Good Day Sunshine!

Student Objective

The student:

- will explain the relationship between sunlight and the power produced by a photovoltaic device
- will predict the performance of a photovoltaic system when given a graph of solar irradiance
- given a graph of a photovoltaic system's power output can deduce what the weather was for the given days
- will infer from a table of irradiance data the relative amount of sunlight in different locations at different times of the year.

Key Words:

hypothesis
irradiance
irradiation
pyronometer

Time:

1 class period

Materials:

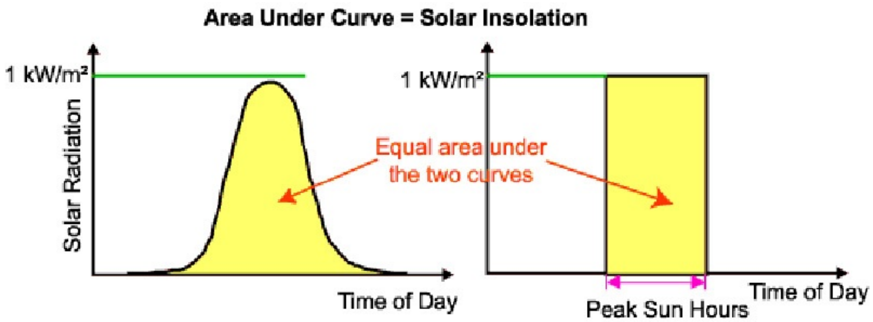
- computer with internet access

Background Information

The performance of a photovoltaic system at any given time depends primarily on the amount of sunlight available to it. On bright, sunny days, the system gradually produces more and more energy throughout the day until the Sun appears directly overhead. A graph showing the energy production of the PV system over time on a sunny day will resemble a smooth, tall, bell shaped curve.

On consistently overcast days, the curve will have the same width but will be much lower, and on partly cloudy days with patches of clouds intermingled with bright sun, the curve will tend to be spiky, showing that the system produces more energy during sunny periods and less energy during cloudy periods.

The power density of sunlight at any given moment is termed irradiance. Scientists have been collecting irradiance data from places all over the world since 1960. This data has been used to calculate the average amount of sunlight at specific places for different times of the year. In order to make the data comparable and even out the effects of daily weather, the raw data is converted into an equivalent number of "Peak Sun Hours". Peak Sun Hours is defined as the number of hours that the sun power equals 1000 watts per square meter. This number is obtained from integration of irradiance over the daylight hours. Basically what is happening is that the total area under the bell-shaped irradiance curve is turned into an equivalent time at a sun intensity level of 1000 watts per square meter.



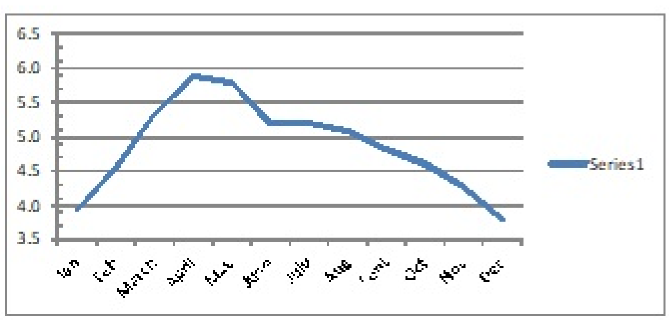
Luckily, the calculations have been done for us and put in insolation tables for easy reference; insolation is the term used for the integral of irradiance. A very sunny day would have a value of 4 - 6 sun hours while a cloudy day may only have the equivalence of 1 sun hour.

Procedure

1. **Engage:** Lead a review discussion on their findings during previous photovoltaic activities as it relates to the seasonal position of the Sun and Earth, and seasonal local weather patterns.
2. **Explore:** Students will research, explore, and analyze data as they complete their Laboratory Manual and related exercises.

Answer Key – Laboratory Manual

1. March has a higher insolation value. Students should take the average of the tilt angles to find that March has an average of 5.3, and August has an average of 5.05 peak hours.
2. Not necessarily true for Orlando, Florida when summer is the cloudy, rainy season and April and March are drier and less cloudy.
3. April. Students should be able to explain what they did to obtain this answer.
4. December. During the winter solstice the Earth is closer, but is also tilted away from the Sun in the Northern Hemisphere. No, in the Southern Hemisphere, the Sun is farther away but Earth is tilted toward the Sun (their summer), therefore more light energy is being received in December.
5.



