Estimating solar energy requirements to meet U.S. energy needs: an outreach event

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Abstract

This paper describes an educational outreach activity based on the following question: How large of an area must be covered with solar photovoltaic panels in order to meet U.S. energy demand? This activity is organized around a flexible structure that can be modified for the target audience (ranging from middle school students to adults) and contains ample opportunities for hands-on participation. After providing an overview of the activity and objectives, we describe the supplies needed to carry out this activity and guidelines for selecting and using them. Materials/supply costs for this activity are around $100-$250 but can be as low as $30. A detailed description of a baseline lesson plan is provided, and optional, add-on activities are described. The activity can be completed in as little as 15 minutes and extended to as long as several hours. Key learning objectives are to introduce the audience to the basic operating principles of solar cells, measure the performance of solar cells, and apply the metric system and order-of-magnitude reasoning skills to the above-stated question.

1. Introduction

1.1 Overview

The sun is a tremendous source of renewable energy, continuously providing the earth with 165,000 terawatts of power—enough to meet all of mankind's energy needs for an entire year with a single hour of sunlight.[1] Despite the high abundance of sunlight across the world, less than 1% of the world's energy supply comes from the solar energy,[2] highlighting the need to develop technology that can harness the energy from the sun in an efficient and cost effective way. One such technology is solar photovoltaics (PV), in which semiconductor-based devices are used to convert sunlight into electricity. Advances in PV technology and manufacture have significantly reduced costs, resulting in an average annual growth of the U.S. PV market of 71% over the past 5 years.[3,4] In 2013, solar electric installations comprised 29% of all new electricity production in the U.S., second only to natural gas.[4] In order to continue this trend such that solar energy contributes a more meaningful percentage of the world's energy mix in the future, it is necessary to educate the general public and the next generation of scientists and engineers about the great potential of solar PV technology to play a major role in a sustainable energy future.

This paper describes an outreach activity for which the broad objective is to educate students and/or the public about solar energy through a hands-on, problem-based exercise that is focused on answering the following question: **How large of an area would one need to cover with solar panels in order to meet all of the energy needs in the U.S.?** This question is of great practical importance to society because the answer speaks strongly to the ability of solar energy to make a meaningful contribution to our energy system. This is no small task, as the U.S. has the world's largest per capita energy use, which equates to a total primary energy consumption rate of nearly 3.5 terawatts (TW).[5] As shown in Figure 1, the audience is initially asked to guess how large of an area (in terms of state size) is needed. While answering this question during the course of the outreach event, the activity will teach the audience about solar energy and introduce them to a number of valuable skills as described in the next section. Following a description of the learning objectives, this paper goes over the materials/supplies needed for this activity (Section 2) and presents a baseline lesson plan for conducting the outreach event (Section 3). A short power point presentation to be used in conjunction with the activity is available from the author's website.[6] In the final section of the paper, (Section 4), variations on the lesson plan are suggested for those who want to adjust the length of the activity or modify the content so that it is appropriate for their target audience.

Note: "Energy" and "power" are two closely-related words that are used throughout this paper, and it is worth clarifying the difference between them. Energy is defined as the capacity of a physical system to do work and is measured in the International System of Units (SI) unit of the Joule (J). Power is the rate of energy consumed or generated per unit of time, and is thus measured in SI units of J s^{-1}, also known as the watt (W). This paper and the activity it describes uses power consumption and generation as the basis for calculations, and thus the unit of the watt is used throughout the paper. For the purpose of discussion, the terms energy and power can often be used interchangeably, but the instructor should be aware of the distinction between the two terms, especially when it comes to calculations.

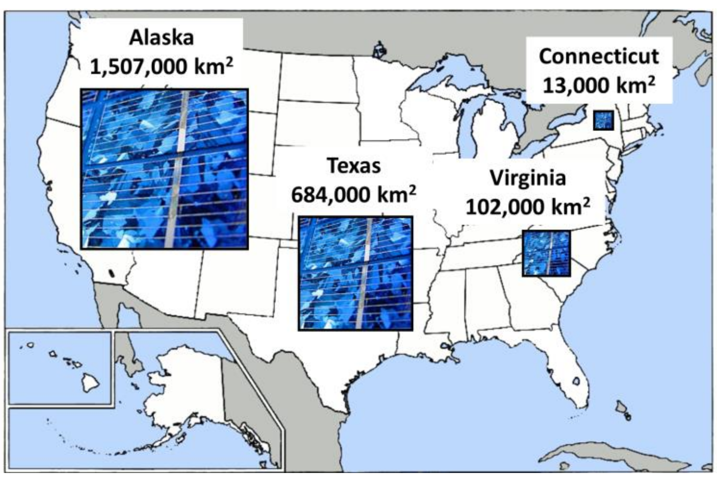

Figure 1. Superposition of hypothetical solar power plants having areas the size of Alaska, Texas, Virginia, and Connecticut on a map of the contiguous United States. This hands-on outreach activity allows students to determine how large of an area must be covered with solar panels to meet the U.S. primary energy needs.

