Physics: Light and Solar Cell Basics

Objectives: Students will be able to:

- Explain how white light is composed of all colors of light
- Compare and contrast the basic properties of light and electricity
- Use a digital multimeter
- Calculate the power output and power conversion efficiency of a solar cell

* It is recommended that this lesson be performed in conjunction with the Biology lesson. (See below for further explanation.)

California Content Standards:

Physics:

Motion and Forces:

1.m. Students know how to solve problems involving the forces between two electric charges at a distance (Coulomb’s law) or the forces between two masses at a distance (universal gravitation).

Conservation of Energy and Momentum:

2.h. Students know how to solve problems involving conservation of energy in simple systems with various sources of potential energy, such as capacitors and springs.

Waves:

4.a. Students know waves carry energy from one place to another.
4.e. Students know radio waves, light, and X-rays are different wavelength bands in the spectrum of electromagnetic waves whose speed in a vacuum is approximately $3 \times 10^8$ m/s (186,000 miles / second).

Electric and Magnetic Phenomena:

5.a. Students know how to predict the voltage or current in simple direct current (DC) electric circuits constructed from batteries, wires, resistors, and capacitors.
5.c. Students know any resistive element in a DC circuit dissipates energy, which heats the resistor. Students can calculate the power (rate of energy dissipation) in any resistive circuit element by using the formula $\text{Power} = IR$ (potential difference) x $I$ (current) = $I^2R$.
5.e. Students know charged particles are sources of electric fields and are subject to the forces of the electric fields from other charges.

Chemistry:

Atomic and Molecular Structure:

1.j. Students know that spectral lines are the result of transitions of electrons between energy levels and that these lines correspond to photons with a frequency related to the energy spacing between levels using Planck’s relationship ($E = hv$).

Conservation of Energy and Stoichiometry:

2.a. Students know how to describe chemical reactions by writing balanced equations.
Physics: Light and Solar Cell Basics

Earth Sciences:

Energy in the Earth System:

4.b. Students know the fate of incoming solar radiation in terms of reflections, absorption, and photosynthesis.

Investigation & Experimentation:

1.a. Students will select and use appropriate tools and technology to perform tests, collect data, analyze relationships, and display data
1.e. Students will solve scientific problems by using quadratic equations and simple trigonometric, exponential, and logarithmic functions.
1.l. Students will analyze situations and solve problems that require combining and applying concepts from more than one area of science.

Before you begin, you may want to watch the DSSC videos to prepare the lab:
http://www.youtube.com/caltech and click on “Resources for Teachers” on the right.
Physics: Light and Solar Cell Basics

Background:
In the search for renewable energy sources to sustain global economic and population growth, solar energy has recently received unprecedented emphasis. The total energy from sunlight striking the earth in 1 hour (4.3×10^{20} J) exceeds the global annual energy consumption in 2001. However, solar energy cannot directly power a house or a car, until it is converted and stored as a ready-to-use form, such as electricity and fuels. A device that turns light into electricity is termed a solar cell or a photovoltaic cell. For this activity, you will investigate two popular types of such devices – a commercial silicon solar cell and a homemade Dye-Sensitized Solar Cell (DSSC) – and discuss their advantages and disadvantages for solar energy conversion.

Light and electricity deliver energy in very different ways. The basic unit contained in light is called a photon whose energy \( E \) is \( E = h \nu = hc/\lambda \), where \( h \) is the Planck’s constant, \( c \) is the speed of light, and \( \nu \) and \( \lambda \) are the frequency and wavelength of light as an electromagnetic wave, respectively. Blue light has higher frequencies (shorter wavelengths) and therefore photons with higher energy, whereas red photons have less energy stored in them. Sunlight, as a mixture of colors, consists of a vast amount of photons each at a different energy. The rate at which photons reach the earth is termed the photon flux (\( q \)) and is the intensity of the sunlight, i.e. how sunny it is. The power \( (P) \) in sunlight, the product of the energy and the flux, as \( P = E \cdot q \), is ultimately what a solar cell is trying to convert to power in electricity. Typical units are: \( P \) is Watts, \( E \) is joules/mole, and \( q \) is moles/sec.

