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Solar Panel Electricity, Efficiency, and Environmental Impacts

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Alternatives to non-renewable energy resources such as wind and solar will be essential components of any plans to address the global warming that has been induced by human activity. Although solar panels are being deployed in large arrays in centralized generation facilities, the deployment of highly decentralized arrays on residential and commercial buildings is becoming very common. In this study, students investigate how the angle of sunlight incidence on a solar panel influences the power output of a panel and the absolute efficiency of solar panels. These data may be used to estimate the contribution that solar panels could make to the average electrical power demands of a home, given the limitations of fixed position panels and limited roof area.

Keywords: guided-inquiry, course-based research, fossil fuel alternatives, global warming, solar panel efficiency

Link to Supplemental Materials: https://doi.org/10.37590/able.v41.sup4

Introduction

Teaching the science of climate change and global warming is incomplete without a consideration of the potential solutions to the problems of carbon-based and non-renewable energy production. Among the simplest non-carbon energy resources is the direct production of electricity from silicon solar panels, and this technology is easily brought into a teaching laboratory since full scale panels are made of small subunits that are wired into a larger array. Students can easily manipulate small solar panels to evaluate power output as a function of the angle on sunlight incidence and coupled with a pyranometer it is easy to calculate the conversion efficiency of sunlight energy to electrical energy. Students are asked to make measurements on power output and efficiency to address the question of how much roof area would be required to meet the average electrical power demand of a home. Are solar panels capable of providing the electrical energy needs of a typical home or would they only be able to address part of our current needs? I have used this study in our Environmental Studies laboratory course, a junior-senior undergraduate-level science majors course that serves as an elective in our Biology major, a required course in our Sustainability minor and an elective in our Environmental Studies minor.

Student Outline

Solar Panel Electricity, Efficiency and Environmental Impacts

Objectives

- Design and perform a set of experiments to evaluate the power output of a small solar panel at different angles of sunlight incidence.
- Evaluate the efficiency of a solar panel in converting sunlight energy to electrical energy.
- Perform an analysis (based on your findings) to determine whether it is realistic to use solar panels covering the roof of a home to meet the electrical needs of the home.

Introduction

Alternatives to non-renewable energy resources such as wind and solar will be essential components of any plans to address the global warming that has been induced by human activity (UN IPCC 2018). Although solar panels are being deployed in large arrays in centralized generation facilities, the deployment of highly decentralized arrays on residential and commercial buildings is becoming very common.

In this study, you will investigate how the angle of sunlight incidence on a solar panel influences the power output of a panel. In addition, you will estimate the absolute efficiency of a solar panel. These data may be used to estimate the contribution that solar panels could contribute to the average electrical power demands of a home, given the limitations of fixed position panels and limited roof area.

Materials

In class, each research team will be provided with the following (Fig. 1): A small solar panel (polycrystalline silicon) with leads, a digital multimeter for measuring voltage (electromotive force) and amperage (electrical current), a pyranometer sensor and digital meter (to measure total sunlight energy), a mounting platform, and an angle meter. Rulers and meter sticks also will be available.

Figure 1. Solar panel mounted on a pivoting stand and connected to a digital multimeter (blue). The black cylinder left of the solar panel is the pyranometer (attached to a leveling base) connected to a digital light meter (tan). An angle locator, the yellow dial device behind the meters, attaches to the steel plate on the top of the platform between the solar panel and the pyranometer.

Safety

The experimental materials you will be using can be hazardous to you. Several warnings:

1. The solar panel is a glass sandwich containing the silicon chips that generate electricity. Use care in handling the glass solar panel, the edges are sharp.

2. You will be evaluating the solar panel by exposing it to sunlight. Looking directly at the sun will damage your eyes, even if you are wearing sunglasses. Estimating the angle of sunlight incidence should be done indirectly by measuring the shadow cast by a stick of known length and using that information to calculate the angle of the sunlight to the earth surface.

Experimental Design

Your task is to design and conduct experiments (and collect information from the internet) to address the following questions: How does the angle of sunlight incidence influence the electrical power output of a solar panel? What is the efficiency of a solar panel in converting sunlight to electricity? Is it realistic to cover the roof of a home with solar panels to provide all the electrical needs of the home?

After you have read the background information and before the laboratory class meeting:

- Describe an experimental design for evaluating how the angle of sunlight incidence influences the power output and efficiency of a solar panel.
- Predict the possible outcomes for your experiment.
- Identify and list the variables you would manipulate in the experiment.
- Identify and list the variables you would keep constant in the experiment.
- Describe the calculations you will need to make to evaluate your findings.
- Describe the statistical analyses that you would carry out to test your predictions.