1.2 Learning Objectives

Based on the information provided in this paper, instructors will be able to:

1. Give a high level introduction on solar photovoltaic energy conversion.
2. Demonstrate basic measurement techniques for determining light intensity and the performance of a solar panel.
3. Reinforce metric system units associated with solar energy conversion.
4. Provide perspective on the scales associated with power generation and consumption through order-of-magnitude examples and reasoning.
5. Calculate the power generated by the solar cell based on the measured quantities and answer the above-stated question that forms the basis of this activity.

2. Materials, supplies, and safety concerns

This section describes the key supplies needed to carry out this outreach activity, most of which are shown in Figure 2. Appendix Table I contains typical/expected costs for these items.

2.1 Solar panel(s) (required)

It is recommended that the instructor obtain solar photovoltaic (PV) panels based on crystalline silicon (c-Si), the most widely used solar cell material. Most c-Si solar cells have energy conversion efficiencies of 10-20% and are thus well-suited for this exercise. If possible, one should avoid amorphous silicon (a-Si) solar cells, which have much lower efficiencies (< 8%) and would not be considered for large-scale commercial PV installations. Appropriately-sized c-Si solar cells can be easily obtained from a variety of online resources and some hobby stores. For example, the lead author has commonly used a 1 watt (W) c-Si solar panel (Fig. 2a) available through RadioShack. Unless the instructor has the luxury of knowing that he/she will be able to

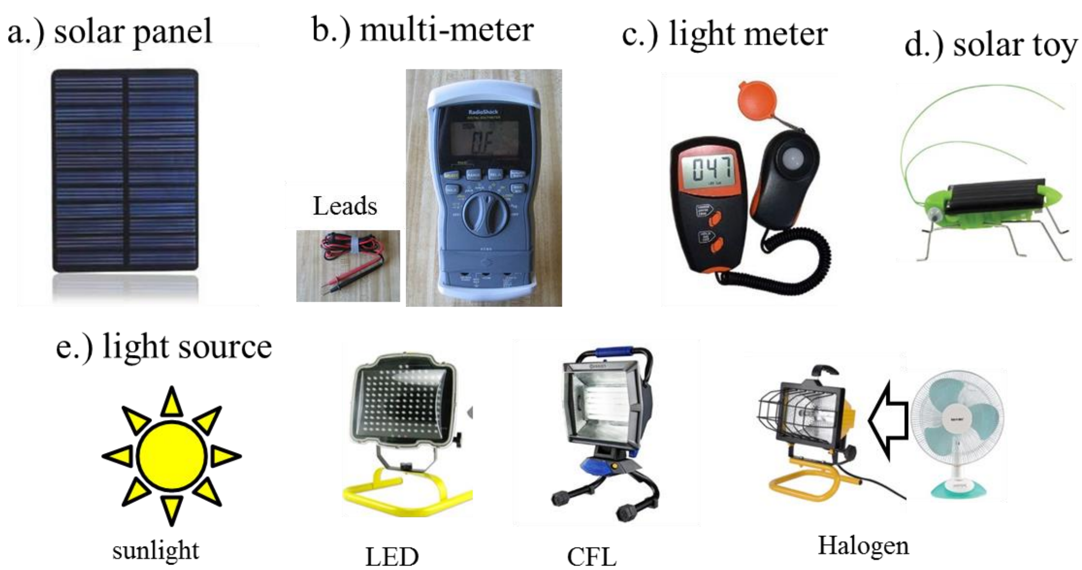

Figure 2. Key supplies used in the outreach activity. There are several light source options as described in the text. Use of a high power halogen work lamp is discouraged, but can be used with caution and under direct supervision.

run the activity outside under natural sunlight, it is important to obtain a solar panel with smaller size, typically less than 120 cm^2. The solar panel shown in Figure 2a has dimensions of (11 cm x 8 cm), which is small enough for the solar panel to be uniformly illuminated by an average-sized work lamp having light intensity similar to that generated by the sun on a cloud-free day. Larger solar panels can be easily operated outside in direct sunlight, but when operated indoors require powerful light sources that can pose safety concerns. See additional comments in section 2.4.

2.3 Multi-meter (required)

A multi-meter (Figure 2b) is used to measure the voltage and current being produced by the solar panel under illumination. Multi-meters can be purchased at hardware stores, electronics stores, or online. Almost any multi-meter is suitable for this activity as long as it can measure direct current (DC) voltage and current. Remember to check that batteries are charged. See product manual for basic operation of a specific multi-meter.

