Lesson Title: **SOLAR PV: MODULE PERFORMANCE**

Grade level: High School

Lesson length: 2-4 hours, depending on coverage, emphasis, and prior student knowledge

Author: Scott Liddicoat

Created: April, 2021

Instructor's Guide

Learning Goals:

- Students will understand the effect of temperature, irradiance, orientation, and shading on the performance of a solar PV module.
- Students will use solar PV tools of the trade to measure temperature, irradiance, volts, and amps to establish solar PV module performance.
- Students will understand that all solar PV modules are tested at a common set of environmental conditions so that valid scientific comparisons may be made between different modules.

Materials

- Solar PV Module
- Multimeter with alligator leads
- Pyranometer
- Module stand
- Pre-cut module shading materials
- Sacrificial leads (with disconnect tool)
- Amp clamp
- Infrared thermometer
- Protractor
- High intensity LED Lamp (optional)

Introduction to the activity:

This laboratory activity must be practiced in advance with the equipment you will use with your students. Doing so will ensure:

- safe and effective performance from your students.
- the timing of the lab matches your expectations.
- the teaching materials and instructions provided here match up with your equipment and specific classroom situation.

Remember that our copyright allows you to edit the materials we provide to suit your students, classroom, and equipment. For this lab, it is almost an expectation. You are always free to add or subtract student questions. Some teachers have been known to remove the last part of the lab (module shading), not doing it at all or doing it separately. You may choose to place images of you and your specific equipment into our instructional PowerPoint. We encourage you to make changes to our materials that improve your teaching of this activity.

Module Performance is best done outdoors, ideally on a day with few or no clouds. While the activity can be done indoors with artificial light, we recommend outdoors as the much more interesting and genuine classroom. Certainly, your students would agree with this. Locate a good weather forecasting app and monitor it!

There are three parts to **Module Performance**.

Prelab Preparation requires students to take critical notes about the activity, the equipment they'll use, and how the lab will be performed. Source material for these notes comes from the **Student Orientation to Module Performance** PowerPoint provided to you with this lesson. It has been set up to be a visual guide to performing the activity. If your students know little about how a PV module works, **Prelab Preparation** will take at least one day to perform. Summary Questions are provided as student homework.

Review our PowerPoint carefully before using it. We remind you once again that you are welcome to make improvements to it within our copyright.

In **Lab Activity, Part One**, students perform the lab to determine the effects of temperature, irradiance, and tilt angle on PV module performance.

At the beginning of Part One, your students will practice the measurements they'll make later as they experiment with their module. These practices were all reviewed in the **Student Orientation to Module Performance** PowerPoint you used to teach them about the lab. The practices are all done in a cool, shaded place.

After that, students take experimental measurements and record their results in the table provided. The sequence in which they take the measurements is critical and must be followed as explained in the PowerPoint and the lab activity. Supervise to make sure students do the lab as directed for student safety, to protect their equipment, and for good lab results.

Lab Activity, Part One should take one class period to complete. Summary Questions are provided as student homework.

In **Lab Activity, Part Two**, students perform a lab to determine the effects of shading on PV module performance. Part Two will be much easier for students to perform after doing Part One. The procedure is shorter, and students are familiar with carrying out many parts of the procedure from Part One. Again, your job is supervision to make sure students do the lab as directed for student safety, to protect their equipment, and for good lab results. Part Two might take less than one class period to complete. Summary Questions are provided as student homework.

There are many good ways to introduce and summarize Module Performance with your students. In general, an inquiry approach works well to introduce the activity in the classroom. Take advantage of your students' prior knowledge and experiences in setting the stage for what they'll be doing. To summarize the lab, review lab results and answer all student questions. Review how their results might have a practical effect on the design, selection, location, and installation of a solar PV system.

Answer Key to the Summary Questions

Note answers are included in brackets.

Summary Questions - Prelab Preparation

1. Complete the following solar module nameplates:

1a.

Detail	Answer
MAXIMUM POWER STC:	**[330]** watts DC
MAXIMUM POWER VOLTAGE VMP (V):	58.0 Volts
MAXIMUM POWER CURRENT IMP (A):	5.70 Amps

1b.

Detail	Answer
MAXIMUM POWER STC:	50 watts DC
MAXIMUM POWER VOLTAGE VMP (V):	**[17.5]** Volts
MAXIMUM POWER CURRENT IMP (A):	2.85 Amps

1c.