6. Spokane

7. Answers will vary, but most will feel that Florida should have had more sunlight (the Sunshine State!)
8. Answers will vary, but should include the facts that during the summer months the Earth's tilt is facing the Sun more directly giving Spokane more daylight hours (earlier sunrises and later sunsets) than during the same dates in Orlando which is a lower latitude. Students may also know that July is Spokane's dry season while it is during Orlando's rainy season.
9. Orlando. Students should be able to explain their method of comparing the tables. Acceptable methods include comparing the 0° data for each location, averaging the monthly data for the tilt angle closest to the site's latitude, or averaging the annual per month averages.
10. Spokane is at 47° N latitude and Orlando is at 28° N latitude, which makes the Sun higher in the sky for Orlando, so the tilt angles for Orlando are less to make the panel surface close to perpendicular to the Sun's rays.
11. The Spokane plant would contribute the most solar energy to the grid during June – August.
12. The Orlando plant would contribute the most solar energy to the grid during January – March.
13. 35°, because the highest annual insolation value is achieved at that angle.

Answer Key - Problems

1. Answers will vary according to your location, but the students should approach the problem by figuring out which angle produces the most electricity each month, selecting the two times in spring and fall that maximize the output.
2. Students should take their answer from question 1 and calculate the increase monthly due to the change from the fixed angle position of the array they have been studying.
3. Students should show the ability to move between different units of measurement.

Key Words and Definitions

- **hypothesis** – an explanation for an observation, phenomenon, or scientific problem that can be tested by further investigation
- **irradiance** – the measure of the power density of sunlight; expressed in watts per square meter
- **irradiation** – the measure of the energy density of sunlight reaching an area summed over time; this is usually expressed in kilowatts per square meter per day
- **pyronometer** – a device to measure the amount of solar irradiance

Related Research

1. Look up irradiation data from: different latitudes worldwide; different climatic regions; and different altitudes. Compare the data and determine how each parameter would affect the output of a photovoltaic array.
2. Look up the yearly insolation data from cities in the northern and southern hemisphere

that have the same latitude and similar weather patterns. Graph both sets of data. Analyze the graphs by comparing and contrasting the curves. What astronomical and sunlight conclusions can be made from the information?

3. Compare insolation data from different Florida cities. What part of the differences appear to be from the difference in latitude and what part appears to be caused by the differing weather patterns in the state?

Math Extension - Calculus

1. Have students use graphs of irradiance data for Orlando and Spokane to understand and apply continuity theorems, derivatives, and integrals.

Internet Sites

http://energywhiz.com/

EnergyWhiz is Florida Solar Energy Center's website for SunSmart Schools data, and student activities. Included are static graphs of an array during various weather conditions that can be used in the classroom for problems and discussions.

https://www.nrel.gov/grid/solar-resource/renewable-resource-data.html
http://rredc.nrel.gov/solar/old_data/nsrdb

National Solar Radiation Database contains 50 years of solar radiation and supplementary meteorological data from 237 NWS sites, plus a user manual to help in reading the tabular information.

http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/solar-radiation/

National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center is responsible for preserving, monitoring, assessing, and providing public access to the Nation's treasure of climate and historical weather data and information. Here you can find data on solar radiation and climate conditions in the United States.

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Florida NGSS Standards & Related Subject Common Core

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nature of Science																					
Standard 4	**SC.912.N.4**		X																		
Earth and Space																					
Standard 5	**SC.912.E.5.**				X																
Standard 6	**SC.912.E.6.**						X														
Life Science																					
Standard 17	**SC.912.L.17.**												X								
Mathematics Standards		MAFS.912.N-Q.1.1, MAFS.912.N-Q.1.2, MAFS.912.N-Q.1.3, MAFS.912.F-IF.2.4, MAFS.912.S-ID.1.3																			

Science – Standard 4: Science and Society

- SC.912.N.4.2 - Weigh the merits of alternative strategies for solving a specific societal problem by comparing a number of different costs and benefits, such as human, economic, and environmental.

Science – Standard 5: Earth in Space and Time

- SC.912.E.5.4 - Explain the physical properties of the Sun and its dynamic nature and connect them to conditions and events on Earth.

Science – Standard 6: Earth Structures

- SC.912.E 6.6 - Analyze past, present, and potential future consequences to the environment resulting from various energy production technologies.

Science – Standard 17: Interdependence

- SC.912.L.17.11 - Evaluate the costs and benefits of renewable and nonrenewable resources, such as water, energy, fossil fuels, wildlife, and forests.

