Artificial Photosynthesis: Fuel for the Future?

Overview
This lesson is designed to strengthen students' understanding of photosynthesis, redox reactions, and renewable energy sources. It is related to a biology lesson on photosynthesis as it analyzes how sunlight can be used to split water and provide a source of fuel for cars, industry, and human society. It's a linking activity between biology, chemistry, and environmental science.

Key Search Words
- Subject: Biology, Chemistry, Environmental Science
- Grade: 10-12
- Topic: Photosynthesis, Electrolysis
- Critical Vocabulary: redox reactions, catalyst, fuel cells, solar power, cathode, anode

Learning Objectives
- Students will be able to explain the connection between electrolysis and the photosynthetic pathway.
- Students will be able to identify the role of water in both processes, the products produced in electrolysis, and the products produced during the light-dependent reactions of photosynthesis.
- Students will be able to describe how a hydrogen fuel cell works and the redox reactions involved.

Curriculum Alignment
- NC Essential Standards
  - Chm.2.2 Analyze chemical reactions in terms of quantities, product formation, and energy.
  - Bio.4.2.1 Analyze photosynthesis and cellular respiration in terms of how energy is stored, released, and transferred within and between these systems.
- NGSS
  - PS1.B: Chemical Reactions

Classroom time required
- Pre-Lab/Background Review - 20 min
- Part 1 - Electrolysis of Water - 30 min
- Part 2 - Hydrogen Fuel Cells - 30 min (Optional Extension)

Materials & Technology
Handouts
- Student Handout - Artificial Photosynthesis Lab Student Sheet

Electrolysis Lab Materials, per group
- Clear plastic cup (sauce cup, 1.5 oz)
- 2 metal thumbtacks (no plastic coating)
- 9V battery
- Distilled water
- Prepared saltwater (baking soda water)
- Baking soda (sodium bicarbonate, $NaHCO_3$)
- Plastic pipettes
- Scissors
- Wood splints
- Lighter/matches

Hydrogen-Fuel Car (Optional Extension)
- Physical Car available via Horizon Education or Flinn Scientific
  - Horizon Education: https://www.horizoneducational.com/horizon-h-racer-2-0/p1216
  - Flinn Scientific: https://www.flinnsci.com/h-racer-fuel-cell-car/ap7329/#variantDetails
- Alternative Video: https://www.economist.com/films/2021/08/25/hydrogen-the-fuel-of-the-future

Safety
Students should exercise caution with the lighters/matches and wooden splints, and teachers should supervise students anytime there is an open-flame. If necessary, teachers can provide thermal gloves for students to use when completing this part of the experiment. Students should not submerge the batteries in the water.

Teacher Preparation for Activity

Teachers should prepare access for students to the Artificial Photosynthesis Lab Sheet at the beginning of the lesson - either digitally or print copies.

Teachers should acquire necessary materials for the electrolysis part of the lab and set up lab stations accordingly.

Student Preparation for Activity

The pre-lab is designed to remind students of the critical information to be successful in the lab, but students should have a foundational background understanding of photosynthesis (at an advanced level), redox reactions, and chemical reaction coordinate diagrams.

Procedure

1. Teachers complete the pre-lab questions alongside the students to ensure correct, foundational understanding to be able to successfully complete the lab investigation and associated analysis.
    a. Teachers should ask for student input prior to sharing the answers. When students share their thoughts for the possible answers, teachers should fill in any missing information and clarify any misconceptions.
2. Teachers should give a brief explanation of the purpose of the lab and safety considerations to take.
3. Students are released to the lab benches to complete their investigation. Students should follow procedural steps on their lab sheets while the teacher circulates between groups.
    a. While circulating, check for appropriate apparatus set-up, safety precautions, and answer student questions as they arise.
4. Upon completion of activity, students should clean up their lab bench and reset for the next group/class to complete. Students should start Part 1 Analysis Questions as they finish the initial investigation.
5. For Part 2, teachers should review the graph in the Student Lab Sheet alongside the class to ensure accurate comprehension of the data.
    a. First, have students look at the graph individually and come up with three observations of what they notice. Students may also choose to write questions about things they are confused about.
    b. Be sure to point out the axis labels, meaning behind energy density, and draw a comparison between the known fuel sources (gasoline, natural gas, coal) to hydrogen gas (the focus of the investigation).
6. For Part 2 #2-4, students should complete with a partner before reviewing as a whole class.
    a. Teacher Notes: #2 - Look for students to use sunlight as a means of breaking the water molecule and products of hydrogen and oxygen. Students should compare the reactions in Photosystem II when the water is split into H^+ ions, electrons, and oxygen atoms. Correct students if they are not specific enough in their diagrams with regards to H^+ and electrons.
7. For Part 2, Optional Extension - Teacher can either use hydrogen-fuel cars purchased, an online video showing a hydrogen-fuel cell car, or skip this part of the lesson.
8. Teachers should wrap-up this lesson with a whole class discussion about what the students discovered and its applications beyond the classroom. This can be done as an exit ticket or homework assignment as well.
    a. Ask students,
        i. “What is the relationship between electrolysis and photosynthesis?”
        ii. “Why are the products of electrolysis relevant to the study of energy sources?
        iii. “How can hydrogen fuel be sustainably produced (not mined and split from methane)?”