2.2 Optical Power or Lux meter for light source calibration (recommended)

Having a light source with intensity similar to that of the sun is important if one is to get an accurate answer to the core question of this activity. The radiant power density (P_L) of the sun at the earth's surface is, on average, about 1000 W per m^2 of incident area. For this activity, it is desirable to have a light source that produces a similar P_L at the surface of the solar panel. P_L (in W/m^2) can be determined with either an optical power meter or a lux meter (Figure 2c.). While a power meter directly measures the radiant power of light (in W or W/m^2), a lux meter measures the luminous intensity of light (P_l), which is the brightness of the light source as perceived by the human eye. The SI unit for luminous intensity is the lux, defined as one lumen per m^2. The luminous intensity and radiant power are directly related, and thus either type of meter can be used for this activity. A power meter is convenient for this exercise because the radiant power it reads out is used for calculations. However, lux meters are generally easier to come by, cheaper, and luminous intensity they measure can be easily converted to radiant power through the following relation:

$$\text{Intensity of the sun} \approx 100{,}000 \text{ lux (luminous intensity)} \approx 1000 \text{ W m}^{-2} \text{ (radiant intensity)} \quad (1.)$$

If the activity is to be conducted outdoors using natural sunlight, no light meter is needed. Otherwise, a power or lux meter should be used to calibrate the light intensity as described in Appendix 7.2. When purchasing a lux meter, be sure that the meter is capable of measuring at least 100,000 lux. There are many low-cost models that go up to 200,000, but one needs to avoid low-intensity models that are intended for measuring low intensity indoor lighting. Appendix 7.2 also describes a means to calibrate the light intensity without a lux meter, simply using the measured current produced by the solar panel under solar illumination.

2.2 Light sources (required for indoor measurement)

If the instructor has the flexibility of choosing the date to perform this activity, they can perform the measurements outside under natural sunlight, meaning that no artificial light source need be purchased for the activity. As long as the sun is not behind a cloud and the activity is not conducted in the shade, the light intensity is automatically set around the desired value (100,000 lux or 1000 W m^{-2}). Note that foggy or hazy conditions can significantly diminish the intensity of light, and the performance of the solar panel will be below its usual output. The remainder of this section discusses selecting an artificial light source, or lamp, if the activity is performed indoors.

Sizing the light source: It is desirable to have a light source that is capable of producing light with intensity of ≈100,000 lumen m^{-2} ≈1000 W m^{-2} over the entire area of the solar panel to mimic operation under sunlight. The overall power and size of the light source needed to obtain this light intensity is determined by the size of the solar panel, the size of the lamp, and set-up dependent coupling losses between the light source and the solar panel (i.e. the fraction of light from the lamp that doesn't shine on the panel). A guideline for sizing light sources is provided in the Appendix section 7.1.

Types of light sources: There are several types of artificial light sources that can be purchased at hardware stores and online, and several types are illustrated in Figure 2e. All of the light sources shown in Figure 3e are commonly referred to as "work lamps", which are usually high intensity light sources built to brightly illuminate working areas. The authors strongly recommend light emitting diode (LED) and compact-fluorescent (CFL) light sources over halogen or incandescent lamps. LEDs and CFLs are recommended because their superior efficacy (lumen/W) or efficiency compared to incandescent and halogen lamps means that they produce much less waste heat. High power halogen and incandescent lamps produce much waste heat, reaching high temperatures when left on. If not careful, a high power halogen or incandescent lamp can melt/damage the solar panel and the surface beneath it, even posing a fire hazard. If a halogen light source is to be employed, do not get an over-sized lamp, and use a fan to cool off the light source and the illuminated solar panel/surface during operation.

Additional safety considerations: Regardless of the type of light source employed for this activity, any light source capable of producing radiant intensity comparable to that of the sun can be a safety hazard to the human eye. Just as one should never stare directly at the sun, one should never stare directly at a very bright artificial light source. Risk can be eliminated or greatly minimized through the following safety precautions:

- At the start of the activity, make it very clear that students should not look directly at the bright light, just as they would not look directly at the sun.
- Modify the lamp set-up such that i.) the light is oriented downward onto the solar panel and/or ii.) the light source is set-up on a table and pointed towards a non-reflective wall such that students cannot position themselves in the path of the bright light and/or iii.) construct shields attached to the sides of the lamp such that it is very difficult for anybody in the audience to look directly into the bright light (see Figure 3).
- Only turn on the bright lamp when it is needed for the demonstration. Turn it off immediately after performing the measurements.

Figure 3. Work lamp with metal shield constructed such that bright light does not shine into the audience's faces and cause a safety hazard.

- If one is still concerned about the brightness and one is working with a smaller audience, consider bringing sunglasses, especially for volunteers who will come close to the set-up.

2.3 Other supplies

In addition to those supplies listed above, this activity makes use of the following supplies:

- An attention-grabbing solar toy. The lead author has used a “solar bug” such as that depicted in Figure 3d that contains a small solar cell attached to a piezo device which makes the bug vibrate upon illumination. Alternative solar toys or small solar set-ups could be used in place of the solar bug.
- Worksheet (optional), basic calculators, and pencils for participants (or a single “calculator” spreadsheet as discussed in Section 3 and available at [6]).
- A ruler or tape measure for measuring the area of the solar panel.
- A power point presentation (optional, example presentation available at [6]).
- Desk lamp or strong flash light to illuminate solar toy (optional).

