EE462L, Power Electronics, Solar Power, I-V Characteristics

Version January 31st, 2014

Report Details

Choose any of the solar stations, but take your measurements only when the short circuit current is at least **3.5 A**. (To test this, make sure the solar panel switch at the yellow lab station is OFF, and short the load with a 14 or 16 AWG wire. Then, flip the switch ON and quickly record the short circuit current value from the current gauge. Then, quickly turn the switch back OFF again and disconnect the wire short across the load terminals.)

The weather forecast from www.weatherunderground.com can help you plan your schedule. Cloud cover forecast provided by the National Oceanic and Atmospheric Administration from http://www.nws.noaa.gov/forecasts/graphical/sectors/southplains.php#tabs can also be helpful.

Ideally, you will want to pick a time to collect your solar photovoltaic (PV) panel measurements when skies are clear, and sun is plentiful. **Thus, solar noon on a clear day, when the sun is near its peak position in the sky would be an optimal time.** Note, do not confuse the acronym for *photovoltaic* (PV) with the symbols for *power* (P) and *voltage* (V)

Avoid rainy, overcast, or even partly cloudy conditions where rogue clouds may negatively affect your solar PV panel's generation output by obscuring direct sunlight. This effect may wreak havoc if one is collecting real-time solar PV data points, for it will change the solar panel's instantaneous I-V curve.

Additionally, note that timing may dictate that you and your partner must meet at an unscheduled lab session time to collect your solar data. For instance, if your lab session normally meets Wednesday evenings, from 6:30 pm – 9:30 pm, you will find it near impossible to collect good solar data during this time period. Thus, you and your lab partner will need to reconvene at a more acceptable time, conducive to your schedules. Check the 2nd Floor lab hours of operation. These should be posted out in the hallway near the parts counter.

Thus, variable weather conditions and timing issues are why students have been given multiple weeks to perform their solar data collections. This should give you and your lab partner ample time to find a good, clear day to collect your solar data measurements closer to peak solar generation.

Also note, there is no "build" for this experiment – the lab time is strictly for data collection using one of the yellow solar panel stations and a load rheostat (variable resistor). The data collection shouldn't take students more than 30 to 45 minutes. Please print out the form provided on page 19 of this document, record your raw data there, perform a rough I-V trace, and then present your data to the TAs or the Professor so they may sign off that your solar data collection is within acceptable limits. Then, you may begin the write-up for your lab report. Make sure to staple your raw data collection form to the back of your lab report, as indicated. Lastly, please heed the Professor's syllabus for exact due dates regarding your solar lab.

Your report should include graphs of I versus V, and P versus V. Both actual data and Excel approximations should be plotted together. When plotting with Excel, be sure to use the "scatter plot" option so that the non-uniform spacing between voltage points on the x-axis show correctly. You should also work out numerical values for Equations (1) – (9) for the day and time of your measurements.

Overview
Incident sunlight can be converted into electricity by photovoltaic conversion using a solar panel. A solar panel consists of individual cells that are large-area semiconductor diodes, constructed so that light can penetrate into the region of the p-n junction. The junction formed between the n-type silicon wafer and the p-type surface layer governs the diode characteristics as well as the photovoltaic effect. Light is absorbed in the silicon, generating both excess holes and electrons. These excess charges can flow through an external circuit to produce power.

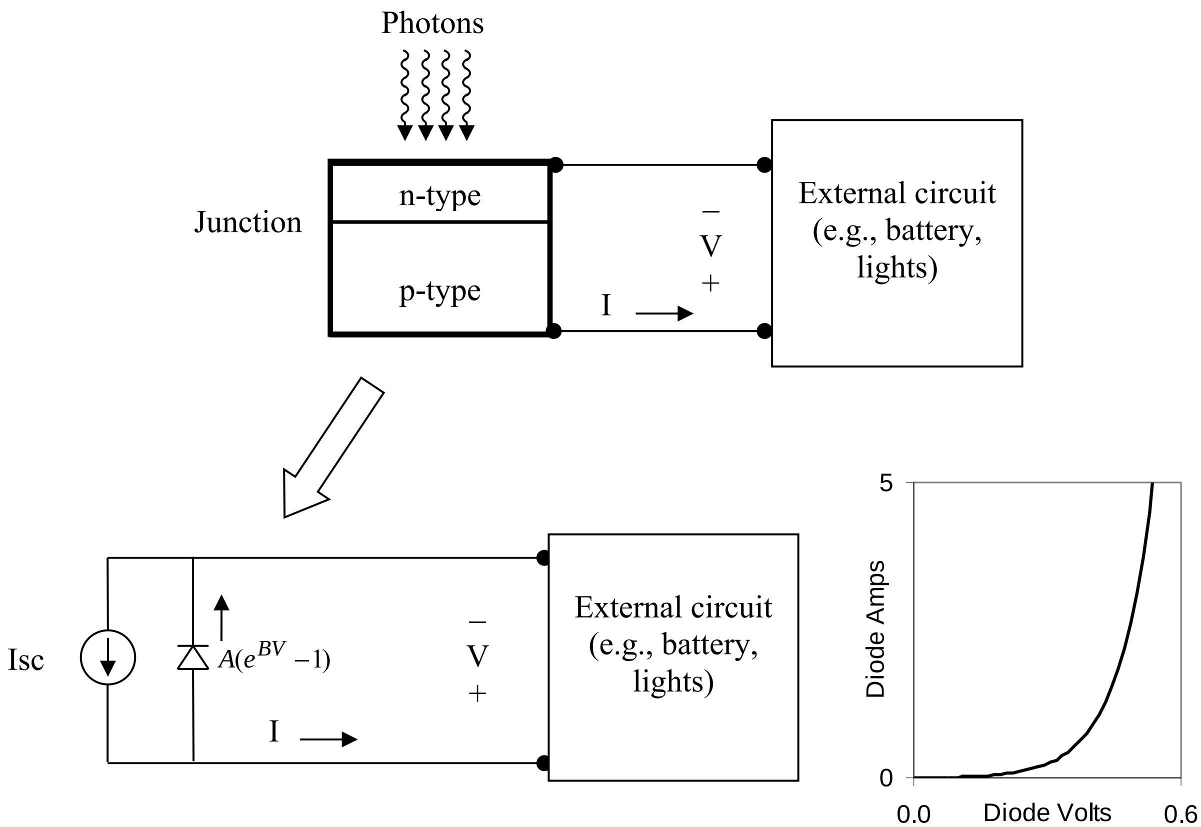


Figure 1. Equivalent Circuit of a Solar Cell

Diode current $A(e^{BV} - 1)$ comes from the standard I-V equation for a diode, plotted above. From Figure 1, it is clear that the current I that flows to the external circuit is $I = I_{SC} - A(e^{BV} - 1)$. If the solar cell is open circuited, then all of the I_{SC} flows through the diode and produces an open circuit voltage of about 0.5-0.6 V. If the solar cell is short circuited, then no current flows through the diode, and all of the I_{SC} flows through the short circuit.

Since the V_{OC} for one cell is approximately 0.5-0.6 V, then individual cells are connected in series as a "solar panel" to produce more usable voltage and power output levels. Most solar panels are made to charge 12 V batteries and consist of 36 individual cells (or units) in series to yield panel $V_{OC} \approx$ 18-20 V. The voltage for maximum-panel-power output is usually about 16-17 V. Each 0.5-0.6 V series unit can contain a number of individual cells in parallel, thereby increasing the total panel surface area and power generating capability.

$I = I_{SC} - A(e^{BV} - 1)$, where A, B, and especially I_{SC} vary with solar insolation

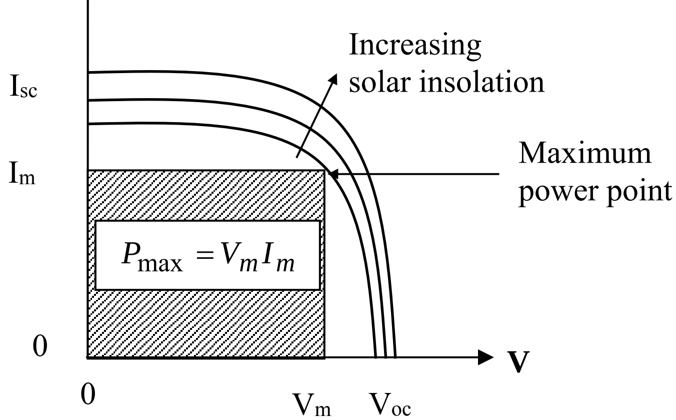


Figure 2. I-V Characteristics of Solar Panel

On a clear day, direct normal solar insolation (i.e., incident solar radiation) is approximately 1,000 W/m^2. Since solar panel efficiencies are approximately 14%, a solar panel will produce about 140 W per square meter of surface area when facing a bright sun. High temperatures reduce panel efficiency. For 24/7 power availability, solar energy must be stored in deep-discharge batteries which have sufficient capacity to power the load through the nighttime and overcast days. On good solar days in Austin, you can count on solar panels producing about 1 kWh of energy per square meter per day.

An everyday use of solar power is often seen in school zone and other LED flashing signs, where TxDOT and municipal governments find them economical when conventional electric service is not readily available or when the monthly minimum electric fees are large compared to the monthly kWh used. Look for solar panels on top of these signs, and also note their orientation.

