# Teacher's Preparatory Guide

## *Silicon solar cell efficiency: Comparing input power to output power of a silicon photovoltaic cell*

**Overview:** Nanotechnology is widely regarded as a key innovation and progress technology in many branches of the world's economy. Energy is one of the most important of these branches. Scientists and engineers continually research new ways of electricity generation, working to solve impending power shortages and address the issue of global climate change brought about by human consumption of power and the pollution associated with it. Solar energy devices, such as photovoltaics (PVs) can use nano-thick films to absorb solar energy and produce electricity. In this activity, students will experiment with silicon PV cells and determine some reasons for why there may exist a need for better alternatives.

**NOTE:** This lesson uses Vernier Go!Link interface and Logger Pro software

**Purpose:** This lab is designed to help students find a measure of a solar cell's power conversion efficiency, by studying output power ($P_{out}$) of a silicon PV cell and comparing it to the input power ($P_{in}$) of incandescent light bulbs illuminating the PV from a set distance. Several incandescent light bulbs with different power ratings will be placed at a distance of 25 cm away from the PV, and the output voltage and output current of the PV will be measured to determine the output power.

**Time Required: (**2) 55-minute class periods (One for experimentation, second for data analysis)

**Level:** High school Physics

**Big Idea:** Quantum Effects; Forces and Interactions

**Teacher Background.** Crystalline silicon-based PVs require much more material than some currently studied alternatives such as pyrite ($FeS_2$). This is due to silicon's inferior light absorption compared to other semiconducting materials. Due to the fact that current silicon-based PV films are expensive and inefficient, research into novel PV nanomaterials is being undertaken at multiple educational institutions, one being the University of Minnesota Twin Cities. The emphasis is put on finding a low-cost alternative material(s) to crystalline silicon that can be fabricated into thin nanoscale films for use in PV.

The feasibility of a material for use in photovoltaics is determined by several factors. Most of them involve cost. While sunlight is free, the most common PV devices in use today are expensive to make; they are manufactured using processes similar to those used in making advanced integrated circuits, and require high purity materials and exacting processes. This makes the silicon PV's conversion to electricity fairly expensive, thus large-scale photovoltaics



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development into an economical energy supply is currently unrealistic. However, solar energy continues to offer a green (low-carbon) and unlimited power alternative to fossil fuels, which leads to a logical conclusion that the cost of solar-to-energy conversion must be brought down to an acceptable level. This can be achieved by lowering material extraction costs, lowering manufacturing costs, lowering operation costs, using earth-abundant materials, and using high-efficiency materials. Many of those conditions can be met by using materials capable of absorbing a lot more of the incoming sunlight per weight compared to silicon allowing for use of several times thinner films, and thus much less potential PV raw source material.

**Sources:**

1. http://www.researchandmarkets.com/research/5zm667/nanotech_making. "Nanotech: Making Photovoltaics Possible." (June 2013).

2. Wadia, C., Alisavatos, A.P., Kammen, D.M. "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment." *Environmental Science & Technology"* Vol. 43, No. 6 (2009): 2072-2077.

3. http://science.howstuffworks.com/environmental/energy/solar-cell.htm. "How Solar cells Work." (June 2013).

4. Bernardi, M. and Grossman, J.C. Optimal Sunlight Harvesting in Photovoltaics and Photosynthesis Journal of Phyiscal Chemistry, J. Phys. Chem. C, 2013, 117 (51), pp 26896–26904 DOI: 10.1021/jp4090348

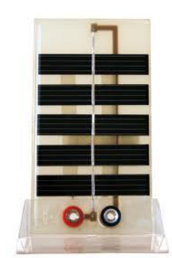
5. Bernardi, M., Palummo, M.,Grossman J.C. "Extraordinary Sunlight Absorption and 1 nm-Thick Photovoltaics using Two-Dimensional Monolayer Materials" Nano Lett., 2013, 13 (8), pp 3664–3670 Publication Date (Web): June 10, 2013 (Letter)
DOI: 10.1021/nl401544y

6.http://www.treehugger.com/renewable-energy/the-electron-nanotechnology-and-solar-power.html. "The Electron, Nanotechnology, and Solar Power." (July 2013).

