Effect of Shading on a Photovoltaic Module

Student Objective

The student:

- can predict how environmental shading will affect the power output of a photovoltaic module
- can predict how shading or cell failure will affect the power output of a photovoltaic array wired in series, parallel, or a combination of both circuits
- will assess a potential site for its suitability for a photovoltaic device.

Key Words:

Crome-Dome
solar window

Time:

1 - 2 class periods

Materials:

- Laboratory Manual
- photovoltaic module (single or poly-crystalline)
- irradiance meter (solar meter)
- multipurpose meter
- single cell results from *Series and Parallel* lab
- protractor
- ruler
- graph paper
- (4) photovoltaic cells
- (6) sets wires with alligator clips
- piece of cardboard
- thermometer
- *Crome-Dome* copied onto transparency film
- scissors
- tape

Procedure

1. **Engage:** Lead a discussion on the findings from the *Series and Parallel Circuits* activity, and answer any questions that the students have from the problem set. General photovoltaic questions from students can be used for further research. Points that may be brought up in discussion that will be covered more thoroughly during this investigation

and can be given a "you will find out today" response:

- Devices connected in series are looped together and work as a unit; the result is that either all are on or all are off.
- Photovoltaic devices connected in series and parallel circuits are affected differently by shadows and shading.

2. Students should work in teams of 3 - 5 per team.
3. **Explore:** Students should complete the investigative, analysis, and assessment activities covered in the Laboratory Manual.

Answers - Laboratory Exercises

1. At this point most students will hypothesize that increasing the percent of shading will decrease the power output proportional to the percent of increase of shade.
2. The exact answers are not important. Data will vary between groups especially in the percentages less than 40% shade, depending on which area(s) of the module the students happen to cover.
3. Graphs will vary, but should be labeled appropriately. The x-axis should be percentage of shade. The scales and lines for voltage, current and power should be clearly labeled.
4. Data will vary but students should show ability to correctly calculate the percentages of the control amount.
5. Graphs will vary but should be labeled appropriately. The x-axis should be the percentage of shade and the y-axis should be the percentage of the control amount. The lines for voltage, current and power should be clearly labeled and the title should include the temperature and irradiance reading.
6. 20%
7. Current (and therefore power output) is the quickest to be affected by shading.
8. Answers will vary, but most students will be surprised by the negative effect that even minimal shading has.
9. Answers will vary, but students should be able to think of some areas of the experiment that could have tighter controls and appropriate design measures to correct the problem. Some of the problems they may notice are: inconsistency within the experiment of the distance between the module and the cardboard shading device, which allows more diffuse light and creates a different sized shaded area; inconsistency in which quadrants of the module are covered first; the shape of the shading pieces (rectangular, round, etc.), and extra shading caused by fingers and the hand which is holding the cardboard over the module.
10. The quick drop in output is because the cells are wired together in series. However, students may not be able to deduce this yet.
11. Students should notice that there are some points on the module that are more sensitive to the shading than others.
12. At this point the students will probably not know the answer to this question, and its purpose is strictly to get them thinking. The correct answer, because of the way the cells in the module are wired together, will be discovered later in this investigation.
13. 2x the voltage, 2x the amperage of the single cell and 4x the power of the single cell.
14. Answers will vary. Diagrams should be legible and clearly show the series and parallel

wiring.

15. Answers will vary depending on the specific output of the cells being used in your class. Covering one cell will reduce the current in one of the parallel strings to zero which will decrease the total current by one fourth.
16. No. Any one cell covered will have the same effect. Students should realize that covering any cell will reduce the current in that string to zero.
17. Answers will vary depending on the specific output of the cells being used in your class. The current will be reduced by one half of the amount from question 15, or one-eighth of the original output current.
18. No. Students should understand that covering any cell reduces the current in that string by 1/2.
19. Answers will vary, but students should realize that even a pencil shading part of a cell reduces the current output drastically.
20. No.
21. No.
22. Answers will vary.
23. Students should describe any obstructions that they observe in the solar window. Students should realize that if the obstruction is not moveable, the best remedy for shading is to install the panel in a different location.
24. Expected output would be 8.32 kw per day; 249.6 kw total for the month.

