A Guide To Photovoltaic Panels

The following discussion is based around autonomous and semi-autonomous systems that use PV panels to charge a bank of lead-acid batteries.

Photovoltaic (PV) Cells

Semiconductor solar cells convert sunlight into electricity using the photovoltaic effect. Incident light falls on the cells and creates mobile charged particles in the semiconductor which are then separated by the device structure to produce electrical current.

The vast majority of solar cells are made from crystalline silicon. Single crystal cells are the most efficient however, cheaper multicrystaline cells are also popular. Even cheaper amorphous silicon cells are also available and used widely for small consumer products but rarely used for power systems.

A single PV cell will produce between 1 and 1.5W at a voltage of 0.5 to 0.6V under standard test conditions. Standard test conditions are: an irradiance of 1kW/m^2, standard reference AM1.5 spectrum*, and a cell temperature of 25°C.

[* The AM1.5 spectrum is the spectrum (i.e. range of wavelengths) provided on a clear day by the sun when its rays have passed through an average depth of atmosphere to the Earth's surface.]

A characteristic I-V curve is shown in figure 1. The important points are:

- *Short Circuit Current* (I_{SC}) – This is the maximum current that the cell can provide and it occurs when the cells is short circuited. Unlike other small scale electricity generating systems PV cells are not harmed by being shorted out.
- *Open circuit Current* (V_{OC}) – This is the maximum voltage that exist between the cells terminals and is obtained when there is no load connected across them.
- *Maximum Power Point* (P_{Max}) – The point on the I-V curve at which maximum power is being produced by the cell. Note that since the graph is not a straight line, the power produced will vary depending on the operating voltage (figure 2); although the voltage at any point on the graph can still be calculated using P=IV. P_{Max} occurs on the 'knee' of the I-V curve.

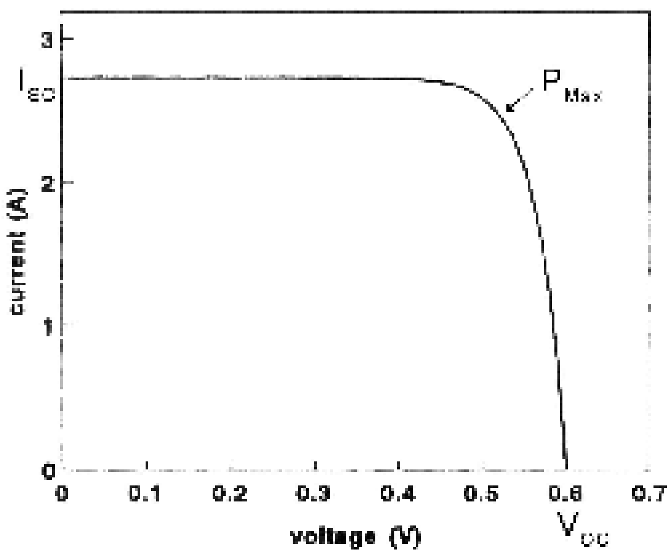

Figure 1: A typical I-V curve for a silicon photovoltaic cell.

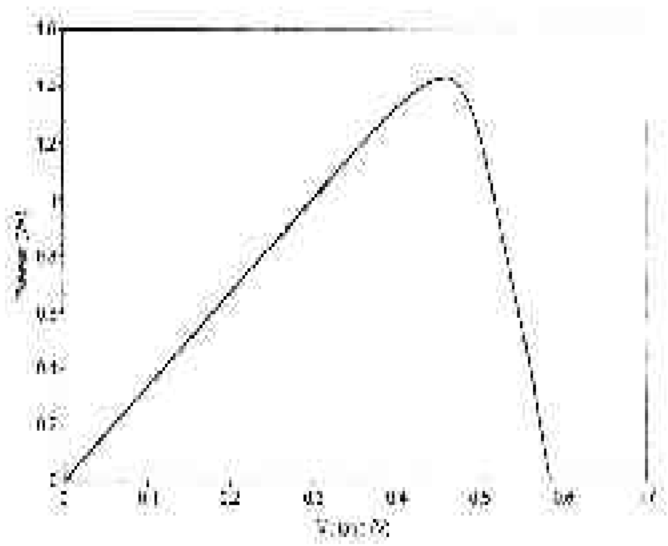

Figure 2: A typical power output vrs. voltage curve for a silicon photovoltaic cell.

In Practice PV cells do not operate under standard conditions. The two parameters that have the most bearing on their performance are (i) temperature and (ii) irradiance.

(i) Temperature

Figure 3 shows the effects of temperature on the I-V curve of a PV cell. I_{SC} increases slightly with temperature by about 6µA per °C for 1cm^2 of cell, this is so small that it is normally ignored. However, a more significant effect is the temperature dependence of voltage which decreases with increasing temperature. Typically the voltage will decrease by 2.3mV per °C per cell.