Electricity has analogs to the terms defined above for light. Electricity, for example as supplied from a power source such as a battery or wall socket, consists of a basic unit called a charge. These charges are in the form of either electrons or ions. Their electrical potential — termed the voltage \( (V) \) — is the analog to the photon energy, while their directed rate of movement — termed the current \( (I) \) — is the analog to the photon flux. The power in electricity is calculated as the product, \( P = V \cdot I \). Typical units are: \( P \) is Watts, \( V \) is joules/coulomb, and \( I \) is coulombs/sec. The major difference between a photon and a charge is that photons are neutral while charges are just that, charged, either positive or negative.

The goal of a solar cell is to convert as much of the power in photons to power in charges, and to externally collect these energized charges and use them to perform work, e.g. power a fan. In a solar cell a neutral photon is absorbed by a negatively charged electron, energizing it. Then, by certain means, the energized electron moves away from its original location, leaving behind a positive vacancy, termed a hole. The ideal case for solar energy conversion would be if the electrical current output due to the movement of charges was equal to the photon flux input, while the electrical voltage output was equal to the photon energy input, although in practice this is not often the case.

Silicon cells are the most mature and widely applied devices for solar energy conversion, powering objects from calculators to office buildings. In a simplistic picture, silicon is a semiconductor that can be made more conducting for positive charges (p-type Si) or negative charges (n-type Si). When these two types of silicon are sandwiched together, they form a p–n junction which, when it absorbs photons, results in a positively charged hole in the p-type side and a negatively charged electron in the n-type side. Silicon solar cells can achieve a power conversion efficiency of 22% at the expense of using highly pure, single-crystalline silicon. This value is roughly two thirds the maximum possible for any single-junction solar cell.

For technical assistance please contact a scientist at Caltech at JuiceFromJuice@caltech.edu
High School Lesson Plan
Dye-sensitized solar cells are an emerging technology using readily available materials and equipment. It utilizes a dye (i.e. an intensely-colored material) to harvest the influx of light, in addition to iodide ions and TiO$_2$ nanoparticles to carry the resulting positive and negative charges, respectively. In particular, the dye molecules are chemically adsorbed on the TiO$_2$ nanoparticles, making intimate contact over an enormous surface area. As a result, it usually takes less than 1 picosecond ($10^{-12}$ s) to split a photon absorbed by a dye molecule into an electron accommodated by TiO$_2$ and a positive vacancy on the dye, termed a dye cation. Subsequently, the dye cation relays its positive charge to an iodide ion in solution and restores the dye to its original state. This process is more specifically described by the following equations:

On the TiO$_2$ electrode (anode): \[ \text{TiO}_2\text{-Dye} + \text{photon} \rightarrow \text{TiO}_2\text{-Dye}^* \rightarrow e^- \text{ in TiO}_2 \text{ and Dye}^*; \]

In the electrolyte solution: \[ \text{Dye}^* + 2 \text{I}^- \rightarrow \text{possible intermediate} \rightarrow \text{Dye} + \text{I}_2; \quad 2 \text{I}_2 \rightarrow \text{I}^- + \text{I}_3^-; \]

On the graphite-coated counter electrode (cathode): \[ \text{I}_3^- + 2 e^- \rightarrow 3\text{I}^-; \]

where Dye* is the common notation used when an electron has absorbed a photon.

For this activity both a silicon solar cell and DSSC will be used to convert light from an overhead projector, or the sun, into electricity. You will measure the voltage and current and calculate the power output and power conversion efficiency. You will show that the current and power output are roughly proportional to the incident light intensity, i.e. photon flux, and that different colors of the spectrum give different currents.
Physics: Light and Solar Cell Basics

TEACHER PRE-LABORATORY PROCEDURE

Materials and Supplies:
- (optional) 1 prism
- (optional) blue, green, and red light-emitting diodes and a drill or small fan
- red, orange, yellow, green, and blue color filters*

*Provided in the Juice from Juice kit

1. Use a prism to demonstrate how white light is really made up of all of the colors of the rainbow. (Glass prisms tend to work better, but there are inexpensive plastic ones available online that are adequate.)

