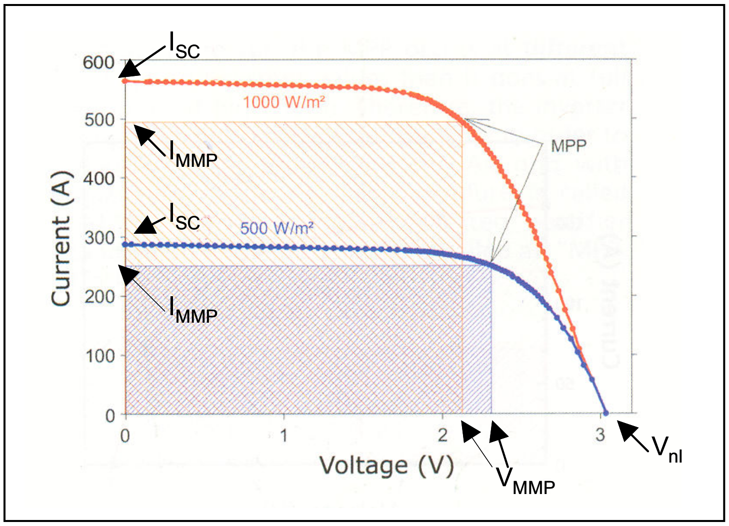
The performance of devices such as solar cells, fuel cells, and electrolyzers is typically demonstrated by plotting the current or current density (current per active area of the unit) versus the voltage of the device. This performance curve along with thermodynamic information (in the case of fuel cells and electrolyzers) permits calculation of efficiency.

In power generating devices, maximum attainable voltage of the cell (measured at equilibrium, i.e. infinite resistance-no current flowing) is a function of (1) the semiconducting materials used in the solar cell or (2) the change in Gibbs free energy for the reactions occurring in a fuel cell. When a finite resistance or load is applied to the cell, the cell moves away from equilibrium and a current flows. There is a trade off between current and voltage at non-equilibrium conditions. By varying the load resistance applied to the cell and recording the corresponding voltage and current, one can generate a characteristic curve.

Solar Cell

A typical current-voltage characteristic curve taken from reference [12] for a solar cell is shown in Figure 3. Unlike the fuel cell, it is possible to measure a short circuit current (maximum current/zero voltage at conditions of no resistance) without damaging the device. The short circuit current varies with the strength of the light source as mentioned previously, however the no-load voltage (a function mainly of the semiconductor materials used in the solar cell) is only weakly affected by light strength. Power (product of the voltage and current) can be determined from these curves. Maximum power point MMP (voltage and current corresponding to maximum power), filling factor, and efficiency are commonly used to describe solar panel performance. Filling factor, FF, is defined as:

Figure 3. Representative solar cell performance curves at varying light intensities



$$FF = \frac{I_{MPP} \cdot V_{MMP}}{I_{sc} \cdot V_{nl}} \qquad \text{(Eqn 10)}$$

where subscript MPP stands for “at maximum power point”, sc “short circuit” and nl “no load”. Optimal operation of the solar cell occurs when the power required by the load is close to the MPP. Efficiency (ε_{solar}) indicates what fraction of the power irradiated onto the solar cell is converted to electrical power by the cell when the cell is operating at its maximum power point:

