An Introduction to PHOTOVOLTAICS

In association with bp solar

PART 1

THE CLEAN, GREEN BUILDING OF THE FUTURE IS HERE. THE USE OF BIPV, WHICH STANDS FOR BUILDING INTEGRATED PHOTOVOLTAICS, HAS PROVEN THAT MANY BUSINESSES AND HOMES CAN PRODUCE ALL, OR NEARLY ALL OF THEIR OWN ELECTRICITY, THEREBY REDUCING GREENHOUSE GASES THAT HARM THE ENVIRONMENT

If a material is said to be photovoltaic (PV), a voltage will be generated in it by the incidence of light upon its surface. It is a catalyst for the conversion of light energy into electrical energy. PV cells are not only environmentally friendly, but are silent as well because they do not contain moving parts.

What materials can be used?

Silicon (Si) is the most important photovoltaic material presently in use: It is benign, widespread and extremely suitable for use as a PV material. It does have disadvantages, though, and these are that it is expensive to purify and prepare in its photovoltaic form, and that this final form can be fragile. Other materials – namely gallium arsenide (GaAs) and cadmium telluride (CdTe) – can be used, but they are either too expensive or have not been proven over a 20 year period of use.

Monocrystalline silicon (where the atoms are regularly arranged within a single crystal) is the most effective form of silicon for use as a photovoltaic. This form of silicon is grown as an ingot from a seed of crystal silicon within a molten silicon solution. A diamond saw is used to slice the ingot into pieces, which are then smoothed so as to remove the rough surfaces. A cheaper way of casting silicon is to pour the molten solution into a tray or mould. This produces polycrystalline silicon (with its multifaceted appearance). This is, however, slightly less effective as a PV material than the single crystal form.

Using thin-film techniques, silicon can be coated onto the glass that will form the window area of the final PV module. This is the least expensive option, but does make the silicon amorphous and this means a lower efficiency and a degradation of the material over time.

Architects may consider the aesthetics of the material to be equally as important. Monocrystalline silicon is blue and regular, polycrystalline silicon is blue and patterned, and thin-film silicon (the kind that powers solar calculators) is brown. Efforts are being made by manufacturers to widen the choice of colours, but this is difficult because with any change in colour there must be some reduction in PV efficiency (as visible light scattered back is light that is lost to the PV process).

How is a PV cell created?

To turn PV material into a PV cell, a pn junction needs to be created just below the front surface (more on which to follow). Two additional processes then need to be applied: The next stage is to bond metal contacts onto the front surface to 'gather' electrical charge without blocking the incoming light too much. Finally, so as to minimise the amount of light lost through reflection, an anti-reflection coating is applied to the silicon.

Silicon photovoltaic cells normally generate up to 0.5V and, providing they are sealed away from moisture in the atmosphere, can have a long and productive lifespan.

The photovoltaic process.

Figure 1 shows a schematic of the electrically active layers within the crystal structure of a PV cell. Pure silicon has a very low electrical conductivity because almost all of its electrons are immobilised in bonds. To increase the conductivity, a very small quantity of boron is introduced into the material. This process is known as 'doping'. Doping silicon with boron introduces positive charge carriers into the material. These can be thought of as gaps in the bonds of the crystal structure where electrons would normally be expected to be. Silicon that has been doped with boron is referred to as being 'p-type', the 'p' representing 'positive'. Similarly, 'n-type' silicon is silicon in which the main charge carriers are electrons (negative), and this is created in the same way but with phosphorous as the dopant instead of boron.

Most of the silicon in the PV cell is p-type, but the surface – where the light enters – is n-type. The most important part of the cell, however, is the interface between the two. Just below the surface, this interface – known as the 'pn junction' – is where the negative and positive charge carriers combine, cancelling each other out. However, because the dopant atoms are fixed within the crystal structure, they cannot move to cancel each other's charge. Instead, they form a charged barrier – positive in the top part of the pn junction and negative in the bottom part.