Answers - Problem Set

1. During the “solar window” from 9:00am - 3:00 pm
2. The time of maximum solar irradiance, 9:00am - 3:00 pm for all seasons of the year. Systems are set up to collect more solar energy during this time.
3. d
4. The voltage and current will both be zero.

5 The current will drop in half, and the voltage will remain the same.

6. Spokane, Washington
7. The higher the latitude, the more tilted the panel is toward the horizon, and the easier for an obstruction to shade an array. (Note: the insolation data charts are not needed for this question, they were included to reinforce good test taking skills)

8a. Tree - Remove the tree or select another location for the array. Trimming the tree won’t work because the tree will continue to grow into the solar window

8b. Power lines - See if you can get the power company to move the line. If not, depending on where the line cuts through the solar window on the array, and the severity of the problem, you could either accept the decreased amount of power, or select a different location for the array.

8c. House obstruction - Pick a different location for the array.

8d. Flag pole - Move the flag pole if possible. If not, depending on where the pole cuts through the solar window on the array, and the severity of the problem, you could either accept the decreased amount of power, or select a different location for the array.

Key Words and Definitions

- ***Crome-Dome*** – a simple device (designed by Charles Cromer of the Florida Solar Energy Center) for students to easily determine if the solar window in a specific location is free of obstructions.
- **solar window** – the critical area of the Sun's path that should be free of obstructions. This area is defined on top and bottom by the Sun's path in the summer and in the winter, and in the east and west by the sun's position three hours before solar noon and three hours after solar noon.

Related Reading

- ***Photovoltaics: Design and Installation Manual*** by Solar Energy International (New Society Publishers, 2004)
  Solar Energy International (SEI) is a non-profit that trains adults and youth in renewable energy and environmental building technologies. This manual is well-suited for those who have some electrical experience, and students in high school tech prep-level courses. The book contains an overview of photovoltaic electricity and a detailed description of PV system components, including PV modules, batteries, controllers and inverters. It also includes chapters on sizing photovoltaic systems, analyzing sites and installing PV systems.

Internet Sites

https://www.fsec.ucf.edu/go/solar_basics/
Florida Solar Energy Center's photovoltaic fundamentals page explains the basics of photovoltaic cells including their manufacture, the components of systems, as well as the pros and cons of photovoltaic power.

http://www.engineeringtoolbox.com/electrical-formulas-d_455.html
Common electrical formulas and conversions.

https://www.energy.gov/eere/education/eere-career-resources
US Department of Energy, Office of Energy Efficiency & Renewable Energy's Career Resource page for renewable energy career paths.

http://www.nmsea.org/Curriculum/7_12/PV/explore_pv.htm
New Mexico Solar Energy Association. A basic explanation of how a photovoltaic cell produces electricity.

https://www.youtube.com/watch?v=2iRfbWOJtog
BOSCH Solar, How It's Made, video follows the manufacturing process from silicon sand to a rooftop.

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Florida NGSS Standards & Related Subject Common Core

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nature of Science																					
Standard 1	**SC.912.N.1.**	X																			
Earth and Space																					
Standard 5	**SC.912.E.5.**				X																
Physical Science																					
Standard 10	**SC.912.P.10.**	X														X					
Mathematics Standards		MAFS.912.A-REI.1.2, MAFS.912.A-REI.4.10, MAFS.912.F-IF.2.4, MAFS.K12.2.1, MAFS.K12.MP.7.1																			

Science–Standard 1: The Practice of Science
- SC.912.N.1.1- Define a problem based on a specific body of knowledge, for example: biology, chemistry, physics, and earth/space science, and do the following: 1) pose questions about the natural world; 2) conduct systematic observations; 6) use tools to gather, analyze, and interpret data; 7) pose answers, explanations, or descriptions of events; 8) generate explanations that explicate or describe natural phenomena (inferences); 9) use appropriate evidence and reasoning to justify these explanations to others; 10) communicate results of scientific investigations; and 11) evaluate the merits of the explanations produced by others.

Science–Standard 5: Earth in Space and Time
- SC.912.E.5.4 - Explain the physical properties of the Sun and its dynamic nature and connect them to conditions and events on Earth.