Come to class prepared to present your experimental design. How many replications would you need to conduct to ensure that your findings did not occur by chance alone?

Is it realistic to power a home with solar panels covering the roof?

Fixed position installations of solar panels are typically set at an angle with respect to the ground equal to the latitude of the location. Explain the logic of this set-up given what you have discovered about the relationship between the angle of incidence of a solar panel with respect to the sun and the power output of the panel. Is the angle of incidence of the sun to the ground constant during a 24-hour period? Is the angle of incidence of the sun to the ground constant during the 12-months of the year? How would variation in the sunlight angle of incidence influence estimates on using solar panels to provide power to a home?

Cited References

UN IPCC. 2018. Special Report on Global Warming of 1.5°C (SR15). http://ipcc.ch/index.htm

Materials

Equipment and Supplies

For a class of 25 students working in groups of 2 or 3:

- 10 small solar panels with screw terminals (62mm x 120mm) (Vernier KW-SP2V, $19 each, Fig. 2) with banana plug (use solderless-screw connector banana plugs, such as Amazon, DIYhz audio speaker cable connectors 20 pack, 4mm red and black, $7.00) leads 2-3' long (16 gauge low voltage copper stranded wire in red and black, Lowes 25' rolls, $6.60 each) replacing the alligator clip leads that come with the solar panels.
- 10 pivoting stands or small tripods fitted with platform to hold solar panel and pyranometer (Fig. 3). Assembly details in Appendix.
- 10 digital multimeters (Amazon.com, MChoice DT830B $4.99 each)
- 10 pyranometer sensors with 2m lead (Li-Cor LI-200R-BNC2, $274 each)
- 10 leveling fixtures for pyranometer sensors (Li-Cor LI-2003S, $55 each)
- 10 digital light meters (Li-Cor LI-250A, $647 each)
- 10 angle locator (Johnson magnetic angle locator, Home Depot, $9.99 each, Figure 3)
- 10 30cm rulers
- 10 wood meter sticks
- 20 9v batteries for the multimeters and light meters
- 5 spot lights to use indoors to simulate solar radiation (rain insurance)

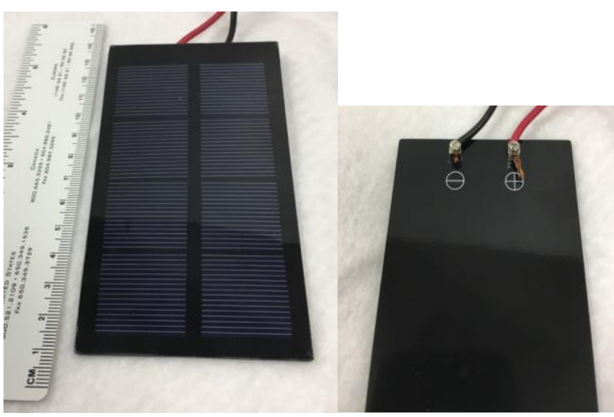

Figure 2. A front view of the solar panel and a rear view showing screw terminals with leads attached. Screw terminals eliminate the need to solder leads to the solar panel.

Figure 3. Pivoting platform to securely hold solar panel and pyranometer sensor and leveling fixture. The image on the left shows how the angle indicator is used to indicate the angle of the platform with respect to level ground (a 15cm ruler is shown for scale). This pivoting platform and base can be easily fabricated from plywood, wood and wood dowels. Fabrication plans are detailed in the Appendix A.

Notes for the Instructor

Presentation of the Study to Students

The format of the Student Handout is not the only way to present this study to students. In the past, I have presented this to students in the form of a case study (see example after Previous Results), or we simply begin with a discussion about global warming and practical existing methods for generating electricity. An ideal means of beginning a conversation with students about their own behavior as it relates to carbon and climate is to have each of them complete an environmental footprint assessment (see Weglarz 2011). Depending on the physics background of your students, a review of basic electricity concepts (Appendix B) may be appropriate.

Safety

Small solar panels consist of an array of silicon crystal sheets that are sandwiched between sheets of glass. This glass will shatter if dropped or crushed and the edges of the solar panel are sharp so some care must be used while handling them.

This study should be conducted by exposing the solar panel and the pyranometer to the sunlight. Students should be cautioned not to look directly at the sun even if wearing sunglasses! It is tempting to look at the sun when trying to set the angle of the pivoting platform. Students should use an indirect method for calculating the angle of sunlight incidence on the solar panel by first measuring the sunlight angle of incidence to the ground.