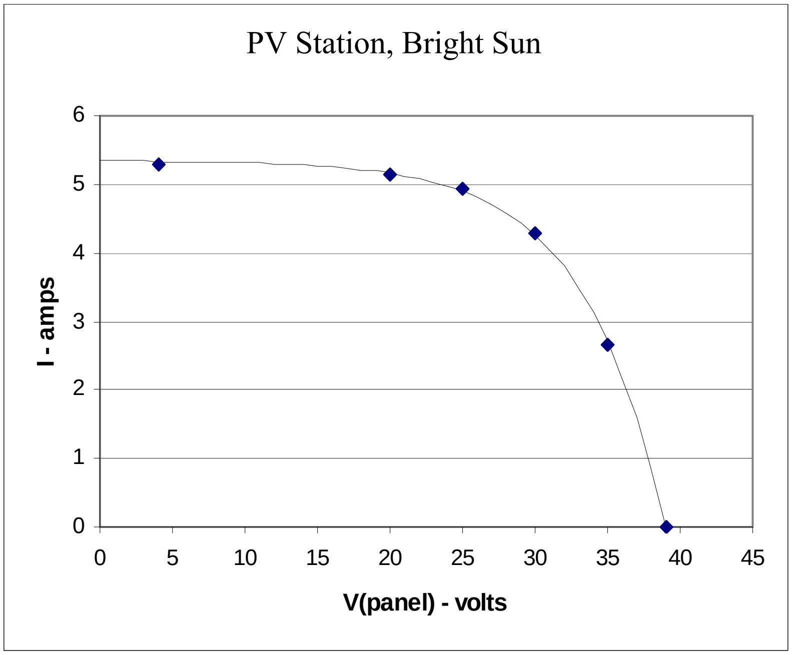
The Solar Panels on ENS Rooftop

The ENS rooftop is equipped with six pairs of commercial "12 V class" panels, plus one larger "24 V class" commercial panel. The panels are:

- three pair of British Petroleum BP585, (mono-crystalline silicon, laser grooved, **each panel** 85 W, voltage at maximum power = 18.0 V, current at maximum power = 4.7 A, open circuit voltage = 22.3 V, short circuit current = 5.0 A). These three pairs are connected to ENS212 stations 17, 18, and 19.
- two pair of Solarex SX85U (now BP Solar) (polycrystalline silicon, **each panel** 85 W, voltage at maximum power = 17.1 V, current at maximum power = 5.0 A, open circuit voltage = 21.3 V, short circuit current = 5.3 A). These two pairs are connected to ENS212 stations 15 and 16.
- one pair of Photowatt PW750-80 (multi-crystalline cells, **each panel** 80 W, voltage at maximum power = 17.3 V, current at maximum power = 4.6 A, open circuit voltage = 21.9 V, short circuit current = 5.0 A). This pair is connected to ENS212 station 21.
- one British Petroleum BP3150U, 150 W panel (multicrystalline), open circuit voltage = 43.5 V, short circuit current = 4.5 A. This is connected to ENS212 station 20.

Each of the seven stations is wired to ENS212 and has an open circuit voltage of approximately 40 V and a short circuit current of approximately 5 A. The I-V and P-V characteristics for one of the panel pairs is shown in Figure 3. The I-V curve fit equation for Figure 3 is

$$I(V) = 5.34 - 0.00524\left(e^{0.1777V} - 1\right).$$



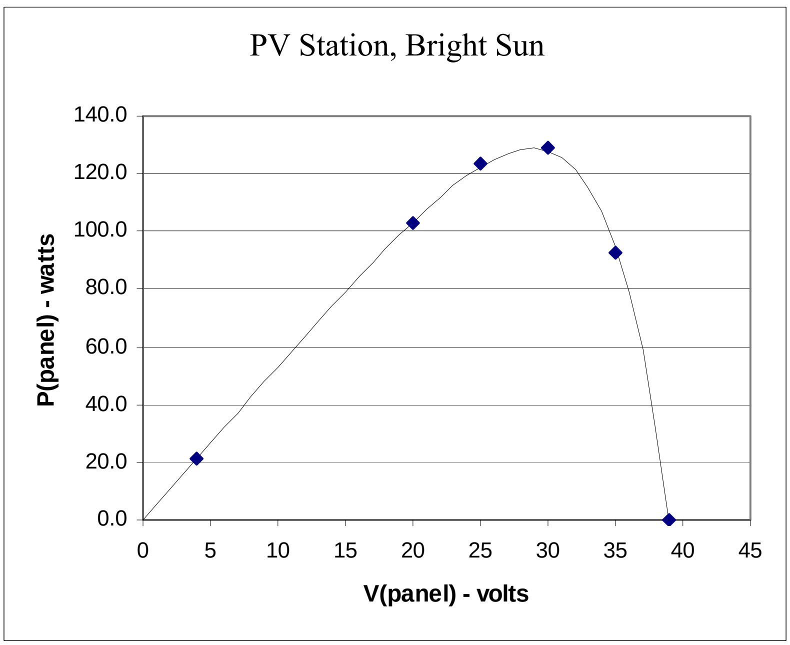


Figure 3. I-V and P-V Characteristics for One of the Panel Pairs
(data points taken by loading the panel pair with a variable load resistor)

Maximum Power

As seen in bottom figure of Figure 3, panels have a maximum power point. Maximum power corresponds to V_m and I_m in Figure 2. Because solar power is relatively expensive (approx. $2-3 per watt for the panels, plus the same amount for batteries and electronics, refer to http://www.nrel.gov/docs/fy13osti/56776.pdf), it is important to operate panels at their maximum power conditions. Unfortunately, V_m, I_m, and the Thevenin equivalent resistance vary with light level. DC-DC converters are often used to "match" the load resistance to the Thevenin equivalent resistance of the panel to maximize the power drawn from the panel. These "smart" converters (often referred to as "tracking converters") also charge the storage batteries in such a way as to maximize battery life.

Sun Position

Ideally, a solar panel should track the sun so that the incident solar rays are perpendicular to the panel surface, thus maximizing the capture of solar energy. However, because of high wind loads, most panels are fixed in position. Often, panel tilt (with respect to horizontal) is adjusted seasonally. Orientation of fixed panels should be carefully chosen to capture the most energy for the year, or for a season.

The position of the sun in the sky varies dramatically with hour and season. Sun zenith angle θ_{sun}^{zenith} is expressed in degrees from vertical. Sun azimuth $\phi_{sun}^{azimuth}$ is expressed in degrees from true north. Sun zenith and azimuth angles are illustrated in Figure 4.

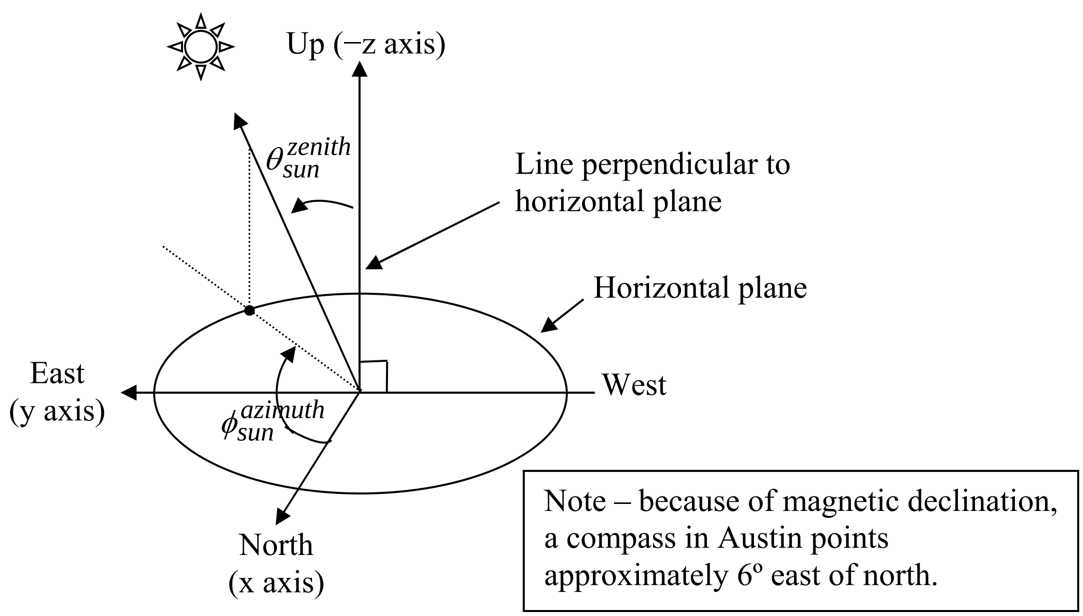


Figure 4. Sun Zenith and Azimuth Angles

Sun position angles are available in many references, and with different levels of complexity. For our purposes, we use the following equations (1) – (8) taken from the University of Oregon Solar Radiation Monitoring Laboratory (http://solardat.uoregon.edu/SolarRadiationBasics.html) as described below:

Sun declination angle (i.e. the angle between the equator and a line drawn from the center of the Earth to the center of the sun) in radians is

$$\delta = 23.45 \bullet \frac{\pi}{180} \bullet \sin\left(2\pi \bullet \frac{(284+n)}{365}\right),\ n = \text{day of year (i.e., 1,2,3, … , 364,365)}. \tag{1}$$

Equation of time (in decimal minutes) is

$$\text{for } 1 \le n \le 106,\ E_{qt} = -14.2 \bullet \sin\left(\pi \bullet \frac{(n+7)}{111}\right),$$
$$\text{for } 107 \le n \le 166,\ E_{qt} = 4.0 \bullet \sin\left(\pi \bullet \frac{(n-106)}{59}\right),$$
$$\text{for } 167 \le n \le 246,\ E_{qt} = -6.5 \bullet \sin\left(\pi \bullet \frac{(n-166)}{80}\right),$$
$$\text{for } 247 \le n \le 365,\ E_{qt} = 16.4 \bullet \sin\left(\pi \bullet \frac{(n-247)}{113}\right). \tag{2}$$

Solar time (in decimal hours) is

$$T_{solar} = T_{local} + \frac{E_{qt}}{60} + \frac{\left(Longitude_{timezone} - Longitude_{local}\right)}{15}, \tag{3}$$

where

- T_{local} is local standard time in decimal hours,
- $Longitude_{timezone}$ is the longitude at the eastern edge of the time zone (e.g., $90°$ for Central Standard Time).