Science–Standard 10: Energy
- SC.912.P.10.1 - Differentiate among the various forms of energy and recognize that they can be transformed from one form to others.
- SC912.P.10.15 - Investigate and explain the relationships among current, voltage, resistance and power.

Mathematics–Algebra
- MAFS.912.A-REI.1.2 - Solve simple rational and radical equations in one variable, and give examples showing how extraneous solutions may arise.
- MAFS.912.A-REI.4.10 - Understand that the graph of an equation in two variables is the set of all its solutions plotted in the coordinate plane, often forming a curve.

Mathematics– Functions

- MAFS.912.F-IF.2.4 - For a function that models a relationship between two quantities, interpret key features of graphs and tables in terms of the quantities, and sketch graphs showing key features given a verbal description of the relationship.

Mathematics–Mathematical Practice

- MAFS.K12.MP.2.1 - Reason abstractly and quantitatively.
- MAFS.K12.MP.7.1 - Look for and make use of structure.

National Next Generation Science Standards

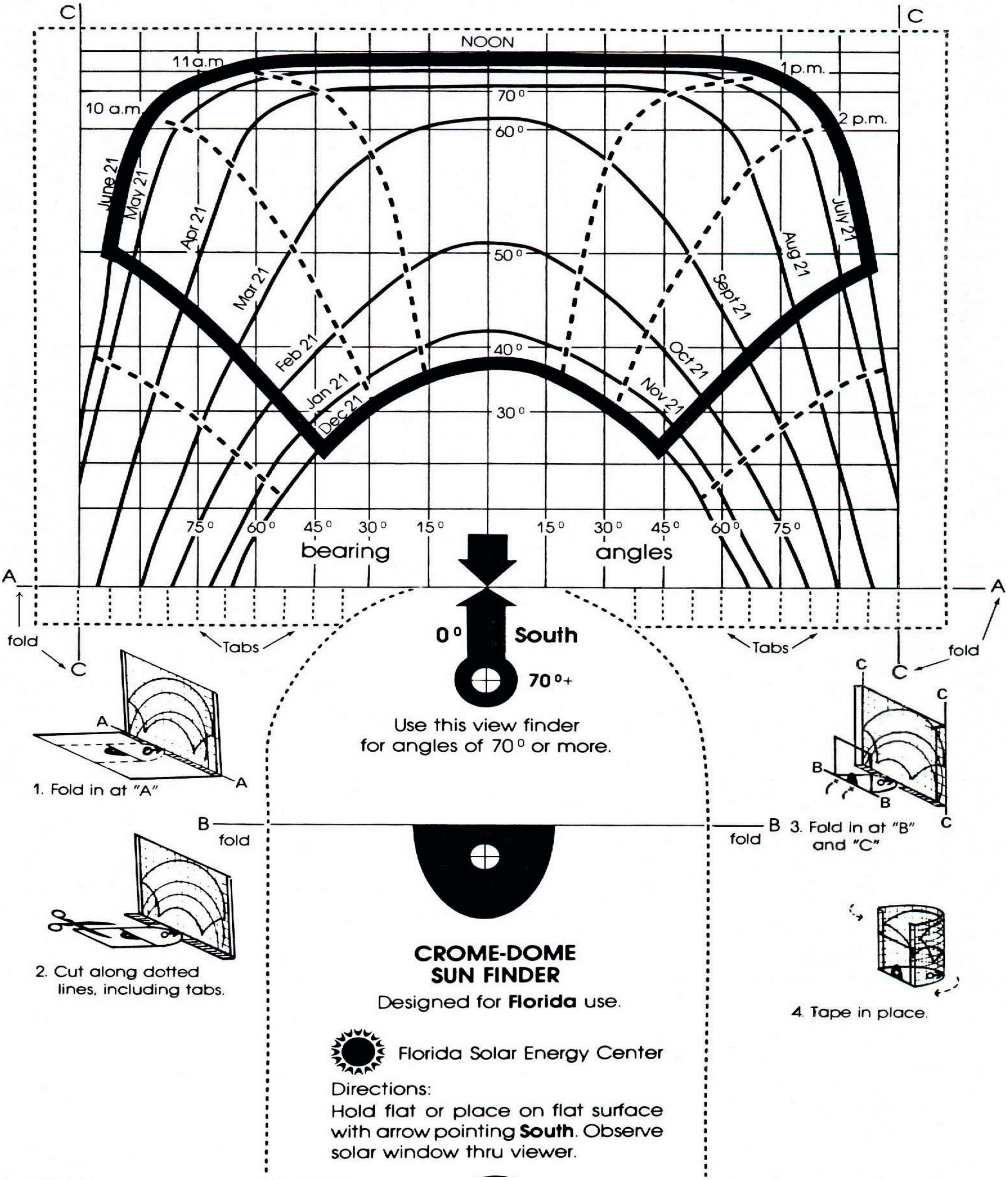
Energy

- HS-PS3-1 - Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other components and energy flows in and out of the system are known
- HS-PS3-3 - Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

Earth and Human Activity

- HS-ESS3-4 - Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

Note: Related Common Core Mathematics Standards are listed in the Florida section above.



C
C
NOON
11 a.m.
1 p.m.
10 a.m.
2 p.m.
70°
60°
50°
40°
30°
June 21
May 21
Apr 21
Mar 21
Feb 21
Jan 21
Dec 21
July 21
Aug 21
Sept 21
Oct 21
Nov 21
75° 60° 45° 30° 15° 15° 30° 45° 60° 75°
bearing angles
A
A
fold
fold
C
C
Tabs
Tabs
0° South
70°+
Use this view finder
for angles of 70° or more.
A
A
1. Fold in at "A"
B
fold
B
fold
2. Cut along dotted
lines, including tabs.
C
C
B
B
C
3. Fold in at "B"
and "C"
4. Tape in place.
CROME-DOME
SUN FINDER
Designed for Florida use.
Florida Solar Energy Center
Directions:
Hold flat or place on flat surface
with arrow pointing South. Observe
solar window thru viewer.

Effect of Shading on a Photovoltaic Module

During your investigation of irradiance and temperature, you learned how clouds and weather affect the power produced by photovoltaic modules. In this activity you will investigate the effects that partial shade from locational factors such as trees, power lines, flag poles, and buildings, have on the power output of a photovoltaic module.

Array Tilt Angle & Solar Azimuth

Date ________________ Time ____________ Daylight Savings Time? ___ yes ___ no