3. Lesson Plan / Instructional Procedures

This section of the paper covers the lesson plan for this outreach activity in 4 parts. Variations and extensions are discussed in Section 4.

3.1 Introduction to the watt, different energy scales, and the objective of the activity

This activity begins with a short discussion about the unit of power, the watt (W), and an exercise in order-of-magnitude reasoning. The authors suggest that the activity begin with the use of an attention-grabbing solar toy such as the “solar bug” in Figure 2d. When a light source is turned on and positioned over the bug(s), the bug(s) begin to jump around as the electricity produced by the small solar cell on their back is converted into kinetic energy. This is a nice opportunity for members of the audience to come up to the front demonstration table and investigate (let them turn the light off and on, change the distance of the light from the bug, etc.).

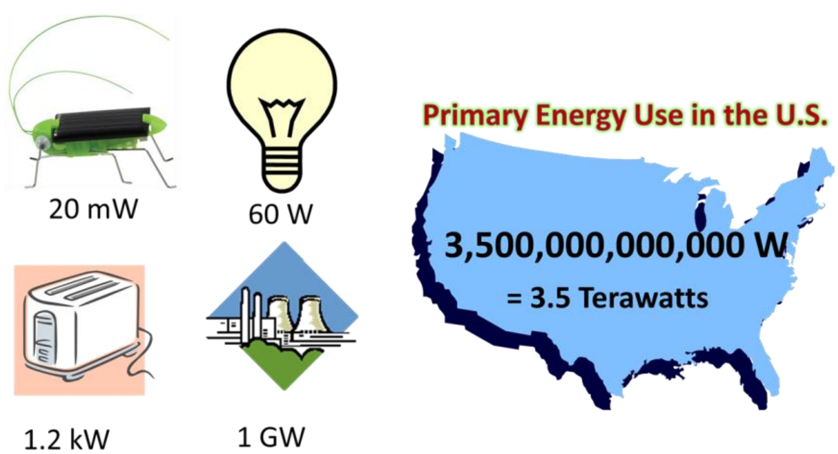

Figure 4. Different energy-related items mentioned in the presentation to introduce different prefixes associated with the watt and give the audience perspective of the scale associated with them. Also illustrated is the total primary energy use in the U.S.

The lead author usually brings a desk lamp or bright flash light to illuminate the solar bugs, which do not require high intensity to move around. Other solar toys could be used in place of the bug. Key discussion points are as follows:

- **Discuss what is happening.** Ask the students why they think that the bug only moves when light is shined on it and only if the light is positioned within a certain distance of the bugs. This simple activity engages the audience and provides a visual example of the milliwatt (mW) scale of energy conversion.
- **Introduce the Watt.** Whereas length is measured in meters, time in seconds, and weight grams, explain that power is measured in watts (W). Most of the audience should be familiar with a 60 W incandescent light bulb (consider bringing one to hold up).
- **Give examples of different power scales**. At this point, explain that the solar bug uses about 20 mW of power to jump around, where one mW is equal to 1/1000th of W. Compare this to other electricity-consuming or producing items that introduce a new scale/prefix. Several examples are shown in Figure 4, including the light bulb (watt), toaster (kilowatt, kW), and nuclear plant (gigawatt, GW).

After providing the audience with a sense of scale associated with power production, ask the audience how much power they believe is consumed in the U.S.—the primary energy usage, which includes all forms of energy consumption (electricity, transportation, heating, etc.). After allowing for a few guesses, reveal the answer: 3.5 trillion watts, where one trillion watts equals one terawatt (TW). This question introduces a new prefix (tera) and serves as a segway to the main focus of the activity, which is to answer the question of whether or not it is possible to meet all U.S. energy needs with solar energy alone.

3.2 Solar energy motivation, solar cells, and measuring the electrical output of a solar cell

Motivation for solar energy: Before measuring the performance of solar panels, it is worth discussing why society should be interested in using solar panels as its primary source of energy. After all, there are many other potential sources of energy. Typically the audience is able to list many of the main reasons, but here is a list in case the instructor needs to help them out:

- Solar energy is extremely abundant—in a given hour of the day enough sunlight reaches the earth to power all of humanity's energy needs for an entire year. The energy of all sunlight striking the earth averages about 165,000 TW.[1]
- Solar energy is readily available around the world, unlike fossil fuels which are concentrated in certain locations (e.g. oil in the Middle East).
- Solar energy is renewable.
- Solar energy conversion technologies do not directly emit any greenhouse gases that contribute to global warming.

What is a solar cell?: The level of detail used in this discussion should be tailored to the specific audience, but typically a number of the following high-level talking points are appropriate::

- Re-state what a solar cell does: it converts sunlight into electricity. Solar cells are also called photovoltaic (PV) cells, where "photo" means light, and "voltaic" pertains to electricity.
- At a high level, a typical solar cell is comprised of five key components: (i.) the semiconductor, (ii.) the front contact, (iii.) the back contact, (iv.) encapsulation and (v.)

electrical wiring. For instructors looking for more detailed descriptions of how a solar cell works, the authors recommend the following freely available educational resource.[7] Briefly, the semiconductor is the most important component, which absorbs light and converts it into electricity. The front and back contacts, along with the wiring, are used to extract the electricity from the solar panel. The encapsulation is used to protect the underlying semiconductor and electrical components from the weather.

