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|  | A More Efficient Solar CellTeacher Edition |
| **Subject(s)/Course(s):** Physical Science | **Grade Level:** High School | **Duration:** Two 80 minute blocks  |
| **Lesson Synopsis/Narrative:** The class will make their own solar panels using LEDs (students will need to know that a photovoltaic cell is made up of lots of highly photosensitive diodes wired together). Some silicon photodiodes are more photosensitive than others. The LEDs we will use in this experiment will be a lot less photosensitive than the photodiodes used in photovoltaic panels. We are using LEDs because the students can see the color that they are photosensitive to by turning them on using a battery. |
| **Prior Knowledge:**Basic electricity, circuits, and how to use a multimeterLight as a wave lesson should be taught first |
| **Background information:**The common conception is that light exhibits a wave, a particle, or both at the same time depending on the situation. The reality is nowhere near this, light it not a wave or a particle, only exhibits properties of each and described incorrectly as such. This idea makes sense when scaffold with the introduction of the standard model using the time dependent Schrödinger equation. This lesson attempts to draw on this idea. |
| **Challenging Question or Problem:** How can we create a more efficient solar cell?Is light a wave or a particle? How can we tell? |
| **Phenomenon and Manufacturing Application:** Solar cells produce electricity based on the principles of the photoelectric effect. Solar city in Genesee County will develop and manufacture solar panels with the intention of creating an affordable and more efficient product. The class will manufacture their own solar cells using LEDs. |
| **Examples (in action):**Manufactured solar panels use photons (light energy) from the sun to generate electricity via the photoelectric effect. The majority of solar panels manufactured today are wafer-based crystalline silicon cells or a cadmium telluride or silicon cell based on a thin-film cell.Diagram of the possible components of a photovoltaic system from a solar cell to a PV system. | **Vocabulary:**DiodePhotodiodeLight Emitting DiodeExtension:EfficiencyIrradianceFluxIntensity |
| **State and National Standards & 21st Century Skills:**HS-PS4-3 Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model (quantum theory), and that for some situations one model is more useful than the other. HS-PS4-4 Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.Emphasis is on how the experimental evidence supports the claim and how a theory is generally modified in light of new evidence. HS-PS4-5 Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology. |
| **Science and Engineering Practices**Engaging in Argument from EvidenceEngaging in argument from evidence in 9–12 builds on K–8 experiences and progresses to using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about natural and designed worlds. Arguments may also come from current scientific or historical episodes in science.* Evaluate the claims, evidence, and reasoning behind currently accepted explanations or solutions to determine the merits of arguments. (HS-PS4-3)

Obtaining, Evaluating, and Communicating InformationObtaining, evaluating, and communicating information in 9–12 builds on K–8 and progresses to evaluating the validity and reliability of the claims, methods, and designs.* Evaluate the validity and reliability of multiple claims that appear in scientific and technical texts or media reports, verifying the data when possible. (HS-PS4-4)
* Communicate technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS- PS4-5)
 | **Disciplinary Core Ideas**PS4.A: Wave Properties* [From the 3–5 grade band endpoints] Waves can add or cancel one another as they cross, depending on their relative phase (i.e., relative position of peaks and troughs of the waves), but they emerge unaffected by each other. (Boundary: The discussion at this grade level is qualitative only; it can be based on the fact that two different sounds can pass a location in different directions without getting mixed up.) (HS-PS4-3)

PS4.B: Electromagnetic Radiation* Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. (HS-PS4-3)
* When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. (HS-PS4-4)
* Photoelectric materials emit electrons when they absorb light of a high-enough frequency. (HS-PS4-5)
 | **Crosscutting Concepts**Cause and Effect* Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects. (HS-PS4-1)
* Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system. (HS-PS4-4)
* Systems can be designed to cause a desired effect. (HS-PS4-5)

Systems and System Models* Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions— including energy, matter, and information flows—within and between systems at different scales. (HS-PS4-3)

Interdependence of Science, Engineering, and Technology* Science and engineering complement each other in the cycle known as research and development (R&D). (HS- PS4-5)

