Section 2: The Science of Solar Energy

Solar Radiation[9]

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. On average the extraterrestrial irradiance is 1,367 Watts/meter2 (W/m2). This value varies by ±3% as the earth orbits the sun. The earth's closest approach to the sun occurs around January 4th and it is furthest from the sun around July 5th. The extraterrestrial radiation is:

Io= 1367 * (Rav / R)2 W/m²

where Rav is the mean sun-earth distance and R is the actual sun-earth distance depending on the day of the year. An approximate equation for the effect of the earth-sun distance is:

(Rav / R)2 = 1.00011
+ 0.034221 * cos(b)
+ 0.001280 * sin(b)
+ 0.000719 * cos(2b)
+ 0.000077 * sin(2)

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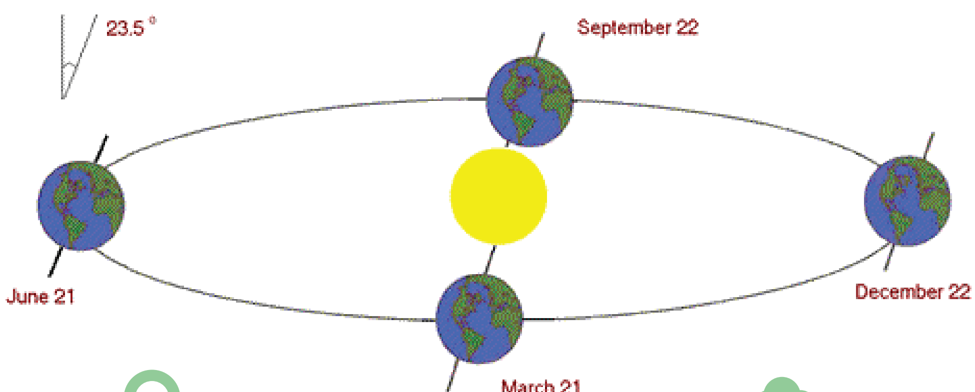
where b = 2pn / 365 radians and n is the day of the year. For example, January 15th is year day 15 and February 15th is year day 46. There are 365 or 366 days in a year depending if the year is a leap year.

Figure 1: Earth's axis is tilted approximately 23.45 degrees with respect to the sun.



The earth's axis is tilted approximately 23.45 degrees with respect to the earth's orbit around the sun. As the earth moves around the sun, the axis is fixed if viewed from space (Figure 1). In June the orientation of the axis is such that the northern hemisphere is pointed towards the sun. In December the earth is on the other side of the sun and the earth's axis in the northern hemisphere is pointing away from the sun. During the spring and fall equinoxes, the earth's axis is perpendicular to an imaginary line drawn between the earth and the sun.

As viewed from earth, the sun is higher in the sky during summer and lower in the sky as winter approaches. (Note that summer in the northern hemisphere is winter in the southern hemisphere and vice versa.) The declination of the sun is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis.

Zenith, Azimuth, and Hour Angles

To describe the sun's path across the sky one needs to know the angle of the sun relative to a line perpendicular to the earth's surface—this is called the zenith angle (q)—and the sun's position relative to the north-south axis, the azimuth angle (a). The hour angle (w) is easier to use than the azimuth angle because the hour angle is measured in the plane of the "apparent" orbit of the sun as it moves across the sky. Since the earth rotates approximately once every 24 hours, the hour angle changes by 15 degrees per hour and moves through 360 degrees over the day. Typically, the hour angle is defined to be zero at solar noon, when the sun is highest in the sky.

Solar and Local Standard Time

To describe the position of the sun in local standard time, the relationship between solar time and local standard time needs to be understood. Local time is the same in the entire time zone, whereas solar time relates to the position of the sun with respect to the observer, and that is different depending on the exact longitude where solar time is calculated. To adjust solar time for longitude, one must subtract (Longlocal – Longsm)/15 (units are hours) from the local time. Longlocal is the longitude of the observer in degrees and Longsm is the longitude for the standard meridian for the observer's time zone.

Equation of Time

As the earth moves around the sun, solar time changes slightly with respect to local standard time. (This is mainly related to the conservation of angular momentum as the earth moves around the sun.) This time difference is called the equation of time and can be an important factor when one is at sea navigating by the sun or stars. It is also important when determining the position of the sun for solar energy calculations. An approximate formula for the equation of time (Eqt) in minutes is:

for year day n between 1 and 106: $Eqt = -14.2 \sin(p(n + 7) / 111)$
for year day n between 107 and 166: $Eqt = 4.0 \sin(p(n - 106) / 59)$
for year day n between 167 and 246: $Eqt = -6.5 \sin(p(n - 166) / 80)$
for year day n between 247 and 365 $Eqt = 16.4 \sin(p(n - 247) / 113)$

Using the longitude correction and the equation of time, the relationship between the solar time and local standard time is:

$$T_{solar} = T_{local} + Eqt / 60 + (Long_{sm} - Long_{local}) / 15$$

Values are in hours. Since equations use sine and cosine functions it is conceptually easier to calculate using the hour angle (w) instead of time. The relationship between hour angle and time is:

$$w = p * (12 - T_{solar}) / 12$$

The hour angle is in units of radians.

