SOLAR ENERGY CONVERSION

Elementary School
Making a Dye-Sensitized Solar Cell

NGSS ELEMENTARY SCHOOL LESSON PLAN

How does a solar cell convert light into electricity? This lesson is designed to help teachers educate students about the chemistry of solar energy.

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

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Image (cover): Each pane of these beautiful windows, found in the Swiss Federal Institute of Technology Convention Center, is composed of a dye-sensitized solar cell. The many colors allow for some artistic innovations when installing the cells.

Image Credit: *EPFL / Alain Herzog*

Before You Start

1. 1. What do I know about solar cells?

Evaluate your prior knowledge of solar cells and how they function. This short assessment is meant to help you identify what you *already* know about solar cells and what you might want to review.

Pre-lab Assessment

1. What are the types of energy into which efficient solar cells can convert light?
    a. A. Chemical
    b. B. Electrical
    c. Heat
    d. Both A and B
    e. Both B and C
    f. All of the above
2. Which of the following compounds allow plants to absorb light effectively?
    a. Titanium dioxide
    b. Chlorophyll
    c. Plant pigments
    d. Both B and C
    e. Both A and C
    f. None of the above
3. How does the size of a semiconductor's band gap affect the wavelength of light it absorbs?
    a. The larger the band gap, the shorter the wavelength of light needed to excite an electron in the semiconductor.
    b. The larger the band gap, the longer the wavelength of light needed to excite an electron in the semiconductor.
    c. The wavelength of light that a semiconductor absorbs is unaffected by the size of the band gap.
4. Assuming that you are presented with the same amount of each, what form of a semiconductor has the largest surface area?
    a. Bulk silicon (i.e. a thin piece of silicon)
    b. Silicon nanoparticles
    c. They should have the same surface area.
5. Mark each statement below as true or false.
    a. In a DSSC, an electrolyte must be present in the cell to return the <u>semiconductor</u> to its ground (unexcited) state.
    b. A DSSC is covered in <u>metal</u> to complete the circuit formed by the light absorber and semiconductor.
    c. While they are simple to fabricate, DSSCs are <u>not used outside of the classroom</u> due to their low conversion efficiencies.
    d. Attaching many DSSCs <u>in parallel</u> will result in the <u>highest observable voltage</u> when the cells are exposed to light.
    e. DSSCs are <u>less expensive</u> to make than silicon solar cells.

Once you have completed the assessment, please correct
your answers using the key on the next page!

Assessment key:

1. D, solar cells convert light into chemical fuel or electricity. Inefficient cells can produce heat.

2. D, chlorophyll is the classic compound that leaves contain to absorb and convert light into energy. Other natural absorbers supplement chlorophyll and are called **accessory pigments**. These pigments include the dyes that make fruit multicolored, such as the anthocyanin dye found in blackberries.

3. A, shorter wavelengths mean higher energy photons. Remember that $E = h\nu = hc/\lambda$. Thus, when a semiconductor has a large band gap, it needs higher energy photons to excite an electron from the valence band to the conduction band.

Not sure what a band gap is? Check out the background information below: What is a bandgap?

4. B, nanoparticles are, as the name implies, very, very small particles. When given the same amount of bulk semiconductor and nanoparticle semiconductor, we would expect the nanoparticles to have a much larger surface area as the total surface area of the particles is the sum of the surface areas of each individual particle, whereas the total surface area of the bulk semiconductor is simply the surface of the wafer.

5a. False, the electrolyte must be present to regenerate the <u>absorber</u> (or <u>dye</u>) used in the DSSC, not the semiconductor.

5b. False, the DSSC is encased in <u>conductive glass</u> to ensure that the cell can still absorb sunlight. Metal would simply reflect the light and heat up the cell.

5c. False, while not as prevalent as their silicon counterparts, DSSCs are <u>available commercially</u> and <u>used around the world</u>.

5d. False, attaching the cells <u>in series</u> will yield the <u>highest voltage</u>. Attaching the cells <u>in parallel</u> yields the <u>highest current</u>.

5e. True, silicon solar cells are <u>very expensive</u> as the silicon used must be extremely pure. DSSCs typically <u>do not have these cost limitations</u>, although the organic components (i.e. the dye) will decompose over time, requiring more maintenance than a silicon solar cell.

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

2. 2. How does a solar cell work?

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

After reading through the four next generation science standards on page 13, 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:

- combine information about ways communities use solar energy to protect the earth
- describe that obtaining and using energy and fuels also affects the environment
- provide evidence that energy can be transferred by light, heat and electric currents
- design, test and refine a dye-sensitized solar cell that converts sunlight to electricity

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

4. 4. Read through the lab procedure.

After you read through the procedure, check out our demonstration videos for a quick refresher on how to make a DSSC. Any questions or concerns? Contact a Caltech scientist! We'd love to visit your classroom and help students fabricate their DSSCs.

5. 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.

Before you instruct your students, you may want to watch the DSSC videos to review the lab procedure: http://thesolararmy.org/jfromj/resources/ and click on "DSSC Playlist" under "Instructional Videos."

Background Information

What is a solar cell?

A solar cell is a light-sensitive material that collects solar energy and converts it into fuel: electrical or chemical. Nature's solar cell is a leaf on a plant as it undergoes ***photosynthesis***. In photosynthesis, the chlorophyll dye in a leaf absorbs light from the sun, solar energy, and converts it into sugar, source of chemical energy. Similarly, a manmade solar cell (Figure 1) takes solar energy but converts it into electrical energy rather than chemical energy.

Figure 1. Solar cells can be found scattered around Caltech's campus.

Recap Question #1:
Where does the power come from when we are using a solar cell?

How do we make a solar cell?

Figure 2. A leaf is nature's solar cell, converting light into chemical fuel.

What components make up a solar cell? Let's look more closely at the example of the leaf (Figure 2). We can break down photosynthesis into two main processes: (1) absorption of solar energy by the leaf dye, chlorophyll, and any accessory pigments and (2) conversion of the absorbed solar energy into chemical fuel. We want our solar cell to mimic photosynthesis, where solar energy does all the work, but our cell will produce electrical energy. Just like the leaf, we need to ensure that our cell can complete both (1) absorption and (2) conversion.

Recap Question #2:
A leaf and a solar cell both convert solar energy into another type of energy. What type does a solar cell make, and what type does a leaf make?