- Pass solar panels or cells around the audience for them to handle and inspect more closely. Let them identify the different components that you just described.
- (optional): Explain the difference between a solar cell and solar panel: a solar cell is the basic energy harvesting unit, and many solar cells are often tied together by wires to make up the solar panel. Point out the individual solar cells that can be seen in the solar panel(s) you pass around the audience.

Measuring the electrical power produced by a solar cell: At this point it is time to measure the performance of the solar panel using the multimeters. The lead author typically uses the following sequence of talking points and actions:

- (optional) Initiate a discussion about electricity. What exactly is electricity, and how do we quantify/measure the amount of electrical power being produced by the solar panel?
- Explain that there are two key properties that determine electrical power (P_e): current (I, measured in Amps (A) or milliamps (mA)) and voltage (V, measured in Volts) where electrical power in watts is given by $P_e = I \times V$. We are interested in knowing how much power our solar panel produces, so we must measure both the current and voltage produced by the solar panel.
- Current and voltage produced by the solar panel can be measured by a multimeter. Pass around the multimeters, explaining how the red and black leads of the multimeters are connected to the wires coming from the solar panel, and the current or voltage being produced by the solar panel are read from the (usually) digital screen. Show students how the measurement mode of the multimeters is switched between current and voltage. **Safety note:** although one should always be cautious around sources of electricity, such as electrical outlets (usually 120 V), recognize that the very small power produced by a small 1-3 W solar panel poses no threat of electrical shock to the audience.
- Use the multimeter to measure the current and voltage produced by the solar panel, illuminated by either natural sunlight or the artificial light source. Encourage audience participation by asking for volunteers to perform the measurement, with one volunteer connecting the multimeters leads to the solar panel wires, another turning the lamp on/off, and a third being in charge of reading the output of the multimeters. If one is using a work lamp as an artificial light source, explain that the intensity of light from the lamp is equal to that of natural sunlight on a cloud-free day when the solar panel is placed at the specific distance away from the light source. Make sure that the solar panel is uniformly illuminated, placed directly in the center of the beam produced by the work lamp. If one has enough time, the instructor can lead the audience/students through the light source calibration process and add a discussion on measuring the power content of light.
- If using individual worksheets, have all students or groups write down the current (usually in milliamps) and voltage (in volts) produced by the solar panel.
- The third measured quantity needed to answer the core question of this activity is the area of the solar panel. Have participants measure the area of the solar panel with a ruler.

At this point, participants have measured the current and voltage produced by a single solar panel with known area. From these values, the electrical power produced by the solar panel can be easily calculated (P_e=I x V). **Technical Note:** The current and voltage measured using the multimeters are the short circuit current (I_{sc}, current at V=0) and open circuit voltage (V_{oc}, the voltage at I=0 A). However, at both short circuit and open circuit operating points, P_e=0. During actual operation, the solar panel doesn't actually operate at short circuit or open circuit conditions, but close to what is called the maximum power point (mpp) with corresponding mpp current (I_{mpp}) and mpp voltage (V_{mpp}). For a typical solar panel, $P_e = I_{mpp} \times V_{mpp} = 0.8 \times I_{sc} \times V_{oc}$, where the fill factor value of 0.8 (typical of a Si solar cell) accounts for the fact that I_{mpp} and V_{mpp} are slightly smaller than I_{sc} and V_{oc}, respectively. For this activity, the lead author often omits the use of the factor of 0.8 to a.) avoid unnecessary confusion and b.) offset the fact that small educational solar panels typically available for this activity have lower efficiency than those that are employed in commercial applications. See reference [9] for a more detailed description of fill factors and operating points in PV cells.

3.3 **Calculating solar panel area needed to meet U.S. energy needs**

Using the measured current, voltage, and area of the solar panel, there are three simple steps for calculating the area of PV panels that would be needed to meet all U.S. power consumption:

Calculating Required Area of Solar Panels:

1. Find electrical power from a single solar panel (P_s) :

   P_s = (Voltage) x (Current) **(unit: Watt)**

2. Find number of Solar Panels required to get 3.5 TW:

   $$\text{Number of Panels} = \frac{3{,}500{,}000{,}000{,}000 \text{ Watts}}{(P_S)\times(6 \text{ hrs}/24 \text{ hrs})}$$

3. Find total area occupied by solar panels

   Total Area = (Number of panels) x (Area of 1 Panel)

- Step 1 calculates the power produced by one solar panel, P_s, as discussed in Section 3.2.
- In step 2, the number of these solar panels needed to produce 3.5 TW of power is given by the value of the total power produced (3.5 TW) divided by the power produced by the single solar panel (P_s). A good question to ask the audience: "why do you think the faction (6/24) is included in the denominator of the equation in step 2? Why is the number 24 familiar?". The answer, of course, is that there are 24 hours in a day. While the U.S. energy consumption rate is a relatively constant 3.5 TW for 24 hours a day, 365 days per year, solar panels placed in most parts of the country will only produce electricity an average of 6 hours per day.
- In the final step, the total required area is given by multiplication of the calculated number of solar panels (step #2) by the measured area of the single solar panel. The area of one solar panel as measured by the audience will typically be measured in cm^2, and should thus be converted to km^2 ($1\ cm^2 = 10^{-6}\ km^2$).