Differentiation

- Academic or Intellectually Gifted Students: The extension activity that is marked as optional on this lab could be made required. Even without access to the physical hydrogen-fuel car, students could complete a research project on how hydrogen-fuel cells work (the science behind them) and the pros/cons associated with scaling this technology up.
- English Language Learners: Students could create a physical paper model of electrolysis with vocabulary labels for each step of the process. Instead of completing the extension activity, students could use paper cutouts to model the process/path of a H_2O molecule as it is split and undergoes electrolysis.

Assessment/Check for Understanding

- No Extension Activity - The assessment of this lab comes from two sources: the analysis questions at the end of Part 1 - Electrolysis of Water, and the discussion questions at the end of the activity. Teachers can collect the student lab sheets and assess the breadth and depth of the student responses to analysis questions. If completing an exit ticket for the discussion at the end of the lesson, teachers can also assess student responses to the foundational questions.
- With Extension Activity - The assessment of this lab comes from two sources: the analysis questions at the end of Part 1 - Electrolysis of Water, and the Summary Question after viewing the hydrogen-fuel car and hydrogen-fuel

cell schematic. Students should be able to draw connections between the hydrogen-fuel cell and light-dependent reactions in photosynthesis. This is appropriate for advanced students.

Required resources

The only required resources are those listed in the materials section above and the Student Lab Sheet.

Author comments

This lab was designed to connect the topic of photosynthesis in advanced Biology courses to the issues of global climate change and energy resource needs. It was based on the author's experience in a solar cell research lab (Cahoon Group at UNC Chapel Hill).,

Sources

- Celebrate Hydrogen and Fuel Cell Day with the Energy Department. (2019, September 23). Energy.Gov. https://www.energy.gov/articles/celebrate-hydrogen-and-fuel-cell-day-energy-department
- Energy Density. (2008, December 22). [Graph]. https://commons.wikimedia.org/wiki/File:Energy_density.svg

Appendices

- Student Lab Sheet - Artificial Photosynthesis Lab
- Answer Key - KEY Artificial Photosynthesis Lab

Artificial Photosynthesis

Fuel for the Future?

Background:

Remember - plants are incredible! Through photosynthesis (including that powerful RuBisCO enzyme!), they can turn gaseous CO_2 and liquid H_2O within the presence of sunlight into a fuel source for their growth, response, and development. Given our globe's heavy reliance on fossil fuels as a fuel source to power our lives, what if there was a way to use the basis of photosynthesis as an alternative energy source?

In fact, there is current, local, and relevant research into a process called "artificial photosynthesis" where researchers are using advancements in technology to mimic pieces of the photosynthetic pathway with the ultimate goal of creating and harvesting fuel from the sun - a renewable energy source! One of the major sources of clean fuel is **hydrogen.** Hydrogen gas can be collected and utilized to power the electricity needs of our society - when combusted, the only products are water and ENERGY (electrical and heat).

Guiding Question: Can an artificial photosynthesis reaction power a car instead of gasoline?