Measuring Devices

The most expensive components of this study are the Li-Cor pyranometer and light meter. These are research quality tools but they only are needed if you wish to evaluate the efficiency of the solar panels by measuring the total energy of the incident sunlight. A less expensive alternative to the Li-Cor equipment is the Vernier pyranometer sensor (PYR-BTA, $215) that will connect to standard Vernier interfaces (such as the Vernier Go!Link interface, $61, with free Logger Lite software) that permit data collection with a laptop computer. However, the most important part of this study is evaluating the effect of angle of incidence on the electrical power output of the solar panel. That evaluation only requires the solar panel and a multimeter to measure DC voltage and current outputs from the panel. Some very inexpensive digital multimeter may be purchased (for example, Amazon, MChoice DT830B $4.99 and Harbor Freight Tools, Item #63604 $5.99) but these meter may require moving the banana plug input on the meter when switching between voltage and amperage measurements. These inexpensive multimeters are fine for the purposes of this study, but students need to be reminded (and sometimes shown) how to appropriately make the different measurements. Showing students the differences between the DC V and DC A settings and the AC settings are essential for meaningful data to be collected. The AC settings typically will show a sine wave symbol while DC settings may show a pair of straight solid or dashed lines. Similarly, it is helpful to show students how the different multimeter settings change the sensitivity and range of measurements possible. For example, at a 600V DC setting the sensitivity may be too low to measure less than 1.0V (and the meter would read 0), but setting the sensitivity down to 200mV would be too sensitive for a voltage greater than 0.2V and would show an error message for a voltage of 1.5V. Readings of DC voltage or current at AC settings are questionable and voltage is not the same as current!

Experimental Design

Students typically measure the voltage and current outputs of the solar panel at three different angles of incidence, 60°, 90° and 120°, when facing the sun. A 90° angle of incidence is perpendicular to the position of the sun, or the most direct angle, so it should be used as a reference for all other measurements. First, you need to know the position of the sun with respect to the ground. Determining the angle of incidence of the sun with respect to the level ground may be accomplished by measuring the length of the shadow (y) cast by a stick of known length (x), such as a meter stick, held perpendicular to the ground. The angle of incidence is the arctan of the stick length (x) divided by the shadow length (y), $tan\theta = \frac{x}{y}$ so $\theta = arctan\frac{x}{y}$ (Figure 4). For example, if a meter stick (100cm) cast a shadow of 58cm on level ground, then x/y = 1.72 and the angle would be 60°. If you wished to set the angle of incidence for the solar panel at 90°, then the sum of the sunlight angle of incidence with the ground plus 90° subtracted from 180° would give you the angle to set solar panel platform with respect to the ground (see Figure 4). For example, if the sun were at 60° from the horizon and you wanted to set the angle of incidence for the solar panel at 90° then you would set the platform at 30° (= 180° - [60° + 90°]) (see Figure 4). Making sample calculations prior to going outside would help make it easier to perform them with real values outside. Discussing ideas for a measurement protocol, number of replicate measurements to make at each angle of incidence and coming to a consensus on the angles of incidence to evaluate would provide independent replicate measurements from multiple groups. Both voltage (DC volts) and current (DC amperage) must be measured for each replicate measurement.

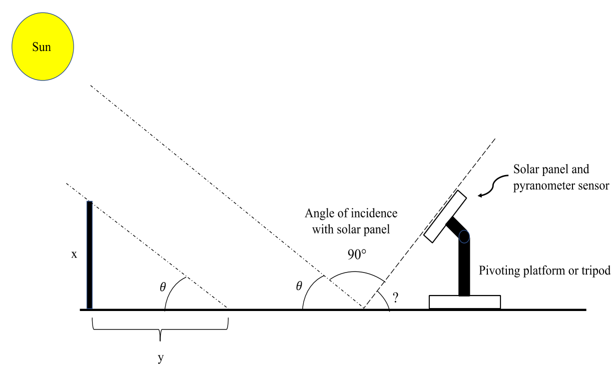

Figure 4. Calculating the angle of sunlight incidence with the ground and setting the solar panel to a selected angle of incidence. Estimating the angle of sunlight incidence with the ground is shown on the left side of this image. The upright dark stick could be a meter stick (length x) casting a shadow of length y on level ground. The $tan\theta = \frac{x}{y}$ so $\theta = arctan\frac{x}{y}$. For example, if a meter stick (100cm) cast a shadow of 58cm on level ground, then x/y = 1.72 and the angle would be 60°. If you wished to set the angle of incidence for the solar panel at 90°, then the sum of the sunlight angle of incidence with the ground plus 90° subtracted from 180° would give you the angle (?) to set solar panel platform with respect to the ground. For example, if the sun were at 60° from the horizon and you wanted to set

the angle of incidence for the solar panel at 90° then you would set the platform at 30° (= 180° - [60° + 90°]).