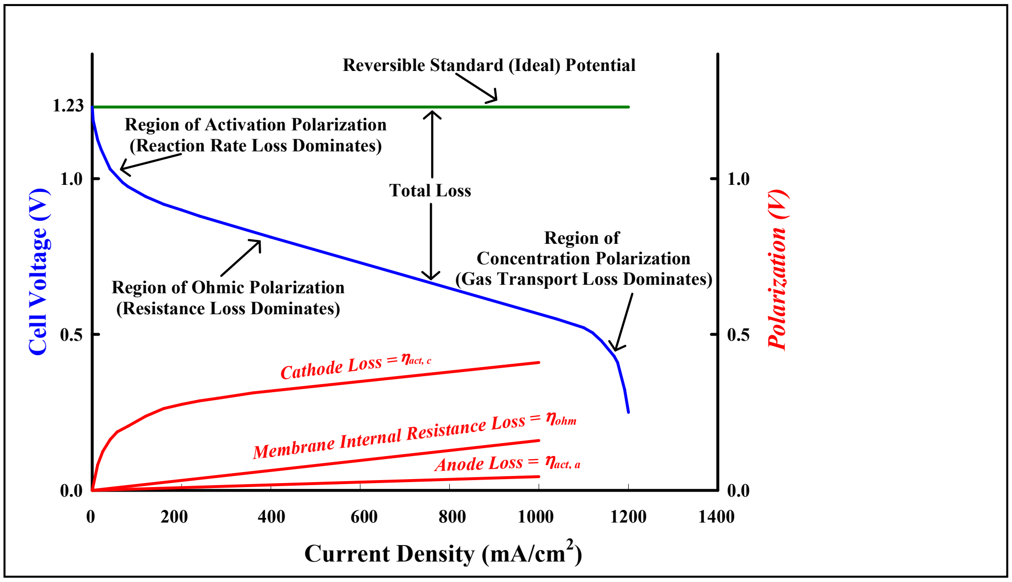
$$\varepsilon_{\mathrm{solar}} = \frac{\text{output power (electrical)}}{\text{input power (light)}} \qquad \text{(Eqn 11)}$$

The efficiency of current solar cells ranges from 15-30% and is primarily dependent on the band gap of the semiconductor from which the cell is made. Efficiencies of a solar panels comprised of multiple solar cells is generally lower than efficiencies of individual solar cells.

Fuel Cell

The current density (i) vs. voltage curve for a typical fuel cell is shown in Figure 4. Note that short-circuiting the fuel cell will cause damage to the device and is not advised. This curve is a function of kinetic, ohmic and mass transfer resistances. Performance losses (commonly referred to as polarization losses) due to these limitations are described in detail in reference [11].

Figure 4. Representative fuel cell performance curve at 25°C, 1 atm



Power can be determined from the performance curve as stated above. Fuel cell efficiency can be defined several ways. In an energy producing process such as a fuel cell, current efficiency, ε_f, is defined as

$$\varepsilon_{\mathrm{f}} = \frac{\text{theoretical amount reactant required to produce a given current}}{\text{actual amount reactant consumed}} \qquad \text{(Eqn 12)}$$

In typical fuel cell operation, current efficiency is 100% because there are no competing reactions or fuel loss. Voltage efficiency, ε_V, is

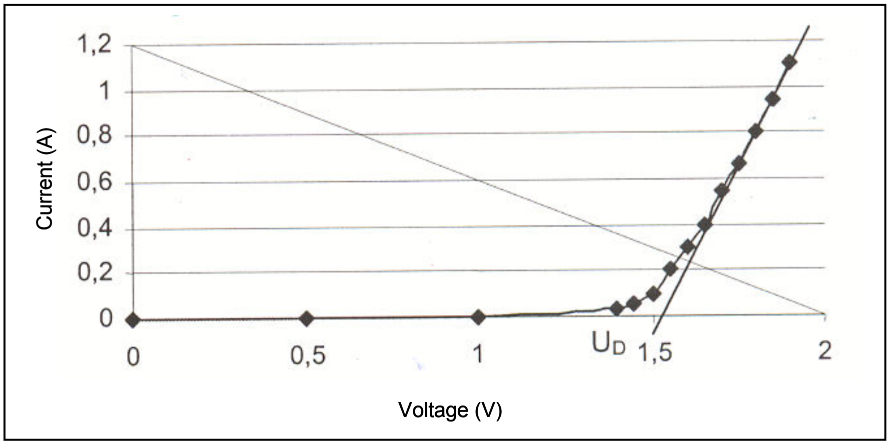
$$\varepsilon_V = \frac{\text{actual cell voltage}}{\text{reversible potential}} = \frac{V}{E} \qquad \text{(Eqn 13)}$$

Overall energy efficiency, ε_T, is defined as the product of the current and voltage efficiencies. Typical fuel cell overall efficiency is about 50%.

Electrolysis

Current-voltage characteristic curves can similarly be generated for the electrolyzer as shown in Figure 5 taken from reference [1].