Pre-Lab Questions:

1. As a class, let's break down the photosynthesis chemical reaction equation and see where the hydrogen atoms are produced.
    a. Write out the full chemical equation for photosynthesis below.

    b. Look at the overall reaction equation - what is the source of the hydrogen atoms?

    c. How are those hydrogen atoms "detached" from the water molecule to form the glucose?

    d. Do you think it's possible to harvest those H ions after the water splitting reaction? What needs to happen to them to be able to collect and store them?

2. What is electrolysis?

3. How is it possible to utilize a renewable source (not a battery or coal-powered electricity) to split water?

Part 1 - Activity: Electrolysis of Water

Materials:

- Clear plastic cup (sauce cup, 1.5 oz)
- 2 metal thumbtacks (no plastic coating)
- 9V battery
- Distilled water
- Prepared saltwater (baking soda water)
- Baking soda (sodium bicarbonate, $NaHCO_3$)
- Plastic pipettes
- Scissors
- Wood splints
- Lighter/matches

Make a Prediction: What will happen as electricity (supplied by the battery) is conducted through water via the metal thumbtacks? Use a model or chemical reaction equation to help explain your prediction! *Hint: Think about what that additional energy will do to the water molecules and covalent bonds…*

Procedure:

1. Punch the two metal thumbtacks through the bottom of the plastic cup so the points of the tacks are pointing up into the cup. The thumbtacks should be spaced the same distance apart as the terminals (the circle and hexagon metal shapes) on the 9V battery.
2. Pour about 25 to 30 mL of water into the plastic cup.
3. Add a small scoop (about 2-3 g) of baking soda to the water and stir to combine. *Why do we need to add baking soda to the distilled water?*
4. Cut the two plastic pipettes near the tip, to allow the tip to have a wider opening so that it can fit around the top of the thumback. Be sure that both pipettes are cut to be the same size.
5. Using the prepared saltwater at your lab bench, fill both pipettes by holding them under the water level until they have filled. *Trying to fill them the "traditional pipette way" will always result in air within the pipette - we want them both filled with just the saltwater!*
6. Holding the pipette end with your finger so that no water escapes, invert the full pipettes into the plastic cup with the thumbtacks - one over each thumbtack. **Do not allow any air bubbles into the pipettes.** You will have to either tape or have a student hold the pipettes in place so they do not fall.
7. Place the cup over the 9V battery so the terminals on the battery touch the tacks. Record observations!
8. After a significant amount of gas has formed in the pipettes, you will test the gas produced by simultaneously completing the steps below. *It takes two people!*
    a. Prepare a wood splint by igniting it.
    b. Use a pair of sharp scissors and cut the tip of one pipette.
    c. Test the gas formed using the prepared burning wood splint. Do this quickly (but carefully!) so that the gas formed doesn't disperse into the air. Record your observations - did it go out immediately? Did it continue to burn?
    d. Repeat the previous step with the other pipette and record observations.

Observations:

- During electrolysis →

- Splint + Pipette 1 →
- Splint + Pipette 2 →

Part 1 Analysis Questions

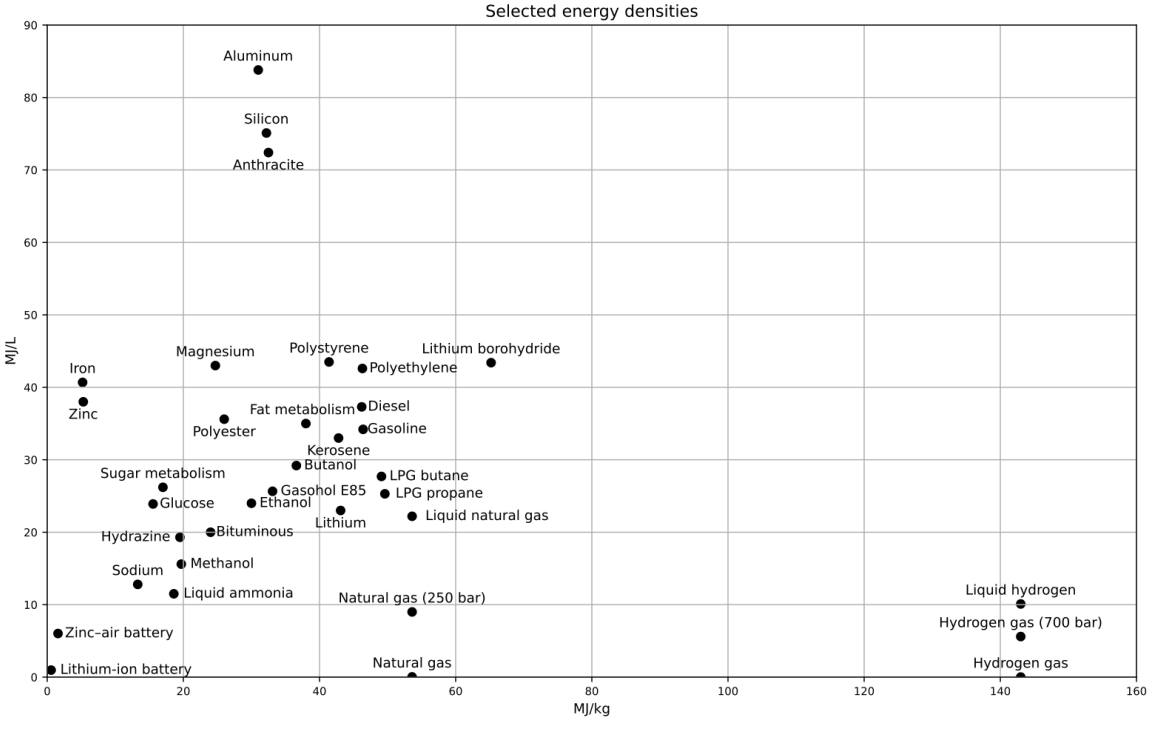
1. You should have noticed that a different amount of gas was produced in each pipette. Based on the chemical formula for water, why did more hydrogen gas form than oxygen gas?

2. Is electrolysis a physical or chemical change? Provide evidence to support your answer.

3. Electrolysis nearly mimics which piece of the photosynthetic pathway? What does the battery serve a similar role to? How are electrons involved in both photosynthesis and electrolysis?

Part 2 - Using Hydrogen as a Fuel

So, now we know that we can produce hydrogen gas. In fact, hydrogen has been used and harvested for quite a while because of its energy capacity. (Energy Density, 2008)



1. What are three things you notice about the graph above?

Currently, the widely used method of acquiring hydrogen is not by splitting water but rather by splitting fossil fuels like methane, CH_4 which is not ideal from an environmental perspective because it still involves mining fossil fuels. **So, the question becomes how can hydrogen be sustainably produced and used as a fuel?**

Let's think about how the **SUN** - a sustainable, renewable energy source - can be used to produce H_2 gas. Recall that within photoautotrophs, the sun is the energy source for exciting the electrons in chlorophyll and activating the catalyst used in the chloroplast to split a water molecule.

2. <u>Draw a model</u> for how you think the water molecule could be split by the sun instead of a battery like we did in our electrolysis experiment in Part 1.

3. Recall: Is this a spontaneous reaction? What evidence do you have to support your claim? What would the energy reaction diagram look like? Label with reactants and products.

4. Extend: What product would form if the H_2 produced from the splitting of water was captured and recombined with O_2 gas in a controlled environment? Would that happen spontaneously or require additional energy? What would the energy reaction diagram look like? Label with reactants and products.