Mathematics – Algebra

- MAFS.912.N-Q.1.1 - 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.
- MAFS.912.N-Q.1.2 - Define appropriate quantities for the purpose of descriptive modeling.
- MAFS.912.N-Q.1.3 - Choose a level of accuracy appropriate to limitations on measurement when reporting quantities.
- MAFS.912.F-IF.2.4 - For a function that models a relationship between two quantities,

interpret key features of graphs and tables in terms of the quantities, and sketch graphs showing key features given a verbal description of the relationship.

Mathematics – Statistics & Probability

- MAFS.912.S-ID.1.3 - Interpret differences in shape, center, and spread in the context of the data sets, accounting for possible effects of extreme data points.

National Next Generation Science Standards

Energy

- 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 component and energy flows in and out of the system is known.

Note: Related Common Core Mathematics standards are listed in the Florida section above.

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Irradiance is the scientific term for the amount of sunshine that strikes an object. Scientists have been collecting irradiance data from places all over the world since 1960. This data has been used to calculate the average amount of sunlight at these places for different times of the year. In order to make the data comparable from place to place and even out the effects of daily weather, the data is converted into a number that can be used in equations and for predictions of the amount of irradiance. This number is "peak sun hours". Peak sun hours is defined as the number of hours that the given amount of sunlight would equal when it is all converted to 1000 watts per square meter. A very sunny day would have a value of 4 - 6 sun hours while a cloudy day may only have the equivalence of 1 sun hour.

The irradiance data (listed as peak sun hours or insolation) for Orlando, Florida is shown below.

Insolation – kWh/m^2-day – for Orlando, FL (28.55º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
15º	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
20º	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
25º	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
30º	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
35º	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
40º	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

1. According to the chart above, which of these two months, March or August, has the greatest amount of available or irradiated sunlight when considering all the listed tilt angles?

   How did you obtain this answer?

2. We usually think of the summer months as being the sunniest and therefore the best for photovoltaic systems. Is this a correct assumption?

Why or why not?

3. Which month out of the year has the greatest amount of sun hours? To justify your answer, briefly explain the procedure you followed to obtain this answer.

4. Which month of the year has the least amount of sun hours?

What contributing astronomical event can be used to justify your answer?

Would someone in the southern hemisphere share this same answer? Why or why not?

5. Draw a line graph on a separate sheet of paper to show the average amount of sun hours (y-axis) for each month of the year (x-axis).

The irradiance data for Orlando and Spokane, Washington are below.

Insolation (irradiance) – kWh/m^2-day – for Orlando, FL (28.55° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
15°	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
20°	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
25°	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
30°	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
35°	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
40°	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

Insolation – kWh/m^2-day – for Spokane, WA (47.63° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	0.99	1.91	3.28	4.72	6.05	6.57	7.44	6.13	4.53	2.65	1.25	0.81	3.86
35°	1.84	2.93	4.13	5.10	5.91	6.14	7.12	6.41	5.45	3.84	2.18	1.63	4.40
40°	1.92	3.01	4.16	5.04	5.76	5.95	6.92	6.31	5.46	3.93	2.27	1.71	4.38
45°	1.99	3.08	4.17	4.97	5.59	5.73	6.69	6.18	5.44	3.99	2.34	1.78	4.34
50°	2.05	3.13	4.16	4.86	5.39	5.49	6.42	6.01	5.39	4.03	2.40	1.84	4.27
55°	2.09	3.15	4.12	4.73	5.17	5.22	6.13	5.81	5.31	4.05	2.44	1.89	4.18
60°	2.12	3.16	4.06	4.58	4.92	4.93	5.80	5.59	5.20	4.04	2.46	1.92	4.07

6. Based on the data above, which city has the greatest amount of sun hours in July?

7. Is this what you would have expected? Why or why not?

8. What factors do you think contribute to this effect?

9. Which location has the greatest yearly average irradiance? How did you obtain this answer?

10. Why are the tilt angles different for the two cities listed in the data tables?

11. Looking at the big picture, supplying electricity to the U.S. using photovoltaic power plants, during which months would the Spokane plant contribute the most solar energy to the grid?

12. During which months would the Orlando plant contribute the most solar energy to the grid?

13. What tilt angle would you recommend for the Spokane solar array? Why?

Good Day Sunshine!

1. Your school decides to design a rack system for your SunSmart array that can be set at two different tilt angles to maximize the output of the system for both winter and summer conditions. For the largest increase in power, what two angles should the array be set at, and what months should the array tilt be changed?