(Note – in the Solar_Data_Analyzer program, $\left(Longitude_{timezone} - Longitude_{local}\right)$ is entered as "Longitude shift (deg)." At Austin, with $Longitude_{local} = 97.74°$, the longitude shift is $\left(90° - 97.74°\right) = -7.74°$. The latitude at Austin is 30.29°.).

Hour angle (in radians) is

$$\omega = \pi \bullet \left(\frac{12 - T_{solar}}{12}\right). \tag{4}$$

Cosine of the zenith angle is

$$\cos\left(\theta_{sun}^{zenith}\right) = \sin(\lambda)\sin(\delta) + \cos(\lambda)\cos(\delta)\cos(\omega), \tag{5}$$

where λ is the latitude of the location.

Solar azimuth comes from the following calculations. Using the formulas for solar radiation on tilted surfaces, consider vertical surfaces directed east and south. The fraction of direct component of solar radiation on an east-facing vertical surface is

$$f_{VE} = \cos(\delta)\sin(\omega)\,. \tag{6}$$

The fraction of direct component of solar radiation on a south-facing vertical surface is

$$f_{VS} = -\sin(\delta)\cos(\lambda) + \cos(\delta)\sin(\lambda)\cos(\omega)\,. \tag{7}$$

Equations (6) and (7) correspond to the projections, on the horizontal plane, of a vector pointing toward the sun. By examining Figure 4, $\phi_{sun}^{azimuth}$ can be found as follows:

$$\text{If } f_{VE} \geq 0,\ \phi_{sun}^{azimuth} = \cos^{-1}\left(\frac{-f_{VS}}{\sqrt{f_{VE}^2 + f_{VS}^2}}\right),$$

$$\text{If } f_{VE} < 0,\ \phi_{sun}^{azimuth} = \pi + \cos^{-1}\left(\frac{f_{VS}}{\sqrt{f_{VE}^2 + f_{VS}^2}}\right). \tag{8}$$

Illustrations of seasonal and daily sun positions for Austin are shown in Figures 5a and 5b.

Using the above procedure to find the sun position for 3pm (i.e., 15.00 decimal hours) on October 25th in Austin yields

Input	n = 298th day	
Compute	$\delta = -13.11^{o}$	
Compute	$E_{qt} = 16.21$ decimal minutes	
Input	Longitude = 97.74º	
Input	Longitude shift = -7.74^{o}	
Input	$T_{local} = 15.00$ decimal hours	
Compute	$T_{solar} = 14.75$ decimal hours	
Compute	$\omega = -41.25^{o}$	
Input	Latitude (L) = 30.29º	
Compute	$\theta_{sun}^{zenith} = 58.81^{o}$	← output
Compute	$f_{VE} = -0.6421$	
Compute	$f_{VS} = 0.5651$	
Compute	$\phi_{sun}^{azimuth} = 228.7^{o}$	← output

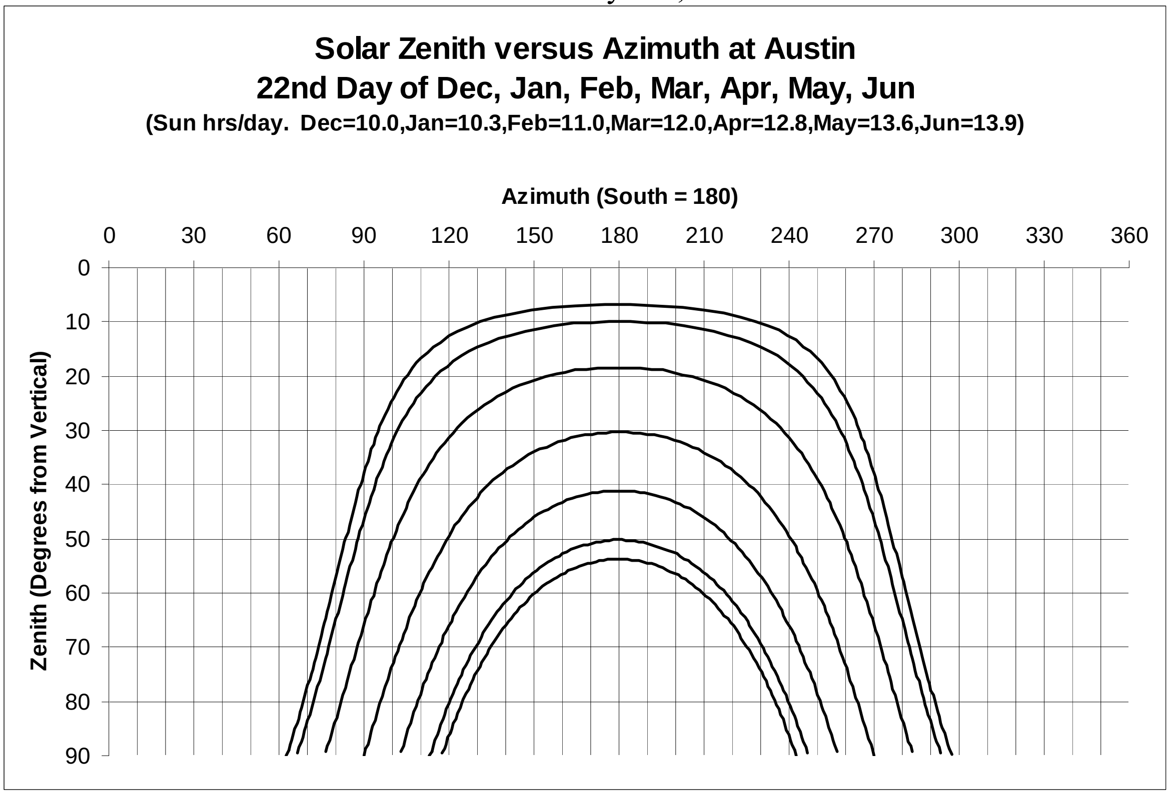


Figure 5a. Sun Position for Winter and Spring Seasons in Austin
(note – solar noon in Austin occurs at approximately 12:30pm CST)

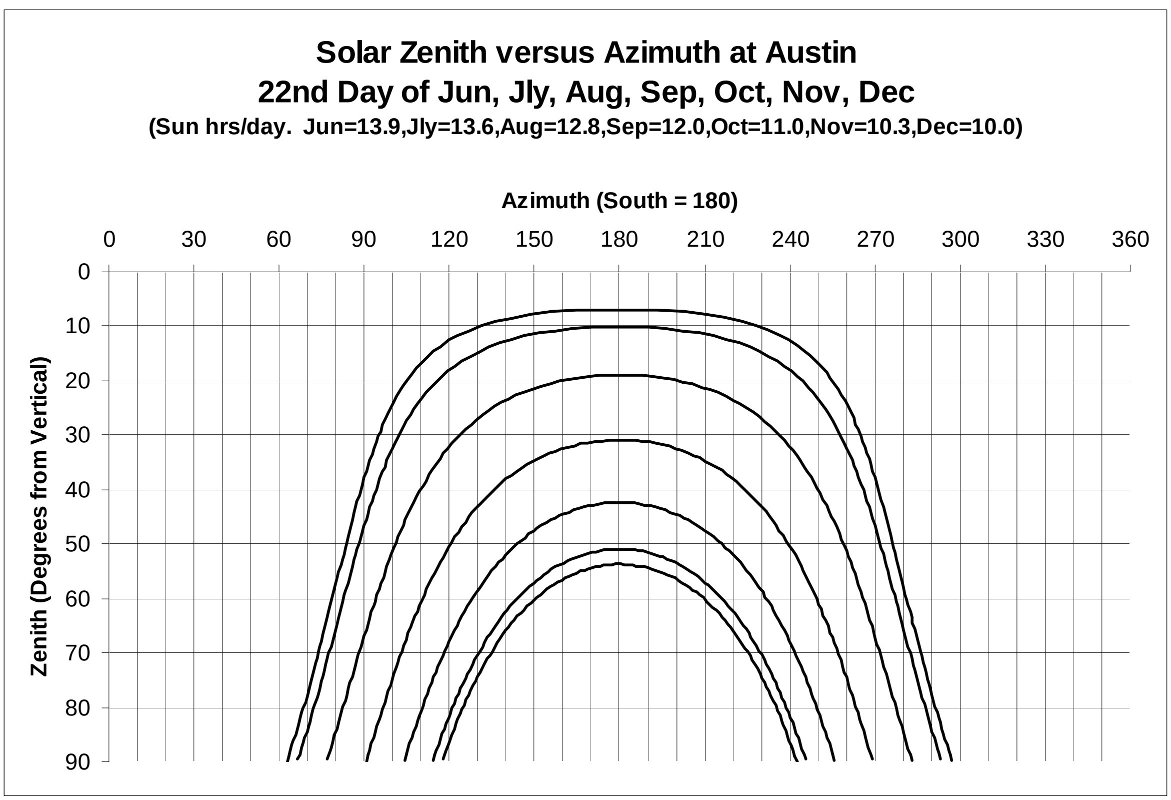


Figure 5b. Sun Position for Summer and Fall Seasons in Austin
(note – solar noon in Austin occurs at approximately 12:30pm CST)

