BIOCHEMISTRY

Photosynthesis and Energy Storage

NGSS HIGH SCHOOL LESSON PLAN

How does a plant store energy? What can photosynthesis teach us about solar cells? This lesson is designed to help teachers educate students about the connection between photosynthesis and modern energy storage challenges.

Juice from Juice
NSF Center for Innovation in Solar Fuels
California Institute of Technology

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Image (cover): A leaf converts carbon dioxide and water into sugar and oxygen, helping us breathe easy.

Before You Start

1. What do I know about the photosynthesis and energy storage in plants?

Evaluate your prior knowledge of photosynthesis and how plants store energy. This short assessment is meant to help you identify what you *already* know about energy storage and what you might want to review.

Pre-lab Assessment

1. What are the products of photosynthesis?
   a. CO_2 and sugar
   b. CO_2 and light
   c. Sugar and water
   d. Sugar and oxygen
2. Which of the following reactions is the *net* reaction for water-splitting?
   a. $H_2O \rightarrow H_2 + \frac{1}{2} O_2$
   b. $6\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 6\ O_2$
   c. $CO_2 \rightarrow C_6H_{12}O_6$
   d. $2\ H_2 + O_2 \rightarrow 2\ H_2O$
3. Mark each statement below as true or false.
   a. Water-splitting by photosynthesis is more efficient than artificial photosynthesis (i.e. water-splitting done in a lab without a leaf).
   b. Artificial photosynthesis will be implemented as an energy storage method within my lifetime.

Assessment key:

1. D, photosynthesis is the process by which plants take carbon dioxide (CO_2) and water and produce sugar (glucose) and oxygen. This chemical transformation is what provides a plant with energy it needs to survive by storing light energy in chemical bonds.

2. A, this is the reaction that shows the splitting of water into hydrogen and oxygen. B shows the net reaction for photosynthesis rather than just water-splitting while C is not a balanced reaction. D is the reverse reaction, in which water is produced when hydrogen is combusted in the presence of oxygen.

3a. False, plants are actually very inefficient at converting sunlight into chemical fuel. Leaves are around 3% efficient while artificial cells in laboratories are 20% efficient or even higher!

3b. True, hydrogen generated from water-splitting is already used as a chemical fuel to power hydrogen fuel-cell cars! While a hydrogen fuel-cell car is expensive, research is being done at Caltech and around the world to reduce the overall cost of similar technologies for this and other applications.

How did you do? Identify the material you need to review from the questions you missed and continue on to #2.

2. How does a plant store energy?

Now that you've identified what you need to review, take some time to read through the background information on the next few pages. This information along with the information provided in the accompanying prelab handouts should serve to fill in any knowledge gaps you may have identified in #1. Once you are done, continue on to #3.

3. Identify 3-4 learning objectives that connect the background information to the standards.

After reading through the three next generation science standards on page 6, what would you like your students to learn from this lab? To help prompt your thoughts, we've provided example objectives using language directly from the NGSS table.

Example objectives:
Students should be able to:

- use a model to explain how photosynthesis transforms light energy into stored chemical energy
- compare and contrast the conversion of light energy into chemical fuel by photosynthesis and photoelectrochemical water-splitting
- evaluate the efficiency of a human-made water-splitting device
- refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium
- design, build, and refine a device to convert one form of energy into another form of energy

What objectives would you like your students to be able to complete?

4. Read through the demonstration instructions.

After you read through the procedure, check out our demonstration videos for a quick refresher. Any questions or concerns? Contact a Caltech scientist! We'd love to answer your questions or clarify any instructions.

5. Assess what you have learned.

At the end of this lab, your students (and you too!) should be able to fulfill all the objectives listed above in #3 along with any alternative or additional objectives you have identified from the NGSS standards. We have suggested some questions to assess what your students have learned. Feel free to use these questions or write your own.

Background Information

What is photosynthesis?