**Materials per lab group of 3-4 students:**

- 1 Photovoltaic cell (solar cell)
- 1 clamp-on lamp with reflector
- 5 incandescent light bulbs with different light output (same glass and type):
  - 15 watts
  - 40 watts
  - 60 watts
  - 75 watts
  - 100 watts





- 1 Vernier current probe
- 1 Vernier voltage probe
- 1 Vernier Go!Link interface
- 1 breadboard (optional)
- Jumper wires (only necessary if using breadboard)
- LED
- Computer with Vernier Logger Pro software and Internet access

- Heat-proof gloves
- 2 alligator clip leads
- Scientific calculator
- Metric ruler
- Spreadsheet software (Excel etc.)
- Printer

**Advance Preparation:**

1. Purchase materials, which may be found in the table below.
2. Check well in advance that your school/lab has Vernier Logger Pro and spreadsheet software installed.
3. Practice data measurement with the different Vernier probes and using Logger pro software prior to the lab, especially if using for the first time.
4. Prior to this lab, students should be introduced to how solar energy works and issues associated with it, such as the high cost of materials, fabrication, and the resulting cost/Watt produced. You could assign this as homework with students submitting report or presenting PowerPoint on the findings.

| **Source/Website** | **Material** |
|---|---|
| http://www.vernier.com/products/interfaces/go-link/ | • 8 Vernier Go!Link interfaces (GO-LINK) - $61 each |
| http://www.vernier.com/products/sensors/voltage-probes/vp-bta/ | • 8 Vernier Voltage Probes - $12 each |
| http://www.vernier.com/products/sensors/current-sensors/dcp-bta/ | • 8 Vernier Current Probes - $39 each |
| https://www.sparkfun.com/products/112 | • 8 breadboards – $9.95 each |
| http://store.sundancesolar.com/misopa120.html | • 8 solar cells - $18.95 each |
| **Hardware or Home Goods Store (Ace, Target, Radio Shack etc.)** | • 10 - 15 watt light bulbs<br>• 10 - 40 watt light bulbs<br>• 10 - 60 watt light bulbs<br>• 10 - 75 watt light bulbs<br>• 10 - 100 watt light bulbs<br>• 10 LEDs (Radio Shack) |

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**Safety Information:** DO NOT TOUCH PLUGGED IN LIGHT BULBS WITH YOUR BARE HANDS. Use a heat-proof glove to handle hot light bulbs.

**Suggested Instructional Procedure:**

| Time | Activity | Goal |
|---|---|---|
| **Day 1** | **Experiment** | |
| **10 min** | Distribute student worksheet, introduce the activity, review terms, and form groups. | To discuss the purpose of the lab and answer initial student questions. |
| **45 min** | Students follow the procedure to complete the experiments (student worksheet). | To gather data for day 2 analysis. |
| **Day 2** | **Data analysis** | |
| **3 min** | Discuss objectives and data manipulation. | To ensure students understand how data should be presented in their final report. |
| **52 min** | Students follow the procedure to complete data analysis and submit their report. | To allow students to learn from the experiments they have conducted. |

**Teaching Strategies:** The lab should be done in small groups (ideally no more than three students). Make sure to discuss nanomaterial use in PV cells and the vocabulary terms below. Have a student read the introduction and facilitate whole class discussion on energy (mainly solar) and what role nanotechnology might play in future development of alternative PV materials.

**Guided Dialog.** Before beginning the lab, review the meaning of these terms:

- ***nanotechnology*** *working with matter, engineering of systems, and building of machines on the size scale between one and about 100 nanometers*
- ***nanomaterials*** *materials that have the size of 1-100 nm*
- ***nanometer*** *$10^{-9}$ m (one billionth of a meter)*
- ***semiconductor*** *material with the conductivity in the range between a metal and a nonmetal*
- ***solar cell (photovoltaic cell, PV cell)*** *device that converts sunlight into electricity using the photoelectric effect*
- ***silicon*** *most commonly used semiconductor in today's PV cells; abundant in Earth's crust, but expensive to fabricate into useful crystalline form; has a relatively low solar absorption (compared to other candidate materials)*



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- ***photoelectric effect*** *the process of electrons being knocked out of the material when it absorbs energy (present in PV cells)*
- ***light intensity (areal)*** *the amount of energy falling on a surface per second, in watts per square meter (W/m$^2$)*
- ***voltage (V)*** *electrical potential difference between two points measured in Volts (V)*
- ***current (I)*** *flow of electrons in an electric device measured in amperes (A)*
- ***power (P)*** *rate of energy transfer in watts (W)*