Detail	Answer
MAXIMUM POWER STC:	240 watts DC
MAXIMUM POWER VOLTAGE VMP (V):	30.6 Volts
MAXIMUM POWER CURRENT IMP (A):	**[7.8]** Amps

2. As you have learned, the standard conditions for testing solar modules are:

- **Module temperature of 25ºC (77ºF).**
- **Light intensity (irradiance) of 1000 Watts/m2.**
- Atmospheric air mass of 1.5.

Explain why it is important that all solar modules be tested under the same set of environmental conditions.

[Standard Test Conditions (STC) are used for every solar module so that all modules can be compared from a controlled set of environmental conditions.]

3a. Why do dual-axis tracking solar PV arrays generate more electricity than their fixed-in-position counterparts?

If needed, do a little research comparing and contrasting fixed vs. dual-axis tracking solar PV arrays if you don't know much about them. In constructing your answer to the question you must use these terms at least once:

- fixed array
- tracking array
- sun
- solar azimuth
- ideal tilt angle
- perpendicular

Underline the terms as you use them in your answer to the question.

[A <u>fixed array</u> usually receives good <u>sun</u>light during the middle part of the day. But because it's fixed in position, it usually doesn't get good sunlight in the morning and evening. However a two-axis <u>tracking array</u> follows, or "tracks" the sun all day long maintaining an <u>ideal azimuth and tilt angle</u> with the sun. In this way the surface of the array is always <u>perpendicular</u> to the sun's rays, receiving the maximum energy available from the sun and generating maximum electricity.]

3b. Dual-axis, or two-axis tracking PV systems usually produce about 50% more electricity than their fixed-in-position counterparts. In view of this, why are more fixed PV arrays installed today?

[Fixed PV arrays are preferred today for several reasons. First, a tracking array must be installed in a place where array modules are able to move. Then, with a motor and moving parts, tracking arrays are more expensive to install. What's more, with a motor and moving parts, tracking arrays require maintenance at least once a year. A fixed array doesn't face these considerations, so it is less expensive to install and maintain. In addition, the installed cost per watt of solar has dropped significantly over the years. Faced with the extra costs involved in a tracking system, most people simply choose to buy more modules and have them installed in the less expensive and simpler to maintain fixed position.]

Summary Questions - Lab Activity, Part One

1a. Which environmental condition (irradiance or temperature) primarily affected Current (Amps)?

[Irradiance affected Current (Amps) the most.]

1b. Explain your answer to 1a. in detail, using specific data from the lab.

[As can be seen from my data, the higher the irradiance, the higher the Amps (or the lower the irradiance, the lower the Amps).]

2a. Which environmental condition (irradiance or temperature) primarily affected Electric Potential (Volts)?

[Temperature affected Electric Potential (Volts) the most.]

2b. Explain your answer to 2a. in detail, using specific data from the lab.

[As can be seen from my data, the lower the temperature, the higher the Volts (or the higher the temperature, the lower the Volts).]

3. Imagine you were to perform this lesson activity in a condition of perfect sun with no clouds. Which module position or orientation would achieve the best performance? Explain your answer choice completely, and in detail.

[Under perfect sun and no clouds, the module would achieve its best performance when turned in the Ideal direction (azimuth) and angled at the ideal tilt angle. This enables the rays from the sun to hit the module at a 90° angle, perpendicular to its surface. Current (Amps) data from this orientation clearly outperformed other orientations. Higher current would translate into better electrical output performance (Volts X ↑ Amps = ↑ Watts).]

4. Most PV modules manufactured today have quick connect wire leads like those you worked with in the lab activity. Quick connectors snap together, make wiring simpler and faster. Connections are sure and secure, they meet National Electric Code requirements, they're UL certified, and most electrical inspectors prefer to see them used. Quick connectors resist corrosion and environmental degradation from the elements. Once connected, they will not disconnect without the use of an unlocking tool.

Quick connectors are also "finger safe." This means you cannot touch any energized part of the electrical connection. Explain why this was an important consideration for you in this lab activity, and why it is an important consideration for solar PV installers.

[Finger safe quick connectors prevent accidents. It should not be a surprise that even experienced electricians can make mistakes in wiring and connecting modules. Finger safe quick connectors do not allow human body parts near the place module wires connect and accidental electrical shock could occur.]