Photosynthesis is the process that plants use to convert carbon dioxide (CO_2) and water (H_2O) into carbohydrates, such as glucose ($C_6H_{12}O_6$), using the energy of light (Figure 1). Special plant chemicals called *pigments* absorb light at specific wavelengths and use the *electrons* generated from this energy absorption to split water. Chlorophyll, the component that makes leaves appear to be green, then converts the water into oxygen molecules and hydrogen ions. More electrons are released through this process and begin the photosynthetic path that eventually leads to the formation of the simple sugar glucose from carbon dioxide. The net reaction is shown below:

$$\text{Light} + CO_2\,(g) + H_2O\,(l) \rightarrow C_6H_{12}O_6\,(aq) + O_2\,(g)$$ *(Note: equation is not balanced)*

Figure 1. Leaves convert sunlight, CO_2, and H_2O into sugar and oxygen in the process called photosynthesis.

Thus, photosynthesis is the process by which plants convert light into chemical fuel through a *water-splitting* reaction. In *water-splitting*, a water molecule is split into its component parts. That is, water is split into hydrogen (H_2) and oxygen (O_2) by the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) respectively.

Why do leaves change color?

The main photosynthetic pigments that give the green color to plants are chlorophylls, the same components that allow leaves to convert light into chemical fuel. They often hide the other pigments that may be present. Chlorophyll a is a bright-green to blue-green color and chlorophyll b is yellow to olive-green to the human eye. This is the color that is reflected by the leaf. All other colors are absorbed by the pigments, especially reds and blues. In addition to chlorophyll many green plants contain one or more other pigments including the yellow/orange carotenes, yellow xanthophylls, and red-to-purple anthocyanins. When leaves begin to die in the fall, the chlorophylls decay, reveling the beautiful pigments underneath.

The OER and HER half-reactions along with the net water-splitting reaction are shown here:

OER: $2\ H_2O\ (l) \rightarrow O_2\ (g) + 4\ H^+ + 4\ e^-$

HER: $2\ H^+ + 2\ e^- \rightarrow H_2\ (g)$

Net: $2\ H_2O\ (l) \rightarrow O_2\ (g) + 2\ H_2\ (g)$

Artificial photosynthesis

"Those who do not store will have no power after four." – Nathan S. Lewis, Caltech Professor

Figure 2. Sunlight is a **diffuse** and **diurnal** resource, which means that solar cells need to be large to collect enough sunlight to generate electricity or split water, *and* they can only do so during a limited number of hours during the day.

One fact with which we are all intimately familiar is the diurnal nature of the sun. That is, the sun only shines for a limited amount of time each day, leading directly to the issue that Professor Lewis highlights. For solar cells to be a source of energy that can meet global demand, scientists need to find a way to store energy for times when the sun is not shining. Storage is especially critical since peak use of electricity does not correspond to peak conversion hours for solar cells!

What solutions are there? There are two main storage methods for solar energy: *batteries*, which store the electricity created by a solar cell, or *chemical fuel*, which is typically generated from a water-splitting reaction. Solar cell batteries are designed to store electricity in the same way that the batteries we use in our households store electricity. In contrast, there are several ways to design a system to store energy as chemical fuel. The two main ways to split water into chemical fuel are (1) with a photovoltaic (PV) solar cell connected to an electrolyzer or (2) with a photoelectrochemical solar cell. The first design converts light to electricity in the PV solar cell. This electricity is then used to split water with an electrolyzer. Passing a current through a solution to split it into its component parts, such as splitting water into hydrogen and oxygen, is called *electrolysis* (lysis – to break down). Thus, an electrolyzer can use the electricity generated by a PV solar cell to split water and make chemical fuel. The second design is an integrated solar cell that converts light directly into chemical fuel without first making electricity.

Hydrogen fuel cell

Once a system like (1) or (2) generates hydrogen gas, we can use that hydrogen as a fuel source. In fact, hydrogen is used in *fuel cells* to release energy. A *fuel cell* is a device that converts chemical fuel into electricity. This process is the reverse of the water splitting reaction, typically using hydrogen and oxygen to form water and release energy. Just like a plant makes glucose, which it breaks down later to

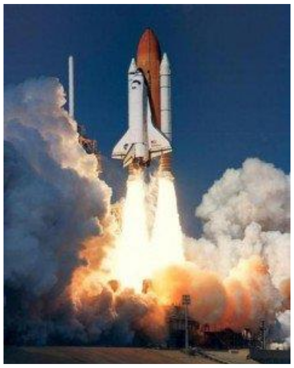


Figure 3. The Space Shuttle has hydrogen fuel cells to power the electricity in the ship and to generate fresh water for the crew.

release the stored energy, we can use solar cells to store energy as chemical fuel and fuel cells to break down that chemical fuel into electricity.

