Off the Grid Unit

Lesson 1: Electrical Energy and Solar Module Efficiency

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DESCRIPTION: This lesson will let students do research to define terms that will be used in this unit. They will record this information in their Journals, which can be scientific or simple homemade notebooks. This lesson will also introduce the **multimeter**, small **solar modules**, and how to calculate **power**. Students will compare the power of the module to its area and create a power/area ratio. This ratio will then be used to check the efficiency of the module using a **pyranometer** (if available) to measure incoming irradiance from the sun (Power per area, or W/m^2). Calculations and practices that students are guided through during this lesson will continue to remain themes throughout the remainder of the "Off the Grid Unit." *This lesson is suitable as a stand-alone lesson.*

GRADE LEVEL(S): 7-12

SUBJECT AREA(S): Electrical Energy and Power

ACTIVITY LENGTH: 3-4 days or 3-4 class periods = 3-4 hours

LEARNING GOAL(S)

1. Students will document necessary terms in their journals
2. Students will be able to set up a **multimeter** to measure voltage
3. Students will be able to set up a multimeter to measure **current**
4. Students will be able to calculate **power** from data collected
5. Students should be able to measure the collector area of a **solar module** (area of solar cell(s) within solar module) and represent this value in square meters (m^2)

NEXT GENERATION SCIENCE STANDARDS:

- 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 component(s) and energy flows in and out of the system are known.

COMMON CORE STATE STANDARDS:

- N-Q 1. Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.
- N-Q 2. Define appropriate quantities for the purpose of descriptive modeling. __

Materials List for group of 2-4

- **Multimeters** (2 per group)
- **Solar Modules** – 3W, 6V, works well, but any modules can be used. I used all the modules in the Solar Cell Classroom Set from Rahus Institute, as well as some 50 Watt "Large" modules. This gave us 4 different sizes from 10 cm^2 up to $150cm^2$. Different sized modules are nice to have so that each group can take several measurements. Different module technology would be nice as well – **crystalline** and a**morphous**
- Journals
- AA batteries to measure voltage – 1 per group

Other Supplies

- Vernier LabQuest with **pyranometer** to measure irradiance of the sun in real time (optional – 1 per class)
- Calculators
- Rulers for data table construction

Vocabulary and Units

Please **bold** the vocabularly words as they appear in the text of this lesson plan.

- Voltage
- Current
- Charge
- Open Circuit
- Volts
- Amperes
- Watts
- Solar Module
- Seconds
- Coulombs
- Electrical Power
- Energy
- Efficiency
- Short Circuit
- Multimeter
- Power
- Pyranometer
- Amorphous
- Crystalline
- Solar Irradiance

Lesson Details

Planning and Prep

Each notebook should be about 15 pages and have a cover that students can decorate with art based on electricity – whatever they come up with is good. These will be used for students to draw data tables, schematics, and write notes throughout the course of the unit.

Student Background

- This is an intro unit and no prior background is needed.

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Educator Background

Educators leading this lesson should be familiar with the following:

- Understand that power developed in a circuit is directly proportional to both voltage and current. **Power = VI**
- Understand the difference between an open circuit and a short circuit
- Understand how to use the meter(s) in this activity
    - Access the Multimeter Cheat Sheet at solar4rschools.org for background info (http://www.solar4rschools.org/sites/default/files/multimeter-cheatsheet.pdf)

Multimeter Tip: When measuring **current** it is very important to start on the 10A setting – you must move the red probe to the 10A and leave the black probe in the common slot. I like to have two different colored meters: I leave my red meters set up for **current** and let students know not to mess with the probes on the red meter and to only set the dial on the 10A setting. (If you are working in very low light conditions, you might need to use the second current setting that is valid for up to 200 mA of current (0.2 A). This setting requires that the red probe is on the "VΩmA" setting.)

I projected the following table on the board for students to create in their journals. I provided rulers for students who had trouble free-drawing straight, parallel lines. Make sure to go over all of the units before starting the Lab part and then again when creating the data table.

Solar Module Size	Module Dimensions (in cm)	Area of Module (in cm^2)	V_{OC} = open circuit module voltage (in volts)	I_{SC} = short circuit module current (in amps)	Max Theoretical Power = V_{OC} x I_{SC} (in Watts, or Joules/s)	Ratio of Theoretical Power to Area P/A (Watts/m^2, or "flux density")	Energy transformed in 10 seconds E = P x t (in Joules, or Watt-seconds)
Tiny (0.5 V module)							
Small (1 or 1.5 V module)							
Medium (2 V module)							
Large (3 V module)							
AA Battery				DO NOT MEASURE		N/A	N/A

* Note: students could also measure the area of the solar cell(s) within each module, but should justify their reasoning for doing so.