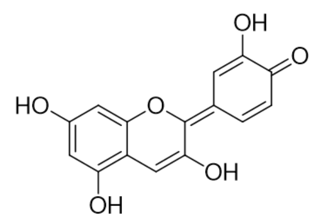
Absorption

Figure 3. The different dyes in this fabric absorb various wavelengths of light, giving the cloth its beautiful hue.

First, we will need dye, such as chlorophyll, to absorb light from the sun (Figure 3). What makes something a good dye, or light absorber? Simply put, we want a molecule that can strongly absorb light. Logic tells us that if light must be absorbed by our solar cell in order to be converted into electricity, absorbing *more* light is better for the efficiency of our solar cell (i.e. more light in = more energy out).

In this lab, we will used the dye found in blackberry juice as our light absorber. Blackberries contain a strongly light-absorbing dye molecule called anthocyanin, which occurs in many types of fruits and berries (Figure 4). It is the compound that gives blackberries, raspberries, blueberries, and pomegranates their color.

Chemical Formula: $C_{15}H_{10}O_6$



Anthocyanin (blackberry dye)

Figure 4. When crushed, blackberries release anthocyanin, the dye that gives the blackberry its dark purple color.

Once the dye absorbs light, the electrons in it get excited to higher energy levels, but having the cell absorb light is only part of the battle! What about converting what we absorb into electricity?

Recap Question #3:

The TiO_2 semiconductor paste used in this lab is white and used in many commercial products: white paint, toothpaste, powdered doughnuts, etc. Why do we need to use the dark-colored dyes from blackberries to make our solar cell work?

What is a band gap?

A band gap is analogous to the energy gap between the highest *occupied* molecular orbital (HOMO) and the lowest *unoccupied* molecular orbital (LUMO) of a chain of conjugated carbon atoms, such as butadiene. In fact, as you add more and more carbons to the chain, the orbital arrangement of an organic molecule begins to approach the arrangement we can observe in a semiconductor (Figure 5). There are so many orbitals with similar energies on either side of the band gap that they are treated as a single **band** rather than individual orbitals. The HOMO becomes the valence band, and the LUMO becomes the conduction band.

Figure 5. The HOMO-LUMO gap is analogous to the gap between the conduction band and valence band of a semiconductor.

Conversion

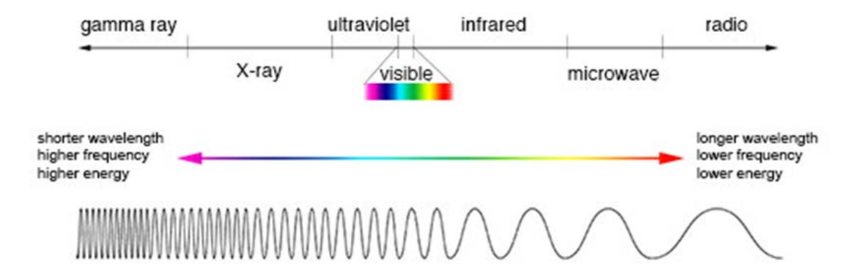
Conversion of the absorbed light proves to be the trickier half of the DSSC equation. We need a material that can take the light *absorbed* by the anthocyanin dye and *convert* it into a current, or moving electrons. To do this conversion, our material must be at the correct energy level to accept the high energy, excited electrons from the dye.

This is where semiconductors make their appearance (Figure 6)! Semiconductors are characterized by the size of their **band gap** (*What is a band gap? sidebar*) ideally between 0.5-3.0 eV for solar cell applications.

To put these values in perspective, remember that the longest wavelength of light that could excite an electron across the band gap of silicon, a 1.12 eV jump from the top of the valence band to the bottom of the conduction band, is about 1110 nm, a long, low energy wave in the infrared region of the electromagnetic radiation spectrum (Figure 7). However, what matters for our DSSC is the location of the **conduction band edge**, the very bottom edge of the conduction band.

Kemi Silicon, Inc.

Figure 6. Small pieces of semi-conductor wafers like those shown above can be found in almost of our modern electronics as well as solar cells.



NASA's Imagine the Universe

Figure 7. Ultraviolet light, the type of light needed to excite an electron across the TiO_2 bandgap is shorter and higher energy than visible or infrared radiation.

For this lab, we will use the semiconductor titanium dioxide, TiO_2 with a band gap of 3.2 eV as its conduction band edge is at the appropriate level to move electrons through our circuit. After an electron is excited in the dye molecule by light, it can then fall **down** into the conduction band of the TiO_2. If the conduction band was too high in energy, the electrons would have nowhere to go and would get stuck in the dye.

Hu et. al., 2015

Figure 8. While a paste made of TiO_2 nanoparticles (left) may not look special, a scanning electron microscope can show us the tiny spheres that compose the paste.

To increase the number of dye molecules that can absorb light in our DSSC, we will use we will use **nanoparticle** TiO_2 instead of bulk TiO_2. These nanoparticles behave the same way the bulk TiO_2 does, but create a much larger surface area to which dye molecules can attach (Figure 8).

Recap Question #4:
Why is it important to use nanometer-sized particles for the film? Use the phrase "surface area" in your explanation.

What is an appropriate circuit?

When we connect the dye and semiconductor in an appropriate circuit, we can collect these moving electrons, or electricity, to do work for us! Some components of our circuit we already know. We have discussed our absorber, blackberry dye, and converter, titanium dioxide, but in order to have a current flow, we need a complete circuit. In the same way that we can observe the reduction and oxidation of different metals through the creation of an *electrochemical cell*, we can create a similar, but more compact, circuit with our absorber and converter (*see our chemistry demonstration to learn more about electrochemistry and solar cells)*.

Let's review what we know so far. After a dye molecule, the blackberry juice, absorbs a photon, electrons are excited in the dye. It takes less than 1 picosecond (10^{-12} s) to move an excited electron from the vacancy (or hole) that is left behind when excited, into a lower energy space on the TiO_2. When an electron is removed from the excited dye, a dye cation is left behind (Figure 9). To generate current, the electrons in TiO_2 must move through an external circuit and recombine with an oxidized electrolyte species (Figure 10). In our cell, the electrolyte solution is an iodide/triiodide solution (I^-/I_3^-).