Where are hydrogen fuel cells used? Hydrogen gas has been used as a fuel by NASA since the 1970s, giving the USA a critical edge in the Cold War as hydrogen was a superior propellant for rockets and satellites. Since the 1970s, hydrogen fuel cells were developed and used in the electrical system of the Space Shuttle, which also supplies the crew with clean water (Figure 3). Now in the 21st century, scientists at many large car companies have also integrated hydrogen fuel cells into cars, creating a series of new no-emission vehicles. A hydrogen fuel cell car has a fuel tank for pressurized hydrogen gas, which can be refilled at special hydrogen gas stations. While stations are not widespread, California has begun to build a series of stations around Los Angeles and San Francisco to encourage the use of these no-emission vehicles.

Basic lab summary

In this lab, we will put together our own electrolyzer to better understand water-splitting. A 9-Volt battery will provide the energy needed to split water into hydrogen and oxygen. Remember water-splitting is the same reaction that plants use to store energy as glucose. We want to improve the efficiency of photosynthesis in nature with our own systems, making it a viable energy storage option for the future. Eventually, ideal cells would produce high energy-density fuels. Future systems are being designed to produce fuels that could go directly into your car like gasoline.

Next Generation Science Standards:

HS-LS1-5. Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy. [Clarification Statement: Emphasis is on illustrating inputs and outputs of matter and the transfer and transformation of energy in photosynthesis by plants and other photosynthesizing organisms. Examples of models could include diagrams, chemical equations, and conceptual models.] [*Assessment Boundary: Assessment does not include specific biochemical steps.*]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models Modeling in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds. • Use a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-LS1-4),(HS-LS1-5),(HS-LS1-7)	**LS1.C: Organization for Matter and Energy Flow in Organisms** • The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen. (HS-LS1-5)	**Energy and Matter** • Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-LS1-5), (HS-LS1-6)

HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.* [Clarification Statement: Emphasis is on the application of Le Chatelier's Principle and on refining designs of chemical reaction systems, including descriptions of the connection between changes made at the macroscopic level and what happens at the molecular level. Examples of designs could include different ways to increase product formation including adding reactants or removing products.] [*Assessment Boundary: Assessment is limited to specifying the change in only one variable at a time. Assessment does not include calculating equilibrium constants and concentrations.*]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Constructing Explanations and Designing Solutions Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. • Refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-PS1-6)	**PS1.B: Chemical Reactions** • In many situations, a dynamic and condition-dependent balance between a reaction and the reverse reaction determines the numbers of all types of molecules present. (HS-PS1-6) **ETS1.C: Optimizing the Design Solution** • Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. *(secondary to HS-PS1-6)*	**Stability and Change** • Much of science deals with constructing explanations of how things change and how they remain stable. (HS-PS1-6)

HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.* [Clarification Statement: Emphasis is on both qualitative and quantitative evaluations of devices. Examples of devices could include Rube Goldberg devices, wind turbines, solar cells, solar ovens, and generators. Examples of constraints could include use of renewable energy forms and efficiency.] [*Assessment Boundary: Assessment for quantitative evaluations is limited to total output for a given input. Assessment is limited to devices constructed with materials provided to students.*]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Constructing Explanations and Designing Solutions Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. • Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.	**PS3.A: Definitions of Energy** • At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. **PS3.D: Energy in Chemical Processes** • Although energy cannot be destroyed, it can be converted to less useful forms—for example, to thermal energy in the surrounding environment. **ETS1.A: Defining and Delimiting an Engineering Problem** • Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them. *(secondary)*	**Energy and Matter** • Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. --- ***Connections to Engineering, Technology, and Applications of Science*** **Influence of Science, Engineering and Technology on Society and the Natural World** • Modern civilization depends on major technological systems. Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks.