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Lesson sequence

Research

Have students will use the internet or other resources to research and write a few sentences in their own words about the topic. Students should ***include any equations*** that involve these concepts, and also list all units that go with the concept. Use whatever research methodology is the standard in your classroom. This could even be done in a quick-write format, asking them to answer a broad question about photovoltaics both with and without access to outside resources. Research should be recorded in student journals. Entries should be neat and legible, and be written so that someone unfamiliar with physics will understand the concept. *Wikipedia* is a good source for information on these physics topics.

Lab Activity Part I

Students will learn to measure voltage on a **multimeter**. They will use AA batteries and **solar modules** for this section. They should understand how to change the scale to get the highest resolution possible on the meter. Then, students will learn to measure current using a multimeter. If you do not set up dedicated "voltage-testing" and "current-testing" multimeters, make sure that students get enough practice with switching between settings and that they remember to move the red test lead cable to the appropriate port.

1. Using the provided data tables (or ones that you have created), have students practice using **multimeters** to measure **open circuit voltage** and **short circuit current** of different sizes and types of **solar modules**. Any type of module should work, but it is great to have a variety of solar cells represented (I used a mix of **amorphous** and **crystalline modules)**.
2. Students should also measure the rectangular dimensions of the cells and then use that data to calculate area in cm^2 and then convert that to an area of m^2.

Equations:

- Power = Volts x Amps (P = VI) Note: I stands for intensity, an old term for current
- Efficiency = e = $Power_{out}$/ $Power_{in}$ e = P_{out}/P_{in}
- Solar Irradiance = I = $P_{\text{of sun at Earth}}$ / Area of earth

Data Gathering Tips:

- Encourage students to use the multimeters to measure the highest level of precision – i.e. use the scales on the meter to find the most precise values the meter can give. If your module can produce over -.2 Amps, it is recommended to set up meters for measuring 10 Amps with students, then let them use that set up for **current** measurement – this can prevent blowing the meter's internal **fuse**.
- If students do not discover it on their own, make sure that they try different tilts and orientations of the **modules** in order to get the maximum values possible – full sun is best! Sometimes students will accidentally shade their solar modules with their bodies—watch for this in the data.
- Units are important and students should include them with values, as it will help them start to understand what units go with which values.

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Calculation Tips:

- Converting cm^2 to m^2, and using powers of 10 should be a separate exercise:
  - $1\ m^2 = 1\ m \times 1\ m = 100\ cm \times 100cm = 10{,}000\ cm^2 = 10^4\ cm^2$ so, $1\ m^2 = 10^4\ cm^2$,
  - Or $1\ m^2/(10^4\ cm^2) = 1$ this is our "unit multiplier"
- An Area example: We have a **module** that is 10 cm x 4 cm.
  - **Area** = **L x W** = 10cm x 4cm = **$40cm^2$**
  - In order to convert this to m^2 we will use our unit multiplier:
- $40\ cm^2 \times [1\ m^2/(10^4\ cm^2)] = .004\ m^2$

Lab Activity Part II

Introduce efficiency for this activity. **Efficiency** Calculation:

Efficiency = (Energy out)/(Energy in) = (Power out)/(Power in) = P_{out}/P_{in}

Note that Efficiency has no units and is often expressed as a percentage (after it is multiplied by 100). Note also that efficiency cannot exceed 1.0 – you never get more out than you put in.

Efficiency is used to denote how much **energy** or **power** is "remaining" after an energy transformation takes place – in this case changing light to electricity. **The energy is not lost! Some of it can be accounted for with close observation – heat, and light account for some because the module warms up and we can see it (some sunlight must be bouncing off of it because it is visible!). Reiterate this with students – energy is conserved!!!!!**

Because we are modeling these solar modules as devices that transform a constant power over time, students could focus on energy or power to identify the efficiency of energy conversion. It is simpler to focus on power to measure at one instance in time and extrapolate what the energy efficiency will be. We will be examining the **power** supplied by the sun and comparing that to the **power** "supplied" (transformed) by the solar module to the electrical device (e.g. a multimeter).

The power we calculate will be our Power Out ($P_{out} = I_{sc} \times V_{oc}$). Note that $I_{sc} \times V_{oc}$ is an optimistic and conveniently calculated number for power that is not possible to attain in the real world. In actuality, the maximum power out from a solar cell follows the curve visible in Figure 1. If your class uses Vernier monitoring equipment, they can take these measurements as an extension activity without too much difficulty using a variable load (variable resistor) and an