Depending on the time available for the activity and the mathematical aptitude of the audience, the instructor can i.) have the students perform the calculations on their own using the worksheet provided in Appendix Section 7.3, ii.) walk the audience through the calculation on a white board, or iii.) use a "calculator" spreadsheet that quickly spits out the answer. The calculator spreadsheet is simply a Microsoft excel spreadsheet that has the formulas already entered such that the instructor can quickly enter the measured values (current, voltage, area) and show the audience the answer. Use of the calculator spreadsheet skips over mathematical details (e.g. unit conversion) and is thus convenient for a time-constrained demonstration. Using this "short-cut", the entire activity can be completed in as little as 20 minutes. The calculator spreadsheet used by the lead author is available for download at reference [6].

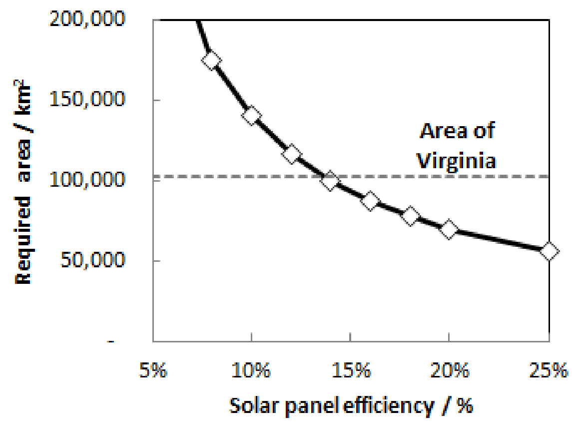

Figure 5. Calculated area required to meet U.S. energy needs as a function of solar panel efficiency. Assumptions: average daily power production period of 6 hours under 1000 W m^{-2} solar intensity.

Besides the hands-on measurement approach taken in this activity, one can also do a simple back-of-the-envelope calculation to estimate the required area of solar panels to produce 3.5 TW of power. This calculation is done by assuming a value for the photovoltaic conversion efficiency (typically 10-20%), 1000 W m^{-2} sunlight, 3.5 TW power production, and an average of 6 hours of sunlight. The result of this calculation is shown in Figure 5 as a function of different PV efficiencies. Figure 5 shows that a solar panel efficiency of ≈ 14%, a reasonable value for a standard c-Si solar panel, requires a total are of around 100,000 km^2, nearly equal to the size of the state of Virginia. This is a good reality check of the answer that you come up with through the hands-on measurements performed in the activity. If your answer is below 50,000 or greater than 200,000 km^2, it is very likely that a mistake was made at some point during the activity. Common mistakes include improper light calibration, use of a damaged (very low efficiency) solar panel, outdoor measurement on a hazy/cloudy day, or a mistake in the calculations.

3.4 Debriefing questions for discussion

- How did the required area of solar panels compare to expectations? How does it compare to the total area of rooftops, farmland, or paved highways and parking lots in the U.S.?
- Does the required area seem acceptable? If not, what should we do? Introduce other options: use a combination of other energy sources, increase energy efficiency, and increase energy conservation. Energy not consumed is energy that need not be generated in the first place!
- While it may be conceivable to generate all of the U.S.'s energy needs with solar energy, what are some other challenges besides finding enough space to put the panels? (cost, intermittency and energy storage)