Figure 5. Current-voltage characteristics of the electrolyzer



U_D in this plot represents the decomposition voltage below which electrolysis cannot occur. It is found by extrapolating the steep part of the curve to its intersection with the voltage axis. Ideally, the decomposition voltage should equal the thermodynamic reversible potential. However, as can be seen from this plot, $U_D > 1.23$ V due to kinetic losses at the electrodes. Overall electrolyzer efficiency is defined as:

$$\varepsilon_T = \frac{\text{power capability of hydrogen generated}}{\text{power required to generate the hydrogen}} \qquad \text{(Eqn 14)}$$

Current and voltage efficiencies for the electrolyzer are inverted versions of Equations 12 and 13 respectively.

Kinetics

The rate at which an electrochemical reaction proceeds is proportional to the current input to or current production from the device. Faraday's Law can be rewritten to show this relationship. For example, for the H_2/O_2 fuel cell the rate of reaction can be represented as

$$\frac{I}{2F} = \frac{d(\text{moles } H_2O)}{dt} = -\frac{d(\text{moles } H_2)}{dt} = -\frac{2\, d(\text{moles } O_2)}{dt} \qquad \text{(Eqn 15)}$$

Thus, kinetic rates can be calculated directly from current measurements in electrochemical devices. The kinetic behavior of the fuel cell can be analyzed using the low current density portion of the characteristic curve. At these conditions, reactants are plentiful (no mass transfer limitations) and the current density is so small that ohmic (=current density × resistance) losses are negligible. Voltage deviations from reversible potential in this region are due primarily to kinetic "losses". The Tafel Equation describes the current density-voltage polarization curve in the kinetically controlled region.

$$\eta_{act} = B \log|i| - A \qquad \text{(Eqn 16)}$$

where η_{act} is the voltage loss (activation polarization) due to slow kinetics (mV), i is the current density (mA/cm^2) and constants A and B are kinetic parameters (B is called the Tafel slope). The theoretical Tafel slope is equal to $2.303RT/\alpha_a F$ where R is the Ideal Gas constant, T is absolute temperature, F is Faraday's constant and α_a is a lumped kinetic parameter equal to 1 for the oxygen reduction reaction occurring on the cathode[13]. According to this theory, the Tafel slope should be independent of reactant concentration. B can be found experimentally by plotting η_{act} (=E-V) vs. log i and measuring the slope of the line in the kinetically controlled portion of the plot (at low values of log i). Figure 4 shows that the cathode activation loss ($\eta_{act,c}$) is much larger than the anode activation loss ($\eta_{act,a}$).

Transport

Fuel cell voltage loss due to mass transport limitations (concentration polarization) occurs when a reactant is consumed on the surface of the electrode forming a concentration gradient between the bulk gas and the surface. Transport mechanisms within the gas diffusion layer and electrode structure include the convection/diffusion and/or migration of reactants and products (H_2, O_2, H^+ ions, and water) into and out of catalyst sites in the anode and cathode. Transport is affected primarily by concentration and flow rate of the reactants fed to their respective electrodes, the cell temperature, and the structure of the gas diffusion and catalyst layers.

The mass transfer-limiting region of the current-voltage polarization curve is apparent at very high current density. Here, increasing current density results in a depletion of reactant immediately adjacent to the electrode. When the current is increased to a point where the concentration at the surface falls to zero, a further increase in current is impossible. The current density corresponding to zero surface concentration is called the limiting current density (i_{lim}), and is observed in Figure 4 at ~1200 mA/cm^2 as the polarization curve becomes vertical at high current density. Limiting current density (i.e. maximum current "flux" attainable) is directly proportional to the maximum mass flux to the electrode. Current density can be expressed using a general mass flux equation

$$i = k_m (P_{O2_{bulk}} - P_{O2_{surf}}) \qquad \text{(Eqn 17)}$$

where k_m is a mass transfer coefficient (typically proportional to flowate raised to some power i.e. $k_m = aQ^b$) and P_{O2bulk} and P_{O2surf} are the partial pressures (atm) of O_2 in the bulk gas fed to the fuel cell and on the electrode surface respectively. When $P_{O2surf} = 0$, $i = i_{lim}$. P_{O2bulk} depends on the whether pure O_2 or air is fed to the fuel cell and on the humidity of the feed gas. The units of k_m are mA/cm^2 atm.