Influence of Engineering, Technology, and Science on Society and the Natural World* Modern civilization depends on major technological systems. (HS-PS4-2),(HS-PS4-5)
* Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. (HS- PS4-2)
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| **Learning Targets:*** Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.
* The photoelectric effect is evidence that light can act as a particle
* Different frequencies of electromagnetic radiation have different effects on diodes when they are absorbed
* The photoelectric effect or photoemission is when there is a production of electrons when light above a certain frequency is shined upon a material.
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| **Materials and Equipment Per Group:**1 Digital multimeter1 300 pc LED kit1 Breadboard10 Connection wires2 Alligator Leads1 Battery box (with batteries, 2AA)1 Red, green, and blue laser1 Pack of fluorescent paper1 photometer (if completing Efficiency Part 2 of the lesson)**Also in kit**LED TesterFog Machine (only if the activity is performed outside or in a room with heat detectors. DO NOT use fog machine in a room with smoke detectors). |
| **Materials not provided in kit, preparation/time:**1 sheet of white paper per groupFluorescent light sourceIncandescent light source**Solar panel extension:**Extension: Determining the resistance values needed if testing a commercial solar panel. A variable resistor box capable of producing resistance values between 100kΩ and 10MΩ is needed for the extension. Alternatively you can use individual resistors with values between 100kΩ and 10MΩ.  |
| **Safety:**Lasers are light sources that can permanently damage the eye. They are not toys. If you stare into a laser beam for a period of time, permanent and irreparable damage to the eye can occur. The Laser BloxTM set provided in the kit is a Class IIIR laser product. At this power rating the human eye blink reflex will prevent any permanent eye damage. To reduce the chance of eye injury, do not completely darken the room as to prevent complete pupil dilation.Laser safety posters should be posted around the classroom when they are in use. Information about laser classifications and safety:<http://www.lasersafetyfacts.com/laserclasses.html>  |
| Procedure and Prompts:

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| Teacher Does and Says | Student Does and Says |
| **Introduction/Warmup:**  |
| Facilitate students reading the article as a warmup and then discuss solar panels | Students read “Solar Power Is About To Get MUCH Cheaper” and answer the text dependent questions.1. Summarize what is happening at Solar City near Buffalo, NY.
2. How is Solar City trying to increase the benefits of solar power? Cite at least two.
3. In what way(s) can Solar City decrease the costs and risks associated with solar power? Cite at least two.
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| **Part A: Threshold Frequency and Activation Energy** |
| Reinforce laser safety and the rules of the classroom when using lasers. Make sure all lasers are pointed below chest level at all times and that students do no play with them.Distribute to each group a pack of the fluorescent paper, 1 red, 1 green, and 1 blue laser, and a piece of white paper.If you are in a room that uses heat detectors instead of smoke detectors (usually chemistry rooms), you can have the students use the fog machine to observe the incident and reflecting light. Check with your operations and management department before using a fog machine.If you are not using the fog machine, students can observe the reflection by shining the laser off of the fluorescent material at a very shallow angle while another group member holds the piece of white paper as a screen (see diagram).Prompt the students to borrow multiple lasers of the same color from other groups to investigate if the intensity of the light will cause the color to change. Have students aim all of the same color lasers on the same spot to increase intensity. | Students investigate by shining lasers on the different fluorescent materials while also looking at the reflection. Alternate between the white paper and the fluorescent material to see the difference. |
| Students will see that if the frequency of the laser is above the threshold frequency (activation energy) of the fluorescent material, causing the material to fluoresce and the light that is seen on the material changes color, however, the reflected light will not change color. Laser light that is below the threshold frequency of the fluorescent material will not change color.<https://www.youtube.com/watch?v=50fHb7jR5dc>Provide a computer with internet access or various physics textbooks for the students to use as resources.  | Investigate why the color change occurs and take notes. |
| **Part B: Putting Into Practice to Create a Better Solar Cell** |
| Students may see a small voltage that changes frequently from the ambient light. Have a discussion with the class about background noise and how to subtract this reading from the measurements in the rest of the experiment.The orientation of the LED when attached to the multimeter does not matter. The voltage setting on the multimeter needs to be above 2V. | Using the multimeter with the alligator clip leads, attach a 5mm green LED to a multimeter and turn it onto the 20V DC voltage setting. The symbol for a diode is The symbol for a Light Emitting Diode (LED) is The symbol for a Photodiode is  |
| The students should know that an LED can also act as a photodiode and the only difference in the symbol is if the light is being admitted or being absorbed. The results should show that below a certain color (blue if it’s a blue photodiode), there isn’t enough activation energy to create additional voltage or current. This is regardless of how many lasers are used on the photodiode. Only when the frequency of the light is above the activation energy of the photodiode will students get a voltage or a current. Above the activation energy, as the number of lasers used the voltage or current will increase. Through this, students should find that the amplitude of the light does not correlate to the energy of the wave (as it would if students think of light as a mechanical wave). The only explanation for this is to describe light as a particle instead of a wave and that the energy of the light is related to the frequency (color) and not amplitude. This is in similar fashion to how Einstein discovered the photoelectric effect (diodes weren’t developed yet, but he was able to accomplish the same thing using the semiconductor materials that diodes are made from [germanium, mercury cadmium, lead sulfide, silicon].  | Shine a red, green, and blue laser directly on the green LED connected to the multimeter and record the voltage for each laser in the table below. Collaborating with another group in the class, shine two red, green, and blue lasers directly on the LED and record the voltage for each pair of lasers in the table below.Replace the green LED with a 5mm red LED connected to the multimeter. Shine a red, green, and blue laser directly on the red LED connected to the multimeter and record the voltage for each laser in the table below. Collaborating with another group in the class, shine two red, green, and blue lasers directly on the LED and record the voltage for each pair of lasers in the table below.Replace the red LED with a 5mm blue LED connected to the multimeter. Shine a red, green, and blue laser directly on the blue LED connected to the multimeter and record the voltage for each laser in the table below. Collaborating with another group in the class, shine two red, green, and blue lasers directly on the LED and record the voltage for each pair of lasers in the table below. |
| Provide students with resources around the photoelectric effect.Resources:<http://physics.info/photoelectric/>PhET has a good simulator of this phenomenon.<https://phet.colorado.edu/en/simulation/photoelectric>  | Investigate the history of the photoelectric effect and how it fundamentally changed the theory of light as a wave. Compose a conclusion or claim that explains why the phenomenon occurs.You must use the following evidence* Choose relevant details from your research. Cite at least three credible sources.
* Elaborate on those details using observational evidence, making sure that they fully support your conclusion and claim.
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| **Construction of a Solar Panel** |
| Introduce to the students how a breadboard works.<https://learn.sparkfun.com/tutorials/how-to-use-a-breadboard>A good tutorial for breadboards: <http://wiring.org.co/learning/tutorials/breadboard/>If students want you can have them light their LEDs by connecting the battery boxes to the breadboard. If their voltmeter is on the 200mV DC setting, it will display 1 which means “out of range.” Have them change the setting to the 20V DC setting to see the output voltage from the battery box (make sure they know that they are not looking at the output voltage of the LEDs in this case).If there are enough LEDs you can instruct the students to use 10 LEDs for their solar panel prototypes. | Solar panels work on the principle of the photoelectric effect. Photovoltaic cells are a bunch of photodiodes wired together in order to increase the overall voltage to a useable voltage.Connect the voltmeter to the breadboard in order to measure the voltage from the LEDs as you add them. Turn the voltmeter to the 200mV DC setting for measuring the output voltage from the LEDsWire 5 (5mm LEDs in this case) of the same color in parallel on one side of the breadboard to create a solar array. The positive side of the LED is the longer lead. The negative side of the LED is the shorter lead.Notice how the voltage changes as you add LED’s |
| If time is an issue One group can wire just red LEDs, another just green LEDs, another just blue LEDs, and finally a third wiring their solar cell with alternating colors.Emphasize the need for the orientation of the solar panel to remain the same when taking all of the data. Students will measure the voltage output for each solar cell produced in direct sunlight. They can compare the output of the solar cell and explain why the one is more efficient than the other. | Dedicate one side of the breadboard to red LEDs, another for blue LEDs. Record your results and then repeat with one side of the breadboard dedicated for green LEDs and the other side for yellow LEDs. Measure the voltage output for each group of colored LEDs in direct sunlight and indoor light. |