**Questions:**

1. How does a solar cell work*? When sunlight strikes the surface of a solar cell, electrons are knocked loose and form an electric current, which can then be used for external applications.*
2. Why is solar energy more expensive than fossil fuel energy? *The photovoltaic technology is still expensive to manufacture; high material costs; low conversion efficiency etc.*
3. Give reasons why solar power may be more desirable than fossil fuel power. *Much lowered carbon emissions; sunlight is free; direct conversion to electricity etc.*

## Procedure Summary

### I. Prior to the lab

1. Go over the Safety, Introduction, Materials, and Question sections with the students prior to starting the lab. Also, tell them that the deliverables include the worksheet as well as the two Excel graphs they will generate.

2. Turn on the computer and open the Logger Pro software. (Make sure you practice this before the actual lab day).

### Part 1. Measuring Voltage

1. Connect the Vernier Go!Link Interface to the Voltage probe and plug it into the computer's USB drive.

2. Plug the LED into a breadboard and use jumper wires to connect the LED in series with the solar cell terminals. Hint: In general the longer end acts as a positive electrode, thus the shorter end is negative. (Your students should know how to breadboard; if they do not, you might want to consider connecting the LED to the solar cell directly via alligator clips. Also, the current should be small enough that use of a resistor is not necessary)

3. Install the 100 W light bulb in the clamp-on lamp. Turn it on, and place it 25 cm away from the solar cell. (Keep the bulb boxes for easy storage, label them for students, and tell them to put them back in the box after each step, so they do not break by rolling of the table etc.)

4. Connect the alligator leads from the Voltage probe to the LED to measure voltage making sure not to short-circuit the LED.



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5. Record the voltage reading from Logger Pro in the data table.

6. Turn off the lamp, unplug it, and USING A HEAT GLOVE replace the 100 W bulb with the 75 W bulb and repeat steps 4–6. Repeat this procedure for the 60 W, 40 W, and 15 W bulbs.

**Part 2. Measuring Current**

7. Connect the Vernier Go!Link Interface to the current probe and plug it into the computer's USB drive.

8. Connect the alligator clip leads to the current probe. (Students will need separate alligator clip leads for the current probe).

9. Install the 100 W light bulb in the clamp-on lamp. Turn it on, and place it in 25 cm away from the solar cell.

10. Measure the current by plugging the current probe into the circuit (in series). This involves temporarily breaking the circuit to connect the alligator clip leads from the current probe. Make sure to match the correct electrodes (+ to +, - to -).

11. Record the current reading from Logger Pro in the data table.

12. Turn off the lamp, unplug it, and USING A HEAT GLOVE replace the 100 W bulb with the 75 W bulb and repeat steps 10-12. Repeat this procedure for the 60 W, 40 W, and 15 W bulbs.

**Analyze the Results:**

1. Calculate the power generated by the solar cell for each light bulb using the formula: P = VI. Record as Output Power in Table 1.

2. Use the spreadsheet program to make a bar graph (Graph 1) of light bulb power (x-axis) vs. solar cell output power (y-axis). Make sure the students title the graph and label both axes. Have the students print out the graph.

3. Each light bulb has a power rating (100 W, 75 W, 60 W etc.) which represents the amount of electrical power it consumes, and not the amount of light power it emits, which we will call "input power". In order to calculate the input power of each light bulb you will have to first calculate its light intensity using the formula:

   $$\frac{P}{4\pi r^2}$$

   where P is the light bulb power in watts, and r is the distance between the solar cell and the light bulb in meters. Record in Table 1.

4. Next, students calculate and record the absorption area of the solar cell in $m^2$.

5. The calculated area and the light intensity are used to calculate input power.



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6. Calculate the efficiency by dividing output power by input power and multiplying by 100. Record in Table 1.
7. Use the spreadsheet software to make a bar graph (Graph 2) of the efficiencies of all the light bulbs used in the experiment. Make sure to title the graph and label both axes. Print the graph.

**Cleanup:** Wait for the light bulbs to cool down; put them back in their respective boxes; and put all of the other materials away.