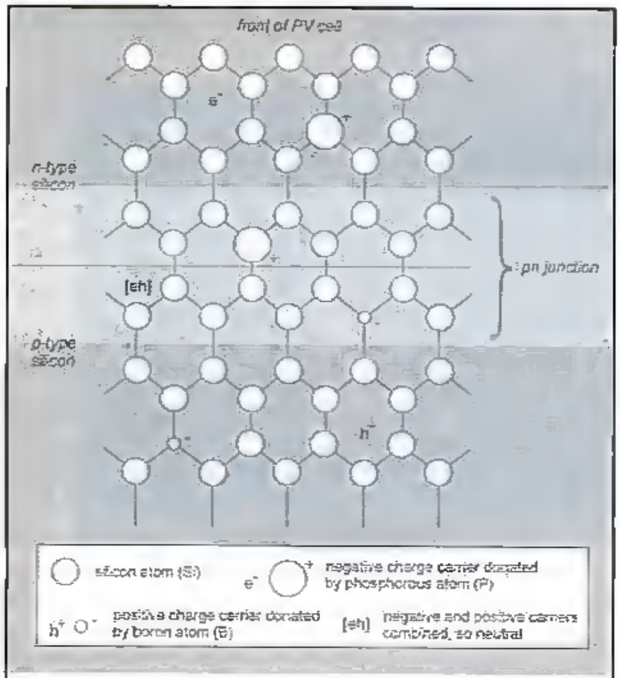


Figure 1.

When a photon is absorbed into a PV cell, it passes its energy to an electron in one of the bonds. The increase in its energy level liberates that electron from its bond, turning it into a charge carrier, free to contribute to electrical conduction. The gap left by that electron is effectively positively charged, and can also contribute to conduction.

The cell is designed so that most of the photons that hit it generate these carrier pairs of electrons and gaps in the junction. Because of their proximity to the unbalanced charges created by the dopant P and B atoms, the two types of carrier are forced to travel in opposite directions. Electrons move away from the boron in the junction and towards the top, and the gaps move downwards into the p-type material.

When the PV cell is connected to a circuit, a route is provided for the electrons to flow from the front (or top) of the PV cell to the back, where they recombine with the gaps. This can alternatively be looked upon as a route for positive current flowing from the back to the front of the cell.

What is the difference between PV cells and solar panels?

Firstly, the name 'solar panel', whilst instantly recognisable by the layman as a panel for turning light into electric, can also include solar water heaters and, as such, should not be used. The preferred name for a group of PV cells is a 'module'. PV modules contain several cells always connected in series. By doing this, the inconveniently low voltage created by a single cell can be added together with that of others, forming a more useful value.

The front of a PV module is a window of low-iron content glass. This both protects the cells and also ensures a high transmission efficiency. The cells are hermetically sealed with either silicone or EVA (ethylene vinyl acetate). A module may or may not need a frame to strengthen it – if the glass is sufficient protection, the module is referred to instead as a 'laminate'.

Electrical connections, labelled positive and negative, are fitted to each end of the series connected cells. The maximum voltage per module is usually 22V dc.

Modules can be connected together in one of two ways to form an array. A series connection of modules (or 'series string') will increase the voltage. A parallel connection will increase the generating capacity without any increase in voltage.

Unfortunately, should one cell be shaded by, for example, the branch of a tree, it can have the same effect as shading the whole module. Parallel connections within an array are important for minimising any losses incurred in such a way.

I-V curves and peak power.

To examine the electrical characteristics of a PV module, an I-V curve (a graph of current against voltage) can be drawn. To obtain the WP (peak watts) value of a module, that module should be illuminated using a solar simulating light source at a constant temperature. With no loads connected, the open-circuit voltage can be measured. This will give a value on the V axis because no current is flowing. The short circuit current can also be measured by shorting the terminals together via an ammeter (this will give a value on the I axis, where V = 0). Unlike a mains supply, which maintains its voltage irrespective of the number of appliances connected, the voltage of a PV module will drop as more current is allowed to flow. By varying the load, a series of values for I and V can be found and plotted on the I-V curve (see figure 2).