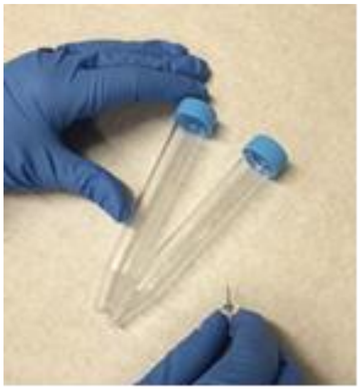
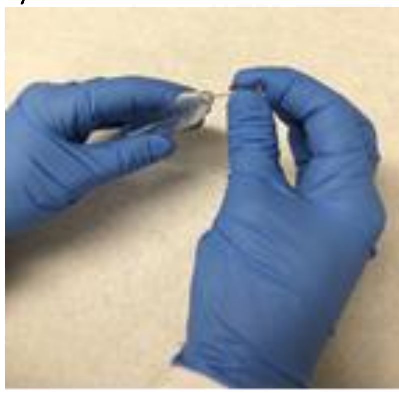
Procedure

Materials and supplies

Per pair or group of students:
2 Falcon tubes
Zip tie
Pushpin
2 Nickel wires (6” pieces)
5 min Epoxy
9V battery
2 alligator clips
0.1 M sodium sulfate solution (approx. 2.5-3.0 g per 200-250 mL water)
Cup or beaker (around 250 mL in volume)
(OPTIONAL) Matches or striker

Making your water-splitting device:

1. Pierce a hole in the top pointy end of each falcon tube using the pushpin.

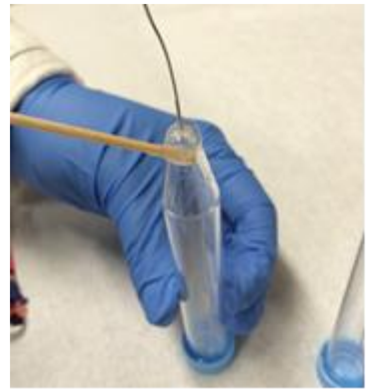




2. Feed a length of nickel wire through the hole in the top of the tube so that the wire fills the length of the inside but does not protrude out the bottom opening. About 1 in of wire should be left sticking out of the top of the tube. Do this to the second tube as well.

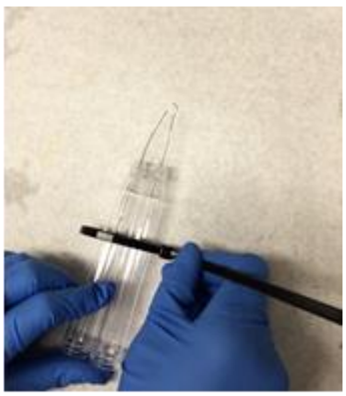


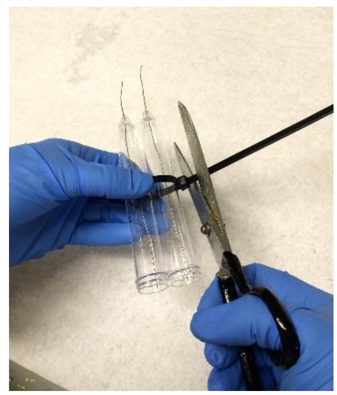
3. Mix the epoxy together on the scrap tray with a disposable applicator. (Epoxy is dangerous and can bond skin. Gloves and goggles MUST be worn for this step. Do not get epoxy on skin or clothing.)


Working quickly, apply the epoxy around the top of the falcon tube to seal the wire in place and close any air hole where gas could escape. Set the tubes aside carefully to dry for at least 20 min.

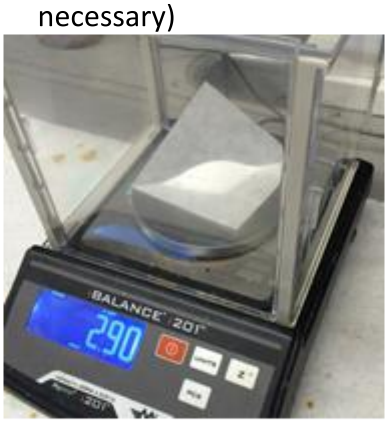


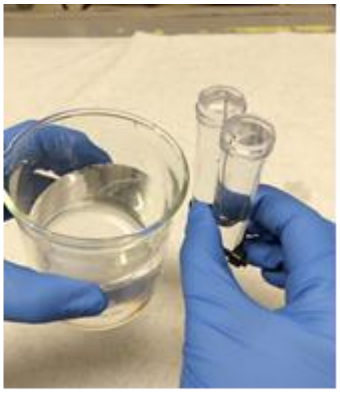
4. Once dry, use a ziptie to tightly bind the two tubes together. Snip off the excess from the ziptie.