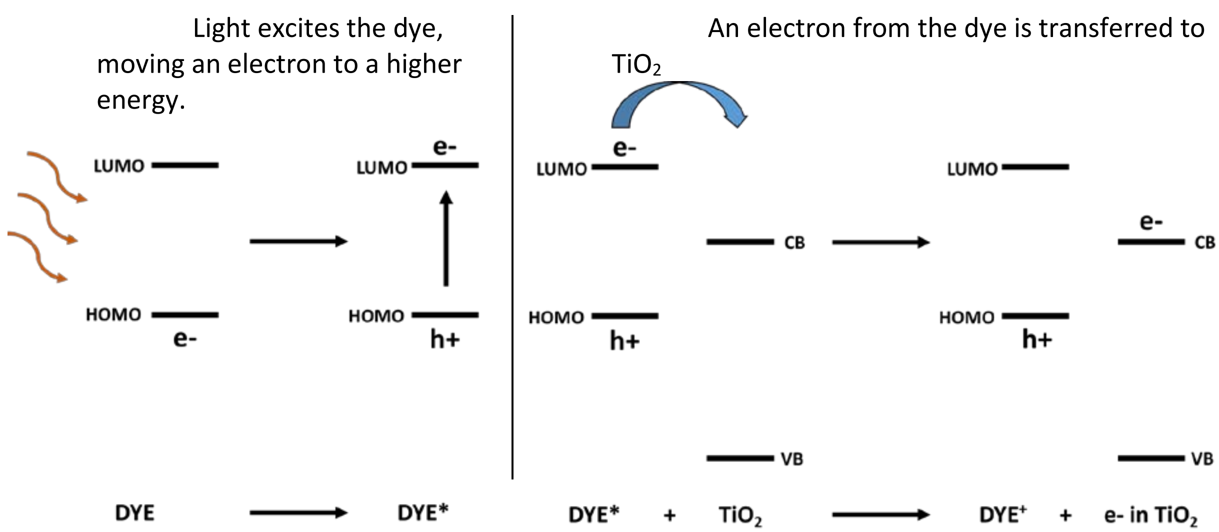


Figure 9. (a) Light excites an electron in the blackberry dye from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). The dye in the excited state is denoted as DYE*. This excitation leaves behind a positively-charged hole (h^+). (b) Once excited, the electron can fall back down to the original lower energy state to yield the original dye molecule (DYE) or it can be transferred into the adjacent low energy state on the TiO_2. This transfer leaves the dye with a positive charge, making it a dye cation (DYE^+).

In order to combine these components all together, we need a way connect the dye to this electrolyte solution that allows the collected electrons to travel through an external wire. In this way, we can place a LOAD, such as a small motor or other device, on our circuit. When we generate electricity for use by people around the world, we force the electricity to light lamps, turn on machines, and power technology by directing it through wires made of various metals. So why don't we put all our components on metal plates and connect them?

Electrons collected from the TiO_2 travel through a wire to reach the counter electrode, where they are used to reduce triiodide

Iodide is oxidized to release an electron back to the dye molecule.

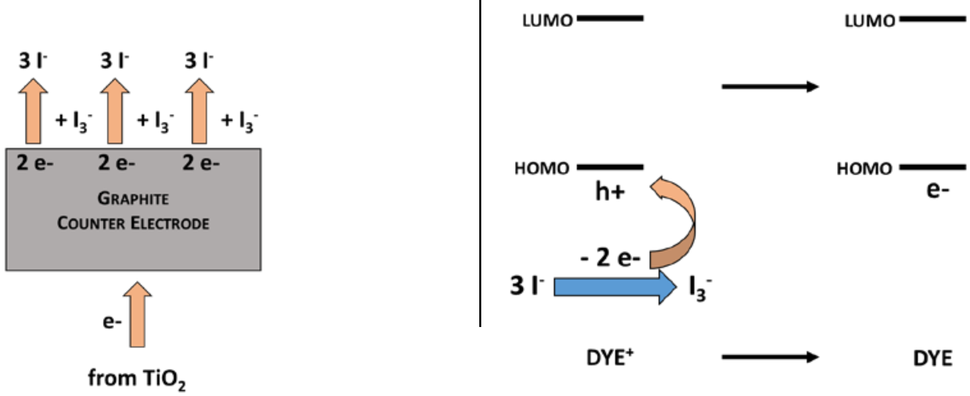


Figure 10. (c) Electrons are collected from the TiO_2 through a wire, which connects to the counter electrode. At the counter electrode, the graphite coating facilitates the transfer of electrons into solution by reducing triiodide to iodide. (d) When the several iodide molecules (I^-) come into contact with a dye cation (DYE^+), the iodide can be oxidized to reduce the dye molecule back to its ground state.

Remember that we need to *absorb* light still! Metal isn't transparent. As a substitute, we will use a special glass that behaves like a metal. This glass is coated with fluorinated tin oxide (or FTO) that greatly lowers the resistance of normal glass, allowing it to conduct electrons. To allow it to pass a large enough number of electrons across the liquid/glass interface, we will coat the FTO glass with a layer of graphite, a layered material made of carbon atoms. This carbon-coated glass acts as our counter electrode, the electrode which provides a balancing flow of electrons *into* the solution as they are *removed* from solution by the dye and TiO_2. We will make a FTO glass sandwich with our absorber, converter, and electrolyte as the filling to complete our circuit (Figure 11).

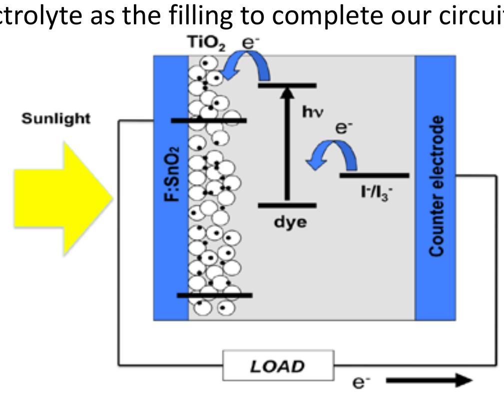


Figure 11. A working DSSC makes a complete circuit. Can you identify all of the elements necessary to complete the circuit? Note that the white circles represent TiO_2 nanoparticles while the black dots are dye molecules attached to the nanoparticles. In addition to the previously mentioned components, this figure also shows the sunlight as it illuminates the solar cell. To run a device off this solar cell, we would connect the device in the position in between the two halves of the cell, marked LOAD in the above circuit. In this lab, we will connect a multimeter at this position to test our DSSCs.