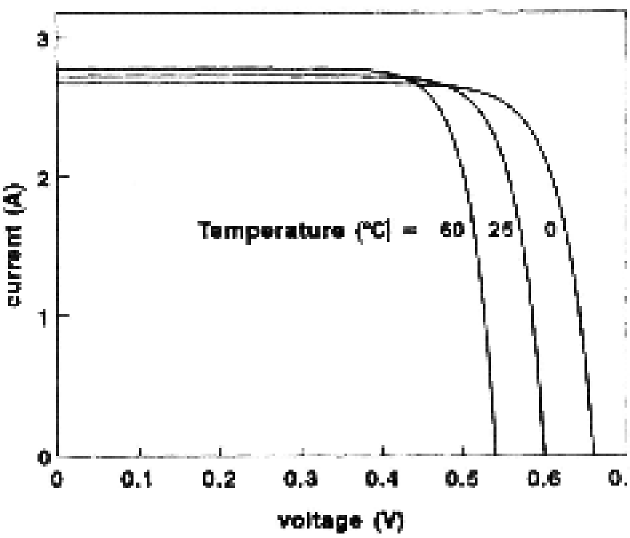

Figure 3: Temperature effects on the I-V curve of a PV cell.

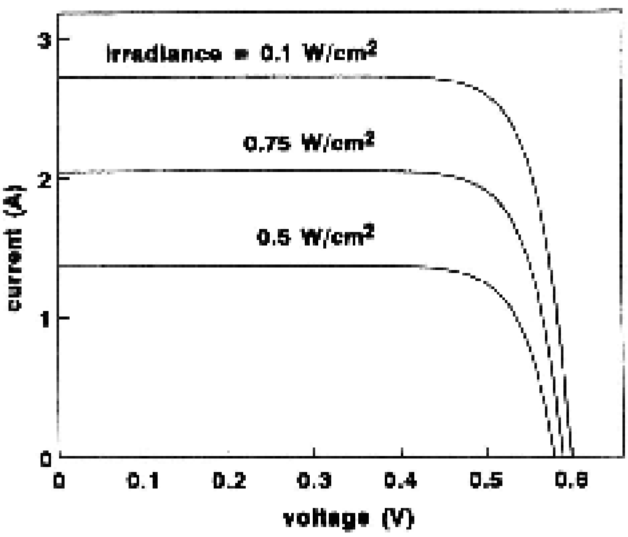

Figure 4: The effects of irradiance on the I-V curve of PV cells.

(ii) Irradiance

Solar irradiance is a measure of the sun's energy, under standard conditions the amount of energy reaching the Earth's surface on a clear day is taken to be 1kW/m^2. The amount of irradiance reduces with the slightest amount of haze and becomes quite small on over cast days. I_{SC} is directly proportional to the irradiance: so that if irradiance halves so does I_{SC}. The voltage variation is very small and usually ignored

The power produced under different conditions, as a function of voltage, is shown in figure 5. Figures 4 and 5 clearly show that the voltage at which P_{Max} occurs does not vary much with irradiance.

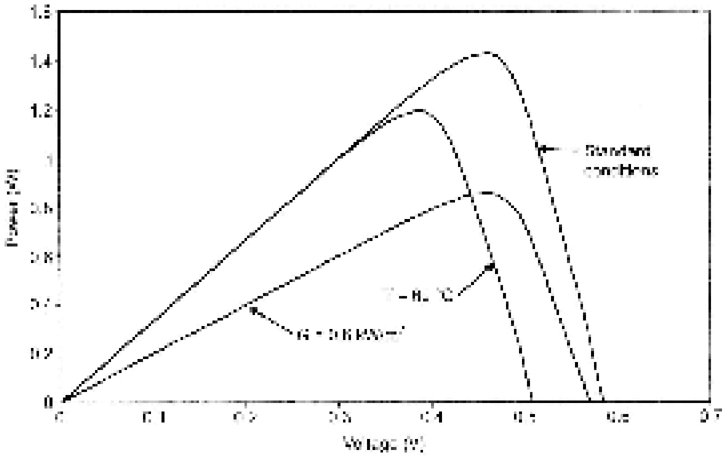

Figure 5: PV cell power output as a function of voltage.

Irradiance values are normally given as an average per day, so that the average global irradiance may be 4.5kW/m^2 per day. If we assume that most of this radiation falls on the solar panels in the six hours between 9am and 3pm we can estimate the average irradiance falling on the panels throughout the day: in this case it will be 0.75kW/m^2. Irradiance is sometimes denoted by I however, to avoid confusion with current it is denoted here by G. When looking up values for G be careful to note whether they are for horizontal panels or panels inverted from the horizontal by an angle equal to the location's latitude.