Latitude _________________________________

Fill in the solar azimuth and optimum tilt angle from *PV Orientation and Power Output* below, unless it is a different time of day or more than two weeks since you calculated these angles. If so, you will need to find the current angles.

Optimum Array Tilt Angle ________________ Azimuth ______________________________

Effect of Partial Shading

1. Based on your past investigations, write a hypothesis below predicting the effect of shading on a module's power performance. Include these percentages of shading: 1%, 5%, 10%, 20%, 40%, 60%, and 100%.

2. To test your hypothesis you will shade different percentages of your module, take voltage and current readings, and use these readings to calculate the power output of your module in the different shading conditions.
   - Measure the surface area of your module.
   - Cut different sized pieces of cardboard to cover varying surface area percentages of your module: 1%, 5%, 10%, 20%, 40%, 60%, and 100%.
   - Measure the amount of solar irradiance using an irradiance meter and record this in the data chart.
   - Set your module in its optimum position both for tilt angle and the solar azimuth.
   - Tape a thermometer on the edge of the module (without covering any of the PV

cells) and record the beginning temperature in the data sheet.

- Connect in series the module to the multipurpose meter, and take a reading of voltage and current for the control condition (no shading).
- Hold the piece of cardboard which covers 1% of the module's surface area over the module to produce shade. Do not put the cardboard piece directly on the surface, instead hold it just barely above the module. Measure and record the voltage and current readings in the data sheet.
- Repeat the same procedure with the various cardboard pieces to create the different shade percentages. Hold the cardboard at the same height above the module each time. Measure and record the voltage and current readings in the data sheet.
- Record the ending irradiance and temperature readings.

	Irradiance (W/m^2)	**Temperature (°C)**
Initial Measurement		
Final Measurement		
Average		

% of shade	**Voltage**	**Current (amps)**	**Power (watts)**
0%			
1%			
5%			
10%			
20%			
40%			
60%			
80%			
100%			

3. Using the data you collected, plot a multiple-line graph to show the change of the voltage, current and power as a function of the different percentages of shade on the module. Include the average temperature and irradiance readings in your graph's title.