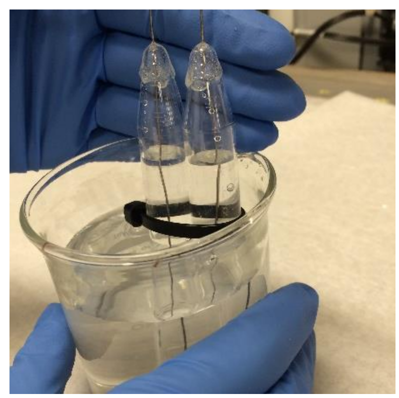
5. Fill the cup or beaker with a 0.1M sodium sulfate solution (exact concentration not necessary)



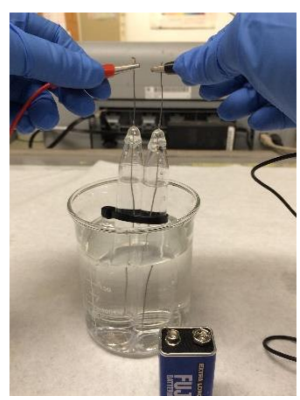


6. Carefully pour some of the solution into both tubes so that they are completely full. The cup should be about half full still. If not, add more solution.

7. Very quickly and carefully flip the falcon tubes over and submerge the bottoms in the remaining solution. The tubes should still both be almost completely full (some loss of liquid inside is unavoidable). Tilting the cup to meet the tubes as you turn them over can help. If there are large air pockets in the tubes, pour the solution back into the cup and try again. Take note of the volume of the air pocket in each tube for future reference.

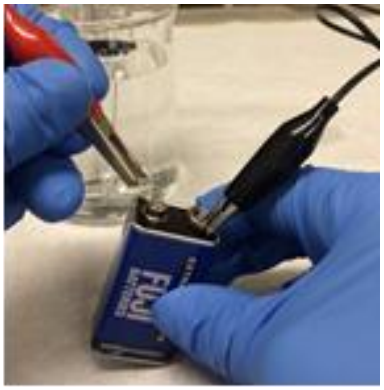


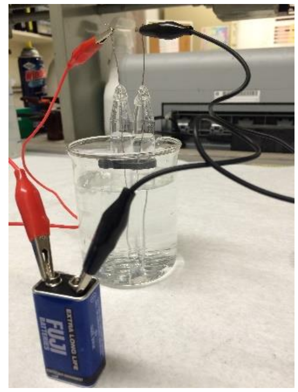
8. Once the tubes are submerged and full of solution, carefully attach an alligator clip to each wire protruding from the top of the tube. Take care that the wires and metal parts of the alligator clips do not touch each other or the circuit will be shorted.



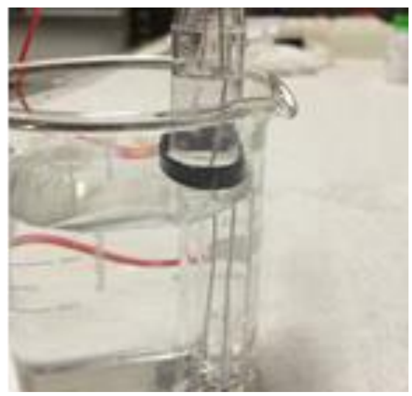
Testing your water-splitting device

9. Attach the other end of each alligator clip to the two nodes of the 9V battery. Record start time.

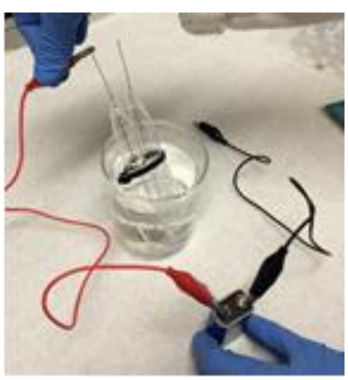




10. Tiny bubbles should start to form on the nickel wire inside the tubes. One tube is generating hydrogen gas, the other oxygen gas.