PV Panels and Manufactures' Data

PV cells are connected in series to produce PC panels. These usually contain 36 or 72 cells to match 12 and 24V systems respectively. 36 cells in series will produce a panel rated at about 75W and 72 cells will produce a panel that is rated at about 160W. Panels must be able to produce a voltage higher than that of the battery bank (the nominal system voltage) otherwise the batteries will not charge, panels for a 12V system normally have V_{OC} in the region of about 17V. Values of I_{SC} for panels will vary from make to make but will be approximately the same for a single cell, 36 cells or 72 cells. The I-V curve for a panel therefore looks the same as that for a single cell, only the voltages are larger (figure 6).

P_{Max} is the preferred point of operation however, if the temperature is too high this may not be possible. If a voltage below P_{Max}, in the linear section of the I-V curve (figure 6), is acceptable the effect of temperature can be eliminated and the output current is dependent only on irradiance. Some modern charge controllers have maximum power point tracking that will alter the voltage across the panel to find the maximum power output for any given conditions. Other charge controllers rely on a charging voltage being set manually (e.g. 15V for a 12V battery bank) and you will have to take whatever current is available at that voltage.

Manufactures provide data for I_{SC}, V_{OC} and P_{Max}, also the characteristic I-V curve can usually be obtained. These figures are quoted for standard conditions: and irradiance of 1kW/m^2, spectral distribution of AM1.5 and a cell temperature of 25°C. Panels are never used under perfect standard conditions and the manufactures' data must be altered to find the true power output under relevant conditions. Figure 6 illustrates how a PV panel's output changes with temperature and irradiance, this curve if for a typical panel from a 12V system.

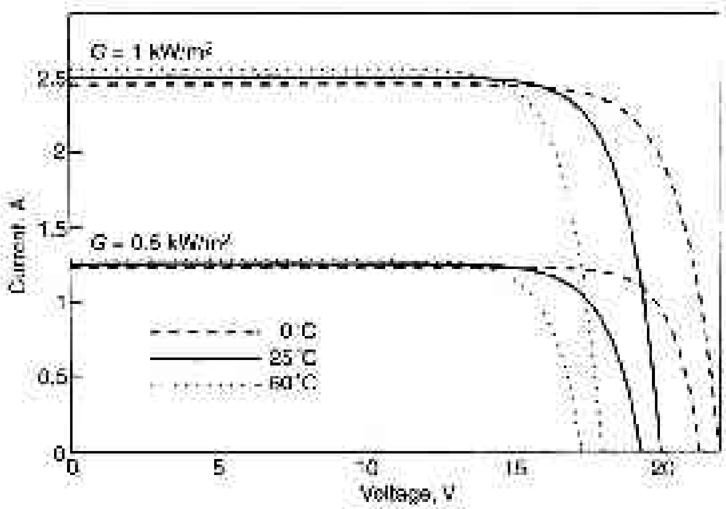

Figure 6: The variation of PV panel output with temperature and irradiance.

Fine Tuning Manufactures' Data

Voltage

V_{OC} must be calculated for the operating temperature (T_C), for each cell it drops by about 2.3mV for each °C over 25°C. For a panel with *n* cells connected in series:

$$\frac{dV_{OC}}{dt} = \frac{V_{OC} - V_{OC}(25°)}{T_C - 25°}$$

Specification sheets may quote a value for the *Temperature Coefficient of Voltage* for particular makes, for example for a BP 585 panel it is -80±10mV per °C. Note that this is almost exactly the same as -2.3mV when multiplied by 36 cells.

The voltage at the maximum power point (V_M) does not vary much with irradiance and can be estimated as 80% of V_{OC} under standard conditions.

Current

I_{SC} is directly proportional to irradiance (G). Therefore the short circuit current at the given irradiance (I_{SC} (G)) is given by:

$$I_{SC}(G) = I_{SC}\ (\text{at } 1\text{kW/m}^2) \times G\ (\text{in kW/m}^2)$$

I_{SC} does not vary much with temperature and this effect is normally ignored. However, manufactures' specification sheets often provide a *Temperature Coefficient of* I_{SC}, for example this is 0.064±0.015% per °C for a BP 585 panel; this is about 3.25mA for a 36 cell panel.

Cell Temperature

The cell temperature will normally be higher than the air temperature because they are black and sitting in the sun. The cell temperature under different conditions can be estimated using the *Normal Operating Cell Temperature* (NOCT), which is defined as the cell temperature under the following conditions: irradiance of 0.8kW/m^2, spectral distribution AM1.5, ambient temperature 20°C and a wind speed < 1m/s. NOTC is normally in the region of 42 to 46°C.