Modules

The Solar Panel/ Water Electrolyzer / Fuel Cell system was used as part of a chemical engineering undergraduate elective course, "Fuel Cell Engineering" in the Spring 2003. The modules described below have evolved from that course but have not yet been inserted into the traditional curriculum. The following steps suggest one way to incorporate a module into an existing lecture course.

1) Present associated principles either before or following the experiment
2) Immediately prior to the experiment engage the students in a discussion of one or more global/societal topics related to the hydrogen economy
3) Run the experiment in a single period in small groups within the classroom
4) Assign homework requiring analysis and discussion of the data and/or extension of the principles for scale-up and design (an assignment requiring research on global/societal impacts or contemporary issues related to the hydrogen economy can accompany this)
5) Follow up with classroom discussion if necessary or time permits

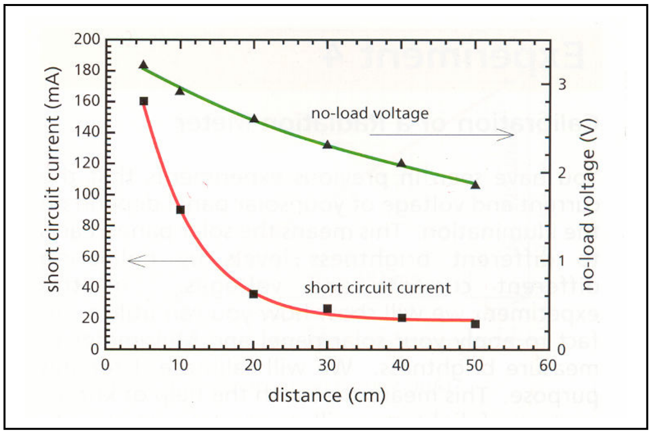
The impact of individual modules on student understanding and retention of the principles can be assessed indirectly via student performance on homework and exams and directly by student feedback on end-of-course surveys.

Photovoltaic Module

1. Current and voltage as a function of distance from light source and observation of steady state flux (of energy) through a varying cross-sectional area

Photoelectric current and no-load voltage of the solar cell can be measured as a function of the distance from the light source. To perform these experiments one needs a light source, tape measure, Junior Basic set and multimeter. Experimental setup and procedures are detailed in the Junior Basic instruction manual[1]. Figure 6[12] shows an example of the data that can be collected from these experiments. Students can use linear and non-linear equation fitting techniques to determine the relationship between current or voltage data and distance.

Figure 6. Photoelectric current and voltage as a function of distance from light source



2. Calibration of a radiation meter

   As illustrated above, current and voltage produced by the solar panel depends on the illumination. To perform these experiments one needs two (or more) light sources, Junior Basic set and multimeter. The solar panel short circuit current (or no-load voltage) is measured to produce a calibration curve using two sources of light of known brightness levels. Incoming radiation from the sun on a clear day in winter is 800 W/m^2 and 1000 W/m^2 in summer. A 60 W bulb (at a distance of 10 cm) provides about 300 W/m^2. The calibration "curve" should pass through the point (0,0) in addition to the sun and light bulb points. Once the calibration is performed, one can estimate input light power (W/m^2) of any source falling in this range, a value that is needed to calculate the efficiency of the solar cell from Equation 11.

3. Current-voltage characteristic of the solar cell, power, and efficiency

   Solar cell performance is based on its current-voltage characteristics. The solar cell efficiency and maximum power point can be determined from these experiments. To perform these experiments one needs a light source, decade resistor or load, Junior Basic set and a multimeter. Again, experimental setup and procedures are detailed in the Junior Basic instruction manual[1].

   Figure 3 above is an example of the data that can be collected from these experiments. The maximum power point can be determined by plotting power versus voltage. Power generated by the device can be compared to power delivered by the light (determined via the calibration) and efficiency calculated. A scale up problem can be introduced at this point; for example students can be asked to predict the solar panel area necessary to run a typical home during daylight hours in a sunny (or not so sunny) location.