Efficiency measurements may be made at any angle of incidence but guiding the class to agree on a common protocol would permit students to compare and combine their findings. The measurements of the pyranometer are in Watts/m^2.

Data Analysis

The power output of the solar panel (Watts) at a given angle of incidence is calculated as the product of electrical force (voltage in DC V) and the amount of electron flow (current in DC A). However, this wattage value is the power output of the actual panel not W/m^2, so comparing the output of the solar panel to the total sunlight energy arriving at the solar panel requires either multiplying the power output to that expected for a m_2 or dividing the incident sunlight energy value by the fraction of a m^2 represented by the solar panel. Students often find this calculation to be confusing but it can help to draw a picture that shows how many small solar panel (62mm x 120mm) would fit in an area that is 1000cm x 1000cm (1.0 m^2). Calculations of efficiency that exceed 100% are not possible in the real world and efficiencies exceeding 20% should be carefully reviewed. Most solar panels currently have efficiencies in the 14-18% range.

Previous Results

This study has been conducted by my students successfully for more than 5 years. In Spring 2019, students in the Environmental Studies laboratory course at Morehouse College evaluated the mean output of the 62mm x 120mm solar panel at three angles of incidence: 90°, 65°, and 45°. The average outputs (mean±SE) were 131.7±10.9 W/m^2 at 90° (N=22), 127.0±4.2 W/m^2 at 65° (N=17), and 108.7±10.0 W/m^2 at 45° (N=18). These calculated output values were the product the observed voltage and current produced by the solar panel which was then scaled up to a m^2 size (estimating that there would be 138.9 62mm x 120mm units in a square meter area). The observed solar panel voltage and current at each angle of incidence was: 2.29±0.06 V and 0.42 ±0.03 A at 90°, 2.26±0.03 V and 0.41±0.01 A at 65°, and 2.24±0.04 V and 0.35±0.03 A at 45° sample sizes as noted previously. The incoming sunlight energy was 1106.1±28.9 W/m^2 at 90°and efficiency at 90° angle of incidence was 11.9±1.0% (N=22).

Example Case Study

You Have the Power!

There are big pollution problems resulting from our energy use, but what can you, one individual, possibly do to make a difference?

There is a full size solar panel, not a small toy-like model, mounted on the roof of this building. That panel measures .754m x 1.593 m, generates 24v DC electricity and has a peak power output of 100W. An electronic device called a voltage inverter receives the DC output of this solar panel and converts it to 110v AC, the same form of electricity we use in our homes, offices, and academic buildings. The output of the inverter is fed to the building power grid, providing some of our electricity directly from sunlight. This type of system is called a grid-tie system.

In this study, your assignment is to address three questions about solar panels (photovoltaic systems):

1) How does the angle of sunlight incidence affect the power output of the solar panel? Evaluate three realistic angles of incidence assuming that the solar panel is in a fixed position on the roof of a building. What would be the best position and angle of incidence for a fixed position panel?

2) How efficient is a solar panel in converting sunlight energy to electrical energy? This evaluation may be conducted at one angle of incidence such as the one that produces the peak power output.

3) How much surface area (m_2) would be required in solar panels to provide 50% of the typical energy needs of a household in the United States?

The total instantaneous sunlight energy arriving at a given location may be measured with a calibrated sensor called a pyranometer and measured in W/m^2. You will be able to measure the voltage and current (amperage) output of a small solar panel using a digital multimeter. Watts are calculated as the product of electrical force (voltage) and the amount of electron flow (current).

Discuss how you will conduct your study, then go outside to make measurements. Then, discuss how you will make your calculations. Each group will present their findings in class next week.

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About the Author

Larry Blumer is Professor of Biology and Director of Environmental Studies at Morehouse College where he teaches ecology, environmental studies, and introductory biology. Blumer also teaches in the SEA PHAGES program (Freshmen research immersion) at Morehouse.

Appendix A: Specifications and Parts

Design Specifications for Solar Panel Support Platform

Solar panel support platforms are easily fabricated with wood, plywood and wood dowels. The entire unit could be fabricated in a basic woodworking shop (Physical Plant or Instrument Shop) or Maker Space laboratory. The assembled stand is shown in Figure 5. The disassembled stand with parts labelled is shown in Figure 6.

Figure 5. Assembled stand for solar panel support platform. Adhesive-backed hook and loop tabs attached to the upper support platform permit the small solar panel to be securely attached to the platform but easily removed after each use (Figure 7). A pyranometer sensor also may be attached to the support platform with adhesive-backed hook and loop tabs. Applying several coats of varnish to the wood prior to adding metal hardware and hook and loop tabs is optional.

