UNDERSTANDING SOLAR PV CELL EFFICIENCY

**Science/Engineering Saturday Seminars – April 11, 2015**

**Introduction:**

Efficiency is an important concept in physical science and engineering/technology education courses and provides an appropriate connection to an understanding of the law of conservation of energy. In this lab activity, you (and your students) will make measurements of the input and output power relating to a typical PV cell/module that will allow you/ them to calculate its efficiency. A logical extension of this exercise is to calculate the efficiency of a large-scale solar PV array and compare the result to accepted values.

**Objectives:**

1. Define efficiency (words and algebraic equation).

2. Design an experiment to determine the efficiency of a solar PV cell or module.

3. Draw a diagram, wire a circuit and collect and analyze data.

4. Compare experimental efficiency values obtained with a bench-top PV cell/module and those for commercial PV modules/arrays.

5. Explain how a solar PV array can be designed to produce useful amounts of electrical power.

**Guiding Questions:**

1. What is efficiency (word and algebra)?

2. What information is required to determine the efficiency of a device?

3. What calculations need to be made to determine the efficiency of a solar PV cell? What quantities are needed for these?

4. What are some typical efficiency values for things we regularly use (lamp, motor – electric and internal combustion, gasoline generator, microwave oven)?

5. What happens to the energy that does not appear as “useful work” at the output of a device?

6. What energy conversion takes place in a solar PV cell?

7. Predict the efficiency of a solar PV cell/array.

8. Describe the design of an experiment to determine the efficiency of a solar PV cell or module.

9. How are the quantities “power” and “energy” related? What assumption is being made when substituting “power” for “energy” in the efficiency equation?

**Possible Assessment Tasks:**

1. Calculate the efficiency of the PV cell/module you are working with. Compare your result with that of other groups. Compare your result with technical spec. data for commercial-use PV modules. Comment on agreement, and possible reasons for differences.

2. Research the topic, and respond to the question: Why is it feasible to use a device like a solar PV cell/module having this kind of efficiency as a large-scale energy conversion device?

**Resources/References:**

Dunlop, J. 2014. Photovoltaic Systems, 3rd Ed. National Joint Apprenticeship and Training Committee and American Technical Publishers,

Typical consumer product efficiencies are included in this power point presentation for Penn State Univ. Course: EGEE 102 Energy Conservation and Environmental Protection

<http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB4QFjAA&url=http%3A%2F%2Fwww.ems.psu.edu%2F~pisupati%2Fegee102%2FLectures%2F5.%2520Energy%2520Efficiency.ppt&ei=36KRVPKPLpLfsASMhYHICg&usg=AFQjCNHqL6VP_eQXBP5AHS3wrtSSYuHn7A&sig2=309tBkRwIq5TQuR0j2E4Hg>

Typical Solar PV Module Spec’s: <http://files.sharpusa.com/Downloads/Solar/Products/sol_dow_NUQ235F2.pdf>

Measuring PV Module Power, Article:

Emery, C. (2014). Making Sense of Solar Cells. *Techdirections,* 73,10, 13-15. <http://www.omagdigital.com/publication/?i=206487>

**Commercial Solar PV Module Specifications (**Sharp NU-Q235F2**)**

Maximum Power (Pmax)\* 235 W

Tolerance of Pmax +10%/-5%

Cell Configuration 60 in series

Open Circuit Voltage (Voc) 37.0 V

Maximum Power Voltage (Vpm) 30.0 V

Short Circuit Current (Isc) 8.60 A

Maximum Power Current (Ipm) 7.84 A

Module Efficiency (%) 14.4%

Maximum System (DC) Voltage 600 V

Series Fuse Rating 15 A

NOCT 47.5°C

\* Illumination of 1 kW/m2 (1 sun) at spectral distribution of A

Dimensions: width = 994 mm; height = 1640 mm

**EFFICIENCY**

**Typical Values**

Incandescent Lamp = ~3%

Wind Turbine = ~ 40%

Electric Motor = 60% to 90%

“Car” Engine = ~25%

Lamp

Electric Motor

Microwave Oven

**Definition**

Ratio of useful energy output to total energy input

**Equation**

Eff. = (EOUT)/(EIN) x 100

Efficiency is expressed as a percent

Co

**Conservation**  **Energy and Power**

Energy = (Power) x (time)

Time cancels, leaving:

Eff. = [(POUT)/(PIN)] x 100

Non-useful energy typically lost as heat

**Determining Electrical Power**

Electric power, in watts:

P = (I) x (V)

Voltage (V, volts) and current (I, amps) measured in a simple circuit.

**Experiment Design:**

A diagram of the system (input, PV module and output) is shown below:

**PHOTOVOLTAIC**

**MODULE**

SUNLIGHT

ELECTRICITY

**Fig. 1**

**Question:** What information/data is needed to calculate efficiency? How could you measure or collect this data? What calculation(s) need to be done to get an answer?

**Measurement Circuit Set-up:** A block diagram is shown below. Use the teacher’s model set-up as an additional reference.

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SUNLIGHT

VARIABLE OR FIXED RESISTOR

**Fig. 2**

**Equipment/Materials:** Sunlight, PV Module (SK-40), 100 ohm potentiometer or 50 ohm fixed resistor, ammeter and voltmeter

**Note:** The input power value (solar irradiance) used for this activity can be measured with a meter, if available. Otherwise, on a clear/bright day, use a value of 1000 W/m2 for this value.