4. Calculate the percent of voltage, current, and power decrease as a function of the percentage of the shaded surface area. Write your calculations in the table below.

$$\text{Percentage of the control} = \frac{\text{shaded measurement (voltage, current, or power)}}{\text{Control (full sun) measurement (voltage, current, or power)}}$$

	Percent of Control (Full Sun Conditions)		
% of shade	**Voltage**	**Current**	**Power**
0% (Control)	100%	100%	100%
1%			
5%			
10%			
20%			
40%			
60%			
80%			
100%	0%	0%	0%

5. Plot another multiple-line graph to show the percent change in voltage, current, and power as a function of the increased percentage of shade on the module surface.

6. At what percentage of shade did the voltage, current, and power output reach a minimum?

7. Compare the differences in the voltage, current and power decreases. Which factor, voltage or current, was most affected by the shade?

8. How did your results compare with your hypothesis? If your results did not support your hypothesis, explain why.

9. Compare your results with another group. How do your results compare? What factors could have reduced the accuracy of your results, and how could you improve the design of the investigation to increase the reliability of the results?

10. Why do you think shade affects performance of the solar panel so dramatically?

11. With a multimeter attached to your module, move the 20% shading around the module and see if there is a difference in the voltage or current readings depending on which area of the module is shaded. State your findings below.

12. What do you think caused the change in readings with changing shade positions?

Effect of Shading on Series and Parallel Wired Modules

13. Create a "module" using four single photovoltaic cells. Connect two cells in series. Connect another two cells in a second series. Then connect your two sets together in parallel. What do you expect the voltage, amperage, and power output of your "module" will be?

14. Use your "module" to determine the effect that shade has on a module wired in series and parallel.
    - Mount your module on a piece of cardboard, and set up the cardboard at the optimum position both for tilt angle and the solar azimuth.
    - Sketch a diagram of your module and its wiring below. Number your cells 1 - 4.

    - With a piece of cardboard, cover each of the cells one at a time (1 - 4) and record the voltage and current readings for each one.
    - Then with a smaller piece of cardboard, cover ½ of each cell in turn and record the voltage and current readings for the module with each ½ section covered. Make sure you cover the comparable ½ of each cell with your shade (in relation to where the wires come out of the cell). Keep it consistent throughout the trials.
    - Next, take a pencil and "shade" each of the cells (like a simulated tree limb or flag pole). Make sure you hold the pencil in each trial so it cuts across each cell in the same direction.

	Full Cell Shaded			½ of Cell Shaded			Pencil Shaded		
	Voltage	Current	Power	Voltage	Current	Power	Voltage	Current	Power
Cell 1									
Cell 2									
Cell 3									
Cell 4									

Analyzing your data

15. What happened when you covered a full cell?

16. Was the power output dependent on which cell was covered in the circuit? Explain, referencing cells in series and parallel.

17. What happened when you covered half of a cell?

18. Was the power output dependant on which cell was partially covered in the circuit? Explain, referencing cells in series and parallel.

19. What happened when you shaded the cell with just a pencil?

20. Was the power output dependent on which cell was shaded by the pencil in the circuit?

21. Does it matter which half of a cell is covered? Try shading the cell halves in different ways to determine if the way a half is covered affects the power output of the module. State your findings below. Use sketches if necessary. (Hint: There are at least six different ways a half can be shaded.)

Site Selection

A photovoltaic device should be mounted in an area receiving unobstructed sunshine during the entire year between the hours of 9:00 am and 3:00 pm. This time range is called the "solar window".

22. Choose a location in the area around your school that you would like to investigate as a possible location for a permanent PV system with an array that will be approximately 2 m x 6 m. For this investigation, your proposed location must be an area that you can physically get to, so roof-tops are not be an option. Write your proposed location below.