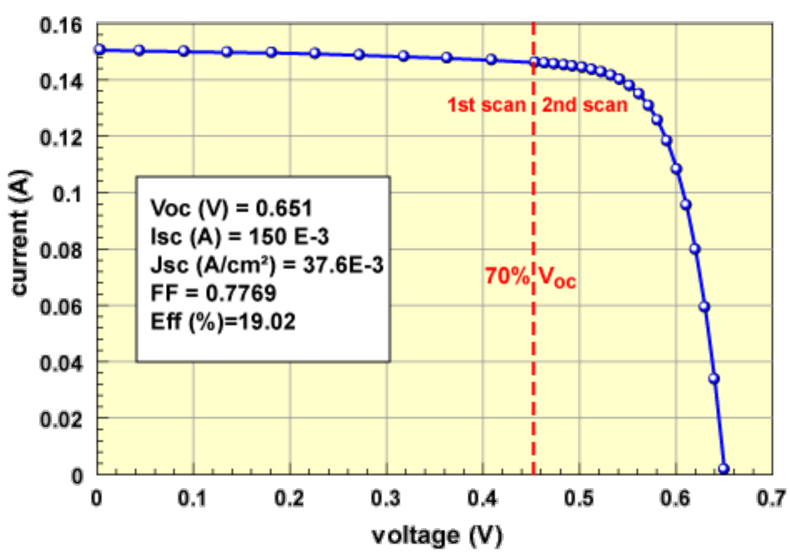

Figure 1. Actual data measurements for Voltage and Current of a Solar Cell. Note that if you want students to take these measurements, they may need to include many measurements with low-resistance resistors. See number of data points on "2 scan" (right side of graph)

energy meter, slowly increasing resistance from 6 Ω to its max of 255 Ω. However, you will need a set of larger resistors (up to 1M Ω) to get the data near the open circuit voltage. For this and other reasons, we stuck with the simple "maximum theoretical power" that we calculated using $I_{sc} \times V_{oc}$.

We have already calculated "Power Out", so next is determining "Power In." This value is supplied by the sun, and can be directly measured using a **pyranometer** (from Vernier) or an irradiance meter (e.g. Daystar DS-05A). Make sure to hold it facing the sun. If you do not have access to measure irradiance, you can use the standard 1000W/m^2 as a good baseline for solar noon. If you are not taking data measurements for solar irradiation, you can still perform calculations using 1000W/m^2 with the understanding that if it is cloudy, or not solar noon (sun at highest point in sky for that day), your efficiency calculation will be lower than accurate. Even with a pyranometer, you will likely note a drop in efficiency of solar modules in the shade or earlier in the day. On a bright, sunny day you should see values of 10-15% efficient for crystalline modules.

To find your peak solar power per area at any time of the year in Watts/m^2, use the same power/area ratio in the table below. Calculate efficiency by taking the ratio of calculated W/m^2 to that of measured irradiance, also in W/m^2.

Solar Irradiance = (Power In measured in Watts)/[Area in (m^2)]
-This tells us the power of the sun for every square meter of surface the sun shines on (area oriented at a right angle to the line to the sun)

[P_{out}/m^2]/[P_{in}/m^2] = P_{out}/P_{in} = Efficiency (the m^2 in both terms cancels out)

We could also have found the "**Power** In" from the sun by using the **Solar Irradiance** and multiplying that by the Area of the solar module – which would give us the Power the sun supplies on the area of the module.

Use the table below to calculate the efficiency of the panels you used

Module measured	**Power Flux for module** **P_{out}/A** (**Watts/m^2**)	**Solar Irradiance** **P_{in}/A** (**Watts/m^2**)	**Efficiency** **P_{out}/P_{in} =** **P_{out}/A ÷ P_{in}/A** No units	**Efficiency x 100** **(%)**
Tiny (0.5 V module)		**1000 W/m^2**		
Small (1 or 1.5 V module)		**1000 W/m^2**		
Medium (2 V module)		**1000 W/m^2**		
Large (3 V module)		**1000 W/m^2**		

(Note that the power found from $I_{sc} \times V_{oc}$ = P, which we are using as our "P_{out}" is an optimistic number for actual peak electrical power transformed in a solar module)

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Lesson Extension – Power Prediction

This extension activity focuses on using data collected to evaluate the modules and to make predictions. Have students answer the following questions:

1. Based on your results which module produces the most power per the area of the panel? When you answer this please include reliable data from your measurements as well as using other student data to support your claim or lack of claim.
2. Using your data, calculate the maximum theoretical power one of your modules would produce on Dec 21 and on June 21 if it were laid out horizontally. You will need to find the maximum solar irradiance for those two days from an online source. The website, http://ptaff.ca/soleil/?lang=en_CA, contains helpful data including maximum solar flux for a given city in the world. You will need to find the solar irradiance from the website and use your solar panel efficiency that you derived above. Use complete sentences and show all calculations and data. At what time of day would this power conversion take place? If you do not have the necessary data, what additional data do you need to answer this question?

Next, have students complete the **Power Prediction Activity:**

Use your data above to make a prediction of how much power a given module (one that has not been used previously) will produce. Note the physical appearance (crystalline or amorphous?), and compare to modules you have used. You cannot use a multimeter except to check your prediction. You must write out your argument and show any relevant calculations. You can use a ruler if you so desire.

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