Stoichiometric/Material Balance Module

1. Demonstration of stoichiometry

   To perform these experiments one needs an external power supply or battery, Junior Basic set and a watch or clock. Setup and procedures are detailed in the Junior Basic instruction manual[1]. The electrolysis experiment is started with water in both H_2 and O_2 storage tanks maintained at an identical level. An external power supply or battery is used to drive the electrolysis reaction at a known current for a fixed amount of time. The volume of gas in the two cylinders is measured after the electrolysis reaction is stopped and a twofold production of hydrogen (with respect to oxygen) observed.

2. Demonstration of Faraday's law

   The electrolysis experiment is performed as described above, with time and current passed carefully noted. The volume of hydrogen generated can be estimated and used to determine the mass of hydrogen, which in turn can be related to the current passed and time of electrolysis by Faraday's law. Similarly, a relationship can be obtained for the amount of oxygen produced. These values can be used to determine the current efficiency of the electrolysis process. Faraday's law can also be used in a similar manner with the fuel cell to calculate current efficiency. A scale up problem can be introduced at this point; for example students can be asked to predict the length of time the electrolyzer would have to be run if 50 ml of H_2 is to be generated. A more difficult problem would be to calculate this amount if the lamp/solar panel is to supply the electricity. From a fuel cell viewpoint, the students can be asked to calculate the amount of hydrogen needed to run an automobile (typically a 50 kW fuel cell) for a specified amount of time, and the pressure in the storage tank (of fixed volume) that would be necessary to accommodate this amount of hydrogen.

3. Unsteady and steady state material balance on electrolyzer/ tank/ fuel cell system

   With the same set-up described in Stoichiometric module (1), accumulation and steady state can be observed and related to the current supplied to the electrolyzer, the electrolyzer current efficiency, the current produced by the fuel cell and the fuel cell current efficiency. Steady state operation is observed when the gas volume in the H_2 and O_2 storage tanks remain constant with time (i.e. when the flowrates of H_2 and O_2 output from the electrolyzer exactly match fuel and oxidant consumption in the fuel cell). These flowrates can of course be related to current input and outputs through the current efficiencies of each device. Accumulation (or volume reduction) will occur when supply is greater than demand or visa versa. Students can be asked to predict steady state input currents (to electrolyzer) and output currents (from fuel cell) based on their calculation of current efficiency (stoic module 2) and test their prediction using the equipment.

Thermodynamics Module

1. Galvanic vs. Electrolytic process

   The concept of spontaneity (with respect to the sign of the change in Gibbs free energy) can be readily demonstrated. Operation in electrolyzer mode (water electrolysis reaction) results in a positive ΔG. The non-spontaneity of this process is evident in that an external power source is necessary to commence the reaction even when the reactant (water) is available in plenty. On the other hand, while running in galvanic mode (fuel cell), the ΔG is an identical number but is negative. The spontaneity of the reaction is seen by the instantaneous movement of the propeller (motor) when the hydrogen and oxygen are allowed to enter the fuel cell. Students can be asked to write a paragraph on the thermodynamic (and practical) feasibility of an electrolyzer – fuel cell system if electricity is to be obtained from the grid.

2. Variation of cell potential with reactant concentration

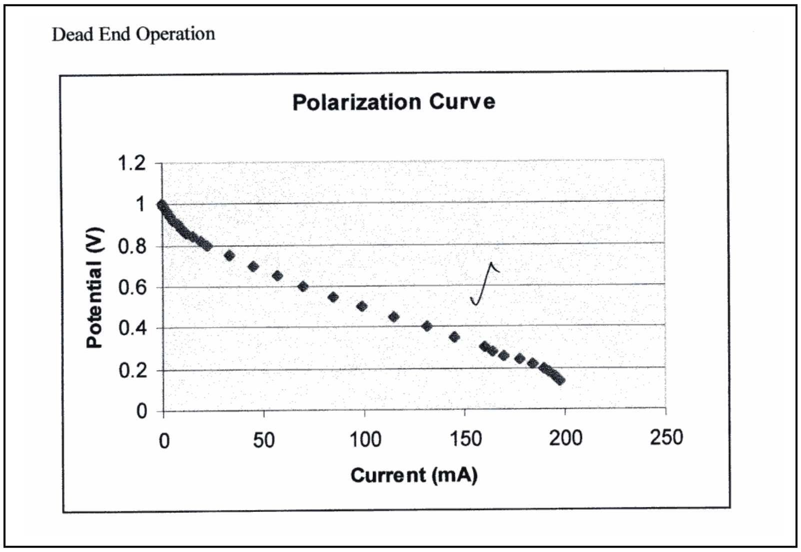
   The cell potential of the fuel cell is related to the reactant concentration by the Nernst equation. The theoretical open circuit potential can be calculated for oxygen and air as oxidants (oxygen concentration changes by a factor of 5) at room temperature conditions. A lower theoretical value will be obtained when air is used in the calculations. This can be experimentally verified by measuring open circuit voltage when the fuel cell is contacted with oxygen (from electrolyzer) and air (from atmosphere) respectively. To perform these experiments one needs a Junior Basic set and a multimeter. Indeed, both values will fall short of the theoretically predicted values. At this point a question can be posed to students about the observed discrepancy and the concept of entropic losses and voltage efficiency can be introduced.