The following equation can be used to calculate the difference between the cell temperature T_C and the ambient temperature T_A (ambient temperature is the air temperature measured in the shade):

$$T_C - T_A = \frac{NOTC - 20}{0.8} \times G(\text{in kW/m}^2)$$

Maximum Power Point (P_{Max})

We can calculate P_{Max} if we know the current at P_{Max} (I_M) and the voltage at P_{Max} (V_M) since:

$$P_{Max} = V_M I_M$$

However, manufactures' usually only provide us with I_{SC} and V_{OC}, also even if we did know I_M and V_M under standard conditions they will change for different conditions. A scaling factor called the *Fill Factor* (FF) is used, once calculated it can be used to scale the modified values of I_{SC} and V_{OC} to find P_{Max} for the true operating conditions (this makes the assumption that FF does not change with temperature or irradiance).

Figure 7 shows an I-V curve, P_{Max} can be found by maximising the area of the rectangle $I_M P_{Max} V_M 0$.

The following equation is used to find FF from the manufacturers' data, which can then be used to find P_{Max} under non-standard conditions.

$$P_{Max} = V_M I_M = FFV_{OC} I_{SC}$$

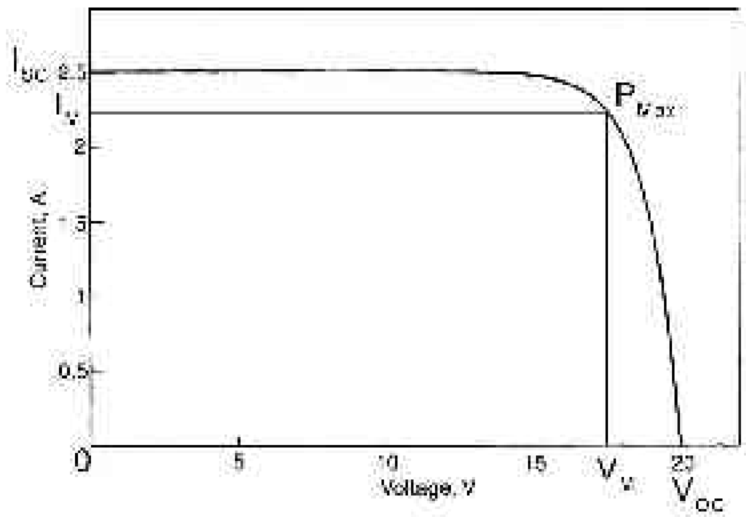

Figure 7. The relationship between I_M, V_{OC} and P_{Max}

<u>Example</u>

Determine the parameters of a panel formed from 34 cells in series, under the operating conditions G = 700W/m and T_A = 34°C. The manufacturer's values under standard conditions are: I_{SC} = 3A, V_{OC} = 20.4V, P_{Max} = 45.9W, NOCT = 43°C.

1. Short circuit current: $I_{SC}(G) = I_{SC} \times G$

$$I_{SC}(700\text{W/m}^2) = 3 \text{ x } 0.7\ (\text{kW/m}^2) = \mathbf{2.1A}$$

2. Soar cell temperature: $T_C = T_A + [(\text{NOCT} - 20)/0.8] \times G$

$$T_C = 34 + 0.7 \times (43 - 20)/0.8 = \mathbf{54.12°C}$$

3. Open circuit voltage: $V_{OC}(T_C) = V_{OC}(25°C)\ 0.0023 \times n \times (T_C - 25°C)$

$$V_{OC}(54.12°C) = 20.4 - 0.0023 \times 34 \times (54.12 - 25) = \mathbf{18.1V}$$

4. If it is assumed that the fill factor is independent of temperature and irradiance:

$$FF = 45.9/(3 \times 20.4) = 0.75$$

$$P_{Max} = (G, T_C) = 2.1 \times 18.1 \times 0.75 = \mathbf{28.5W}$$

Note that this is 62% of the manufacturer's P_{Max} value.

<u>Other Reductions</u>

The manufacturing process is not perfect and some PV panels will be rated slightly higher than others so that the total power of an array of panels will be slightly less than the down rated power of a panel multiplied by the number of panels. This phenomena is known as *mismatch* and the array output should be down rated by the manufacturing tolerances; normally in the region of 2-4%. Another 2 to 6% can be subtracted for a further mismatch caused by dirt and dust on the panels.

Fixed Panel Angles

Most small PV systems have the panels fixed so that they do not track the sun across the sky throughout the day. For fixed panels the maximum power output can be achieved when their surfaces are