**Data Table:**

**Table I**

|  |  |  |
| --- | --- | --- |
| **Quantity** | **Value** | **Comments** |
| **Solar Irradiance**  **(W/m2)** |  |  |
| **PV Cell/Module Area**  **(m2)** |  |  |
| **Input (Sun) Power**  **(W)** |  | **Show calculation:** |
| **PV Cell/Module Voltage**  **(V)** |  |  |
| **PV Cell/Module Current**  **(A)** |  |  |
| **Output (Electric) Power**  **(W)** |  | **Show calculation:** |
| **PV Cell/Module Efficiency**  **(%)** |  | **Show calculation:** |
| **Efficiency value for a similar cell/module**  **(%)** |  | **Determine from online research or module spec’s** |

**Data Analysis:**

Calculate and record (Data Table) the efficiency of your cell/module.

**Summary/Conclusions:**

1. What is the approximate efficiency of commercially available PV cells/modules?

2. What is the efficiency of a PV cell/module used for a school lab? How could you calculate it?

3. How does the efficiency of the lab PV cell you used in this activity compare to the efficiency of the school’s STEM Solar Lab array?

4. The efficiency of the module and of the SSL is less than 100%. Does this mean that energy is not conserved? Explain.

**SAMPLE DATA**

Collected 12/27/14, 12 PM

**Table I**

|  |  |  |
| --- | --- | --- |
| **Quantity** | **Value** | **Comments** |
| **Solar Irradiance**  **(W/m2)** | (1) 890 = SUN  (2) 900 = SUN  (3) 1050 = 100W LAMP | Values depend on sun intensity, PV module tilt angle and/or proximity to 100W lamp |
| **PV Cell/Module Area**  **(m2)** | 3.9 X 10-3 m2 | SK-40 has 9 individual cells each measuring  7 mm x 62 mm |
| **Input (Sun) Power**  **(W)** | (1) 3.5 W  (2) 3.5 W  (3) 4.1 W | **Show calculation:**  (3) 1050 W/m2 x 3.9 x 10-3 m2  = 4.095 W |
| **PV Cell/Module Voltage**  **(V)** | (1) 2.43 V  (2) 3.4 V  (3) 4.0 V |  |
| **PV Cell/Module Current**  **(A)** | (1) 74 mA  (2) 92 mA  (3) 95 mA |  |
| **Output (Electric) Power**  **(W)** | (1) 180 mW  (2) 313 mW  (3) 380 mW | **Show calculation:**  (3) 4.0 V x 95 mA = 380 mW  = 0.38 W |
| **PV Cell/Module Efficiency**  **(%)** | (1) 5.1%  (2) 8.9%  (3) 9.3% | **Show calculation:**  (3) 380 mW / 4.1 W = 9.3% |
| **Efficiency value for a similar cell/module**  **(%)** | 14.4% for commercial PV modules | **Determine from online research or module spec’s** |

**Sample Problem: Calculating the Efficiency of a Commercial PV Module**

This problem could be presented to students in several different ways.

* It could be written as a traditional word-problem with required information contained in the prompt;
* It could be posed as a “verification problem” where students are asked to confirm the manufacturer’s efficiency specification;
* It could be used as a problem requiring students to determine what information is needed to solve the problem and using the module data sheet as a resource.

The spec sheet for the Sharp NU-Q235F2 commercial solar PV module states that the efficiency of this device is 14.4%. Using relevant information from the spec sheet, determine whether or not this figure is corret.

Problem solution:

Efficiency = (Useful energy output) / (Energy input) or, Eff. = (EOUT) / (EIN) x 100

Energy is equal to (power) x (time), and since the time interval for the measurement/calculation is the same for both input and output, efficiency can also be defined and calculated using power.

Efficiency = (power output) / (power input) or, Eff. = (POUT) / (PIN) x 100

Needed info: PV module input power and output power

From data sheet: Output power = P(MAX) = 235 watts

Illumination = 1000 W/m2

Module area = (0.994 m) x (1.640 m) = 1.63 m2

Input power = (1000 W/m2) x 1.63 m2) = 1630 watts

Calculation: Eff. = (235 W) / (1630 W) = 0.144 = 14.4%

Checking this result with the specification sheet data shows agreement.

**Understanding System Efficiency**

A small portable electric generator typically uses a gasoline engine as a source of mechanical energy to spin the armature of an electric generator. This system illustrates a two-stage conversion process where the stored chemical potential energy of the gasoline is converted into heat/mechanical energy within the internal combustion engine and this is then transformed into electricity – and more heat – by the generator. This process is shown in block-diagram form in Figure 1.

**Fig. 1**

**GAS**

**INTERNAL COMBUSTION ENGINE**

**MECH. ENERGY**

**GENERATOR**

**ELECTRICITY**

**Question:** How does combining multiple energy transforming devices together affect the efficiency of the system as a whole?

|  |  |
| --- | --- |
| **Background Information/Assumptions:** |  |
| Operating time/fuel consumption | 1 gallon |
| Energy stored in gasoline | 33 kWh/gallon |
| Efficiency of internal combustion engine | 25% |
| Efficiency of electric generator | 52% |

**Problem Solution:**

Useful mechanical energy output from the engine = (0.25) x (33 kWh/gal) x (1 gal) = 8.25 kWh

Input energy to the generator = 8.25 kWh. Output from the generator = (0.52) x (8.25 kWh) = 4.3 kWh

Overall system efficiency = (4.3 kWh) / (33 kWh) x 100 = 13%

Note that this result is the same as the result of multiplying the efficiencies of the system components together: Total efficiency = (25%) x (52%) = 13%

This model solution provides the basis for understanding how individual series-connected energy transforming devices impact the overall efficiency of complex systems.

This result is consistent with the generator’s spec sheet which gives an operating time of 9.5 hours on a full tank of gas (3.5 gallons) at half rated power (1.6 kW).

Input: (3.5 gal ) x (33 kWh/gal ) = 115.5 kWh Output: (1.6 kW) x (9.5 h) = 15.2 kWh

Efficiency = (15.2 kWh) / (115.5 kWh) = 13.1%