Figure 6. The disassembled solar panel support platform. The steel plate attached to the plywood panel is a steel mending brace 6.5cm x 3.5cm that will permit a magnetic angle locator to attach to the support platform. This steel plate could be attached to the platform with adhesive-backed hook and loop tabs rather than screwed to the plywood. The holes in both the plywood platform and the wood base are countersunk and wood screws pass though those holes to attach to the wood dowels.

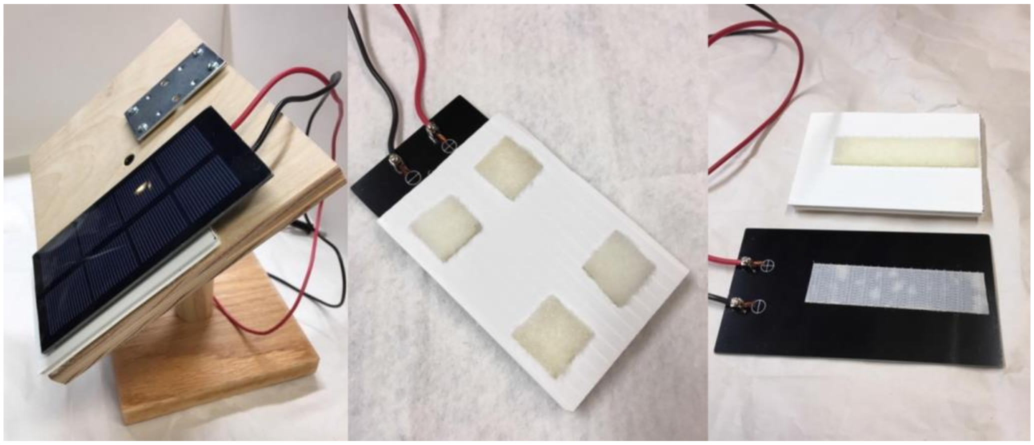

Figure 7. A small solar panel (Vernier KW-SP2V) may be easily attached to the platform with adhesive-backed hood and loop tabs. Attaching the solar panel to a small piece of corrugated plastic sheet elevates the panel so the screw terminals on the back side do not rest on the platform. The plastic sheet, if cut wider than the solar panel, makes it easy to remove the solar panel from the support platform for storage after use.

Parts List for Each Solar Panel Support Platform

The parts list that follows is for one support platform. All materials are available from hardware stores, Lowes and Home Depot home improvement stores, and similar lumber-hardware stores.

Plywood upper platform 15cm x 22cm x 1.25cm

Wood base 15cm x 15cm x 2cm

Wood screws (2) 4cm long #8

Wood dowels 32mm diameter (1) 7.5cm, (1) 11.5cm each cut in half for 43mm, 8mm hole bored perpendicular to cut face centered 16mm from end

Steel bolt 6mm diameter, 5cm long, flat metal washer, flat plastic or nylon washer, butterfly nut

Steel mending brace (1) 6.5cm x 3.5cm

Hook and loop (Velcro) adhesive-backed tabs or rolls cut as needed

Nylon feet for wood base (4)

Appendix B:Review of Electricity Basics

The following is a very basic review of the terminology and calculations necessary for conducting the solar panel efficiency study:

Voltage: The electromotive force on electron flow (V). Millivolts (mV) are 1/1000 of a volt.

Amperage: The rate of electron flow in a circuit, the current (A). Milliamps (mA) are 1/1000 of an ampere.

Direct Current: This is electrical current in one direction that has a constant voltage when electrons are flowing. A solar panel electrical output is direct current so it is necessary to measure both voltage and amperage using DC settings of a multimeter. Domestic electrical grid power systems are alternating current (AC) in which the voltage changes and the current flow direction alternates (typically at 50 or 60 cycles per second).

Wattage: The power output or power use of a given device or circuit (W). Power is the mathematical product of electrical potential and current flow: W = V*A

Multimeter: Used to measure the electrical output of the solar panel, both voltage and amperage.

Pyranometer: Used to measure the power of light energy (the entire electromagnetic spectrum) arriving from the sun at a given surface. This device measures the total input power arriving on the surface of the solar panel in W/m^2.

Efficiency: The ratio of output per unit input. Thus, in this study, the efficiency of the solar panel would be the power output of the solar panel (Watts calculated as the product of the multimeter measurements of volts and amps) per unit input from sunlight (measured by the pyranometer in W/m^2). Multiplying the efficiency ratio by 100 gives a percentage efficiency.

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