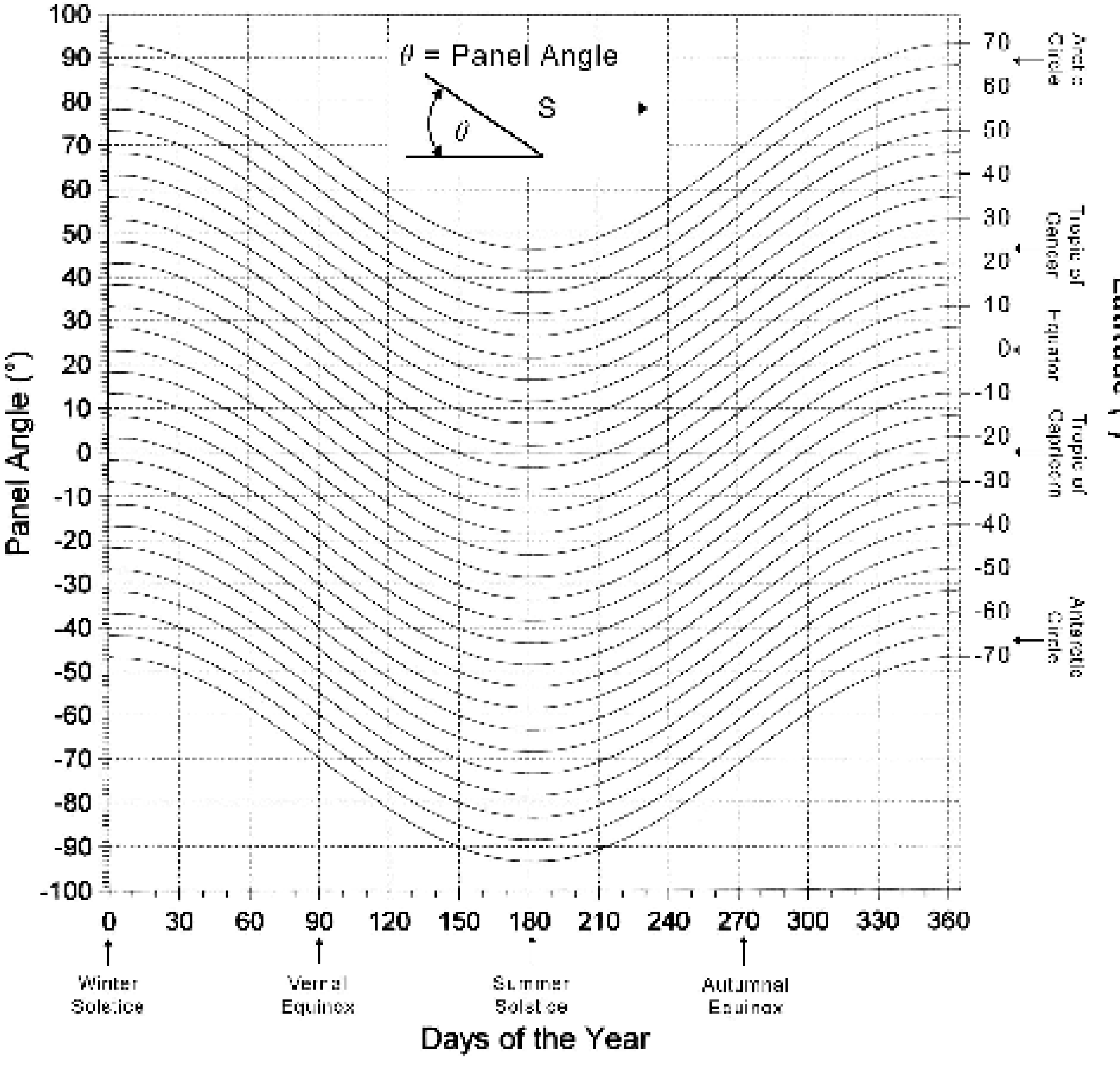

Figure 8: Panel angles for latitudes from 70° to -70°, negative panel angles indicate that panel is inclined to face north.

perpendicular to the sun at solar noon. Note that due to the vagaries of national time keeping solar noon is unlikely to be 12pm, rather it it the point in time at which the sun is at its daily zenith.

Panels should be fixed on the north-south axis since at all times of year, at solar noon, the sun will be directly on this line. If your system is in the northern hemisphere and above the Tropic of Cancer (i.e. has a latitude greater than +23.45°) your panels will always be inclined to face south because the sun's daily zenith will always be in the southern skies. Similarly, if your system is in the southern hemisphere and below the Tropic of Capricorn (i.e. has a latitude less than -23.45) your panels will always be inclined to face north. Note that outside the tropics the sun is never directly overhead.

If your system is in the tropics (i.e. has a latitude between -23.45° and +23.45°) matters are not so simple. At the equator the sun is directly overhead at solar noon on the equinoxes (21st-23rd March and 22nd-23rd September), but reaches its daily zenith in the northern skies from March to September and the southern skies from September to March. In the northern tropics (i.e. latitudes between 0° and +23.45°) as the latitude increases the sun follows a similar pattern, although it will be directly overhead on days that approach the summer solstice (21st-22nd June). If your site is on the Tropic of Cancer the sun's daily zenith will always be in the southern skies and will be directly overhead on the summer solstice. The sun in the southern tropics (i.e. latitudes between 0° and -23.45°) is in the southern skies for some of the year between the autumnal equinox and the vernal equinox and will be directly overhead on dates approaching the winter solstice as the latitude decreases, until at the Tropic of Capricorn the sun is always in the northern skies and directly overhead on the winter solstice.