**Enhancing Understanding:** Cover this section *after* the activity.
Pose this question to the students:
*If silicon is so inefficient, why do we continue to use it in solar cells?*
Answer: *Due to a combination of factors:*
*a) the manufacturing systems for silicon-based PVs are the most developed of all PV alternatives, due to the advanced integrated circuit manufacturing industry, so silicon PVs can be mass produced readily;*
*b) even though they are no more than about 30% efficient, silicon-based PVs are the most efficient solar conversion technology currently available.*

**Review the findings with students:** At the beginning of day 3, the teacher may choose to lead a class discussion and go over the results and conclusions students drew. This can also be done with individual groups while they are completing their analyses and conclusions at the end of day 2.

**Going Further:** Students who have a good grasp of the content of the lab can be further challenged with these questions.

1. What advantages would you expect an "ideal" PV material to have? *Low cost of material (abundant), relatively easy to fabricate and mass-produce, low weight-to-power ratio (thin film), high sunlight absorption, and high-conversion efficiency, etc.*
2. What do nanotechnology and solar cells have in common? *There is an increased push to use thin nano-thick films, or layers of film for PV cells to decrease cost and increase their efficiency. These involve fabrication and use of semiconductors that may be only a few nanometers thick.*

**Assessment:** Students should be able to successfully perform all of the steps of the experiment, collect, and analyze data critically. They will be assessed on data organization and interpretation, as well as their team's ability to draw meaningful conclusions.

**Resources:**


- Wadia, C., Alisavatos, A.P., Kammen, D.M. "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment." *Environmental Science & Technology"* Vol. 43, No. 6 (2009): 2072-2077.
- http://science.howstuffworks.com/environmental/energy/solar-cell.htm. "How Solar cells Work." (June 2013).
- Teach Engineering Photovoltaic Efficiency accessed at: http://www.teachengineering.org/view_curricularunit.php?url=collection/cub_/curricular_units/cub_pveff/cub_pveff_curricularunit.xml





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- NASA How do photovoltaics work accessed at : http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/
- NREL  Solar Photovoltaic Technology Basics accessed at: http://www.nrel.gov/learning/re_photovoltaics.html

**National Science Education Standards (Grades 9–12)**

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry

Content Standard B: Physical Science

- Structure of atoms
- Structure and properties of matter
- Motions and forces
- Interactions of energy and matter

Content Standard E: Science and Technology

- Abilities of technological design

**Next Generation Science Standards**

HS-PS3 Energy

HS-ETS1.C Optimizing the Design Solution



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Name:________________________________Date:_______________Class:____________

# Student Worksheet *(with teacher notes and answers)*

## *Silicon solar cell efficiency: Comparing input power to output power of a silicon photovoltaic cell.*

**Safety**

DO NOT TOUCH PLUGGED IN LIGHT BULBS WITH YOUR BARE HANDS. Use a heat-proof glove to handle hot light bulbs. Replace the light bulb into its original box immediately after use.

**Introduction**

What do nanotechnology and solar power have in common? To answer this question let's think of an electron as the ultimate currency of modern society and technology. The electrons which might power your cell phone and make tweeting during class possible reside in nano-environments. These nano-environments made up of different atoms and molecules can influence electron behavior as much as our environment influences us. Scientists believe that through studying these tiny environments we can come up with better ways of collecting, storing, and transporting energy. In a typical solar cell, electrons flow creating electric current as a result of sunlight striking the surface of a silicon semiconductor. In this lab you will compare the electrical power in watts that a silicon solar cell generates to the power given off by a light bulb with a given power rating. You will also research some other possible photovoltaic materials and compare them to silicon.

**Materials per lab group of 3-4 students**

- 1 Photovoltaic cell (solar cell)
- clamp-on lamp with reflector
- 5 incandescent light bulbs with different light output (same glass and type):
  - 15 watts
  - 40 watts
  - 60 watts
  - 75 watts
  - 100 watts
- 1 Vernier current probe
- 1 Vernier voltage probe
- 1 Vernier Go!Link Interface
- Computer with Vernier Logger Pro software and a spreadsheet program (Excel etc.) and Internet access


- 1 breadboard
- Jumper wires (2)
- LED
- Heat-proof gloves or hot hands
- 2 alligator clip leads
- metric ruler
- Scientific calculator

**Question:** Is silicon a good material to use in solar cells? *This is to focus the students on what they are trying to determine.*

**Make a Prediction** (Predict the efficiency of your solar cell as a percentage)

*Answers will vary but may include - I think that the solar cell will be 25% efficient or 50% efficient.*______________________________