Power (in watts) is simply the product of current and voltage. To find the maximum power we need to find the largest product of current and voltage, and on the I-V curve this can be represented as a rectangle touching both the origin and the 'knee' of the line drawn to connect up the plotted points. The 'peak power' of a module is taken in such a way using a standard solar irradiation of 1,000 W/m^2 and a cell temperature of 25°C.

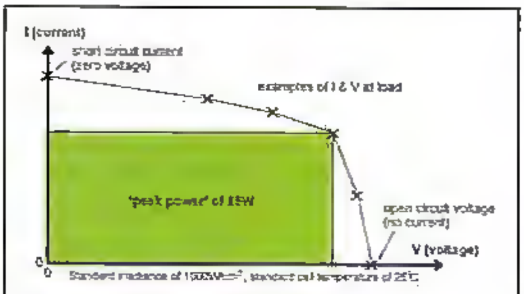


Figure 2.

The term 'peak power' applies only to test conditions – 'maximum power' should be used under all other circumstances. Maximum power is dependant on irradiance, which is in turn dependant on cloud conditions and time of day.

Test conditions aside, PV cells should be kept as cool as possible to maximise their power output. For each °C rise in cell temperature, there is a decrease in power of 0.3%. Modules are built with minimal covering over their backs so that air can flow over them and keep them cool. However, the test irradiance mentioned above can cause a rise in cell temperature of around 30°C, resulting in an actual temperature of 55°C, and this will reduce the maximum power attainable by approximately 10%. Only if the ambient temperature is below 0°C might maximum power reach peak power at standard or peak levels of irradiance.

Though the maximum power can be derived for any value of irradiance, can it just as easily be extracted? It is now common for inverters to include a peak power tracker. In the dc to ac conversion process, a peak power tracker constantly adjusts its input voltage in order to maximise the product of I and V. The tracker is important because it maximises power extracted as the temperature and irradiance vary.

What angle should the modules be tilted at?

If PV modules are to be incorporated into a structure that is already there and is immovable, such as the roof of a house, there may not be much of a choice. If, however, a PV array is to be incorporated into the structure of a building at the design stage, then there are some very clear choices to be made. Firstly, at what time of the year is the power going to be of most importance? The tilt angle can be optimised for the summer, the winter or a compromise. To maximise annual yield, designers optimise the tilt of their arrays for the summer. This might usually be the latitude angle of the site minus about 20°. To raise the minimum output, designers optimise instead for the winter – the latitude angle of the site plus about 20°.

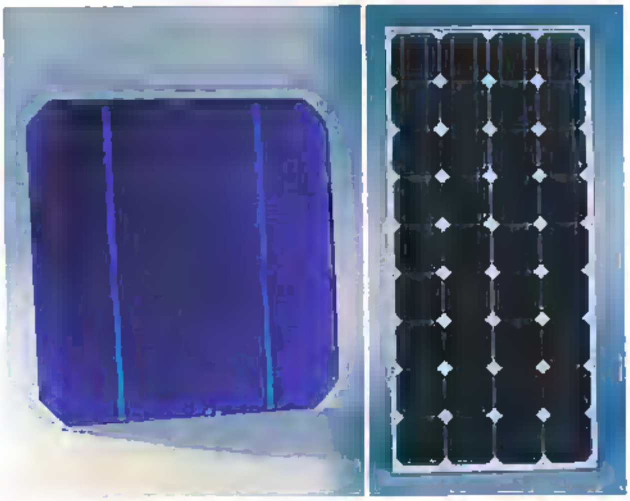
It is also possible to incorporate a system that will constantly adjust the tilt so as to give the best yield. This can be very expensive, but there is a cheaper alternative and that is to incorporate a hinge system into the modules so that they can be adjusted manually with each change of season.