The Arctic Circle is at 66.5° and the Antarctic Circle is at -66.5°, beyond these latitudes the sun will be completely absent for some of the year and ever present at other times. When the sun never sets it circles in the sky, never being directly over head.

The above discussion illustrates that PV panels sited in the tropics will need to be inclined to face south for some of the year and north at other times. Figure 8 shows a diagram that makes choosing panel angles relatively simple. Find the latitude of your site on the y-axis on the right hand side, then follow the line that corresponds most closely to your site and using the numbered days on the x-axis read the panel angle off on the y-axis on the left hand side.

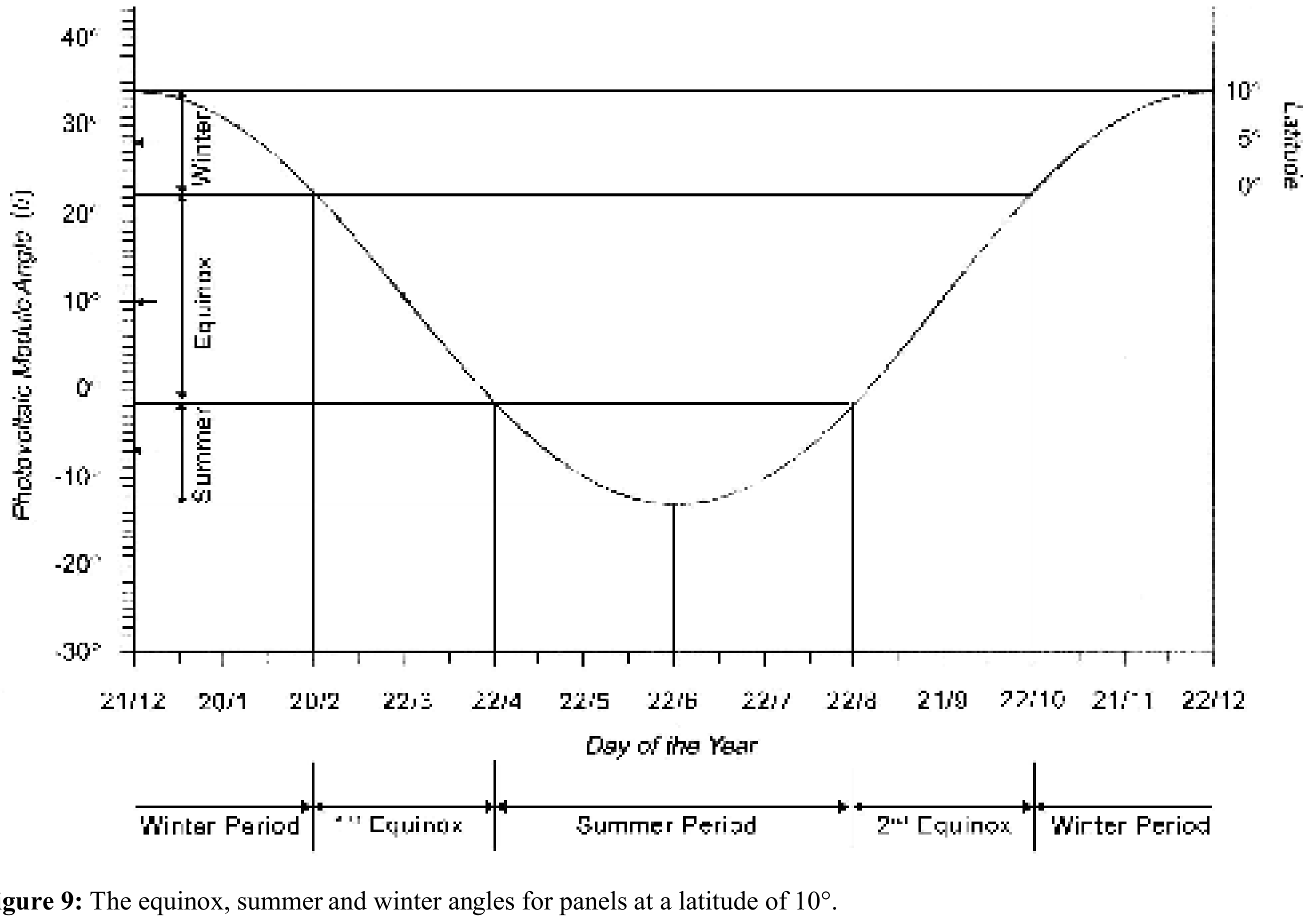

Figure 9: The equinox, summer and winter angles for panels at a latitude of 10°.