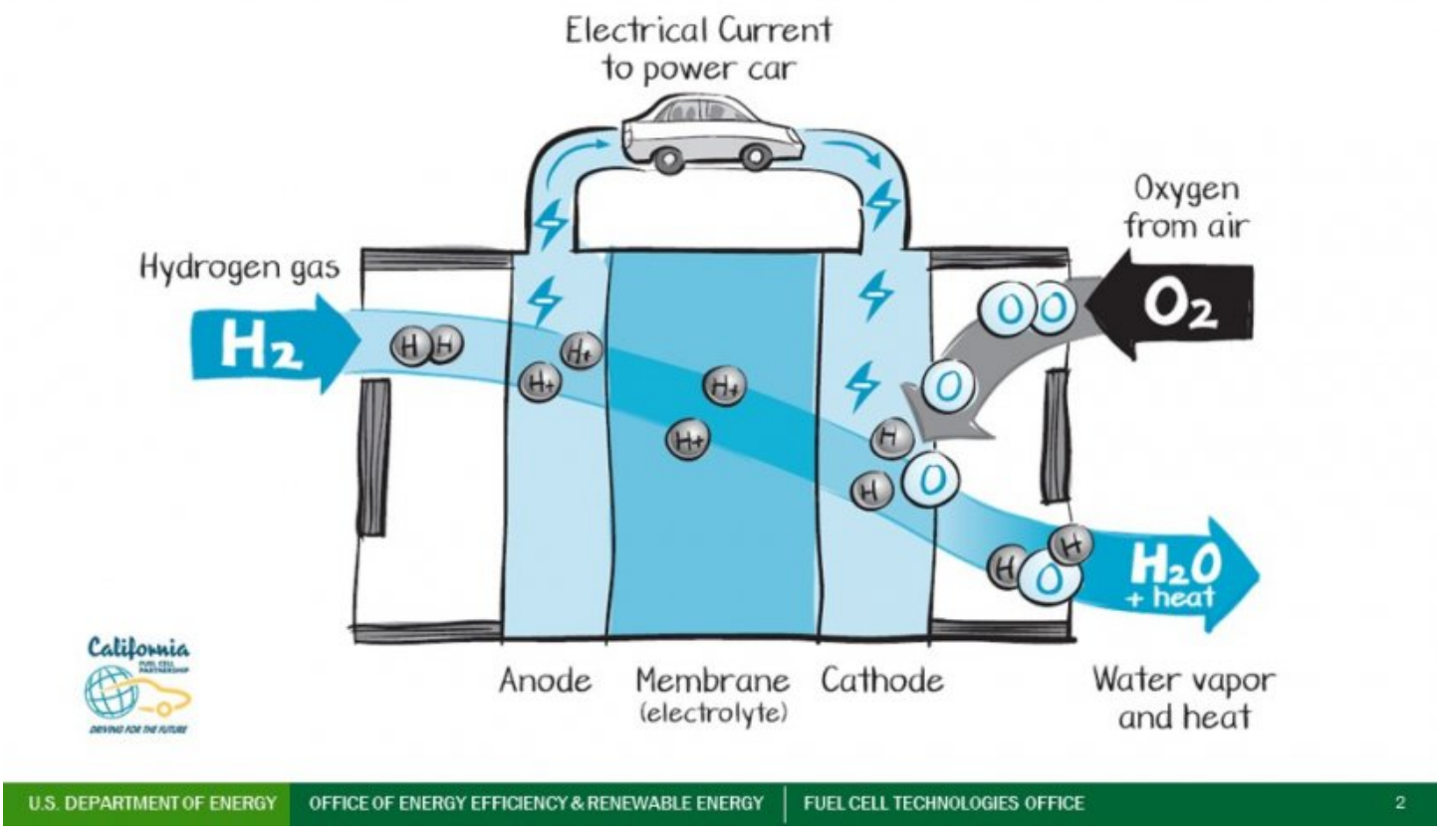
Optional Extension Activity: In simplified terms, this synthesis of H_2O from H_2 and O_2 alongside a controlled transfer of electrons can be used to power a vehicle! Let's look at an example of a hydrogen-powered car, the H-Racer Fuel Car from Horizon Educational. *(Note: If you don't have a physical car, use this video or another video on hydrogen-fuel cell cars.)*

Observations: Write down THREE observations you have about the hydrogen-powered car.

Below is a schematic diagram of a hydrogen fuel cell that could exist in a hydrogen-powered car. Let's assume the hydrogen gas was produced from the solar splitting of water and not steam-methane reforming (using methane as the initial source).

Summarize, in bullet points or an annotated diagram, what is happening within this fuel cell - be sure to address where the energy to power the car comes from! *Hint: This is a redox reaction, and identifying the half reactions (at both the anode and cathode catalysts) will help you figure out just how this fuel cell works!*

Highlight or annotate where in your summary there are connections to photosynthesis.



(Celebrate Hydrogen and Fuel Cell Day with the Energy Department, 2019)

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KEY Artificial Photosynthesis

Fuel for the Future?

Background:

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In fact, there is current, local, and relevant research into a process called "artificial photosynthesis" where researchers are using advancements in technology to mimic pieces of the photosynthetic pathway with the ultimate goal of creating and harvesting fuel from the sun - a renewable energy source! One of the major sources of clean fuel is **hydrogen.** Hydrogen gas can be collected and utilized to power the electricity needs of our society - when combusted, the only products are water and ENERGY (electrical and heat).