Definitions from www.weatherground.com

Twilight	This is the time before sunrise and after sunset where it is still light outside, but the sun is not in the sky.
Civil Twilight	This is defined to be the time period when the sun is no more than 6 degrees below the horizon at either sunrise or sunset. The horizon should be clearly defined and the brightest stars should be visible under good atmospheric conditions (i.e. no moonlight, or other lights). One still should be able to carry on ordinary outdoor activities.
Nautical Twilight	This is defined to be the time period when the sun is between 6 and 12 degrees below the horizon at either sunrise or sunset. The horizon is not defined and the outline of objects might be visible without artificial light. Ordinary outdoor activities are not possible at this time without extra illumination.
Astronomical Twilight	This is defined to be the time period when the sun is between 12 and 18 degrees below the horizon at either sunrise or sunset. The sun does not contribute to the illumination of the sky before this time in the morning, or after this time in the evening. In the beginning of morning astronomical twilight and at the end of astronomical twilight in the evening, sky illumination is very faint, and might be undetectable.
Length Of Day	This is defined to be the time of Actual Sunset minus the time of Actual Sunrise. The change in length of daylight between today and tomorrow is also listed when available.
Length Of Visible Light	This is defined to be the time of Civil Sunset minus the time of Civil Sunrise.
Altitude (or Elevation)	First, find your azimuth. Next, the Altitude (or elevation) is the angle between the Earth's surface (horizon) and the sun, or object in the sky. Altitudes range from -90° (straight down below the horizon, or the nadir) to +90° (straight up above the horizon or the Zenith) and 0° straight at the horizon.
Azimuth	The azimuth (az) angle is the compass bearing, relative to true (geographic) north, of a point on the horizon directly beneath the sun. The horizon is defined as an imaginary circle centered on the observer. This is the 2-D, or Earth's surface, part of calculating the sun's position. As seen from above the observer, these compass bearings are measured clockwise in degrees from north. Azimuth angles can range from 0 - 359°. 0° is due geographic north, 90° due east, 180° due south, and 360° due north again.

Hour Angle of the Sun	The Solar Hour Angle of the Sun for any local location on the Earth is 0° when the sun is straight overhead, at the zenith, and negative before local solar noon and positive after solar noon. In one 24-hour period, the Solar Hour Angle changes by 360 degrees (i.e. one revolution).
Mean Anomaly of the Sun	The movement of the Earth around the Sun is an ellipse. However, if the movement of the Earth around the Sun were a circle, it would be easy to calculate its position. Since, the Earth moves around the sun about one degree per day, (in fact, it's 1/365.25 of the circle), we say the Mean Anomaly of the Sun is the position of the Earth along this *circular* path. The True Anomaly of the Sun is the position along its real elliptical path.
Obliquity	Obliquity is the angle between a planet's equatorial plane and its orbital plane.
Right Ascension of the Sun	The Celestial Sphere is a sphere where we project objects in the sky. We project stars, the moon, and sun, on to this imaginary sphere. The Right Ascension of the Sun is the position of the sun on our Celestial Sphere
Solar Noon (and Solar Time)	Solar Time is based on the motion of the sun around the Earth. The apparent sun's motion, and position in the sky, can vary due to a few things such as: the elliptical orbits of the Earth and Sun, the inclination of the axis of the Earth's rotation, the perturbations of the moon and other planets, and of course, your latitude and longitude of observation. Solar Noon is when the sun is at the highest in the sky, and is defined when the Hour Angle is 0°. Solar Noon is also the midpoint between Sunrise and Sunset.
Sun Declination	The Declination of the sun is how many degrees North (positive) or South (negative) of the equator that the sun is when viewed from the center of the earth. The range of the declination of the sun ranges from approximately +23.5° (North) in June to -23.5° (South) in December.

Panel Orientation and Solar Incident Angle
Unless there are obstructions, panels should face due south (i.e., have an azimuth angle of 180º). Recommended panel tilt angles (above horizontal) are latitude + 15º in winter, and latitude – 15º in summer. In Austin, with latitude = 30º, these recommendations correspond to 45º in winter, and 15º in summer. If no seasonal adjustments are made, then the best fixed panel tilt angle is latitude (i.e., 30º in Austin). The tilt angles of our panels are adjusted twice each year, at the spring and fall equinoxes. Our tilt angles are 20º in summer, and 45º in winter.

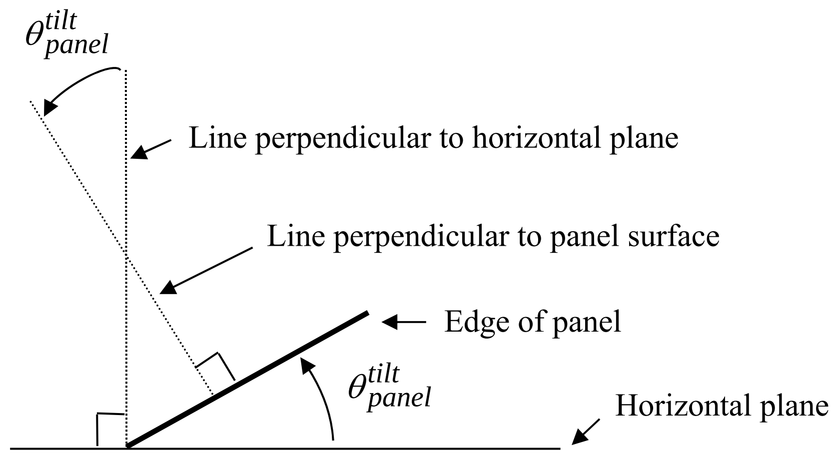
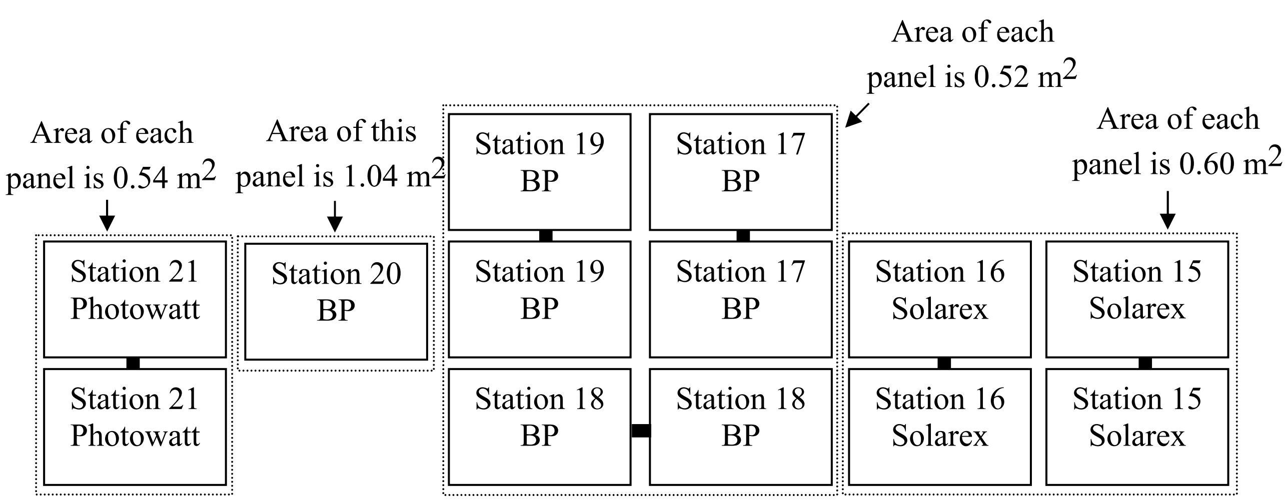
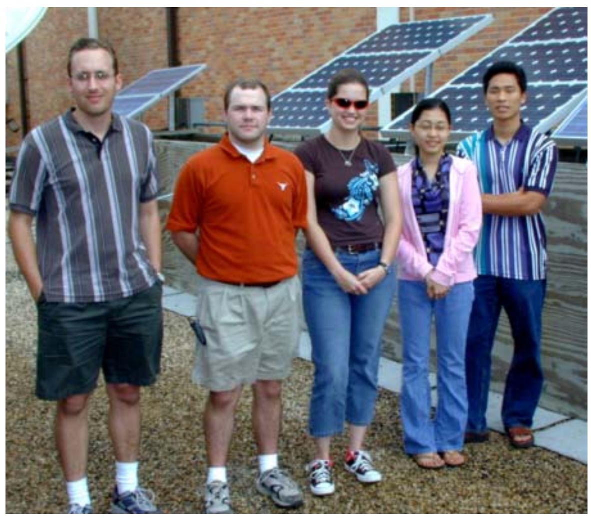


Figure 6. Panel Tilt Angle



All panels atop ENS have azimuth angle = 190º

View Facing Front of ENS Panels (i.e., looking toward north)
(Note – areas shown are for individual panels, so for a pair, double the values shown)



Panels atop ENS

The angle between the rays of the sun and a vector perpendicular to the panel surface is known as the angle of incidence ($\beta_{incident}$). The cosine of $\beta_{incident}$ is found by first expressing a unit vector pointed toward the sun, and a unit vector perpendicular to the panel surface, and then taking the dot product of the two unit vectors. When $\cos(\beta_{incident}) = 1$, then the sun's rays are perpendicular to the panel surface, so that maximum incident solar energy is captured. The expressions follow.