Recap Question #5:

Graphite is made up of layers of carbon. What do you think will happen to the performance of the DSSC if it was illuminated through this electrode rather than through the dyed side?

The origin of the dye-sensitized solar cell

Nature, 2010

Figure 12. Michael Grätzel holding a panel of dye-sensitized solar cells.

Brian O'Regan and Michael Grätzel at the École Polytechnique Fédérale De Lausanne in Switzerland made the first efficient DSSC (Figure 12). The approach used in DSSCs has many advantages over other solar energy conversion technologies because of its simple device construction and inexpensive TiO_2 particles and dyes that can be fine-tuned to increase their light-absorbing properties. Although there is still much room for improvement, state-of-the-art DSSCs convert solar energy into electricity with efficiencies over 11%, rivaling some silicon-based technologies (commercial silicon is typically around 20 – 30%). These devices use specially prepared dyes that absorb a great deal more sunlight than the anthocyanin dyes extracted from blackberries.

The basic procedure

In this lab, we will make a DSSC using dyes extracted from a blackberry. The blackberry will be crushed, thus releasing its dyes (Figure 13). Then, electrodes that contain a thin layer of white TiO_2 paste will be soaked in the crushed blackberries so that the electrodes become colored and absorb visible light.

Figure 13. A crushed berry releases juice that we can use to dye our TiO_2 slide.

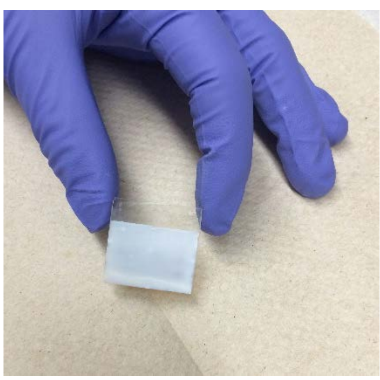


Figure 14. This slide is covered in tiny, white semiconductor nanoparticles.

The electrodes are made using a paste of TiO_2 nanoparticles that are spread out in a thin layer on transparent conductive glass electrodes (Figure 14). The thickness of the TiO_2 thin film ends up being roughly the thickness of a human hair. Remember that these particles provide a huge surface area for the dye molecules to bind and provide an electron pathway for the generated electrical current to be collected. Since the dyed electrode goes from white to dark purple when dyed, a significant portion of light is absorbed by the dye, even though only a single layer of dye molecules is attached to the surface.

The final steps include drying the electrode and then assembling the device with an additional counter electrode to form a "sandwich" solar cell (Figure 15). The device has a total of two electrodes, the dyed TiO_2 photoelectrode and a graphite counter electrode. The electrolyte solution is introduced between the two electrodes and is composed of potassium iodide and iodide/triiodide.

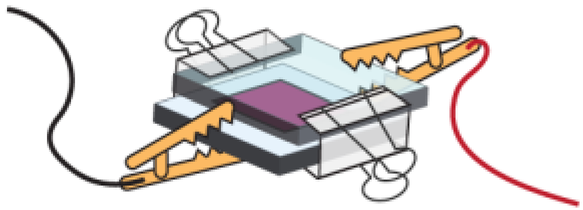


Figure 15. The completed DSSC is a TiO_2, blackberry, electrolyte, and graphite sandwich that converts sunlight into electricity.

What can you expect from the blackberry DSSCs?

The solar power conversion efficiency of these types of berry-sensitized TiO_2 DSSCs can reach ~0.7% with demonstration cells attaining 200-600 $\mu A/cm^2$ of photocurrent (current observed under illumination) when using an overhead projector as a simulated sun illumination source. Students typically observe photovoltages (voltage observed under illumination) well over 400 mV and good photovoltaic cell stability (Figure 16). Attaching many cells electrically in series results in larger voltages as the voltages of the individual cells are additive; attaching them in parallel results in larger photocurrents.

Figure 16. A completed DSSC can be tested using a multimeter.

Inquiry Opportunity: Renewable Energy

Help your students consider the importance of living sustainably. In what ways, other than installing solar panels, can we help make the world's energy use more sustainable? What is renewable energy and why is it important?

Answers to Recap Questions

Where does the power come from when we are using a solar cell? (What causes the electrons in the dye to move?)

The electrons in the dye are excited by photons, or light waves. This energy from the sun generates the current and voltage we can measure in a solar cell.

A leaf and a solar cell both convert solar energy into another type of energy. What type does a solar cell make, and what type does a leaf make?

A leaf collects carbon dioxide and sunlight and converts them into glucose and water. These two products are chemical fuels. The energy from the sunlight is stored in the chemical bonds of the glucose and water. In contrast, a solar cell takes sunlight and converts it into moving electrons, or electricity.

The TiO_2 semiconductor paste used in this lab is white and used in many commercial products: white paint, toothpaste, powdered doughnuts, etc. Why do we need to use the dark-colored dyes from blackberries to make our solar cell work?

When something appears white, it is reflecting all wavelengths of the visible spectrum that are hitting it. White is the reflection of all light. If we want our solar cell to work, we need to absorb sunlight rather than reflect it. Thus, we dye our solar cell dark colors, such as blue, purple, or red, to ensure that the cell is absorbing as much light as possible.

Why is it important to use nanometer-sized particles for the film? Use the words “surface area” in your explanation.

<u>Nanometer</u>-sized particles are very small. One strand of human hair is <u>about 100,000 nm wide</u>! These tiny particles are important, because they increase the surface area of our solar cell. When we spread a thin layer of nanoparticles on our conductive glass, FTO glass, and then dye it with the blackberries, we have increased the surface area over which sunlight can be absorbed dramatically. Instead of a simple flat surface, we have a very bumpy, rough surface that allows more dye molecules to attach to the TiO_2 and then absorb sunlight for conversion into electricity.

Graphite is made up of layers of carbon. What do you think will happen to the performance of the DSSC if it was illuminated through this electrode rather than through the dyed side?

The graphite is a dark gray so it would absorb sunlight. However, since the carbon cannot efficiently absorb sunlight and then subsequently excite electrons to move through a circuit, the DSSC would simply heat up and dry out.

Next Generation Science Standards:

5-ESS3-1. Obtain and combine information about ways individual communities use science ideas to protect the Earth's resources and environment.