5. By now you know that the electrical power output of a PV module or array is calculated this way:

Electric Potential **(Volts) X** Current **(Amps) =** Electric Power Output **(Watts)**

The table below describes four different sets of environmental conditions. With each set of conditions, assume you have a two-axis tracking solar PV array that is always ideally positioned to harvest sunlight.

Environmental Conditions: Sunlight	Environmental Conditions: Temperature	PV Array Orientation
[(▼A)] Very Low Sunlight	**[(▲V)]** Very Low Temperature	Ideal
[(▼A)] Very Low Sunlight	**[(▼V)]** Very High Temperature	Ideal
[(▲A)] Very High Sunlight	**[(▲V)]** Very Low Temperature	Ideal
[(▲A)] Very High Sunlight	**[(▼V)]** Very High Temperature	Ideal

5a. In which set of conditions will the PV array output be the highest? Explain your answer by making reference to your experience in this lab activity.

[Output will be highest under conditions of very high sunlight and very low temperature. Under these conditions a module achieves the highest Volts and highest Amps, respectively. Highest Volts X highest Amps = highest output in Watts.]

5b. In which set of conditions will the PV array power be the lowest? Explain your answer by making reference to your experience in this lab activity.

[Output will be lowest under conditions of very low sunlight and very high temperature. Under these conditions a module endures the lowest Volts and lowest Amps, respectively. Lowest Volts X lowest Amps = lowest output in Watts.]

5c. Why is it important to know the extremes of sunlight and temperature? Explain your answer completely and in detail.

[Knowing these extremes will help to determine the other equipment that we can use with a planned solar PV array. A well planned system has the rated capacities of its components properly matched to avoid equipment damage and perform effectively.]

6. As you have learned, the standard conditions for testing solar modules are:

- **Module temperature of 25ºC (77ºF).**
- **Light intensity (irradiance) of 1000 Watts/m2.**
- Atmospheric air mass of 1.5.

Why were the environmental conditions of temperature and irradiance selected for standard testing (especially compared to a variety of other environmental conditions that could have been selected)? [You may ignore the standard test condition of atmospheric air mass in answering this question.]

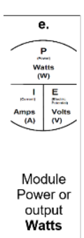
[These environmental conditions were selected for standard testing because they have the greatest influence on module electrical power output. Recall that irradiance affected Current (Amps) the most and temperature affected Electric Potential (Volts) the most. Since Volts X Amps = Electric Power Output, it should be easy to understand why irradiance and temperature were selected as standard module testing conditions.]

7. Describe the most important idea, concept, principle, or fact you learned while completing this this part of the lesson. Explain why it is important for you (and probably other people) to know and understand.

[This is a reflection and judgement question. Student reasoning and reaction should be evident in a good answer. No two student answers should be the same.]

Summary Questions - Part Two

1. Label **column e.** in **Table 2**. as shown below. Then go through each row (module position or orientation) and perform the Watts calculation to complete the table.

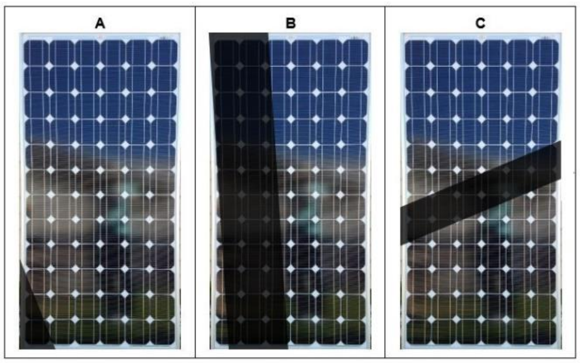


*

2. Consider **Table 2**. Most people assume that shade over just a small portion of a module will not affect its performance very much. Is this true? Explain your answer completely, making reference to your results.

[Shade over just a small portion of a module will affect the module different ways. For example, shade over a column of cells did not affect the module a great deal. However, shade over a row of cells (less shade), affected the module much more dramatically.]

3. Which of these types of shading would produce the greatest effect on your module's power output? Explain why that type of shading would produce the greatest effect on performance.



[One row of shaded cells affected module output the most dramatically. This is because the shade cut across—and interrupted—every electrical circuit running up and down the module.]

4. Describe the most important idea, concept, principle, or fact you learned while completing this this part of the lesson. Explain why it is important for you (and probably other people) to know and understand.

[This is a reflection and judgement question. Student reasoning and reaction should be evident in a good answer. No two student answers should be the same.]