The ins and outs of solar cells

Energy derived from fossil fuels — the world's major source of energy today — was originally provided by the sun, converted by photosynthesis with an efficiency of about 0.025%! Compared to modern solar cells, which have an efficiency around 12%, we're on a real loser with fossil fuels. However, at the moment, they're convenient — but they won't always be so.

Here is a short, practical guide to solar cells, their uses and abuses.

WE HAVE ALL BECOME vitally concerned about our energy resources, and rightfully so. Most people see the energy crisis in terms of paying more for a tank of petrol, but the implications run much deeper than that. Just think how many commodities are based on the oil industry – the pen I use to write with is plastic, the table top is plastic veneer, even the carpet is synthetic – all made from petroleum products.

A very large percentage of our business trade is in oil-based products e.g: clothing, photography, medicine, and household goods, to mention just a few. In fact Western economies are based so heavily on oil products that, if anything suddenly happened to the supply, most western nations would collapse.

An enormous amount of energy is radiated by the sun. It is, in fact, our primary energy source. On a clear day the Earth receives about one kilowatt of solar energy per square metre on its surface. About 30% is reflected back into space, 47% is converted into heat, the rain cycle uses another 23% (which can be tapped to provide hydroelectric power in suitable mountainous areas) while wind, waves, and convection currents account for about 0.25%.

The remainder, about 0.025% (!), is stored by photosynthesis in plants. It is this energy that eventually goes to make coal, oil, and shale oil. The energy derived from petroleum which we use so extensively today is the accumulation of this trickle of energy into photosynthesis over millions of years. No wonder it's running out!

In fact it has been estimated it would take six million years of photosynthesis to provide us with an extra six months of oil and coal!

Solar energy can be harnessed in many different ways. Hydro-electric power is a result of the rain cycle; thermal gradients in tropical oceans have been used in an experimental generating station off Cuba as long ago as 1929; wind power is showing promise with experimental generating stations using large windmills and solar collectors have been devised to capture some of the heat which would otherwise be re-radiated and lost, converting it to hot water for domestic and commercial heating.

A set of experimental 'demonstration' solar cells made here by Philips at their Hendon, S.A., plant.

What solar cells offer

Solar cells offer a much brighter future (. . . pardon the pun) as a source of electrical energy. Firstly, they provide energy in a clean, transportable, convenient form – electricity. The predominant source of energy for electrical generation today comes from fossil fuels and hydro-electric schemes. A very few generating schemes use hydrothermal energy from natural hot springs.

Secondly, solar cells can provide energy very close to the point of consumption without requiring the transmission of energy across a distance or replenishment of fuel. Very handy in isolated locations.

Thirdly, they're relatively efficient . . . and they have a long life.

One shouldn't forget, too, that they are made from the most common substance on Earth – silicon.

To date, the most extensive use of solar cells has been in space. They have been employed as power sources for satellites for many years. Research has improved the efficiency of solar cells over the years, and the position is likely to steadily improve with continuing research.

Solar power satellites are currently being studied (see ETI, April issue this year). It is proposed to assemble huge solar cell arrays in space and beam the energy back to Earth via a high power microwave transmission, enormous antennas ("rectennas") on Earth converting the microwave energy directly to electricity for distribution.

Terrestrial use of solar cells has expanded rapidly in the last few years. Remote telecommunications installations seem to be making the greatest use of the advantages offered. Some radio amateur VHF repeater stations in

TYPICAL VOLTAGE-CURRENT CHARACTERISTICS C 200

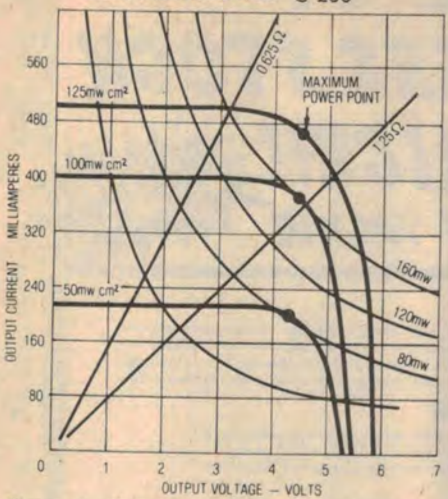


Figure 1. **Typical voltage/current characteristics of a solar cell. (Sensor Technology, type C200, distributed by Amtex Electronics).**

Australia employ solar cells to maintain charge in storage batteries used to power the installation. They are also used to charge batteries on ocean-going yachts. So you can see that hobbyists as well as professionals have been getting into the act.