Considering Figure 4, the unit vector pointed toward the sun is

$$\hat{\boldsymbol{a}}_{\boldsymbol{sun}} = \left[\sin\theta_{sun}^{zenith}\cos\phi_{sun}^{azimuth}\right]\hat{\boldsymbol{a}}_{\boldsymbol{x}} + \left[\sin\theta_{sun}^{zenith}\sin\phi_{sun}^{azimuth}\right]\hat{\boldsymbol{a}}_{\boldsymbol{y}} - \left[\cos\theta_{sun}^{zenith}\right]\hat{\boldsymbol{a}}_{\boldsymbol{z}} .$$

Considering Figure 6, the unit vector perpendicular to the panel surface is

$$\hat{\boldsymbol{a}}_{\boldsymbol{panel}} = \left[\sin\theta_{panel}^{tilt}\cos\phi_{panel}^{azimuth}\right]\hat{\boldsymbol{a}}_{\boldsymbol{x}} + \left[\sin\theta_{panel}^{tilt}\sin\phi_{panel}^{azimuth}\right]\hat{\boldsymbol{a}}_{\boldsymbol{y}} - \left[\cos\theta_{panel}^{tilt}\right]\hat{\boldsymbol{a}}_{\boldsymbol{z}}$$

The dot product of the two unit vectors is then

$$\cos\beta_{incident} = \hat{\boldsymbol{a}}_{\boldsymbol{sun}} \bullet \hat{\boldsymbol{a}}_{\boldsymbol{panel}} = \left[\sin\theta_{sun}^{zenith}\cos\phi_{sun}^{azimuth}\sin\theta_{panel}^{tilt}\cos\phi_{panel}^{azimuth}\right]$$

$$+ \left[\sin\theta_{sun}^{zenith}\sin\phi_{sun}^{azimuth}\sin\theta_{panel}^{tilt}\sin\phi_{panel}^{azimuth}\right] + \left[\cos\theta_{sun}^{zenith}\cos\theta_{panel}^{tilt}\right].$$

Combining terms yields

$$\cos\beta_{incident} = \sin\theta_{sun}^{zenith}\sin\theta_{panel}^{tilt}\left[\cos\phi_{sun}^{azimuth}\cos\phi_{panel}^{azimuth} + \sin\phi_{sun}^{azimuth}\sin\phi_{panel}^{azimuth}\right]$$

$$+ \cos\theta_{sun}^{zenith}\cos\theta_{panel}^{tilt} .$$

Simplifying the above equation yields the general case,

$$\cos\beta_{incident} = \sin\theta_{sun}^{zenith}\sin\theta_{panel}^{tilt}\cos\left(\phi_{sun}^{azimuth} - \phi_{panel}^{azimuth}\right) + \cos\theta_{sun}^{zenith}\cos\theta_{panel}^{tilt} . \qquad \textbf{(9)}$$

Some special cases are

1. Flat panel (i.e., $\theta_{panel}^{tilt} = 0$). Then,

   $\cos\beta_{incident} = \cos\theta_{sun}^{zenith}$.

2. Sun directly overhead (i.e., $\theta_{zenith}^{sun} = 0$). Then,

   $\cos\beta_{incident} = \cos\theta_{panel}^{tilt}$.

3. Equal azimuth angles (i.e., azimuth tracking, $\phi_{sun}^{azimuth} = \phi_{panel}^{azimuth}$). Then,

   $$\cos\beta_{incident} = \sin\theta_{sun}^{zenith}\sin\theta_{panel}^{tilt} + \cos\theta_{sun}^{zenith}\cos\theta_{panel}^{tilt} = \cos\left(\theta_{sun}^{zenith} - \theta_{panel}^{tilt}\right).$$

4. Sun zenith angle equals panel tilt angle (i.e., zenith tracking, $\theta_{sun}^{zenith} = \theta_{panel}^{tilt}$). Then,

   $$\cos\beta_{incident} = \sin^2\theta_{sun}^{zenith}\cos\left(\phi_{sun}^{azimuth} - \phi_{panel}^{azimuth}\right) + \cos^2\theta_{sun}^{zenith}.$$

To illustrate the general case, consider the following example: 3pm (standard time) in Austin on October 25. The sun position is

$$\phi_{sun}^{azimuth} = 228.7^o,\ \theta_{sun}^{zenith} = 58.8^o, \text{ so that } \hat{\boldsymbol{a}}_{\boldsymbol{sun}} = -0.565\hat{\boldsymbol{a}}_{\boldsymbol{x}} - 0.643\hat{\boldsymbol{a}}_{\boldsymbol{y}} - 0.517\hat{\boldsymbol{a}}_{\boldsymbol{z}},$$

and the panel angles are

$$\phi_{panel}^{azimuth} = 190^o,\ \theta_{panel}^{tilt} = 45^o, \text{ so that } \hat{\boldsymbol{a}}_{\boldsymbol{panel}} = -0.696\hat{\boldsymbol{a}}_{\boldsymbol{x}} - 0.1228\hat{\boldsymbol{a}}_{\boldsymbol{y}} - 0.707\hat{\boldsymbol{a}}_{\boldsymbol{z}}.$$

Evaluating the dot product yields $\cos\beta_{incident} = 0.838$, so $\beta_{incident} = 33.1^o$.

Solar Radiation Measurements

The three most important solar radiation measurements for studying solar panel performance are global horizontal (GH), diffuse horizontal (DH), and direct normal (DN). GH is "entire sky," including the sun disk, looking straight up. DH is "entire sky," excluding the sun disk, looking straight up. DN is facing directly toward the sun. The units for GH, DH, and DN are W/m^2.

The direct measurement of DN requires a sun tracking device. The Sci Tek 2AP tracker takes DN, GH, and DH readings every five minutes using three separate thermocouple sensors. The DN sensor tracks and sees only the disk of the sun. The GH sensor points straight up and sees the entire sky with sun disk. The DH sensor points straight up, but a shadow ball blocks the disk of the sun, so that it sees entire sky minus sun disk.

Rotating shadowband pyranometers use one PV sensor, pointed straight up, to measure GH and DH every minute, and then save average values every 5 minutes. Once per minute, the shadow band swings over, and when the shadow falls on the sensor, the DH reading is taken. Using GH and DH, the rotating shadow-band pyranometer estimates DN.

Rotating Shadowband Pyranometers

Rotating shadow band pyranometers are simple in that they do not track the sun. Instead, they merely rotate a shadow band every minute across the PV sensor. When there is no shadow on the sensor, the sensor reads GH. When the shadow falls on the sensor, the sensor reads DH.

Computing Incident Solar Power on a Panel Surface

To compute the incident solar power on a panel surface, we assume that the panel captures all of the diffuse horizontal (DH) power, plus the fraction of (GH – DH) that is perpendicular to the panel surface.

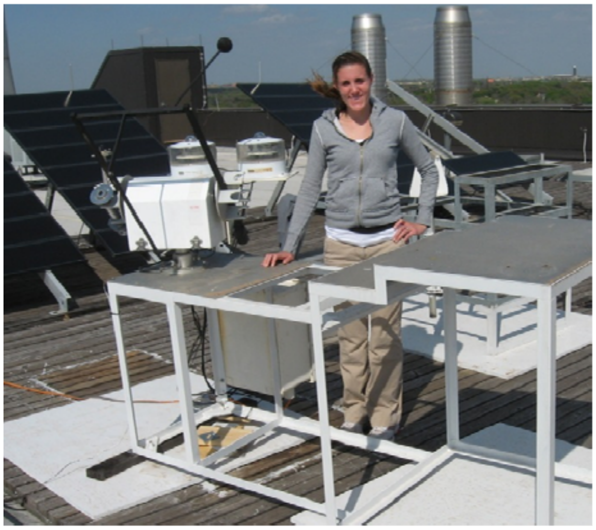
$$P_{incident} = DH + \frac{(GH - DH)}{\cos(\theta_{sun}^{zenith})} \bullet \cos(\beta_{incident}) \text{ W/m}^2. \quad \textbf{(10)}$$

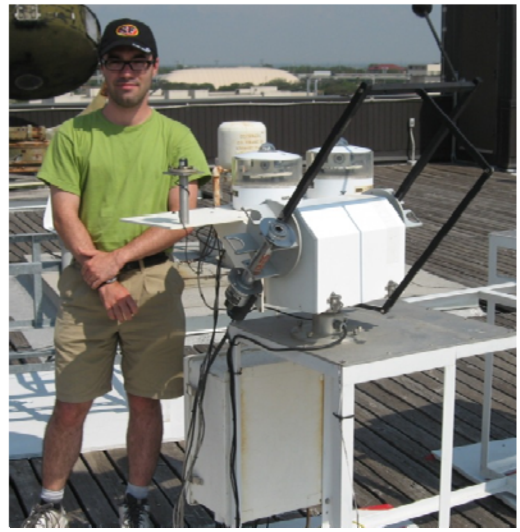
The above value, in W/m^2, is then multiplied by the panel surface area to yield total incident solar power $P_{incident}$. Multiplying by panel efficiency yields maximum expected electrical power output. Integrating the electrical power output over the hours of the day and dividing by 1000 yields the daily energy production in kWh.