Guiding Question: Can an artificial photosynthesis reaction power a car instead of gasoline?

Pre-Lab Questions:

1. As a class, let's break down the photosynthesis chemical reaction equation and see where the hydrogen atoms are produced.
    a. Write out the full chemical equation for photosynthesis below.

$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$

    b. Look at the overall reaction equation - what is the source of the hydrogen atoms?

The hydrogen atoms come from the water molecules.

    c. How are those hydrogen atoms "detached" from the water molecule to form the glucose?

The hydrogen atoms are split from the water molecule at PS II and become H^+ ions that are chemically attached to a $NADP^+$ carrier molecule that transports them to the Calvin Cycle to be introduced to CO_2, undergo a series of chemical reactions and form glucose, $C_6H_{12}O_6$.

    d. Do you think it's possible to harvest those H ions after the water splitting reaction? What needs to happen to them to be able to collect and store them?

Yes, the $NADP^+$ molecule attaches to the H^+ ions, so it might be possible to attach them chemically to other substances as well and then collect that substance. Or those ions could (in theory) recombine with electrons to form H_2 gas.

2. What is electrolysis?

Electrolysis is using electricity (electro-) to chemically decompose (lysis-) a substance.

3. How is it possible to utilize a renewable source (not a battery or coal-powered electricity) to split water?

Use another source of energy - like the sun to break apart the bonds in a water molecule.

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Answers will vary.

Procedure:

1. Punch the two metal thumbtacks through the bottom of the plastic cup so the points of the tacks are pointing up into the cup. The thumbtacks should be spaced the same distance apart as the terminals (the circle and hexagon metal shapes) on the 9V battery.
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Observations:

- During electrolysis → Answers will vary.

- Splint + Pipette 1 → Answers will vary.
- Splint + Pipette 2 → Answers will vary.

Part 1 Analysis Questions

1. You should have noticed that a different amount of gas was produced in each pipette. Based on the chemical formula for water, why did more hydrogen gas form than oxygen gas?

There are more hydrogen atoms than oxygen in a single water molecule.

$2\ H_2O \rightarrow 2\ H_2 + 1\ O_2$

2. Is electrolysis a physical or chemical change? Provide evidence to support your answer.

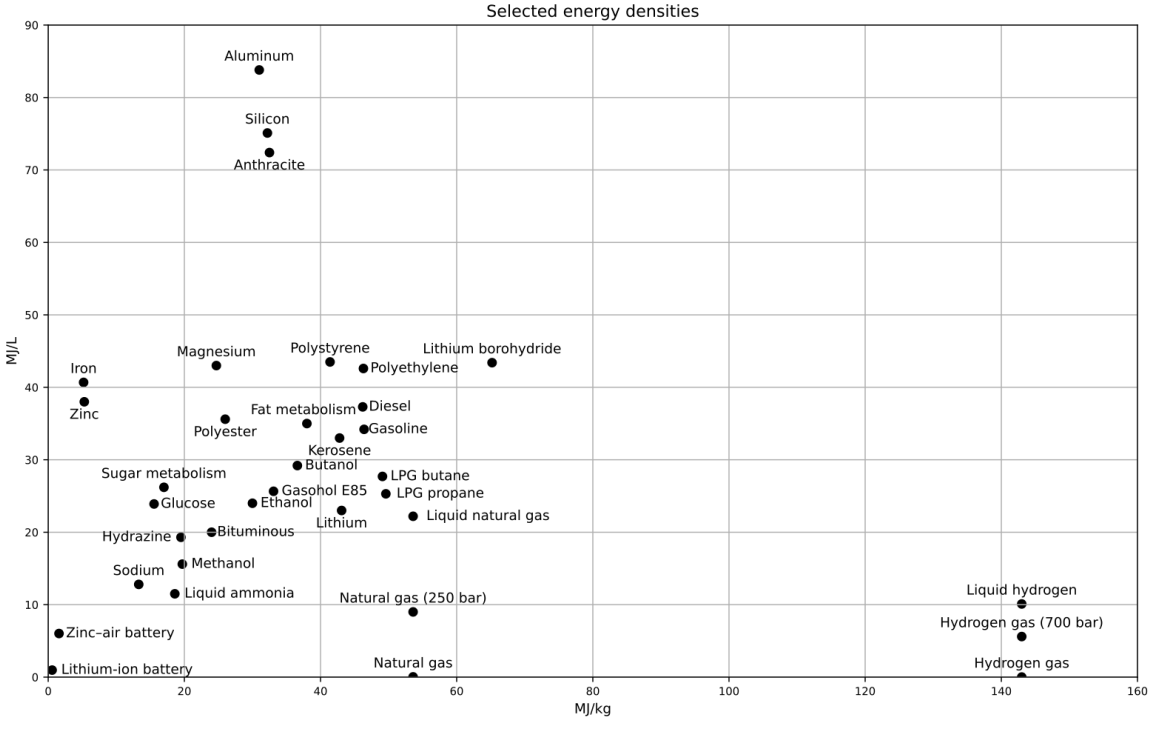
A chemical change - involves the creation of a new product(s). In this case, the water is split into two different gasses (oxygen and hydrogen). We know they are different because of the differing results from the flame test - the flame was extinguished with the H_2 gas and continued to burn with the O_2 gas.