**Procedure:**

1. Turn on the computer and open the Logger Pro software.

**Part 1. Measuring Voltage:**

2. Connect the Vernier Go!Link Interface to the Voltage probe and plug it into your computer's USB drive.
3. Plug the LED into a breadboard and use jumper wires to connect the LED in series with the solar cell terminals.
4. Install the 100 W light bulb in the clamp-on lamp. Turn it on, and place it 25 cm away from the solar cell.
5. Connect the alligator leads from the Voltage probe to the LED to measure voltage making sure you do not short-circuit the LED.
6. Record the voltage reading from Logger Pro in the table below.
7. Turn off the lamp, unplug it, and USING A HEAT GLOVE replace the 100 W bulb with the 75 W bulb and repeat steps 4–6. Repeat this procedure for the 60 W, 40 W, and 15 W bulbs.



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**Part 2. Measuring Current:**

8. Connect the Vernier Go!Link Interface to the current probe and plug it into your computer's USB drive.
9. Connect the alligator clip leads to the current probe. *(You will need separate alligator clip leads for the current probe)*
10. Install the 100 W light bulb in the clamp-on lamp. Turn it on, and place it in 25 cm away from the solar cell.
11. Measure the current by plugging the current probe into the circuit (in series). This involves temporarily breaking the circuit to connect the alligator clip leads from the current probe. Make sure to match the correct electrodes (+ to +, - to -).
12. Record the current reading from Logger Pro in the table below.
13. Turn off the lamp, unplug it, and USING A HEAT GLOVE replace the 100 W bulb with the 75 W bulb and repeat steps 10-12. Repeat this procedure for the 60 W, 40 W, and 15 W bulbs.

**Analyze the Results:**

8. Calculate the power generated by the solar cell for each light bulb using the formula: P = VI. Record as Output Power in Table 1.
9. Use the spreadsheet program to make a bar graph (Graph 1) of light bulb power (x-axis) vs. solar cell output power (y-axis). Make sure to tile the graph and label both axes. PRINT IT.
10. Each light bulb has a power rating (100 W, 75 W, 60 W etc.) which represents the amount of electrical power it consumes, and not the amount of light power it emits, which we will call "input power". In order to calculate the input power of each light bulb you will have to first calculate its light intensity using the formula:

    $$\frac{P}{4\pi r^2}$$

    where P is the light bulb power in watts, and r is the distance between the solar cell and the light bulb in meters. Record in Table 1.
11. Next, calculate the absorption area of the solar cell in $m^2$. Record here: *Depends on cell used*
12. Finally, use the calculated area and the light intensity to calculate input power. Record in Table 1.



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13. Calculate the efficiency by dividing output power by input power and multiplying by 100. Record in Table 1.
14. Once again, use the spreadsheet software to make a bar graph (Graph 2) of the efficiencies of all the light bulbs used in the experiment. Make sure to title the graph and label both axes. PRINT IT.

**Table 1. Solar Cell Output Voltage, Current, and Power**

| Light bulb power (W) | Voltage (V) | Current (A) | Output Power (W) | Light Intensity ($W/m^2$) | Input Power (W) | Efficiency (%) |
|---|---|---|---|---|---|---|
| 100 W | *0.930 V* | *0.142 A* | *0.130 W* | *127* | *?* | *?* |
| 75 W | *0.660 V* | *0.125 A* | *0.083 W* | *95* | *?* | *?* |
| 60 W | | | | | | |
| 40 W | | | | | | |
| 15 W | | | | | | |

*? - dependent on the absorption area of the solar cell used in the experiment*

**Draw Conclusions:**

1. In your opinion, is silicon an efficient material for use in photovoltaics? Use your data to explain your answer.

   *Dependent on results. However, efficiency of <10% can be expected, so Si does not seem to be an ideal material for PV applications.*

2. Does solar cell efficiency increase or decrease as the input power increases? Use your data to explain the correlation.

   *Dependent on results. Generally, silicon solar cells are more efficient when low-wattage bulbs are used.*____________________________________________

3. What happens to the remaining power produced by the light bulb if not all of it is used by the solar cell?

   *Loss to heat (air), light radiates in all directions, not all the light that strikes the solar cell is converted to electricity etc.*

4. Research two alternative solar cell materials, describe their pros and cons, compare them to silicon and describe their connection to nanotechnology. Provide the source of your information.

   *Answers will vary, but should have 2 materials. Some possibilities are CIGS, CdTe, GaAs, pyrite, copper(II) oxide, zinc phosphide etc.*



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