23. To find out if your proposed area has an unobstructed solar window, you will use a simplified device, the Crome-Dome Sun Finder. (Note: The Crome-Dome is designed for use in Florida, and is not appropriate for use further north than 31^{o} latitude)
    - Assemble your Crome-Dome according to the directions printed on it. Secure with tape.
    - Stand a few feet in front of your proposed PV site facing south (use a compass to determine south).
    - Hold the Crome-Dome base as level as possible and several inches up and away from your eye. Look upward through the sighting circle at the bottom.
    - Align the cross hairs within the sighting circle with the lower edge of the solar window (the bold lines).
    - Any trees or objects that you see through the viewer will shade the PV site.
    - When checking for high summer angles, tilt your head all the way back and peer through the viewer on the base of the Crome-Dome, as the summer sun path goes almost directly overhead.

    Describe the conditions of your proposed site's solar window. Are there any obstructions? If you have a shading problem, at what times and during what seasons of the year do you predict it being a problem? What could be done to rectify the shading problem?

24. How much power would your proposed 2m x 6m array produce (assuming that spacing between the panels and line losses are negligible), in Orlando Florida for the month of June (average irradiance = 5.78), if the modules are rated at 12% efficiency? State both daily average power output and the monthly total. (Hint: refer back to the *PV Power Output* and *PV Orientation* activities if necessary).

Effect of Shading on a Photovoltaic Module

1. What time(s) of day is it most important for the solar module to be clear of shade?

2. What does the term “solar window”mean, and why is it important?

3. If only 20% of the surface area of a module is shaded
   (a) the current will be reduced to zero
   (b) the current does not change
   (c) the power output will be reduced to a minimum
   (d) both (a) and (c)

4. How would a broken cell affect the voltage in a system with two modules connected in series. How would a broken cell affect the current of this circuit?

5. Consider two modules connected in parallel; how would a broken cell affect the voltage and current of this circuit?

6. Below is the insolation table for Orlando, Florida (28.55° north latitude). On the next page is data for Tonopah, Nevada (38.07° north latitude), and Spokane, Washington (47.63° north latitude). In reviewing this data, which of these three cities would an obstruction, at a given height, be more likely to cause a shading problem?

7. What evidence do you have to justify your answer?

Insolation – kWh/m^2-day – for Orlando, FL (28.55° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
15°	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
20°	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
25°	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
30°	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
35°	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
40°	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

Insolation – kWh/m²-day – for Tonopah, NV (38.07° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	2.90	4.02	5.61	7.10	8.13	8.80	8.53	7.69	6.44	4.80	3.25	3.61	5.82
25°	4.40	5.38	6.56	7.45	7.91	8.28	8.15	7.81	7.21	6.12	4.75	4.17	6.52
30°	4.63	5.57	6.65	7.41	7.73	8.04	7.94	7.71	7.25	6.29	4.97	4.41	6.55
35°	4.83	5.72	6.69	7.31	7.52	7.76	7.69	7.57	7.24	6.42	5.16	4.63	6.55
40°	5.00	5.84	6.70	7.18	7.27	7.44	7.40	7.38	7.19	6.50	5.31	4.81	6.51
45°	5.14	5.92	6.67	7.01	6.98	7.08	7.07	7.16	7.10	6.55	5.44	4.96	6.43
50°	5.24	5.96	6.60	6.80	6.65	6.70	6.71	6.89	6.97	6.56	5.52	5.08	6.31

Insolation – kWh/m²-day – for Spokane, WA (47.63° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	0.99	1.91	3.28	4.72	6.05	6.57	7.44	6.13	4.53	2.65	1.25	0.81	3.86
35°	1.84	2.93	4.13	5.10	5.91	6.14	7.12	6.41	5.45	3.84	2.18	1.63	4.40
40°	1.92	3.01	4.16	5.04	5.76	5.95	6.92	6.31	5.46	3.93	2.27	1.71	4.38
45°	1.99	3.08	4.17	4.97	5.59	5.73	6.69	6.18	5.44	3.99	2.34	1.78	4.34
50°	2.05	3.13	4.16	4.86	5.39	5.49	6.42	6.01	5.39	4.03	2.40	1.84	4.27
55°	2.09	3.15	4.12	4.73	5.17	5.22	6.13	5.81	5.31	4.05	2.44	1.89	4.18
60°	2.12	3.16	4.06	4.58	4.92	4.93	5.80	5.59	5.20	4.04	2.46	1.92	4.07

8. What would you suggest to a homeowner that wants to install a PV array on a roof shaded by:
   a) a tree?
   b) power lines?
   c) two story homes?
   d) flag pole?