4. Lesson plan variations and additional exercises

- ***Measuring and calibrating light intensity***- In the baseline lesson plan, we have advised the instructor to arrange the light source and solar cell test station ahead of time. However, for a longer lesson plan, one can incorporate the measurement of luminous intensity and light calibration into the planned activity. In this longer version of the activity, the instructor will have the students use the lux meter to identify the combination of light power or light/solar cell separation distance such that the solar cell will be illuminated. On a sunny day, the students should be encouraged to compare the output of the solar panel illuminated by the lamp to the output measured under natural sunlight.
- ***How much PV area to power ____?*** The baseline lesson plan asks participants to figure out how much area must be covered by solar panels in order to provide enough energy to meet the entire U.S. primary energy demand. Alternately, or additionally, one can ask for the area of PV panels required to power a larger or smaller component of the primary energy demand. For example, one might consider investigating the area required to meet world energy demand, U.S. electricity needs, or powering the entire U.S. private vehicle fleet if all vehicles were converted to plug-in electric vehicles (EVs).
- ***Explore influence of solar cell efficiency***- Besides total power demand, another variable that has a large influence on the required area of solar panels is the efficiency of the solar panel. More efficient solar panels produce more electricity per unit area, and thus fewer solar panels are needed to produce a given amount of energy. In this optional activity, the instructor can use two solar panels with different efficiencies to illustrate the importance of solar panel conversion efficiency. In addition to the c-Si solar cell used for the baseline lesson plan, one can obtain a thin film amorphous Si (a-Si) solar panel, which will have lower conversion efficiencies (5- 8 %). Thus, the amount of area required to meet a certain amount of energy would be doubled compared to the c-Si solar cell with ~ 15 % efficiency. Conversely, repeating the exercise with a high efficiency solar cell (efficiency > 20%), one could show that the amount of land required to produce a given amount of energy is significantly reduced.
- ***Explore the influence of location***- It is well known that average yearly solar irradiance varies substantially across the globe, and that identical solar panels placed at different locations will produce different amounts of energy as a result. For example, the average yearly irradiance in Phoenix AZ is about 43% higher than in New York City, and 138% higher than in Anchorage, Alaska. The power produced by a solar cell will be directly related to the average yearly irradiance, and as a result, the land area covered by solar panels in Phoenix would be significantly less than that in Alaska. A complete data base of 30-year average irradiance values for major U.S. cities is maintained by the National Renewable Energy Laboratory (NREL) and can be found on the following website.[10] As an additional exercise, one can calculate this difference in required area by adjusting the distance between the solar panel and light source such that the incident power (as measured by the lux meter) is decreased by an amount proportional to the average solar irradiance of various locations.

5. Conclusions

Photovoltaic energy conversion represents an important technology to help society achieve a more sustainable energy future and represents an important growth area in both the U.S. and global economies. It is thus essential that educators at all levels (community outreach, middle school, high school, and college) more aggressively expose and educate students and the community about solar energy conversion technology. This paper has presented a simple hands-on solar activity that educates its audience about solar photovoltaic cells and highlights the potential of this technology to have a major impact on the energy landscape in the U.S. More generally, this activity also educates its audience about SI units associated with power use/consumption, as well as guiding them through an order-of-magnitude reasoning exercise to provide some perspective on scale in energy conversion technologies.

6. References

1. Smalley, R. "Future Global Energy Prosperity: The Terawatt Challenge". MRS Bulletin, **30**, 2005, 412-417.

2. "2013 Key World Energy Statistics", International Energy Agency, report freely available at: http://www.iea.org/publications/freepublications/publication/KeyWorld2013_FINAL_WEB.pdf

3. Gelman, Rachel, "2012 Renewable Energy Data Book". Produced by U.S. Department of Energy, Energy Efficiency & Renewable Energy Office, Ed. Mike Meshek, 2012, book freely available at http://www.nrel.gov/docs/fy14osti/60197.pdf

4. "Solar Market Insight Report 2013 Year in Review". Produced by Solar Energy Industries of America and GTM Research, 2014, Report freely available at: http://www.seia.org/research-resources/solar-market-insight-report-2013-year-review

5. "Annual Energy Outlook 2012", prepared by the U.S. Energy Information Agency, freely available at: http://www.worldenergyoutlook.org/

6. http://danesposito.wordpress.com/courses-outreach/ or http://cheme.columbia.edu/daniel-esposito

7. PVCDROM, PV education resource, http://www.pveducation.org/pvcdrom/

8. "Light bulb comparison", ISG Illumination Systems, LLC, last accessed 3/9/14. http://www.isglighting.com/About-Us/The-ISG-IS-Advantage.aspx

9. PVCDROM, PV education resource, http://www.pveducation.org/pvcdrom/solar-cell-operation/fill-factor

10. "30-Year Average of Monthly Solar Radiation, 1961-1990", database, National Renewable Energy Laboratory, http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

7. Appendix

Table I. Average cost of supplies used in this outreach activity.

Item	Required?	Price range	Source
0.5-1.5 W Solar panel	Yes	$10-$20	hobby store, online
multimeter	Yes	$10-$100	hardware store, online
work lamp	Yes/No^	$25-$100	hardware store, online
lux meter#	recommended	$15-$100	online
ruler	Yes	$1-5	office supply store, online
solar toy	recommended	$1-$20	hobby store, online
Typical total supply cost*=		$ 155	
Notes			
#make sure that lux meter is capable of measuring light intensities >= 100,000 lux			
^required if activity is run indoors, optional if outdoors			
*not included: calculators (optional), pencils, and paper if you use a worksheet			

7.1 Calibrating your light source

If the activity is to be conducted outdoors using natural sunlight, your light source is automatically calibrated and no light meter is needed.