2. Further illustrate this by showing that the three primary colors, which our eyes can detect, add up to white light. One way to show this is to use “fingertip” light-emitting diodes (LEDs), using the red, blue and green lights. Tape each of the small LEDs onto a drill or plastic fan, at the same radial distance. Make sure the LEDs are fully secured. Then, with the lights off, briefly turn on the drill/fan.

Note: another pre-activity could be showing your class these fun videos:
(Episodes 1 & 2) by Dr. Carlson: [http://web.ics.purdue.edu/~mjcarlso/ST/videos.html](http://web.ics.purdue.edu/~mjcarlso/ST/videos.html)
Physics: Light and Solar Cell Basics

STUDENT (or TEACHER) LABORATORY PROCEDURE
* There are enough supplies to perform this activity with one group of students. It is advised to run this lesson in conjunction with the Biology lesson; as such, students should rotate into and out of this lesson while performing the Biology lesson. The size of the group for this lesson should be larger than that of the Biology lesson so that all students can perform this lesson in a class period.

Materials and Supplies (per class or breakout sub-group from Biology lesson):
• 1 commercial silicon solar cell*
• 1 homemade DSSC from the main module (if that activity was performed prior to this lesson)
• 2 multimeters with probes*
• 4 alligator clips*
• 1 overhead projector
• 1 black cloth/board/sheet to block light
• 2 – 3 gray transparencies
• red, orange, yellow, green, and blue color filters*
• direct-current electric motor*
• metric ruler

*Provided in the Juice from Juice kit

SAFETY NOTE: Never look into the light output from the overhead projector! It is as bright as looking directly into the sun on a sunny day.

1. Turn the projector on and let it warm up for a few minutes.

2. Place a color filter on the overhead and note the color that is transmitted. Repeat this with all color filters. Now place the red, green, and blue filters all on the overhead; what color is transmitted? Why is this so? What colors are blocked?

3. Measure the exposed area of your DSSC. Using black electrical tape, mask off an area on the commercial silicon solar cell that is approximately the same area as your DSSC. Also, attach two binder clips to the silicon cell in the same way as the DSSC, so that the silicon cell is parallel to the projector lens and at a similar height as the DSSC.

4. Connect the two leads of the silicon cell to a multimeter via the alligator clips, with the red probe to the positive pole and the black probe to the negative pole.

5. Place the silicon cell on the lens of an overhead projector, with the face of the silicon cell facing downward to the light source.

6. Measure the voltage and record this value in the data table. To measure voltage, switch the indicator to DCV (Direct Current Voltage) (upper left on the Cen-Tech Multimeter) to the lowest setting, 200m. If it reads a 1, the voltage is too large for that setting and you must switch to the next level, 2000m, by turning it clockwise. Continue this process until you observe a reading other than 1.

7. Measure the current and record this value in the data table. To measure current, switch the indicator to DCA (upper right on the Cen-Tech Multimeter) to the lowest setting, 200µ. Again, if you...
see 1 on the display, switch the indicator clockwise to the next setting and repeat until a meaningful value is obtained.

8. Place a color filter between the solar cell and the lens, and then record the voltage and current output. Repeat this for two other color filters, or combinations of color filters, noting which color(s) were used each time.

9. Remove the color filters and diminish the light to the solar cell first by using a piece of gray transparency, and then two of them in a stack. Record the voltage and current output under each condition.

10. Block the light using a black piece of cloth and record the voltage and current in the dark, under room light.

11. Repeat steps 4 through 10 with the DSSC.

12. Attach the commercial silicon solar cell to the motor and illuminate the solar cell with the full projector light. Measure the current and voltage. Make sure you get nearly the same values that you obtained from steps 6 and 7.

13. Connect two multimeters to the circuit and measure the current and voltage of the device simultaneously. Hint: One multimeter must be in the circuit and the other parallel, or external, to the circuit.