Performance Characteristics and Efficiencies Module

1. Determination of performance characteristics

The performance characteristics of the fuel cell may be obtained by connecting the fuel cell output to a variable resistor load, and changing the resistance to obtain different current outputs. The voltage can be simultaneously measured across the fuel cell using a multimeter. Setup and procedures are detailed in the Junior Basic instruction manual. These characteristics can be obtained for different steady state hydrogen and oxygen flow rates (controlled by maintaining desired electrolyzer current and feeding the gas product directly to the fuel cell rather than to the storage tanks). Experiments can also be run using air as the oxidant rather than oxygen. The current (or current density which is the current divided by the active area of the fuel cell) is plotted versus voltage to yield a polarization curve similar to Figure 7. The power characteristics may be obtained by multiplying each current by the corresponding voltage to yield power, and plotting against current. The curves obtained using different reactant flow rates can be compared. A similar procedure (with light sources of varying intensity) can be used to produce solar cell characteristics. Similarly, electrolyzer performance characteristics can be obtained by measuring the voltage across the electrolyzer as it operates under different currents dialed in using the power supply.

Figure 7. Junior Basic fuel cell performance characteristics: data taken at UConn



2. Determination of operating efficiencies

The overall energy efficiency of the solar panel can be calculated using Equation 11. The voltage efficiency of the fuel cell at a given current density is given by Equation 13 as the ratio of the operating voltage V to the theoretical voltage E (electrolyzer voltage efficiency is the reciprocal of fuel cell voltage efficiency). The current efficiency (Equation 12) of the fuel cell at a given flow rate is the ratio of the current generated to the current that can be obtained if Faraday's law is followed, and for the electrolyzer is the amount of hydrogen produced to the amount that would be produced if Faraday's law is followed. The overall energy efficiencies of the solar panel, fuel cell and electrolyzer can be compared, and the total system efficiency obtained. The students can be posed with the hypothetical question “What aspect of the system would you concentrate your R&D efforts (money) if you wished to improve system performance”.

Kinetics Module

1. Reaction rate as a function of reactant concentration

The dependence of reaction rate on reactant concentration may be experimentally verified by obtaining current – voltage characteristics of the fuel cell while operating on pure oxygen (fed from electrolyzer and throught the tank) and air (from the atmosphere). During these experiments, the fuel cell should be operated in dead-ended mode (with the gas outlets from the fuel cell clamped shut). The characteristics may be obtained as described above. Care must be taken to collect the data at very low current densities so that ohmic and mass transport effects do not convolute the data. The results can be analyzed using Equation 16 by plotting (E-V) vs. log i. The Tafel slope B (theoretically not a function of the oxygen concentration) should remain unaffected by O_2 concentration, while the intercept (exchange current density= the equivalent oxidation and reduction currents that exist at no-load potential) will be lower in the case of air. Thus, the O_2 and air curves should be parallel to each other, with the air curve displaced downwards by a fixed voltage.

2. Reaction order

The ratio of the currents produced by O_2 vs. air for a given voltage in the “kinetically controlled” operating range of the fuel cell should be proportional to the respective ratio of the oxygen concentrations raised to the power of the reaction order. This may be used to estimate the order of the reaction.