| Solar panel efficiencies are limited because diodes only operate within specific frequencies of light. The diodes themselves also have a specific efficiency depending on the manufacturing process and materials used. Matching the frequencies of light in the environment that the solar panel will be used to the diode can increase the overall efficiency of the solar panel. | Based on your results, design a solar panel that maximizes efficiency across all three lighting sources. The panel should contain no more than 10 LEDs and no more than three of any one type of diode.Measure the voltage output for your solar panel under each lighting condition. Record your values in the table. |
| **Solar Panel Efficiency Extension** |
| The aim of this extension is to give the students the tools and understanding needed to test and examine a solar cell.For this extension you will need a variable resistor box capable of producing resistance values between 100kΩ and 10MΩ. Alternatively you can use individual resistors with values between 100kΩ and 10MΩ. The different resistors values or loads that should be used in order to put the solar panel under different operating load conditions will vary. You may have to test out a solar panel you are using in order to find the appropriate resistors prior to this lesson.If you are testing a large solar panel you can make things a little easier by inserting an ammeter in series next to the voltmeter. The current produced by our 10 LED solar panel prototype is too small to be accurately read by the ammeter.  | Determine the output power of the solar panel under different loads. Connect the solar panel prototype consisting of the 10 LEDs to a resistor or a variable resistor box and a voltmeter in parallel as depicted in the schematic. Turn the multimeter dial to 200mV DC.Measure the voltage output for your solar panel with the resistor attached in the environment where the solar panel is to be used. |
| Direct students on how to use the photometers. Emphasize that the orientation of the photometer detector assembly has to be the same as the solar panel with respect to the light for each voltage recorded. See Table 1 below for an example of student data.Depending on the light in the environment, you will have to set the photometer to 20μW, 200μW, 2mW, or 20mW. Start by attempting to take a reading on the 20μW range selector switch setting and pressing down the ON/OFF switch. If the display reads a “1” then you are out of range. Change the selector switch to the next range by turning it to the right and pressing down on the ON/OFF switch again. When you get a reading, wait 15 seconds for the detector to stabilize before you record the value.Students may need a review on unit conversions and navigating the powers of ten. | Record the power from the environment where the solar panel is to be used using the photometer. |
| It may be helpful for students to derive the Power equation $P=\frac{V^{2}}{R}$ from P=VI using the V=IR relationship.See Table 2 below for an example of student data. | Convert the voltage that is in mV to volts (V). Then determine the power output of the solar panel under the different load conditions (resistance values). The equation for power using resistance and voltage is $P=\frac{V^{2}}{R}$ where V is voltage (V) and R is resistance (Ω). |
| See Table 3 and Graph 1 below for an example of student work.Extension: If you would like students to example an inverse exponential function or logarithmic function, have the students create a graph of resistance vs voltage. See Graph 2 below for an example. | Graph the power produced (W) vs the voltage produced (V). You should get a curve that peaks at a certain voltage value.Using the graph, determine the maximum power produced at a certain voltage.This maximum means that the solar panel is best suited for a circuit that operates at the maximum voltage produced since it is able to produce the most power at that voltage. For example, if you used this solar panel to charge a battery you would ideally want that battery to operate at the maximum voltage produced. |
| Efficiency is the measure of how much work or energy is converted to useful work or energy in a process. The equation for efficiency is $Efficiency= \frac{Output Power or Energy}{Input Power or Energy} x 100\%$. Using the power from the photometer (W) that corresponds to the maximum voltage produced as the input power and the maximum power produced (W) by the solar panel for the output power, determine the absolute efficiency of the solar panel. See Table 4 below for an example of student work. | Determine absolute efficiency of your solar panel.  |
| Have students’ research solar panel efficiencies so that they can compare theirs to what is expected. Students should start by learning about LEDs, the manufacturing process and the materials that they are manufactured from. Then research the same components of photodiodes and compare.The efficiency of the LEDs as a photodiode is very poor. The main reason is due to the size of the actual (photo)diode area. Real solar cells have all of their area dedicated to photodiode space. Either diodes that are manufactured to have a large photodiode space, or the panel itself is made up of thousands of photodiodes. LEDs are mostly made up of a clear lens with a small portion dedicated to the diode. | How does your efficiency compare to the typical efficiencies found in commercial solar panels?Why do you think it’s so different? What is different about your solar panel when compared to commercial ones? |
| **Efficiency Part 2 (Actual Efficiency)** |
| One issue with the efficiency value that the students just calculated is that it doesn’t take into account the size of the solar panel. If they were to stuff more LED’s or photodiodes into the same size solar panel they would see the efficiency of the panel increase. Explain to the students that in order to calculate the actual efficiency of the panel you must compare the irradiance flux density, or intensity of the light shining on the panel to the power produced per area of the solar panel. Both having units of watts per square meter. Have them add irradiance flux density and intensity to their vocabulary.See Table 5 and 6 below for an example of student work. | Determine the area of the photometer detector active area in meters if the listed area is 38mm2. Show all work below and record the value in the table below.Determine the total area in meters of the solar panel if each LED has a diameter or 5mm and there are 10 LEDs. Show all work below and record the value in the table below.Determine the irradiance flux density of the light by dividing the power from the photometer (W) by the detector active area (m2). Record the value in the table below.Determine the power produced per area by dividing the maximum power produced (W) by total area of the solar panel (m2). Record the value in the table below. |
| See Table 6 below for an example of student work. | Calculate the actual efficiency of the solar panel. |
| **Final Product** |
| Developing, Critiquing, and Revising Products:The solution to the problem, reflection on the problem itself – how it was designed, implemented, or solved. Students should understand photodiodes are manufactured to maximize the diode surface area (in the direction of the light) while light emitting diodes are manufactured to produce a small but bright light source. | Test your product, how can it be improved? Devise a plan to improve your solar panel and make the necessary improvement.Explain how you can increase the efficiency of your solar panel. |
| Presenting Products:Produce guidelines for the students when creating their presentations. | As a group present your finished product to the other groups in the class. |
| **Part C: Is light a particle?** |
|  | Compose a conclusion or claim that explains why light is a particle. You must use the following evidence* Choose relevant details from your research that explains why light can be a particle.
* Elaborate on those details using observational evidence, making sure that they fully support your conclusion and claim.
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**Table 1**