With the above information, one can now calculate the cosine of the zenith angle:

$$\cos(Z) = \sin(l)\sin(d) + \cos(l)\cos(d)\cos(w)$$

where l is the latitude of the location of interest.

Sunrise and Sunset Times

The calculation of sunrise and sunset times provides an easy exercise to test your understanding of the information presented so far. Sunrise and sunset occur when the sun is at the horizon and hence the cosine of the zenith angle is zero.

The sunrise and sunset hour angles are not exactly the same value as the sunrise and sunset times that appear in the local paper. The sunrise reported in the paper will be earlier and the sunset times will be later. The reason for this difference is that the sunlight is refracted as it moves through the earth's atmosphere and the sun appears slightly higher in the sky than simple geometrical calculations indicate. This is the same effect that makes a stick appear to bend when it is placed in water. During the middle of the day the effect is small, but during the sunrise or sunset periods, the effect can change the apparent solar time by about 5 minutes.

Solar Cells and Electricity[10]

To understand how solar cells work, we must first understand two facts about photons. First, sunlight is composed of photons of various energies. Second, photons can interact with atoms, and if a photon has sufficient energy, it can break the bond between an electron and an atom.

The trick to making solar cells produce electricity is the ability to "collect" an electron once it has been separated from an atom. The resulting flow of electrons is called the photocurrent. To illustrate the general principles of solar electricity, we will examine solar cells made from single crystal silicon.

Silicon is an atom with four valence electrons. In single crystal silicon, each of the valence electrons forms a bond with a valence electron of a neighboring silicon atom. This electron to electron bond is very strong, and in a perfect crystal there are no free valence electrons waiting to bond with another electron. Electrons bond in pairs when possible.

Pure single crystal silicon is a very poor conductor because all the valence electrons are bonded with their neighbors. To collect the photocurrent, solar cells are constructed like a battery. This is done by taking two semiconductors of opposite charge and putting them together.

To make solar cell semiconductor material from silicon approximately 2x1016/cm^3 acceptor atoms (atoms with three valence electrons such as boron) or approximately 1019/cm^3 donor atoms (atoms with five valence electrons such as phosphorous) are substituted for the silicon atoms with four valence electrons.

When phosphorous is substituted for a silicon atom, four of the five valence electrons form strong bonds with the nearest silicon electrons, and the remaining electron is very loosely bound by the slightly more positive charge of the nucleus of the phosphorous atom. However, this electron travels easily around the crystal lattice in the area of the phosphorous atom. Silicon that contains a large number of atoms with an extra valence electron is called n type silicon (n is for negative).

If a boron atom is substituted for a silicon atom, the three valence electrons form strong bonds with the nearest silicon electrons, but there is one silicon electron that is left looking for a partner to bond with. This missing electron that is being sought for bonding is called a hole. Because the hole is a missing electron, it can be treated mathematically like the free electron when phosphorous is substituted, but it effectively has a positive charge (the absence of a negative electron). Silicon that contains a large number of atoms with one less valence electron is called p type silicon (p is for positive). The process of substituting boron or phosphorous atoms for silicon atoms is called doping. This is often done by thermal diffusion.

A solar battery is created when n- and p-type silicones are placed next to each other. The extra electrons from the phosphorous are attracted to the holes created by the doping of the silicon with boron. This occurs because binding of the electron pairs is much stronger than the electromagnetic attraction between the outer electrons and the nucleus of the atoms that is masked by the electrons that are surrounding each atom in the crystal structure.

Near the junction of the n- and p-type material, holes on the p-side are filled with the free electrons from the n-side forming strong, stable electron pair bonds. This results in a shift in charge that creates an electric field in the material. When the free valence electron from the n-side combines with the single bound valence electron on the p-side, the phosphorus atom is surrounded by one less electron than there are positive protons in the phosphorus nucleus.

Similarly, the boron atom is surrounded by one more electron than there are positive protons in the boron nucleus. While this n-p 'junction' is only a few atoms thick, the resulting electric field creates a barrier that prevents additional crossover of holes from the p-side and electrons from the n-side. This electric field (resulting in an electromotive force, EMF, of approximately 0.5 volts) makes it possible to create the photocurrent when light breaks the electron-electron pair bond.

When the photon enters the material and breaks apart an electron pair, a negative electron and a positive hole are created. If it weren't for the electric field, the electron and the hole would attract and recombine. With the electric field, the negative electron goes one direction and the positive hole goes the other direction. This is the source of the electricity of a solar cell.

The minimum energy that it takes to break up the electron-electron bond is called the band gap. Photons with energy less than the band gap won't separate the electron pairs. Photons with more energy than necessary to separate the electron pairs result in electrons and holes with more kinetic energy.