3. Electrolysis nearly mimics which piece of the photosynthetic pathway? What does the battery serve a similar role to? How are electrons involved in both photosynthesis and electrolysis?

The reactions occurring at PS II when the water molecule is split into H ions, electrons, and oxygen atoms. The battery serves a similar function as the sun. The electrons are transferred through substances in both.

Part 2 - Using Hydrogen as a Fuel

So, now we know that we can produce hydrogen gas. In fact, hydrogen has been used and harvested for quite a while because of its energy capacity. (Energy Density, 2008)



1. What are three things you notice about the graph above?

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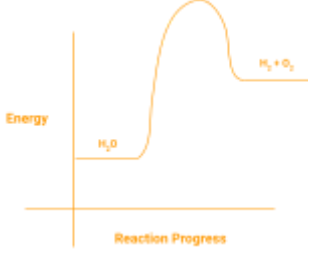
Let's think about how the **SUN** - a sustainable, renewable energy source - can be used to produce H_2 gas. Recall that within photoautotrophs, the sun is the energy source for exciting the electrons in chlorophyll and activating the catalyst used in the chloroplast to split a water molecule.

2. Draw a model for how you think the water molecule could be split by the sun instead of a battery like we did in our electrolysis experiment in Part 1.

Student model should show sunlight and solar energy as a means of energy to split a water molecule into H and O atoms or H_2 and O_2 gasses.

3. Recall: Is this a spontaneous reaction? What evidence do you have to support your claim? What would the energy reaction diagram look like? Label with reactants and products.

No, this is not a spontaneous reaction. The splitting of water requires the input of energy (electrical or solar) and does not happen spontaneously.



4. Extend: What product would form if the H_2 produced from the splitting of water was captured and recombined with O_2 gas in a controlled environment? Would that happen spontaneously or require additional energy? What would the energy reaction diagram look like? Label with reactants and products.

H_2O would form if those products were recombined - it would essentially be the reverse reaction as to what is occurring in #3. This would happen spontaneously and would not require an input of energy but would release energy (heat).

Optional Extension Activity: In simplified terms, this synthesis of H_2O from H_2 and O_2 alongside a controlled transfer of electrons can be used to power a vehicle! Let's look at an example of a hydrogen-powered car, the H-Racer Fuel Car from Horizon Educational. *(Note: If you don't have a physical car, use this video or another video on hydrogen-fuel cell cars.)*

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Answers will vary, but should contain the following information:

- At the anode, the hydrogen gas is converted to hydrogen ions and free electrons are also produced.
    - Connection to photosynthesis and PS II reactions.
- The free electrons move through current in the direction of the cathode. The movement of electrons generates energy for the car to run.
    - Connection to photosynthesis and electron transport chain.
- While the electrons are moving through the current, the hydrogen ions move through a membrane and flow towards the cathode (diffusion).
- The electrons and hydrogen ions rejoin alongside O_2 gas molecules from the air to form H_2O and heat energy.