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Obtaining, Evaluating, and Communicating Information Obtaining, evaluating, and communicating information in 3–5 builds on K–2 experiences and progresses to evaluating the merit and accuracy of ideas and methods. Obtain and combine information from books and/or other reliable media to explain phenomena or solutions to a design problem.	**ESS3.C: Human Impacts on Earth Systems** Human activities in agriculture, industry, and everyday life have had major effects on the land, vegetation, streams, ocean, air, and even outer space. But individuals and communities are doing things to help protect Earth's resources and environments.	**Systems and System Models** A system can be described in terms of its components and their interactions. - *Connections to Nature of Science* **Science Addresses Questions About the Natural and Material World.** Science findings are limited to questions that can be answered with empirical evidence.

4-ESS3-1. Obtain and combine information to describe that energy and fuels are derived from natural resources and their uses affect the environment. [Clarification Statement: Examples of renewable energy resources could include wind energy, water behind dams, and sunlight; non-renewable energy resources are fossil fuels and fissile materials. Examples of environmental effects could include loss of habitat due to dams, loss of habitat due to surface mining, and air pollution from burning of fossil fuels.]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Obtaining, Evaluating, and Communicating Information Obtaining, evaluating, and communicating information in 3–5 builds on K–2 experiences and progresses to evaluate the merit and accuracy of ideas and methods. Obtain and combine information from books and other reliable media to explain phenomena.	**ESS3.A: Natural Resources** Energy and fuels that humans use are derived from natural sources, and their use affects the environment in multiple ways. Some resources are renewable over time, and others are not.	**Cause and Effect** Cause and effect relationships are routinely identified and used to explain change. - *Connections to Engineering, Technology, and Applications of Science* **Interdependence of Science, Engineering, and Technology** Knowledge of relevant scientific concepts and research findings is important in engineering. **Influence of Engineering, Technology, and Science on Society and the Natural World** Over time, people's needs and wants change, as do their demands for new and improved technologies.

4-PS3-2. Make observations to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents. [*Assessment Boundary: Assessment does not include quantitative measurements of energy.*]

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Planning and Carrying Out Investigations Planning and carrying out investigations to answer questions or test solutions to problems in 3–5 builds on K–2 experiences and progresses to include investigations that control variables and provide evidence to support explanations or design solutions. Make observations to produce data to serve as the basis for evidence for an explanation of a phenomenon or test a design solution.	**PS3.A: Definitions of Energy** Energy can be moved from place to place by moving objects or through sound, light, or electric currents. **PS3.B: Conservation of Energy and EnergyTransfer** Energy is present whenever there are moving objects, sound, light, or heat. When objects collide, energy can be transferred from one object to another, thereby changing their motion. In such collisions, some energy is typically also transferred to the surrounding air; as a result, the air gets heated and sound is produced. Light also transfers energy from place to place. Energy can also be transferred from place to place by electric currents, which can then be used locally to produce motion, sound, heat, or light. The currents may have been produced to begin with by transforming the energy of motion into electrical energy.	**Energy and Matter** Energy can be transferred in various ways and between objects.

4-PS3-4. Apply scientific ideas to design, test, and refine a device that converts energy from one form to another.* [Clarification Statement: Examples of devices could include electric circuits that convert electrical energy into motion energy of a vehicle, light, or sound; and, a passive solar heater that converts light into heat. Examples of constraints could include the materials, cost, or time to design the device.] [*Assessment Boundary: Devices should be limited to those that convert motion energy to electric energy or use stored energy to cause motion or produce light or sound.*]

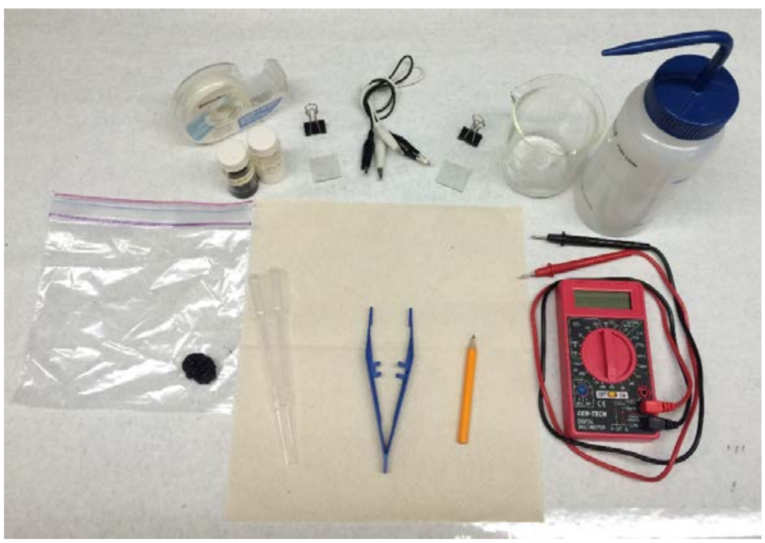
Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Constructing Explanations and Designing Solutions Constructing explanations and designing solutions in 3–5 builds on K–2 experiences and progresses to the use of evidence in constructing explanations that specify variables that describe and predict phenomena and in designing multiple solutions to design problems. Apply scientific ideas to solve design problems.	**PS3.B: Conservation of Energy and EnergyTransfer** Energy can also be transferred from place to place by electric currents, which can then be used locally to produce motion, sound, heat, or light. The currents may have been produced to begin with by transforming the energy of motion into electrical energy. **PS3.D: Energy in Chemical Processes and Everyday Life** The expression "produce energy" typically refers to the conversion of stored energy into a desired form for practical use. **ETS1.A: Defining Engineering Problems** Possible solutions to a problem are limited by available materials and resources (constraints). The success of a designed solution is determined by considering the desired features of a solution (criteria). Different proposals for solutions can be compared on the basis of how well each one meets the specified criteria for success or how well each takes the constraints into account.*(secondary)*	**Energy and Matter** Energy can be transferred in various ways and between objects. - *Connections to Engineering, Technology, and Applications of Science* **Influence of Engineering, Technology, and Science on Society and the Natural World** Engineers improve existing technologies or develop new ones. - *Connections to Nature of Science* **Science is a Human Endeavor** Most scientists and engineers work in teams. Science affects everyday life.