When solar cells get hot, the electrons and atoms are vibrating faster and the effectiveness of the electric field to separate the electrons and holes is diminished. The randomly directed kinetic energy becomes the dominant factor governing the motion of the electrons and holes. Typical loss in efficiency is about 0.1%/degree Celsius measured solar cell temperature. (A solar cell that is 16% efficient at 25º Celsius will be 9% efficient at 100º Celsius.)

Semiconductors[11]

A solar cell consists of semiconductor materials. Silicon remains the most popular material for solar cells, including these types:

- Monocrystalline or single crystal silicon
- Multicrystalline silicon
- Polycrystalline silicon
- Amorphous silicon

The absorption coefficient of a material indicates how far light with a specific wavelength (or energy) can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material. The absorption coefficient of a solar cell depends on two factors: the material making up the cell and the wavelength or energy of the light being absorbed.

The bandgap of a semiconductor material is an amount of energy. Specifically, the bandgap is the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the "valence band." The higher energy level where an electron is free to roam is called the "conduction band." The bandgap (often symbolized by Eg) is the energy difference between the conduction band and valence band. Solar cell material has an abrupt edge in its absorption coefficient. Because light with energy below the material's bandgap cannot free an electron, it isn't absorbed.

Series and Parallel Circuits

Voltage increases when voltage sources are connected in series. Series wiring does not increase the amperage produced. When wiring in series, the positive (+) contact is connected to the negative (-) contact in a circuit. Series circuits can also be illustrated with the batteries in a flashlight. Each battery in the flashlight is 1.5 volts. The flashlight requires 6 volts to function. To create 6 volts, the batteries are connected in series by setting the positive terminal against the negative when they are inserted into the flashlight.

The current increases when voltage sources are connected in parallel wiring. Parallel wiring does not increase the voltage produced. When wiring in parallel, the positive (+) is connected to the negative (-) contact in a circuit. Batteries are also often connected in parallel to increase the total amps, which increases the storage capacity and prolongs the operating time.

Solar Modules[12]

The majority of PV modules in use since the inception of the modern solar panel by Bell Labs are made of single or multicrystalline silicon. Satellites and other space applications use single crystal silicon or single crystal gallium arsenide modules because these materials are capable of producing a high power output. The other major types of modules on the market today are known as amorphous, thin-film technology.

Thin-film modules are manufactured from a few different materials including cadmium telluride (CdTe) and copper indium dieseling (CuInSe2 or CBS). Thin-film technology is more costly than single or multicrystalline silicon. The difference between the two solar technologies is the space required to produce equivalent power. While a single or multicrystalline PV cell is capable of producing 220 watts in 12 square feet, a thin-film panel of the same size produces roughly half the output.

But size is not always the determining factor when working with solar technology. Location, shading, and building integration are also considerations when installing solar electricity. Thin-film modules have the advantage when shading is a concern. A single or multicrystalline cell is comprised of many cells wired together in series. If one or more of the cells in the module is shaded, the power production decreases dramatically. Thin-film modules are made of a single sheet of material. Thin-film modules will still produce near their rated output even when roughly twenty percent of the panel is shaded. Thin-film technology is also useful when integrating solar into a building. Some thin-film modules are translucent and can be used anywhere a regular window pane is located. This gives the advantage of producing electricity while still allowing light to penetrate the interior space of a building. Another major difference in these solar technologies is the cost. Single and multicrystalline modules are dominant on the market today because they are the most cost-effective application of solar currently available. These cells are generally considered to cost approximately five dollars a watt, while amorphous technology costs approximately nine dollars a watt.

Solar Arrays

A solar array (also referred to as PV array) is a group of PV modules put together to generate electricity. A solar array may consist of one module or thousands of modules. Likewise, the array output may vary from a few watts to tens of Megawatts.

Solar arrays produce direct current that is used to power the load, which can range from charging a battery in a calculator, to powering a communications system, to powering a building or city. When a solar array is connected to the utility grid, it must first be connected to an inverter that changes the direct current (DC) to alternating current (AC). Most inverters run at about 90% efficiency.

Today's inverters are very sophisticated and produce clean power at a stable voltage. The inverters are able to produce clean power because the AC is in the form of a sine wave with very little distortion or higher order harmonics. The grid-connected inverters are designed to stop the flow of electricity to the utility grid if power from the grid fails. This prevents injury to those who work on the power lines to restore power. To attain the most electricity from the solar cell array, inverters contain a module that monitors the voltage and current from the array and the load and makes adjustments to maximize the energy output from the array. This module is called the max power point tracker.

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9 Text for *Solar Radiation* adopted form Solar Radiation Monitoring Lab.

10 Text for *Solar Cells and Electricity* was adopted from the Solar Radiation Monitoring Lab.

11 Text for *Semiconductors* was adopted from the Department of Energy.

12 Text for *Solar Modules* and *Solar Arrays* was adopted from Solar Radiation Monitoring Lab.