14. Turn off the projector and put the solar cells away.

Fill out the following table with the measured area, voltages, currents, and color filters used.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Silicon solar cell Area: _____ cm²</th>
<th>Dye-sensitized solar cell Area: _____ cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage (mV)</td>
<td>Current (mA)</td>
</tr>
<tr>
<td>Full output</td>
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<tr>
<td>Filter 1</td>
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<tr>
<td>Color(s):</td>
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<tr>
<td>Filter 2</td>
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<tr>
<td>Color(s):</td>
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<td>Filter 3</td>
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<tr>
<td>Color(s):</td>
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</tr>
<tr>
<td>Single gray filter</td>
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</tr>
<tr>
<td>Double gray filter</td>
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<td></td>
</tr>
<tr>
<td>Dark</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With Motor Attached</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Physics: Light and Solar Cell Basics

Checking for Understanding

1. What do the prism, light-emitting diodes (LEDs), and color filter results, without the solar cells, suggest about the additive nature of light and the additive nature of pigments? Also, what do all colors add up to and what color do no colors represent for both light and pigments?

2. What do the gray and color filters do to the current and voltage outputs? And why? The current is linearly proportional to the photon flux (light intensity); using this, can you determine the dependence of the voltage on the photon flux?

3. What types of charges are arriving at the (+) and (−) poles of a silicon cell or DSSC at the multimeter?

4. What was the total power delivered by sunlight onto the earth in 2001? (Hint: Use the energy listed above and the fact that this can supply the world’s power needs for an entire year.)

5. Calculate the power outputs (in mW) of the silicon cell and the DSSC with zero, one, and two gray filters. Calculate the power density (in mW/cm²) by dividing power output by area.

6. Obtain the light power output of the overhead projector from the teacher. Calculate the power conversion efficiencies (in percent) of the silicon solar cell.
Teacher’s Guide

[Review of key concepts]
- Light, color, wavelength, frequency, photon, light energy;
- Light absorption and transmission, complementary colors;
- Electricity, charge, electron, ion;
- Current, voltage (magnitude and sign for both);
- Power, work, energy conversion, efficiency;
- Measurement of current and voltage using a multimeter.

[Additional Materials]
- Silicon solar cells are available from retail and online electronics stores, such as Arbor Scientific, P6-7201, http://www.arborsci.com/ or sundancesolar.com, #700-11341-00.
- Color filters and dc motors can be ordered from Flinn Scientific, #AP4786 and #AP6041.
- Gray transparencies can be made by printing or photocopying a simple black or dark grayscale box onto a clear transparency, and then cutting them into small pieces.

[Answers]
1. Adding colors of light to other colors of light results in a lighter color of light. All colors of light add up to white light; no colors means black. The opposite is true for pigments where adding colored pigments results in a darker colored pigment; all pigment colors add up to a black pigment; and no pigments means white.

2. The color filters attenuate the both the current and voltage, but more so the current. The darker filters attenuate light more and thus result in the lowest currents and voltages. Plotting the filter results with x being current and y voltage, you will see that there is an exponential dependence of voltage on current, i.e. for every 10x more current there is a constant larger amount of voltage.

3. For silicon cell: (−) — n-type side and thus electrons; (+) — p-type side and thus holes.
   For DSSC: (−) — TiO2 side and thus electrons; (+) — graphite side and thus holes.

4. Power ($P$) = Energy ($E$) / time ($t$)
   \[ P = \frac{E}{t} = \frac{4.3 \times 10^{20} \text{ J}}{1 \text{ yr}} = \frac{4.3 \times 10^{20} \text{ J}}{(365.25 \times 24 \times 60 \times 60) \text{ sec}} = 13.6 \times 10^{12} \text{ W} = 13.6 \text{ TW}, \text{ where T = tera. Currently, the world’s power needs are > 16 TW.} \]

5. Power (mW) = Current (mA) x Voltage (V)
   Power Density (mW/cm²) = Current (mA) x Voltage (V) / area (cm²)


   The silicon solar cell (Sundance solar #700-11341-00) is rated to generate a short-circuit current of 302 mA under normal sunlight (100 mW/cm²). This can be utilized to quickly estimate the power density of light from the overhead projector:

   Power density (mW/cm²) = Short-circuit current (mA) / 0.302 = Short-circuit current (mA) × 0.33