2. What would be the increase in kWh of electricity over the course of a year for the array with the new racking system?

3. If the new racking system cost $1000 to fabricate, how long would it take for the additional savings in electricity cost to pay for the new rack? (Assume electricity at 12 cents per kWh)

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Insolation data below is from National Renewable Energy's Solar Resource Data and Tools
https://www.nrel.gov/grid/solar-resource/renewable-resource-data.html

Insolation – kWh/m^2-day – for Daytona Beach, FL (29.18º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.1	3.9	5.0	6.2	6.4	6.1	6.0	5.7	4.9	4.2	3.4	2.9	4.8
15º	3.8	4.5	5.5	6.4	6.4	6.0	5.9	5.8	5.2	4.7	4.1	3.6	5.2
30º	4.3	4.9	5.7	6.3	6.0	5.5	5.5	5.6	5.3	5.0	4.6	4.1	5.2
45º	4.6	5.1	5.6	5.9	5.4	4.8	4.9	5.1	5.1	5.1	4.8	4.4	5.1

Insolation – kWh/m^2-day – for Jacksonville, FL (30.50º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	2.9	3.7	4.7	5.9	6.1	6.0	5.8	5.4	4.6	4.0	3.2	2.7	4.6
15º	3.6	4.3	5.2	6.1	6.1	5.8	5.7	5.5	5.0	4.5	3.9	3.4	4.9
30º	4.2	4.7	5.5	6.0	5.7	5.4	5.4	5.3	5.0	4.9	4.4	3.9	5.0
45º	4.4	4.9	5.4	5.6	5.1	4.7	4.7	4.9	4.8	4.9	4.7	4.2	4.9

Insolation – kWh/m^2-day – for Key West, FL (24.55º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.7	4.4	5.5	6.3	6.3	6.1	6.1	5.8	5.2	4.6	3.8	3.4	5.1
10º	4.2	4.9	5.8	6.5	6.3	6.0	6.0	5.9	5.4	5.0	4.4	4.0	5.4
25º	4.9	5.5	6.1	6.4	6.0	5.5	5.6	5.7	5.5	5.4	5.0	4.7	5.5
40º	5.3	5.7	6.0	6.0	5.3	4.8	5.0	5.2	5.3	5.5	5.3	5.1	5.4

Insolation – kWh/m²-day – for Miami, FL (25.80º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.5	4.2	5.2	6.0	6.0	5.6	5.8	5.6	4.9	4.4	3.7	3.3	4.8
10º	4.1	4.7	5.5	6.2	5.9	5.5	5.7	5.6	5.1	4.7	4.2	3.9	5.1
25º	4.7	5.2	5.7	6.1	5.6	5.1	5.4	5.5	5.1	5.1	4.7	4.5	5.2
40º	5.0	5.4	5.6	5.7	5.0	4.5	4.8	5.0	4.9	5.1	4.9	4.9	5.1

Insolation – kWh/m²-day – for Tallahassee, FL (30.38º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	2.9	3.7	4.7	5.9	6.3	6.1	5.8	5.5	4.9	4.3	3.3	2.7	4.7
15º	3.6	4.3	5.2	6.1	6.2	6.0	5.7	5.6	5.3	5.0	4.1	3.4	5.0
30º	4.0	4.7	5.4	6.0	5.9	5.6	5.4	5.4	5.3	5.4	4.6	4.0	5.1
45º	4.3	4.9	5.3	5.6	5.2	4.9	4.7	4.9	5.1	5.5	4.8	4.2	5.0

Insolation – kWh/m²-day – for Tampa, FL (27.97º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.2	4.0	5.1	6.2	6.4	6.1	5.8	5.5	4.9	4.4	3.6	3.1	4.9
15º	3.9	4.6	5.5	6.4	6.4	5.9	5.7	5.5	5.2	5.0	4.2	3.8	5.2
30º	4.5	5.1	5.8	6.3	6.0	5.5	5.3	5.4	5.2	5.4	4.8	4.4	5.3
45º	4.8	5.3	5.7	5.9	5.3	4.8	4.7	4.9	5.0	5.5	5.1	4.7	5.1

Insolation – kWh/m²-day – for West Palm Beach, FL (26.68º North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0º	3.3	4.0	5.0	5.9	6.0	5.7	5.9	5.6	4.8	4.2	3.4	3.1	4.7
10º	3.8	4.5	5.3	6.1	5.9	5.6	5.8	5.6	5.1	4.6	4.0	3.7	5.0
25º	4.4	5.0	5.6	6.0	5.6	5.2	5.4	5.4	5.1	4.9	4.5	4.3	5.1
40º	4.7	5.1	5.5	5.6	5.0	4.5	4.8	5.0	4.9	5.0	4.7	4.7	5.0