**Title:** Photovoltaic System Design: Running the numbers

**Type:** Energy

**Provided by:** Hathaway Brown School, Shaker Heights, OH

**Grade Levels:** 9-12

**Lesson Topic:** Energy

**Learning Standards Addressed:**

Hathaway Brown does not align curriculum to state standards.

**Performance Objectives:**

* Students will compare available solar energy in Cleveland with available solar energy in other parts of the country and/or world.
* Students will apply their understanding of Watts, Watt\*hours and peak sun hours to calculations of available solar energy at a given location and actual energy production from a PV system at that location.
* Students will examine PV system efficiency using real data.
* Students will design a PV system for their homes and assess how realistic such a system would be (exclusive of cost considerations).
* Students will become familiar with the real-time monitoring systems for weather and PV production at Hathaway Brown.

**Required Materials:**

* Access to HB’s solar charging station and view of HB’s PV system
* Online access
* Access to family electricity records/bills

*Useful resources:*

Data tables of average solar radiation for different locations in the US. Can get monthly and annual, and can get data on fixed panels, tracking panels, and panels at different tilt angles. <http://rredc.nrel.gov/solar/pubs/redbook/PDFs/OH.PDF>

Average monthly solar radiation in Cleveland for fixed panels tilted to latitude (data taken from website above)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | January | February | March | April | May | June |
| Avg daily kWh/ms | 2.4 | 3.3 | 3.9 | 5.0 | 5.6 | 6.0 |
|  | July | August | September | October | November | December |
| Avg daily kWh/ms | 6.1 | 5.6 | 4.7 | 3.6 | 2.2 | 1.7 |

Solar radiation maps of the US, available for monthly averages and annual averages: <http://www.nrel.gov/gis/solar.html>

Solar radiation maps for Europe (note these show solar radiation for the year, not the average day, as the US maps do): <http://re.jrc.ec.europa.eu/pvgis/countries/countries-europe.htm>

6 Things that affect Solar PV system efficiency: <http://livingonsolarpower.wordpress.com/2013/03/06/6-factors-that-effect-solar-pv-system-efficiency/>

**Anticipatory Activity:**

Visit the solar charging station. Review educational posters above the charging station. Have students write down what questions they have about the charging station.

Go up to the third floor of the Atrium and look out at the Link roof to see the solar panels. Have students write down questions they have about the solar panels.

Ask students if they think we get enough sun in Northeast Ohio to use solar panels to make electricity.

Show students a solar radiation map of Ohio and of Germany (see “*Useful Resources*” above), explaining that Germany has made major investments in solar power in recent years. (Maybe this was a good investment, and maybe it wasn’t…) Have students explain how the available solar energy in Cleveland compares with that of Germany or other parts of the US and/or Europe.

Tell students that they will be calculating the potential energy production of our small PV system and comparing it with actual energy production over time. In addition, they will be designing a PV system for their homes as homework and assessing whether PV is a viable option for their homes (exclusive of cost considerations).

**Lesson Activities and Procedures:**

Review with students the following units:

* Watt
* Watt\*hour
* kilowatt
* kilowatt\*hour

Because the amount of solar radiation available varies geographically, in order to determine how many panels a PV system needs, we need to know how many “peak sun hours” the intended location gets daily, on average.

Northeast Ohio gets, on average, 4.1 hours of peak sun daily. Peak sun is standard measure of solar irradiance equal to 1 kW/square meter. When we say that the average daily peak sun in NEO is 4.1 hours, this tells us that if you sum the total Watts of solar energy that hits a square meter over a year, and package it so that it shines at a constant intensity of 1 kW, there would be enough energy to shine on that one square meter for 4.1 hours each day of the year. In other words, that square meter would have received (4.1 hrs)(1000 watts)=4100 watt-hours=4.1kWh daily.

If your students are having a hard time understanding the concept of peak sun and peak sun hours, see the Supplement on **Understanding Peak Sun Hours**.

**Understanding Peak Sun Hours**

The sun does not shine at a constant intensity through the course of a day or a year. However, when we talk about “peak sun” we are referring to a specific intensity of the solar radiation received on a 1 m2 area. Peak sun hours is a way of describing how much energy a particular location receives in a set period of time.

To understand this better, consider the day described in the chart below. Each sun represents 100 watts of solar energy received per square meter over the course of an hour. In other words, each sun represents 100 watt\*hours of energy. The intensity of the sun increases from 12 am to 1 pm, and then decreases over the remainder of the day.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 12 am | 1 am | 2 am | 3 am | 4 am | 5 am |
| 6 am | 7 am | 8 am | 9 am | 10 am | 11 am |
| 12 pm | 1 pm | 2 pm | 3 pm | 4 pm | 5 pm |
| 6 pm | 7 pm | 8 pm | 9 pm | 10 pm | 11 pm |

= 100 watts/m2 for 1 hour

*How many watt\*hrs/m2 total were received at this location on this day?*

“Peak sun” is defined as 1000 Watts/m2 (this is the same as 1 kW/m2). “Peak sun hours” refers to 1000 Watt\*hours/m2 (or 1 kWh/m2). Even though there is no hour in the day that received 1000 W/m2, if we add up the total amount of solar radiation received (4700 Watt\*hours), we see that, if compressed into units of peak sun hours, this site has received the energy equivalent of 4.7 hours of peak sun.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 1 hour | 1 hour | 1 hour | 1 hour | 1 hour |  |

How did we determine this? Take all the energy received over the course of the day, and consolidate it so that every hour, the plot receives 1000 Watts. We have enough energy to provide 4.7 hours of energy at this intensity.

Our solar panel modules are rated to produce 250 Watts of power per module at peak sun intensity. We have 5 modules and each module is 1.65 square meters.