You could reset your panel angle every week however setting it four times a year will give good results. Firstly in November set a winter angle, then in February set an equinox angle until April when a summer angle is set and finally reset the equinox angle in August. Figure 9 shows how these angles can be calculated, the correct angles for the beginning and end of each period should be bisected to find the average angle for that period: for a latitude of 10° the winter angle is 28°, the summer angle is -7° and the equinox angle is about 10°. A rule of thumb is that the equinox angle will be about equal to your latitude, the summer angle will be about 15° less and the winter angle will be about 15° greater. You may wish to change the panel angle every month around the equinoxes since the recommended angle is changing rapidly from week to week at these times of year.

PV Panel Arrays and Wiring

When the panel angles are connected together they are known as an array. The voltage of the array must be matched to the voltage of the battery bank (if one is being used). Typically the bulk charging of a 12V battery bank will be done at about 15V. It is clear from figures 10 and 11 that both the 85W and 160W panels of 15V will deliver about 5A at 25°C therefore paying for 160W panels would be a waste of money.

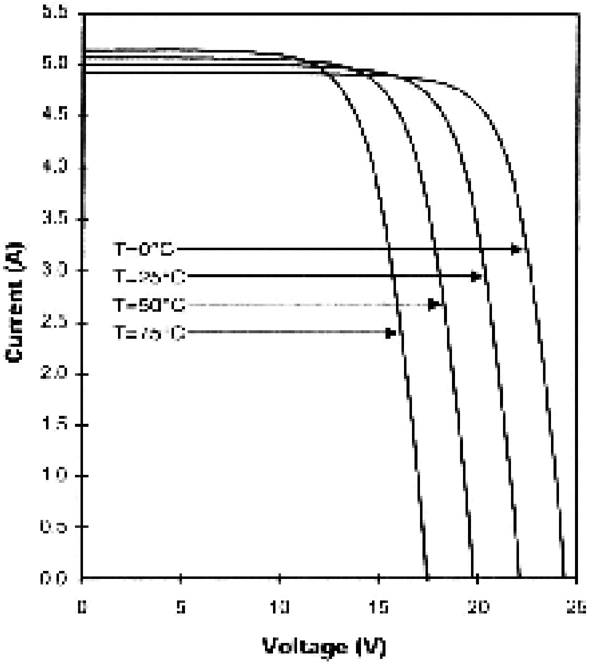

Figure 10: I-V curves for a BP 585 85W panel

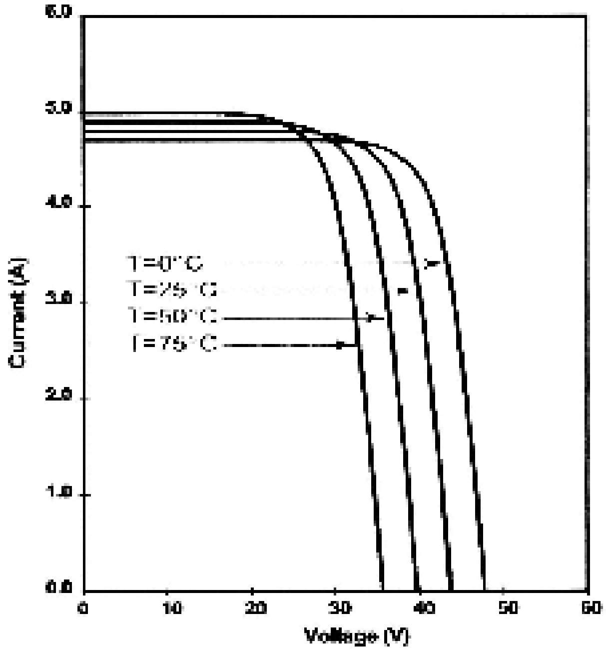

Figure 11: I-V for a BP 4160 160W panel.

When panels are connected together in parallel, shown in figure 12a, they will operate at the same voltage: if a parallel array of 85W panels are charging a twelve volt battery bank all of the panel will be operating at the charging voltage (i.e. about 15V). The current from each panel in a parallel array are added together so that two 85W panels in series will produce (2 x 5) 10A at 15V giving (10x15) 150W. Note that the panels have not been down rated from the manufacturer's specifications.

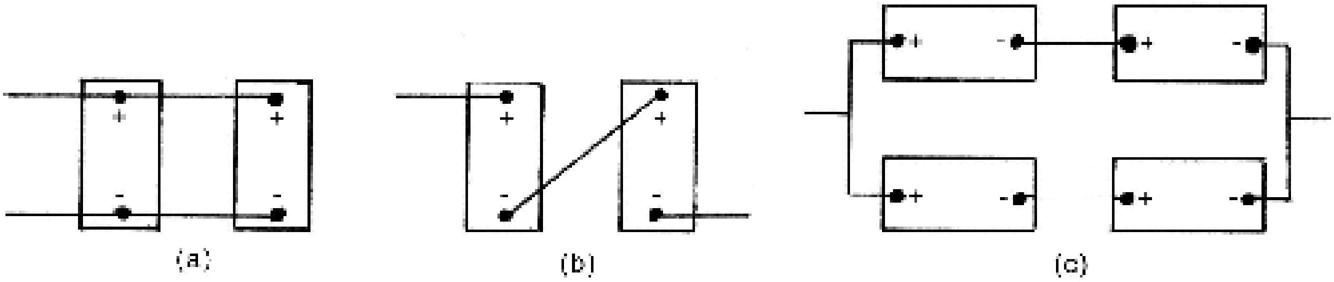

Figure12: (a) two panels in parallel; (b) two panels in series; (c) four panels, two lots of two in series connected in parallel.