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| **Resistance (Ω)** | **Voltage Produced (mV)** | **Power from Photometer (W)** |
| 250,000 | 9.3 | 0.000104 |
| 500,000 | 17.6 | 0.000104 |
| 750,000 | 23.0 | 0.000104 |
| 1,000,000 | 26.5 | 0.000104 |
| 2,000,000 | 33.6 | 0.000104 |
| 3,000,000 | 37.2 | 0.000104 |
| 4,000,000 | 40.1 | 0.000104 |
| 5,000,000 | 41.7 | 0.000104 |

**Table 2**

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| **Resistance (Ω)** | **Voltage Produced (V)** | **Power Produced (W)** |
| 250,000 | 0.0093 | 3.5x10-10 |
| 500,000 | 0.0176 | 6.20x10-10 |
| 750,000 | 0.0230 | 7.05x10-10 |
| 1,000,000 | 0.0265 | 7.02x10-10 |
| 2,000,000 | 0.0336 | 5.64x10-10 |
| 3,000,000 | 0.0372 | 4.61x10-10 |
| 4,000,000 | 0.0401 | 4.02x10-10 |
| 5,000,000 | 0.0417 | 3.48x10-10 |

**Graph 1**

**Graph 2**

**Table 3**

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| **Maximum Voltage Produced (V)** | **Maximum Power Produced (W)** |
| 2.50x10-2 | 7.10x10-10 |

**Table 4**

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| **Maximum Power Produced (W)** | **Power from Photometer (W)** | **Efficiency %** |
| 7.10x10-10 | 1.04x10-4 | 6.83x10-4 |

**Table 5**

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| **Power from Photometer (W)** | **Detector Active Area (m2)** | **Maximum Power Produced (W)** | **Total Area of Solar Panel (m2)** |
| 1.04x10-4 | 3.8x10-5 | 7.10x10-10 | 1.9635x10-4 |

**Table 6**

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| **Irradiance Flux Density of Light (W/m2)** | **Solar Panel Power Produced per Area (W/m2)** | **Actual Efficiency %** |
| 2.74 | 3.62x10-6 | 1.32x10-4 |