** Blackberry juice is a pH indicator. Try crushing some berries from the DSSC lab and adding the juice to your water-splitting device. Do you observe a color change? Record which tube changes color. You may need to refill the tubes for the blackberry juice to mix well with each side.



11. Once the tubes are almost completely full of gas, disconnect the battery and take note of the final volume of the air pockets in the table below. Record the final time

12. OPTIONAL: Prepare the match or striker. Lift the tubes up and quickly bring the flame or spark over the cup where the gases were released. You should hear a quick pop of the hydrogen gas burning. This test works best when you allow the water-splitting device to sit for at least 20 minutes.

	Start V (mL)	**End V** (mL)	**Total V** (mL)= End V – Start V
Tube 1 color:			
Tube 2 color:			

Start time:
End time:
Total time:

Review questions

1. What are the two half-reactions for water splitting?

2. What is the net reaction for water-splitting in the tubes?

   Net reaction:

3. Based on the volumes you measured, which tube contains oxygen and which side contains hydrogen?

   Tube 1: Tube 2:

4. When one side is connected to the positive (+) side of a battery (shown below), which half reaction occurs? The negative (-) side? Remember that the cathode is where reduction happens and the anode is where oxidation happens. It may help to look at the set-up of your own water-splitting cell.

   If you switched the nodes of the battery so that the side that was connected to the (+) was connected to the (-) and the side that was connected to the (-) was connected to the (+), would the gases, hydrogen and oxygen, still collect in the same tubes as before?

5. We can understand which tube contains oxygen and which contains hydrogen by using a pH indicator. H-Ind is used to refer to the protonated version of a pH indicator; Ind^- is the deprotonated indicator. Our pH indicator, blackberry juice, turns red (HInd) in acidic solutions and green (Ind^-) in basic solutions. The reactions of a pH indicator with acid (H^+) and base (OH^-) are shown below:

$HInd \rightleftarrows H^+ + Ind^-$ $\qquad$ $HInd + OH^- \rightleftarrows H_2O + Ind^-$

Using Le Chatelier's Principle, justify why the hydrogen half-reaction makes the water in one tube basic and turns the solution green.

Optional Analysis

How do we evaluate whether or not students can successfully fulfill the objectives we set out at the beginning of the lesson? Here are some sample assessment activities based on our example objectives.

Example Objectives:
Students should be able to:

1. Use a model to explain how photosynthesis transforms light energy into stored chemical energy.

   Split your class into groups of 2-4. Have each group draw out a poster explaining photosynthesis. Each poster should have the net chemical reaction for photosynthesis along with a pictures to support their written explanation. Each group can present in front of the class or to the teacher as time permits.

2. Compare and contrast the conversion of light energy into chemical fuel by photosynthesis and artificial photosynthesis.

   As a class, write a list of similarities and differences between photosynthesis and artificial photosynthesis. Discuss aspects of each, including cost, efficiency, reactants, products, etc. Have each student write a short paragraph summarizing the comparisons the class made.

3. Evaluate the efficiency of a human-made water-splitting device in comparison to the 3% efficiency of photosynthesis.

   Each student can calculate the efficiency of their water-splitting device. Efficiency here is comparison of potentials: $V_{MIN}/V_{IN}*100$, where V_{MIN} is the ideal (minimum) voltage needed to split water (1.23 V, the difference between the formal potentials of the two half-reactions) and V_{IN} is the voltage provided to the system (9 V, from the battery chosen). Which device is more efficient? Are there any drawbacks to water-splitting with a battery?

4. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium

   Work through review question #5 as individuals, in groups of 2-4, or as a class.

5. Design, build, and refine a device to convert one form of energy into another form of energy

   After working through the whole lab, discuss with your class ways to improve the efficiency of your water-splitting device. How would you change the design? Have each group come up with a list of changes to make and let them test their hypotheses. What works? Examples would include changing the type or concentration of salt in solution, using a different type or voltage of battery, etc.