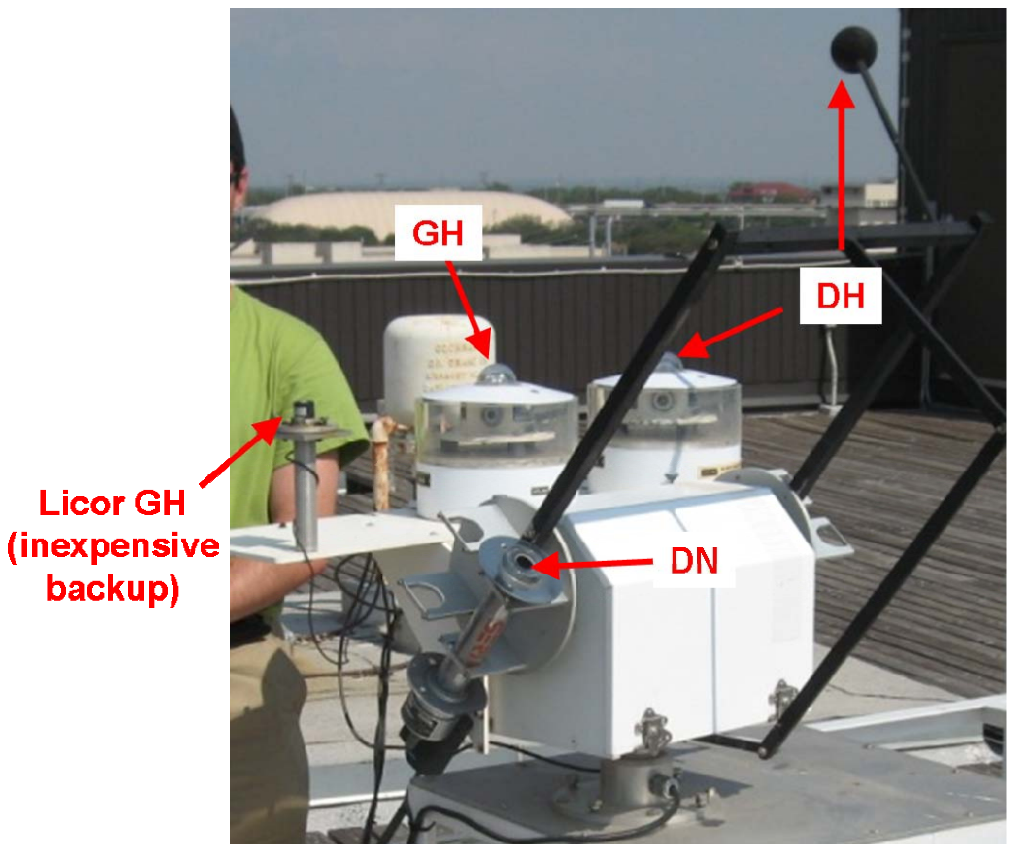
To avoid serious overcorrection when the sun is near the horizon, ignore the $\cos(\theta_{sun}^{zenith})$ term when $\theta_{sun}^{zenith} > 85^o$. For the 3pm, October 25th example, the readings are GH = 535 W/m^2, and DH = 38 W/m^2, and,

$$P_{incident} = \left[38 + \frac{(535-38)}{\cos(58.9°)} \bullet \cos(33.1°)\right] \bullet A_{panel} = 844 \bullet A_{panel} \ W/m^2,$$

which means that a PV panel or array would produce 844 W per kW rated power.







NREL Sci Tec Two-Axis Tracker

The Experiment
Your assignment is to measure the I-V and P-V characteristics of a solar panel pair, plot the points, determine maximum power, estimate panel efficiency, and use the Excel Solver to approximate the I-V and P-V curves using

$$I = I_{SC} - A(e^{BV} - 1)\ ,\ P = VI = V \bullet \left[I_{SC} - A(e^{BV} - 1) \right],$$

where the Solver estimates coefficients I_{SC}, A, and B from your measured I-V data set. See the Appendix for a description of the Excel Solver.

Experimental Procedure

You will need about 30 minutes to take the experimental data. Go to an available panel station, and check the short circuit current. Take your measurements when the short circuit current is at least 3.5A (try for a sunny day, between 11am and 3pm.). (Note - weather site www.weatherunderground.com can help you make your plans for upcoming days.) Then, using the voltage **at the panel (i.e., the left-most meter in the yellow solar panel interface box)**, and the panel ammeter (the right-most meter), perform the following steps given below, **recording and plotting your data on the experimental form and on the graph as you go**:

Voltage at solar panel | Voltage at lab bench | Current (at both places)

EE462L, Power Electronics, Solar Power, I-V Characteristics

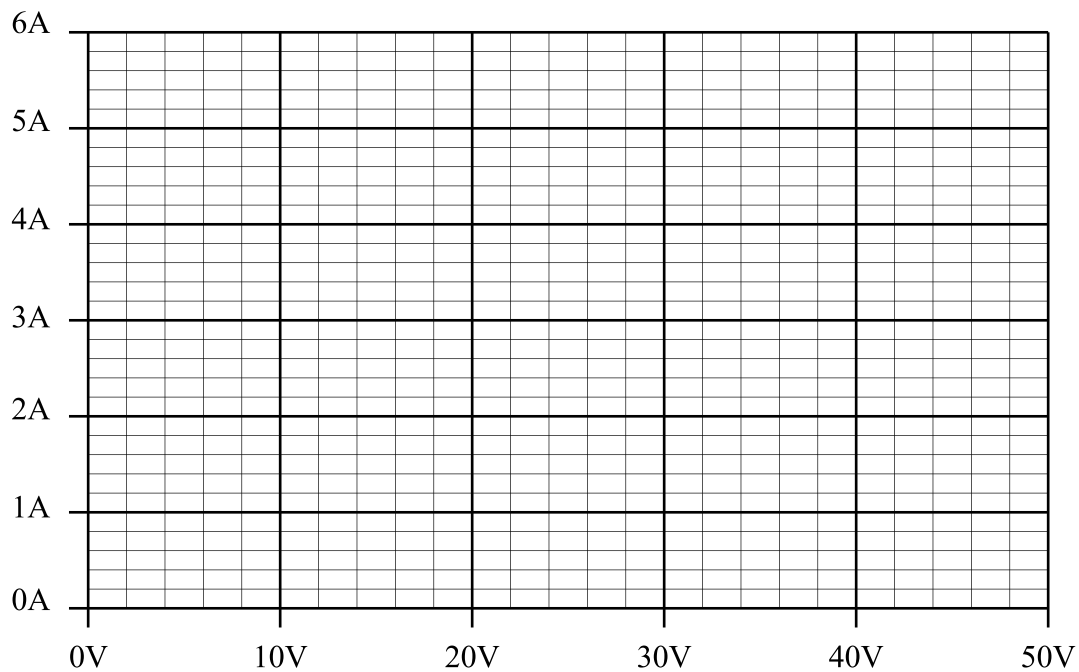
Version January 31st, 2014

Form and Graph for Recording and Plotting Your Readings as You Take Them
(have this page signed by your Professor or one of the TAs before beginning your report)

Panel Station = ____ Date and Time of Measurements= ___________, Sky Conditions = _____

	V_{panel}*	I_{panel}*	P (i.e., $V_{panel} \bullet I_{panel}$)	Notes
	V_{oc} =			Open circuit condition
≈2V spacing for V > 25V				
≈5V spacing for V ≤ 25V				
		I_{sc} =		Short Circuit Condition

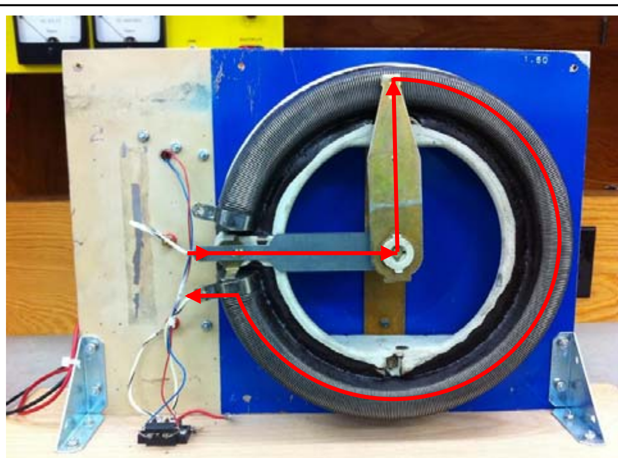
* V_{panel} (**i.e., at the panel**) is the left-most meter in the yellow interface box, and I_{panel} is the right-most meter.



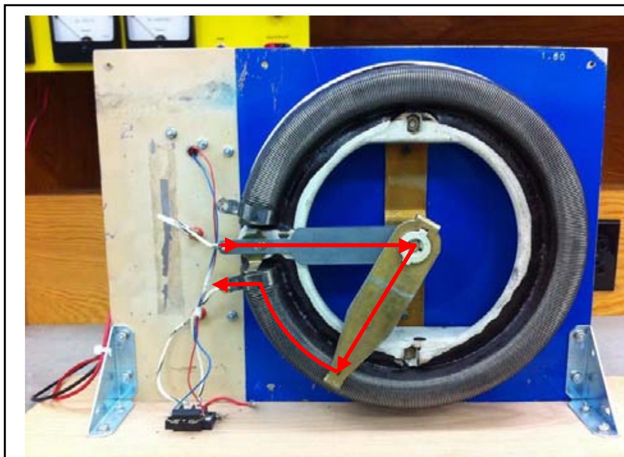
Steps

1. Measure the panel pair's open circuit voltage, and record in the table and on the graph. The current is zero for this case.
2. Short the output terminals with a wire. Measure the short-circuit current and panel-pair voltage. Record both and add the point to your graph. The panel voltage will be very small for this condition.
3. Connect one of the Ohmite rheostats (i.e., the heavy-duty variable-resistor boxes with the large knobs) to the panel-pair output terminals. You will use the 0 – 100 Ω variable resistor to sweep the solar panel's entire I-V curve.
4. Beginning with the near-open-circuit condition, (i.e., maximum resistance), lower the solar-tester resistance so that the panel-pair voltage decreases from the open-circuit value toward zero in steps of approximately 2 V between 25-40 V, and in 5 V steps below 25 V. Record panel-pair voltage and current at each step, and hand plot I versus V results as you go. If your points do not form a smooth curve, you may want to retake the outliers. Cloud movement can cause these variations.