Transport Module

1. Limiting current as a function of oxidant composition

With the fuel cell operating in dead-ended mode, students can obtain performance curves and attempt to identify the limiting current using pure O_2 in one case and air in the other. With the outlets clamped shut, transport in the fuel cell is mainly by diffusion, eliminating any “flowrate” effects. Students will be able to identify limiting current density when air is used and they will observe a shift of the limiting current density to higher current with increasing O_2 concentration. The limiting current density may not be obvious with pure O_2 as the oxidant as shown in Figure 7 (however under diffusion-only conditions it should be identifiable). The transport theory proposed in Equation 17 ($i_{lim} \propto P_{O2bulk}$) can be tested if i_{lim} is clearly identifiable in both air and O_2 runs. Students should keep in mind that when comparing performance curves, it is difficult to single out transport, kinetic and ohmic loss contributions i.e. the shape of the curve is affected by all three phenomena.

2. Limiting current as a function of O_2 and H_2 flowrates

One can explore the effect of flowrate on limiting current by plotting performance curves for the fuel cell when it is directly connected to the electrolyzer (bypassing the tanks) at varying current inputs to the electrolyzer. In these experiments the gas outlets from the fuel cell should be open, permitting convective flow through the device. As mentioned above, limiting current per se may not be measurable but students will observe a shift of the limiting current to higher current with increasing flowrate. Mass transfer coefficients can be calculated at limiting current conditions.

Concluding Remarks

This paper presents an overview of how a simple, commercially available device can be used to promote active learning in the chemical engineering classroom, raise awareness of renewable energy economies and stimulate interest in fuel cell technology. To this end, the "chemical engineering" aspects of a solar panel/ electrolyzer / fuel cell system are described and linked to modules that can be used for active learning within the curricula. The authors welcome feedback on the proposed strategy.

Bibliography

1. H-Tec Wasserstoff-Energie-Syteme GmbH, *Fuel Cells Instruction Manual: Suggestions for Classroom Instructions and Experiments*. Manual comes with Junior Basic kit and is also available as a downloadable PDF file from http://www.h-tec.com (retrieved 1/05/04).
2. Hirschhorn, J. and K. Oldenburg, Prosperity Without Pollution: The Prevention Strategy for Industry and Consumers, Van Nostrand Reinhold, New York, (1991).
3. Graedel, T. and B. Allenby, Industrial Ecology and the Automobile, Prentice-Hall, New Jersey, (1998).
4. Veziroglu, T. N., "Hydrogen Energy System: A Permanent Solution to Global Energy-Environmental Problems," presented at the 35th IUPAC Congress, Istanbul, Turkey, August (1995). Paper available on International Association for Hydrogen Energy web page, http://www.iahe.org (retrieved 1/05/04).
5. Barbir, F., "Safety Issues of Hydrogen Vehicles," presented at Fuel Cell Vehicles Conference, IIR Ltd., London, (1999). Paper available on International Association for Hydrogen Energy web page, http://www.iahe.org (retrieved 1/05/04).
6. Flavin, C. and N. Lenssen, Power Surge: Guide to the Coming Energy Revolution, W. W. Norton & Company, (1994).
7. Dunn, S., Hydrogen Futures: Toward a Sustainable Energy System, Worldwatch Paper 157, (2001).
8. Bockris, J., T. N. Veziroglu and D. Smith, Solar Hydrogen Energy: The Power to save the Earth, Optima, (1991).
9. Van Overstraeten, R. J. and R. P. Mertens, Physics, Technology and the Use of Photovoltaics, Adam Hilger Ltd., Briston, (1986).
10. Thomas, S. and M. Zalbowitz, "Fuel Cells-Green Power", Los Alamos National Laboratory, LA-UR-99-3231 (1999).
11. Lin, J., H.R. Kunz, J.M. Fenton, and S.S. Fenton, "The Fuel Cell- An Ideal Chemical Engineering Undergraduate Experiment," *Chemical Engineering Education*, Vol. 38(1), (2004).
12. Bahnemann, D., C. Berge, and F. Pujiuala-Kruger, *Thames& Kosmos Fuel Cell Car & Experiment Kit Lab Manual*, (2001). Manual comes with kit available at http://www.thamesandkosmos.com.
13. Prentice, G., Electrochemical Engineering Principles, Prentice Hall, New Jersey, (1991).

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