What about orientation and location?

In a northern latitude, a south facing array will collect the most light throughout the year and will thus produce the most energy. Failing this, east and west facing facades can still produce significant quantities of energy from PV.

When it comes to measuring the amount of sunshine available at the site, daily insolation is the measurement that needs to be looked at, rather than hours of sunshine. Daily insolation is measured in kWh/m², otherwise referred to as 'peak-hours per day'. Because the standard irradiance of the specified peak power of 1,000 W/m2 (1 kW/m²) is also close to the maximum irradiance received by a surface facing the sun, a figure for the energy received during the day can be worked out from the equivalent number of hours in which a constant 1 kW/m² is received.

Meteorological records for daily insolation can be consulted, but these mostly measure from a horizontal plane. In some places, the daily insolation is available for a plane tilted in respect to the angle of latitude. PV arrays are rarely mounted horizontally – they are usually tilted at an angle or set vertically into the structure of larger buildings.



BP 'Saturn' Cell and Module

The Oxford Solar House (main photo) was set up in 1994 as a project for exploring the issues surrounding the use of PV technology in the built environment. It has 3 series strings consisting of 16 modules each, and these face due south with a tilt angle of 40° from horizontal (site latitude is 51.8°). Horizontal surface daily insolation records for the Oxford area show an annual mean of 2.6 peak-hours per day, with means of 0.6 for mid-winter and 4.4 for mid-summer. Data is also available for the same area at a tilt of 45°, and this shows an annual mean of 3.3 peak-hours per day, with 1.3 for mid-winter and 4.5 for mid-summer. This latter set of statistics is more relevant to the Oxford Solar House than the horizontal set, and the difference between the two illustrates how important it is to use the right daily insolation data whilst still at the planning stage.

If the required daily insolation figures are not available in that area for the tilt angle being considered, there are other ways of working them out, and these require more sophisticated calculations. In addition, further conversions are needed for directions of tilt other than due south.

Measuring performance.

The amount of energy generated varies from day to day, so to simplify the problem of measuring performance, the total generation should be measured over the course of one year. A convenient unit of measurement is the kilowatt-hour. The annual energy yield of the Oxford Solar House is around 3,000 kWh.

The total electrical output divided by the peak power of the array gives another parameter that can be used to compare systems and their relative performance – the 'annual specific yield'. The Oxford Solar House has a total array output of 4kWP, so its annual specific yield is 750 kWh/yr/kWP.

The annual specific yield depends on the following factors:

- Insolation: The annual insolation of the site at given angles of tilt and deviation from due south.
- Cell temperature: The operating temperature of the cells – related to the ambient temperature, moment-to-moment insolation and the effectiveness of cooling.
- Electrical coupling efficiency: The effectiveness of peak power tracking and the inverter.

For the Oxford house, an estimate of the maximum attainable value for the annual specific yield has been worked out as follows:

3.3 (peak-hours per day, annual mean) x 365 (days) x 0.85 (a 15% reduction for the effects of cell heating above the standard testing temperature) x 0.9 (90% efficiency of inverter, including effectiveness of peak power tracking) = 921 kWh/yr/kWP.

The value of 750 kWh/yr/kWP observed in the house compares well with this estimate of the maximum, although it may have be set unattainably high by the estimate of the effects of cell heating being a little too conservative.

PV integration on a larger scale.

BIPV (Building Integrated PV) is becoming more and more widely used in the construction / refurbishment of larger commercial buildings. BP Solar is a major manufacturer of PV arrays and technology, and their PowerWall panels have been designed to substitute directly for materials such as glass or granite, traditionally used in these buildings. As well as providing useful energy, these panels can also appear quite aesthetically pleasing when the building is designed with their inclusion in mind.

Next month we take a closer look at BIPV, courtesy of some real life buildings which utilise BP Solar's photovoltaic modules to create buildings that are not only environmentally friendly, but attractive to look at as well.