Procedure

Materials and supplies

Per pair or group making a cell:

- 1x1" FTO glass (2)
- Small ziploc bag
- 1 Blackberry (fresh or frozen)
- Plastic pipette (2)
- Tweezers
- Paper towel
- Multimeter
- Alligator clips (2)
- Golf pencil
- 1" Binder clip (2)
- Water
- Cup/beaker (optional)
- TiO2 paste
- Iodide/triiodide electrolyte
- Scotch tape
- Hotplate (one or two for whole class)

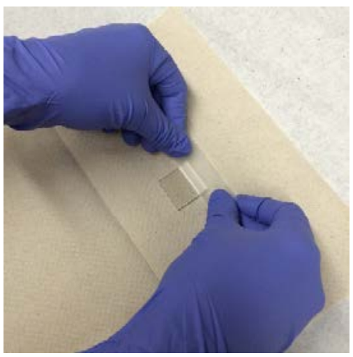


Preparing the TiO_2 electrode

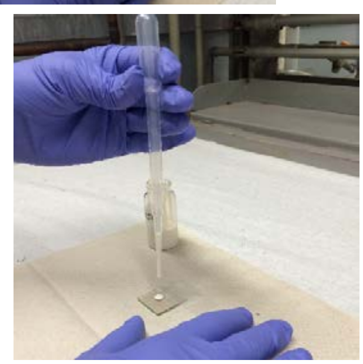
Take one piece of the FTO glass and use the multimeter to find the conductive side. Set the multimeter to the resistance setting denoted by the symbol ohm (Ω). If using the model included in the kit, the multimeter dial should just be pointing straight down pointing to 200 ohm.

Press the points of the two metal probes onto the surface of the glass, careful that the metal points don't touch. The conductive side will have a reading around 30 ohms. If you don't get a reading (i.e. still see the overflow value of "1"), flip the glass over and try the other side.

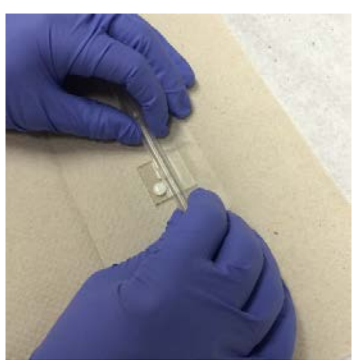
Once you have found the conductive side of the glass (the side with a resistance reading), set that side face up on the table. Take a piece of scotch tape and cover approximately 1/8" of the surface of the glass as shown here. The remaining open surface area will be covered with the TiO2 paste. The taped off strip will be blank glass which is necessary for assembly in the end.

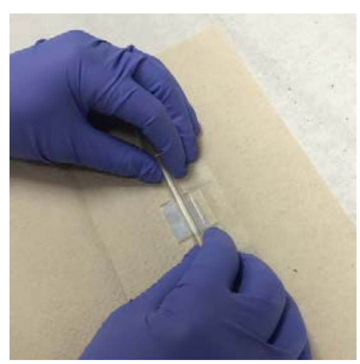


Using the plastic pipette, drip a couple drops of the TiO_2 solution in the center of the exposed glass. Don't add too much!

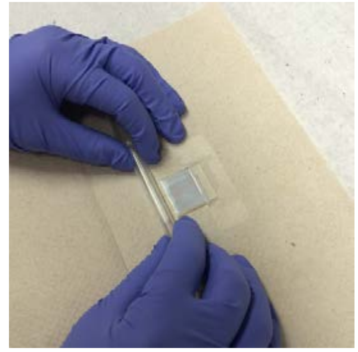


Use the smooth side of the pipette (i.e. no engraved numbers or seam) and immediately squeegee the solution down and up once or twice with the side of the pipette. Aim for a thin, even coating of the paste.





If the TiO_2 does not coat the entire exposed surface, quickly add another drop of TiO_2 paste and re-squeegee the whole plate. It should be a slightly transparent white color. Allow the paste to dry, undisturbed, for a minute or two. Once dry, remove the tape from the glass.



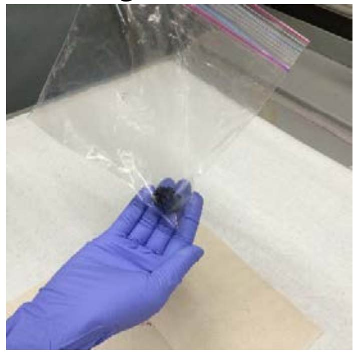
Transfer the glass to a hotplate and leave the TiO_2 film face up. The exact temperature of the hotplate is not important. Simply the hotter the plate, the faster it will be done.

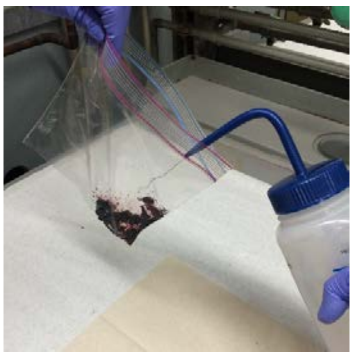
The surfactant and solvent in the paste will evaporate while on the hotplate, leaving behind just the TiO2 nanoparticles. The glass will appear to turn brown or burned, and then white again.

When the glass is done (i.e. the slide turned brown and then back to white), turn off the hotplate and let the glass cool down slowly. If the glass is moved too quickly from hot to cold it will crack. Even touching it with the tweezers can sometimes be enough of a temperature shock to cause cracking. A small crack usually won't cause problems with the effectiveness of the cell, but best to avoid. The plastic tweezers can also melt so wait for the plate to cool mostly.

Dyeing the TiO_2 electrode and assembling the DSSC

Prepare the dye by thoroughly (but gently) crushing 1 blackberry inside a closed plastic bag by squeezing the outside of the bag.

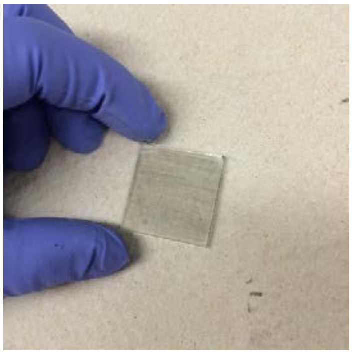




Careful not to poke any holes! Open the bag and add approximately 1 tsp of water to make it a little "juicier".

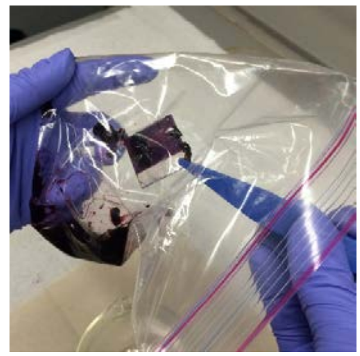
Take the TiO_2 coated piece of glass and place it into the blackberry juice in the bag for 1-5 minutes. Be sure that the glass is completely covered. The white TiO_2 paste should turn completely purple so there is no white left. The darker the better!