Ohmite (0 – 100) Ω Solar PV Resistor Load



Resistor Depicting ≈ 75 Ω Load
and showing the resistance path (**in red**)



Resistor Depicting ≈ 17 Ω Load
and showing the resistance path (**in red**)

The laboratory measurement portion of the experiment is now completed. Your graph should be fairly smooth and free of outlying points. You can now leave the lab bench.

Next, you will

5. Download Excel file "Solar_PV_Plots_Solver.xls" from the course web page, open it, and then enter your V and I values in Excel. You will likely have to "Insert Rows" within the Excel Plots Solver to have enough room to enter all your data points in the yellow cells, as well as copy down (fill in) the appropriate formulas for the additional column calculations, to the right. Then, modify the each chart's data points by right-clicking on each chart and using Select Data / Edit Data to ensure all the data for your experiment will be plotted accordingly. Plot I versus V points, and P = V • I versus V points **using the "scatter plot" option**.

Coefficients of I Equation

PV Station 13			Isc=	5.340E+00
			A=	5.232E-03
			B=	1.778E-01
Vpanel	I	I equation	(I error)^2	Ppanel = VI
39	0	-1.837E-02	0.000337	0.0
35	2.65	2.711E+00	0.003701	92.8
30	4.3	4.262E+00	0.001448	129.0
25	4.95	4.900E+00	0.002531	123.8
20	5.15	5.162E+00	0.000142	103.0
4	5.3	5.334E+00	0.001179	21.2
			0.009338	

Add rows so you can enter all your data points

Currents Predicted by I Equation

Sum of Squared Errors

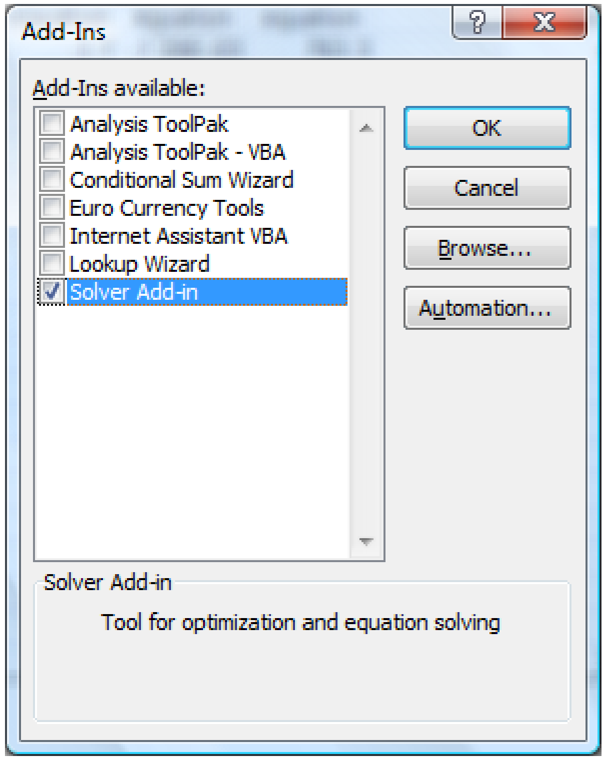
Individual Squared Errors

6. Visually estimate V_m, I_m, and P_{max} (i.e., peak power conditions) from your plots.

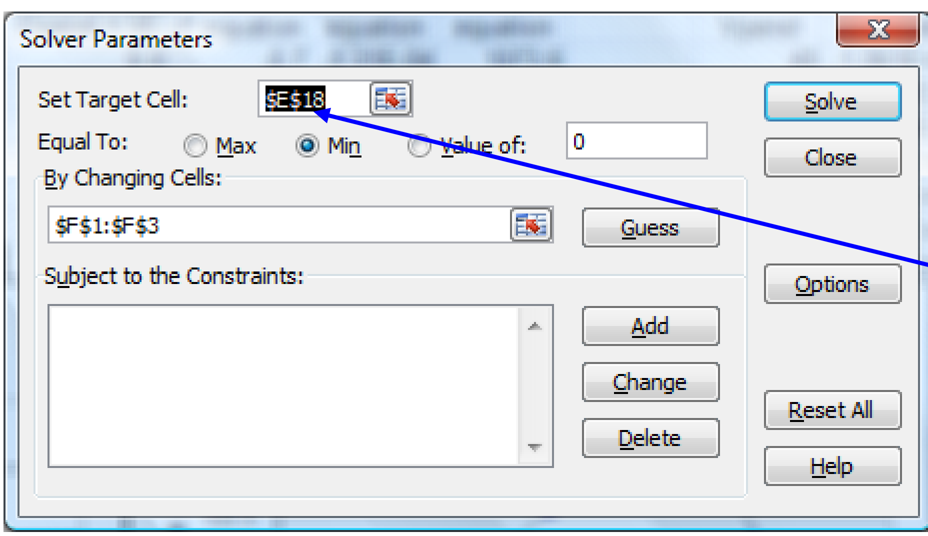
7. Next, use the Excel Solver Add-In to perform a least-squares curve fit and compute coefficients I_{sc}, A, and B from your I-V data.

Using the Excel Solver to Curve-Fit Measured Data

Note: The Excel Solver is not part of the "Typical User" installation. Thus, you will need to make sure it's enabled. To do so in Excel 2007, click on the Office button in the top left. Then, click "Excel Options" and then "Add-Ins". Then, select "Manage: Excel Add-Ins", and click "Go…". From there, you should be able to check the "Solver Add-In" and click "OK". *(Aside: For older Excel versions, the "Add-Ins" function was located under the "Tools" menu.)*

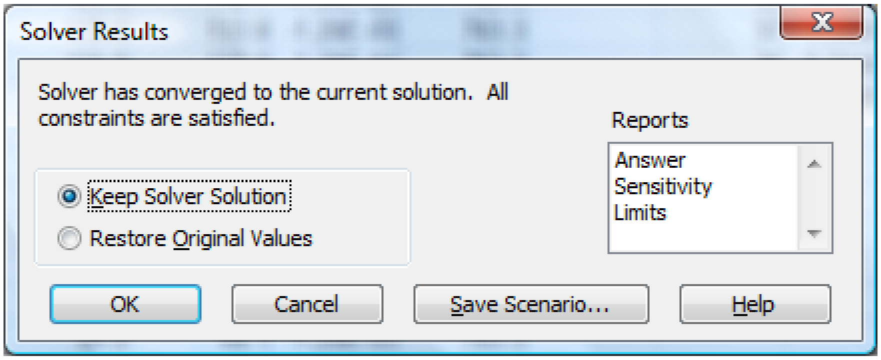


Now, when you click on the "Data" menu within Excel, you should see the "Solver" Add-In to the far right. When you select "Solver", you should see it already pre-set to minimize the sum of the square of the error terms by manipulating cells $F$1:$F$3, which should be the Isc, A, and B terms of your solar cell's I-V equation: $I = I_{sc} - A(e^{BV} - 1)$. Just make sure all your error^2 terms have been copied down so the SUM(error^2) cell that's being minimized has been updated to reflect all rows of your data points. Then click "Solve".



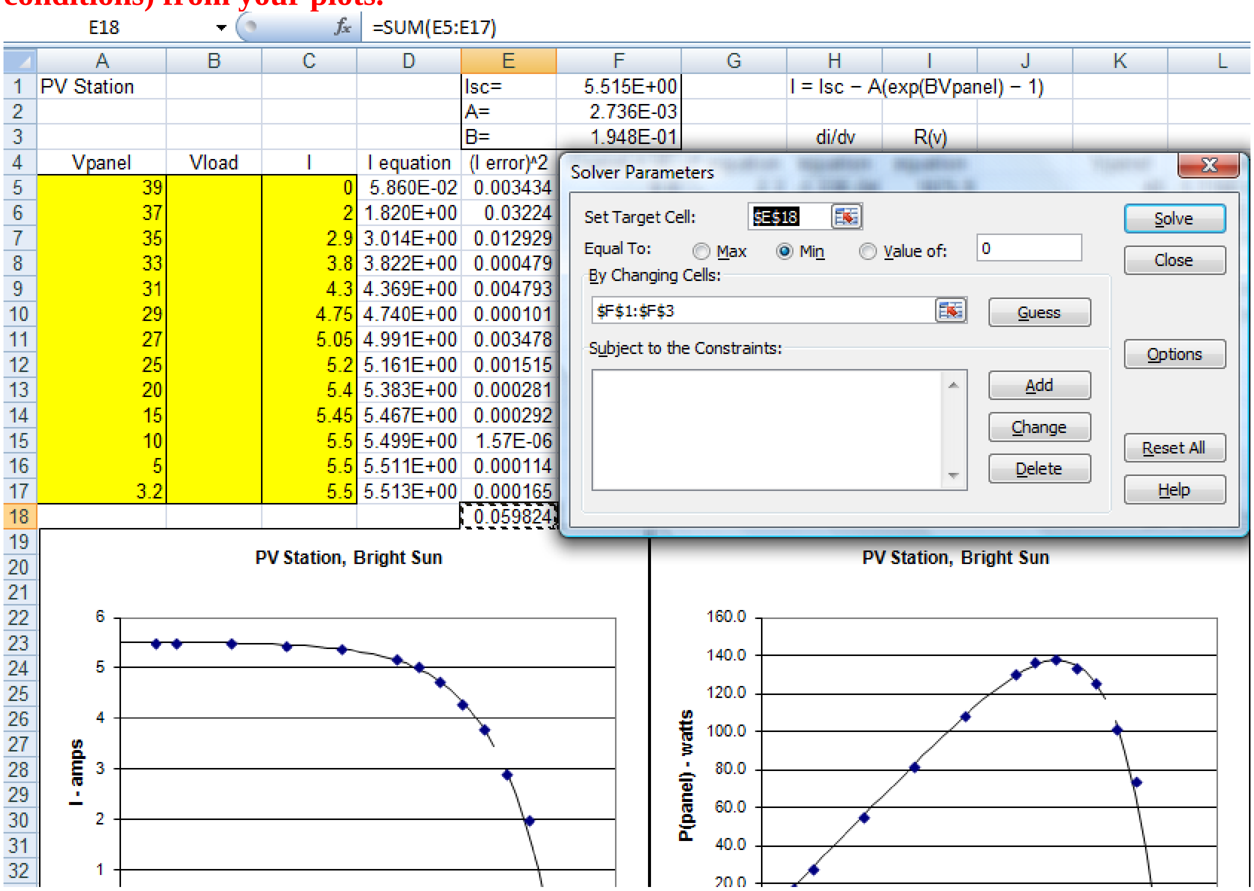
This cell number SUM(error^2) is based upon how many rows of data points you have added. Thus, yours may not be $E$18…