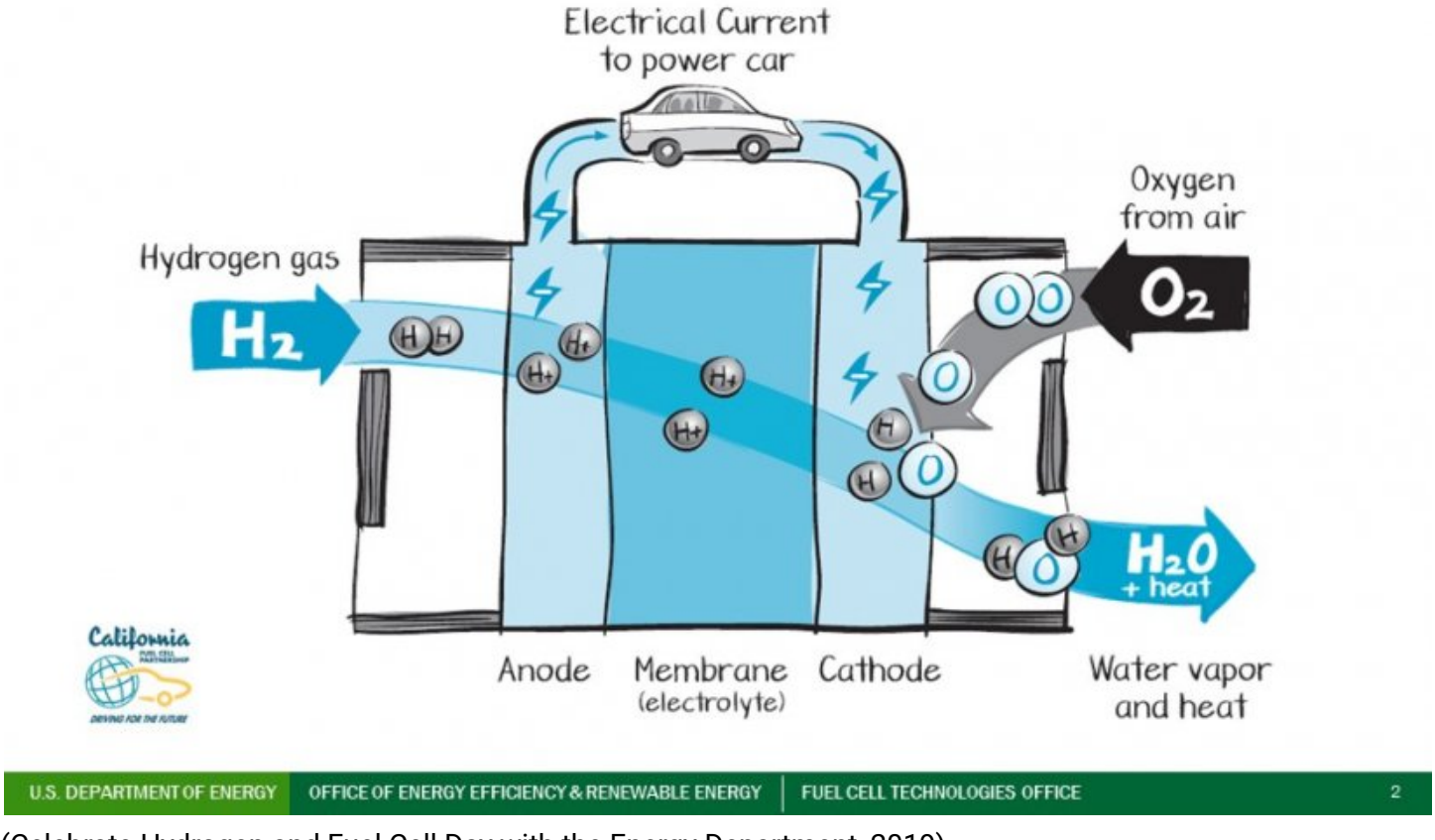
Anode Half-Reaction - OXIDATION

- $H_2 \rightarrow 2\ H^+ + 2\ e^-$

Cathode Half-Reaction – REDUCTION

- $4\ H^+ + 4\ e^- + O_2 \rightarrow 2\ H_2O$

Highlight or annotate where in your summary there are connections to photosynthesis.



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