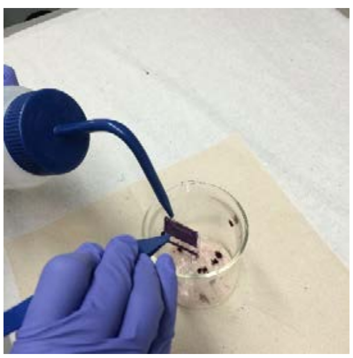
While you wait, take your other piece of FTO glass and find the conductive side as in step 1. Set the conductive side face up and use the pencil to coat the entire surface with graphite (pencil lead).



It can be hard to see but as long as you colored there should be graphite on the surface. Set it aside but keep the conductive side face up.

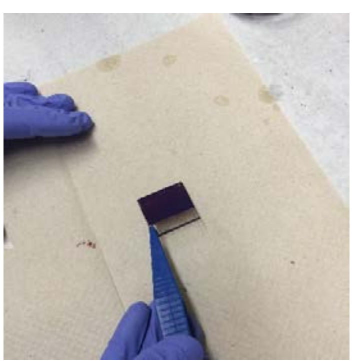
Using the tweezers grab the dyed TiO_2 piece of glass out of the blackberry juice (try to avoid scratching the film with the tweezers as it will chip off).

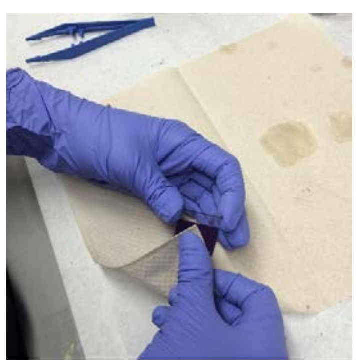


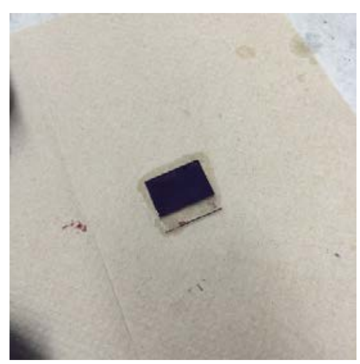


Holding the glass over the opening of a cup or beaker, rinse off the excess blackberry pieces and juice with a squirt bottle of water. Catch the drippings in the cup or beaker. (You can also rinse over the bag being held open by your partner to minimize supplies needed).

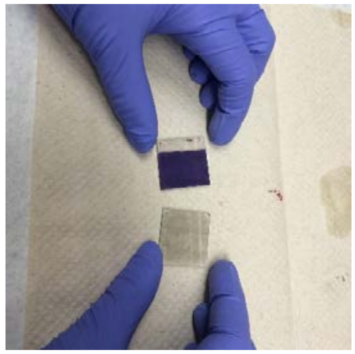
Set the rinsed glass onto a paper towel and very gently dab it with the towel to dry it off. DO NOT WIPE the glass as the TiO_2 coating will come off.

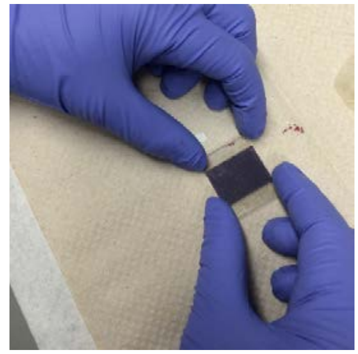




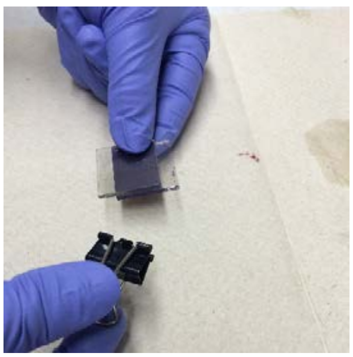


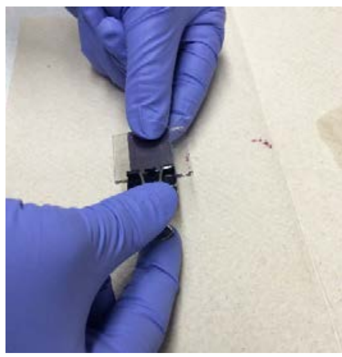
Take the two pieces of glass and assemble them into a sandwich with the two conductive and coated sides facing in. Think of a PB&J sandwich: the coated sides face in.

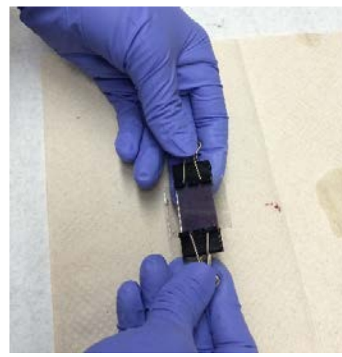




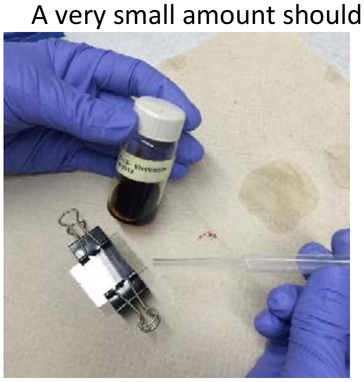
Then, slide the graphite glass out so that its edge aligns with the beginning of the purple TiO_2 coating on the other piece. Then using binder clips, clip together the two sides of the glass that are not offset.

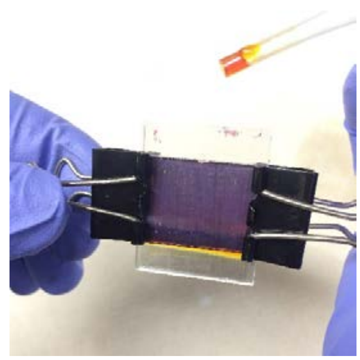




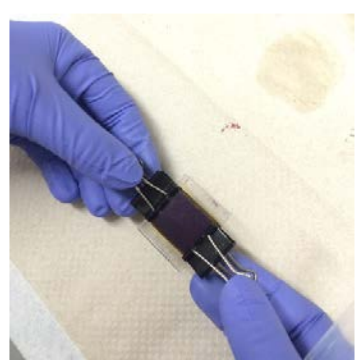


Lastly, add the iodide/triiodide (I^-/I_3^-) electrolyte solution using a pipette to the seam of the glass. A very small amount should be sufficient.