For most artificial light sources, the easiest way to modulate the luminous intensity (lumens/ m^2) is to adjust the distance between your solar panel or light meter and the light source. By this means, one can identify the distance away from the light source that the solar panel should be placed in order to measure its performance under light intensity similar to that of the sun, 100,000 lux ≈ 1,000 W m^{-2}. A couple of additional notes on calibrating the light source:

- The conversion between radiant power of light and luminous intensity (100 lux ≈ 1 W m^{-2}) is only approximate and will depend on the specific light source that is used. In fact, the units of lumens m^{-2} and W m^{-2} are not equivalent. Different lamps have different spectral output, meaning they emit light at different wavelengths or colors, and thus the conversion between P_L and P_l is different for different light sources due to the wavelength-dependent sensitivity to brightness of the human eye. However, the error incurred by using the conversion (100 lux ≈ 1 W m^{-2}) should be within the error introduced by other assumptions in this activity. A good way to check the accuracy of your light intensity calibration is to compare the output (current/voltage) of your solar panel in sunlight compared to its output when measured under the artificial light source at the calibrated distance.
- A less direct, but simpler alternative to calibrating the intensity of an artificial light source with a light meter is to use the output of the solar panel. On a sunny day, use a multi-meter to measure the electrical current produced by the solar panel. Next, illuminate the solar panel with your artificial light source/lamp, and adjust the power of the light source or distance between

the panel and the light source until the current produced from the solar panel is the same as that which it produced under natural sunlight.

7.2 Guide to sizing artificial lights or lamps

It is desirable to have a light source that is capable of producing light with intensity of ≈100,000 lumen m^{-2} ≈1,000 W m^{-2} over the entire area of the solar panel to mimic operation under sunlight. Typically, the net luminous power (in lumens) and/or electrical power consumption (in W) of the light source is provided by the manufacturer. By knowing the net luminous power of the light source ($P_{l,net}$) and the area of your solar panel, A_{pv}, the minimum required $P_{l,net}$ of the light source is given by:

$$P_{l,net,min}\text{ (lumens)}=(100{,}000\text{ lux}) \times (A_{pv}) \qquad (1.)$$

where A_{pv} is in m^2. For example, the standard solar panel (A_{pv}= 11x8 cm^2) used by the authors requires a light source that produces $P_{l,net}$ >880 lumens. However, it must be emphasized that equation (1.) gives the minimum required luminous power of the lamp because it assumes that the shape of the lamp perfectly matches that of the solar panel such that all of the light emitted by the lamp falls on the solar panel. In reality, there will always be a coupling loss due to the divergent nature of most light sources and the mismatch in shape between the lamp head and the solar panel. The coupling loss depends strongly on how focused the light source is and the distance between the solar panel and light source. When one calibrates the power of the light source by adjusting the distance between the solar panel and the light source, one is adjusting the intensity of light at the solar panel by altering the coupling loss. Even for a relatively focused light source having size and shape similar to that of the solar panel being used, it is safe to assume a coupling loss that is greater than 50 %, meaning that greater than 50% of the light is not incident on the solar panel. Thus, a light source should be chosen with $P_{l,net}$ >= 2 x ($P_{l,net,min}$). Sometimes the $P_{l,net}$ of a light source is not specified by the manufacturer, but only the electrical power consumption in W. In this case, one can estimate $P_{l,net}$ based on the typical luminous efficacies of various lamp types:[8] (LED: 100 lumen/W, CFL: 60 lumen/W, incandescent/halogen: 15 lumen/W).

7.3 Worksheet for student calculations (next page)

Estimating Solar Energy Requirements to Meet U.S. Energy Needs

Question: How large of a land area must be covered with solar panels in order to produce all of the energy currently consumed in the U.S.? Currently, the U.S. uses 3.5 terawatts of power (3,500,000,000,000 watts!). Start the activity by taking a guess: (circle one)

a.) 13,000 km^2 (area of Connecticut) **c.) 684,000 km^2 (area of Texas)**

b.) 102,000 km^2 (area of Virginia) **d.) 1,507,000 km^2 (area of Alaska)**

The answer to this question is found through three calculations based on the measured current, voltage, and area of the solar panel used in this activity:

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1. Write down the current and voltage produced by a single solar panel, and calculate the amount of electrical power produced using those values:

Current= _________ A Voltage=_________Volts

Power from single panel = (Current) x (Voltage)

Power from single panel = (_______A) x (_________V) =_________W

---

2. Determine the number of solar panels required to generate 3.5 TW of power:

$$\text{Number of panels} = \frac{3{,}500{,}000{,}000{,}000\ W}{Power\ from\ a\ single\ panel\ (W)} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ panels$$

---

3. Find the area occupied by the number of solar panels determined in step #2 and the area of a single solar panel:

Area of one solar panel= (length) x (width) = ______________ cm^2

Total area of solar panels= (# of solar panels) x (Area of one solar panel)

= ___________________ x _____cm^2=__________________ cm^2

Now convert this value to km^2 based on the conversion: 1 km^2=10^{10} cm^2=10,000,000,000 cm^2

Total area of solar panels = _____________cm^2 x(10^{10} km^2/cm^2)

=______________km^2

How does the answer compare to your guess at the top of this worksheet? Does it seem reasonable to set aside this much land area for energy production?