Upon a successful least-squares fit, you should receive a message box saying:



… your plots should reflect a nice curve-fit to your data points, and the Isc, A, and B values should update, accordingly. If unsuccessful, try changing the default A and B starting constants, and re-run the Solver. **But keep your own measured short-circuit current for I_{sc}.** *However, if for some reason the Solver isn't working correctly, you can manually adjust A & B (since you already know Isc) until you get an approximate equation. <u>But please try this option only as a last recourse</u>.*

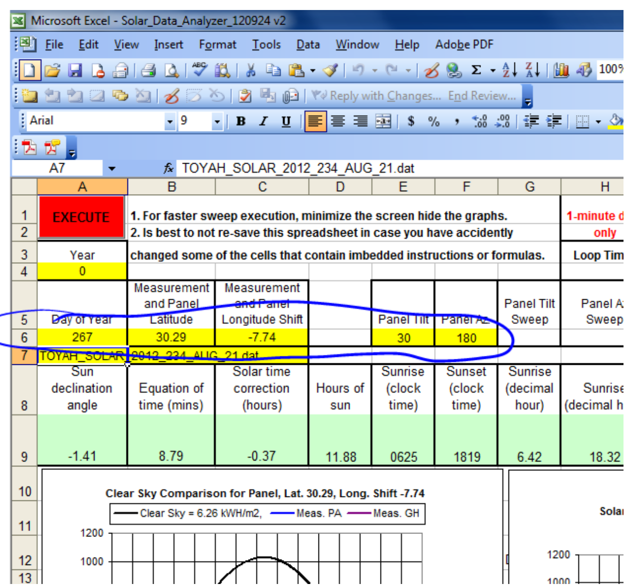
Include your I-V plot, P-V plot, constants (i.e., Isc, A, B), and finalized solar panel equation in your lab report. Also include your estimations for V_m, I_m, and P_{max} (i.e., peak power conditions) from your plots.



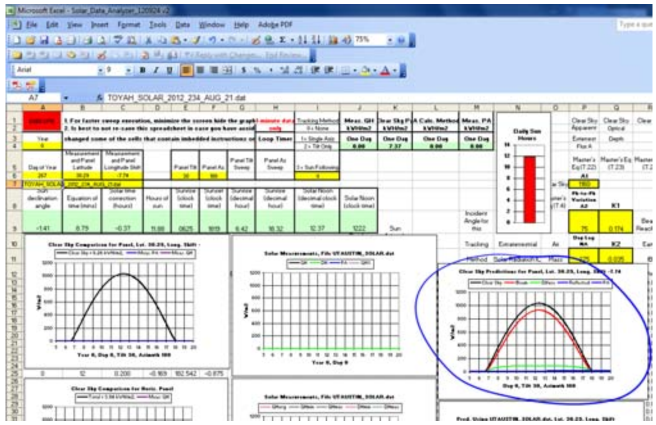
Now, use the following steps to estimate panel-pair efficiency:

8. **For the minute that best represents your time of measurements, work through the Big 9 equations, (1) – (9) given in this PDF lab document.** Be careful with units such as radians vs. degrees!

9. Go to the class web page and download the Excel spreadsheet Solar_Data_Analyzer.xls. Macros should not need to be enabled.
10. Input your year and calendar day (note – these data are given in Central Standard Time).
    - Do NOT press the red EXECUTE button (GUI). If you do happen to press the red execute button, then simply "stop" the GUI.
    - Simply adjust values in the yellow highlighted cells in row 6, as needed, based upon your solar criteria of interest.
    - "Day of Year" corresponds to a numerical value (0 to 365), relating to the day you recorded your solar data measurements (e.g. day 267 = Sept 24, ignoring leap year).
    - The latitude / longitude shifts for Austin, TX are 30.29º and -7.74º, respectively.
    - The solar panel orientations atop ENS are 45º tilt, with an azimuth of 190º.



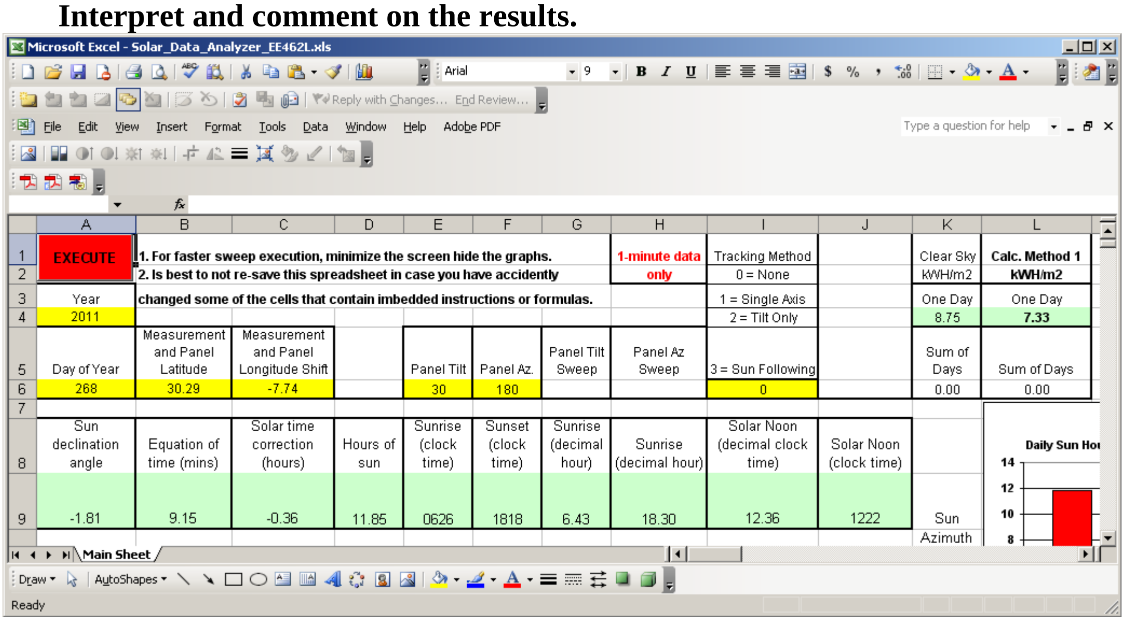
    - You can read information of expected solar measurements on a clear day on the right of the program.



11. Compare your Big 9 equations to the Solar_Data_Analyzer spreadsheet values for your day/minute.
12. For your day, use the Solar_Data_Analyzer spreadsheet to predict Method 1 daily kWh per installed kW for the following solar panel conditions:
    - for fixed panel azimuth = 180°, and panel tilts 20°, 30°, and 40°,
    - for single axis tracking, azimuth = 180°, tilt = 20° and 30°,
    - for two-axis tracking *(also known as "Sun Following")*

    It may be helpful to know that a 150 W rated panel is approximately 1 m².

    Interpret and comment on the results.



Appendix A: For More Information

Excellent web sites for information on solar power are Southwest PV Systems (www.southwestpv.com), and the National Renewable Energy Laboratory (www.nrel.gov).

The following applet from NREL works well to approximate the amount of solar generation a household roof installation might produce in a calendar year, as well as the financial cost savings one should expect (in terms of energy savings from your electric utility provider):

NREL PV Watts program

http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/

Acknowledgments

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Appendix B: National and State Solar Insolation Data

Direct Solar Insolation Levels

(courtesy of Texas State Energy Conservation Office, www.infinitepower.org)

AVERAGE DIRECT NORMAL INSOLATION MAP LEGEND			
COLOR KEY	per day (kWh/m^2-day)	per YEAR	
		(MJ/m2)	(quads/100 mi^2)
	<3.0	<3,940	<1.0
	3.0 - 3.5	3,940 - 4,600	1.0 - 1.1
	3.5 - 4.0	4,600 - 5,260	1.1 - 1.3
	4.0 - 4.5	5,260 - 5,910	1.3 - 1.5
	4.5 - 5.0	5,910 - 6,570	1.5 - 1.6
	5.0 - 5.5	6,570 - 7,230	1.6 - 1.8
	5.5 - 6.0	7,230 - 7,880	1.8 - 1.9
	6.0 - 6.5	7,880 - 8,540	1.9 - 2.1
	6.5 - 7.0	8,540 - 9,200	2.1 - 2.3
	>7.0	>9,200	>2.3