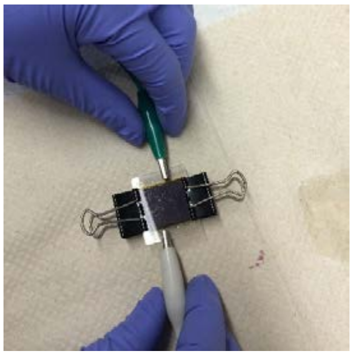
The purple area of the glass should turn darker as it is filled with the electrolyte. If there are any spots that don't get coated, try removing a binder clip and then clipping it back on to move the liquid around. If that doesn't fix it, add a little more electrolyte to the seam.

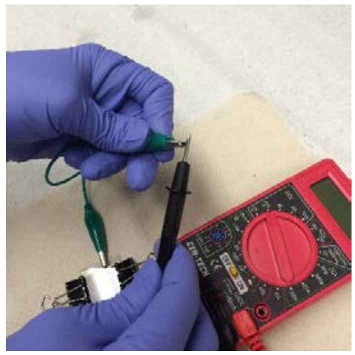


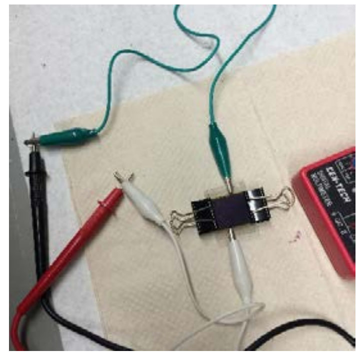
Testing the DSSC

The DSSC is ready to generate electricity. All it needs is some sunlight and a way to measure its output! Think of the DSSC as a battery. It has the capacity to generate electricity but you can't see it until it is used to power a device or tested with a multimeter, which is what you will do.

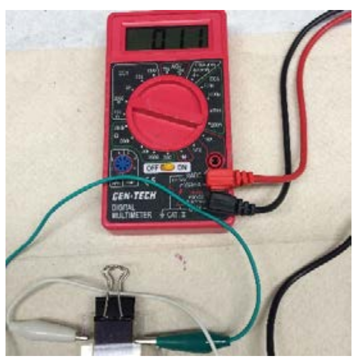
To test your solar cell, clip one end of an alligator clip to one of the overhanging pieces of glass. Clip the other end of the alligator clip to one of the metal multimeter probes. Use the second alligator clip and clip it to the other piece of overhanging glass and the other multimeter probe.







Switch the multimeter setting to DCV (Direct Current Voltage) to measure the voltage of the DSSC. The 2000m setting is usually sufficient to measure the output in millivolts. An average reading in full sunlight is around 350 mV.



If the reading is negative, this just means the meter is measuring electricity flowing in the opposite direction. Simply switch which electrode the alligator clips are attached to and the reading will become positive.

* Flipping the DSSC over so the dye is closer to the sun can sometime increase voltage dramatically.

Then switch the multimeter setting to DCA (Direct Current Amperage) to measure the current. The setting of 2000µ is usually sufficient to measure the current output. A typical reading in full sunlight is about 700 µA.

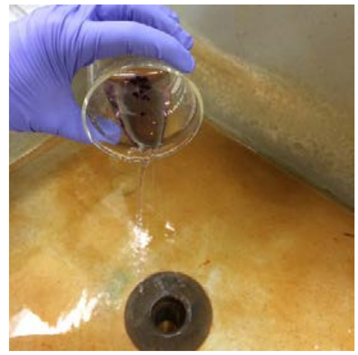
Finally, the voltage and current readings can be multiplied together to obtain the overall power of the cell. Power is defined as follows: P = current*voltage = I*V. Be sure to convert the voltage from mV to V and µA to A before multiplying. See the lesson on scientific notation for help with this process. Remember to record the weather conditions (sunny, cloudy, etc.) and light source!

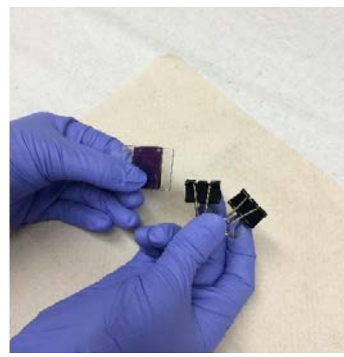
Data Table (include units for voltage and current)	
	DSSC dye:
Voltage	
Current	

Light Source (room light, projector light, sun):
Weather conditions (sunny, cloudy, rainy):

Cleaning up

Bags of blackberry juice can go in the trash and any rinsing of juice in a cup can go down the sink. Paper towels go in the trash. You can choose to toss plastic pipettes or rinse and reuse them for future classes.





Save the FTO glass and simply wipe clean with water and a towel. Graphite is easily removed by a rubber eraser.

All other parts are reusable and should be packed away for future use.

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. Combine information about ways communities use solar energy to protect the earth

   There are many ways that sunlight can be used to generate electricity and power for human consumption. List as many technologies as you can that use sunlight as a source of energy. Next, research to see if there are any other ways scientists and others around the world use sunlight that you didn't previously know. Work as a class to generate a combined list of solar power technologies that will help protect the earth. Is the use of DSSCs on your list?

2. Describe that obtaining and using energy and fuels also affects the environment

   Assign groups of students a form of energy to research and discuss (wind, hydroelectric, coal, natural gas, etc). Find out how that type of energy is generated, captured and used. Are there negative effects to the environment? Any positive effects? Each group will present their findings to the class, prompting discussion on which forms of energy are best for our planet.

3. Provide evidence that energy can be transferred by light, heat and electric currents

   In groups of 2-4, draw a diagram of a dye-sensitized solar cell, label the components, and explain on how the cell converts light into electricity. Remember to consider the absorber and converter in your explanation. Think about where losses in efficiency come from, how some energy is lost as heat. Make sure your solar cell forms a complete circuit.

4. Design, test and refine a dye-sensitized solar cell that converts sunlight to electricity

   Before or after introducing the information from the background section, provide your students with a list of the basic components necessary to make a DSSC. Have them try to place them in the correct order and present their design to the class. Discuss the designs as a class or in small groups. Then, give them the lab procedure and let them build a DSSC.

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