Panels connected in series, as depicted in figure 12b, work the other way round so that the voltage will be the sum of the voltages across both panels but the same current will flow through both panels. Therefore, two 85W panels in series can comfortably operate at 30V charging a 24V battery bank with 5A, once again the total power is (5x30) 150W. However, if these two panels in series were connected to a 12V battery bank they would operate at 15V and still produce about 5A, thus the power produced would only be (15x5) 75W.

Panels can be combined in series and parallel to get the desired current at the battery bank voltage (figure 12c).

If batteries are not being used and the panels are connected to a electricity supply grid through an inverter the panels are usually connected in a long series string. This has the advantage of keeping the current small and thus losses can be kept to a minimum and thinner, cheaper wires can be used. This is not possible with a battery system because the voltage across each panel is summed so that the operating of voltage of a 20 panel series array may be about 300V.

A moderately sized 12V system will require about ten 85W panels in parallel, producing about 50A. This is quite a large current therefore quite thick wires are needed to connect the panels together and to convert the panels to a battery charger. Wires with a large diameter cause a smaller voltage drop and will not burnout when substantial currents are fed through them.

Another consideration when wiring PV panels is that at night or when in deep shade the cells tend to draw current from the batteries rather than sending current to them, this effect obviously causes the batteries to lose charge. Most charge modern controllers contain diodes to prevent the flowing of a reverse current

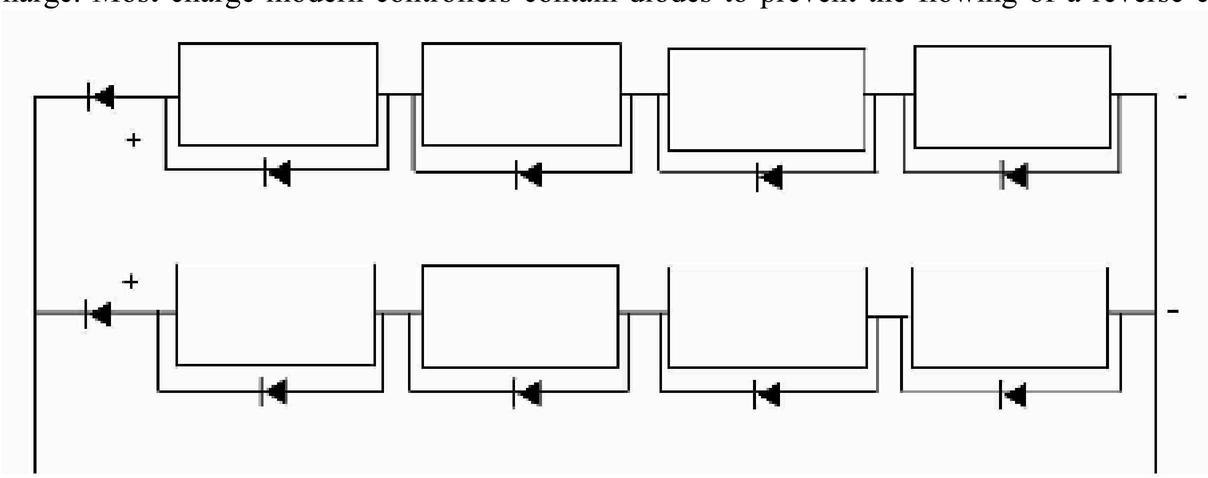

Figure 13: diodes fitted to a large array.

however, if the charge controller does not take account of this phenomena or if no charge controller is being used diodes must be fitted to the panels. If the system has a voltage above 30V it is recommended that diodes are fitted as a matter of course (figure 13) due to partial shading of the array, charge controllers can only prevent reversed current from the array as a whole, not from individual panels.

References

Solar Electricity (2nd Edition), Edited by Tomas Makvart, John Wiley & Sons (2000).

Many panel specification sheets can be found at http://www.oksolar.com

Find out the latitude of locations around the globe at http://www.calle.com/world/index.html

Data for monthly mean solar irradiation on a horizontal plane. The database contains listings from thousands of weather stations around the globe. http://energy.caeds.eng.uml..edu/fpdb/irrdata.asp

An in depth scientific guide to solar power can be found at http://www.powerfromthesun.net/book.htm

A relatively simple article on panel angles www.eea.freac.fsu.edu/solarworld/solarw.pdf