*At peak sun, how many Watts of solar energy is each panel receiving?*

*How many Watts is each panel supposed to produce at peak sun?*

*What percent of the solar power are the panels able to capture if working at their rated performance?*

*Is this a well-designed system, or is it inefficient at capturing the sun’s energy? Read the Scientific American article, “*[*Plants versus Photovoltaics: Which are Better to Capture Solar Energy?*](http://www.scientificamerican.com/article/plants-versus-photovoltaics-at-capturing-sunlight/)*” (May 12, 2011 by David Biello) to help you answer this question.*

*Based on the average daily peak sun for our region, how many kWh should our system produce each year if it were functioning at its rated efficiency?*

*Calculate yesterday’s incoming solar energy using the data available from HB’s weather station.*

To access HB weather station data:

1. Open either Firefox or Chrome as your web browser.
2. Go to [www.hobolink.com](http://www.hobolink.com)
3. Login using username “HBMS” and password “hbrown”
4. Click on “Weatherstation”
5. Scroll down until you see “Latest Data” on the left side of the page.
6. Click on the most recent .cvs data file. When it asks, open the file with Microsoft Excel. Alternatively, save the file, and then open it with Excel.

You should now have a spreadsheet with a column showing the W/m2 received on the Link building roof in five minute intervals. Use the spreadsheet to calculate the total Wh or kWh received yesterday by our solar panels. (Don’t forget, our panels cover more than 1 m2.)

*How many KWh did the system produce yesterday?*

*Compare the solar energy available yesterday to yesterday’s energy production.*

To access yesterday’s solar energy production data:

1. In your web browser, go to [www.enlighten.enphaseenergy.com](http://www.enlighten.enphaseenergy.com)
2. Login using username “hbsolar@hb.edu” and password “hbrown”
3. On the “Energy Production” page that should then open, click on “day” on the top menu bar, and then choose the day you are interested in on the graphical calendar below.
4. The kWh of energy produced that day will show up just below the calendar.
5. Alternatively, you can download the energy data in an Excel file by selecting either “daily,” “weekly,” or “current energy” from the “Energy Reports” section at the bottom of the page. (“Current energy” will give you the past week’s production in 5 minute increments.”) Once you have selected your desired format, choose the Excel icon in the upper right of the page to download the data.

*What was the overall efficiency of the system? (In other words, what percentage of the solar energy is the system able to convert to usable electricity?)*

While the solar cells in the panels are unable to capture the full value of the solar radiation that hits them, there are other factors that influence the system efficiency, as well. While the modules are rated to produce 250 Watts at peak sun, on average, only 77% of this power is truly is available for use. The other 27% is lost to system inefficiencies from:

* panel mismatch (XXX – get explanation)
* wiring losses (some power is lost due to resistance in the wires)
* diodes (XXX – get explanation)
* inverter efficiency (power lost in the process of converting DC power to AC power. Our Enphase inverters are rated as 96.5% efficient.)
* soiling (if the panels have any dust or dirt on them, they do not produce as much power)
* aging (0.3% loss/year)

In addition, the season and the weather on any given day will affect the amount of power the system produces. For example, the panels produce better in colder weather than in hot weather.

*Draw a diagram that shows the flow of energy through the system at a given moment in time. Remember, energy is neither created nor destroyed, it simply changes forms. The total energy going into the system should be equal to the total energy coming out of the system.*

**Plans for Independent Practice:**

*Design a system for your house. Using what you learned above about sizing a PV system to generate a certain amount of energy, determine the number of solar modules you would need to install to provide power to your home for a year. Do not forget to take into account losses from inefficiencies in the system.*

*To do this, you will need to find out how much electricity your house uses in a year (ask your parents/guardians to look at the electric bills with them).*

*Disregarding cost, is it realistic for your family to produce all its electricity using on-site solar? Why or why not?*

*If not, what percentage of your family’s electricity could you realistically produce using on-site solar at your home (again, disregarding cost of the system)? What could you do to increase this percentage?*

**Closure:**

As a class

Review key concepts:

* Units of energy: Watts, kilowatts, kilowatt hours
* Conservation of energy
* Loss of power from system inefficiencies
* Solar irradiation, peak sun hours
* Home electricity use

Discuss findings from home energy system design.

Concluding discussion about the strengths and limitations of solar power

**Assessment and Follow-up:**

Teacher should review student work on the activities above and provide feedback to students.

**Adaptations and Accommodations:**

1. For more advanced students, have them draw a diagram that shows where the energy goes in each part of the system, accounting for all incoming energy as it moves through the system. They should be able to demonstrate that energy is neither created nor destroyed, but that it simply changes forms.
2. For less advanced students, allow them to reference the “Process” section of the HB website (www.hb.edu/chargingstation) for a model of how to do the calculations to determine how many panels are needed. They should read through the explanation of the calculations first, and then use them as a reference while they do their own calculations.

**Enrichment Activities:**

1. Look up peak sun hours for different regions of the country/world. Calculate the differences in potential electricity production based on the differences in peak sun.
2. Research the differences in peak sun in Northeast Ohio at different times of year. Calculate the theoretical differences in electricity production at different times of year.
   1. Using the data on electricity production from our solar panels (available on at <https://enlighten.enphaseenergy.com/login>; email for login=hbsolar@hb.edu, password=hbrown), graph monthly solar electricity production. How does the actual solar electricity production compare to theoretical production? Explain your findings.
   2. Research the angle at which the sun’s rays hit the earth in our region at different times of year. How does this sun angle affect the solar radiation our panels receive? Our panels are tilted at a 10 degree angle from horizontal. Is this the best angle to optimize our solar energy production? Why do you think we chose this angle?