Solar cell characteristics

The voltage/current characteristics of a typical single solar cell are illustrated in Figure 1. Power output contours are also shown.

At low loads (relatively high load resistance), output from the cell will be pretty nearly a constant voltage — around 0.55 V to 0.6 V — depending on the amount of energy received. If the load is increased (by reducing the load resistance), output current (and load power) will increase in proportion until a point is reached where the output voltage rapidly 'turns over', dropping sharply if the load resistance is further decreased. In this region, the load current will remain virtually constant. Maximum power output, for a given level of energy falling on the cell, occurs at the 'knee' region of the characteristics.

The performance of a solar cell depends on the spectral distribution of the irradiation impinging on it, thus, the amount of power per unit area falling on a solar cell is not a measure of the total irradiation. The term *insolation* is used to specify both the amount of power and the spectral distribution of radiation falling on a solar cell.

The relative spectral response of a typical solar cell is illustrated in Figure 2. Part of the efficiency loss in solar cells results from the fact that their spectral response does not match the spectral output of the sun. Further energy is lost in the unused excess of energy of the absorbed photons. Conversion efficiencies at an insolation of 1 kW/m^2 (100 mW/cm^2) for typical solar cells ranges between 8% and 12%.

Solar cell arrays

The most convenient way to obtain power from solar cells is to mount a number of them in an array and connect them so as to provide a useful voltage at some convenient current or power rating. Accordingly, manufacturers make 'panels' of solar cells, constructed by encapsulating individual cells in silicon resin between two plates of glass, generally with an extruded aluminium surround for the edge, with the cells connected in series. The glass plates are chemically hardened (tempered) and made very smooth to reduce the build up of dust or other residues. This is especially important where the panels are used in remote locations.

Since most of the energy falling on the panels is converted to heat and lost, the panels have to be able to conduct the heat away by convection (primarily) or conduction. Some panels are ▶

RELATIVE SPECTRAL RESPONSE

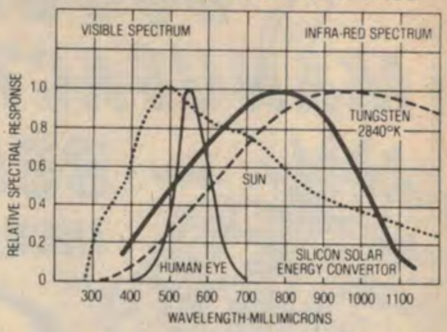


Figure 2. **Relative spectral response of a solar cell. Efficiency would be better if the response matched the Sun's output more closely.**

SILICON SOLAR CELL – HOW IT WORKS

A SOLAR CELL can be considered as a large-area silicon diode. Because it consists of a p-n junction, the junction will have a barrier potential associated with it (harking back to your diode theory) when no radiation falls on the cell. There will be an excess of electrons on the n-side of the junction (supplied by donor atoms from the doping material), some of which will diffuse across into the low electron density region on the p-side of the junction. This diffusion leaves ionised donor atoms ('holes') which create a positive space charge in the n-region close to the junction. The electrons which diffuse into the p-region will find acceptor atoms and will no longer be free to roam. This creates a negative space charge near the junction. That's how the barrier potential comes about. But, you won't be able to measure it.

The barrier potential, V_B, can be thought of as a contact potential. If contacts are made to the p-region and the n-region (with the same metal) and a high impedance voltmeter connected, no voltage will be measured. The contact potentials will cancel. Looking at the diagram, with no light falling on the cell, V_B will typically be −0.7 V, V_{C1} +0.5 V and V_{C2} +0.2 V. Hence, you won't read a thing on the meter.

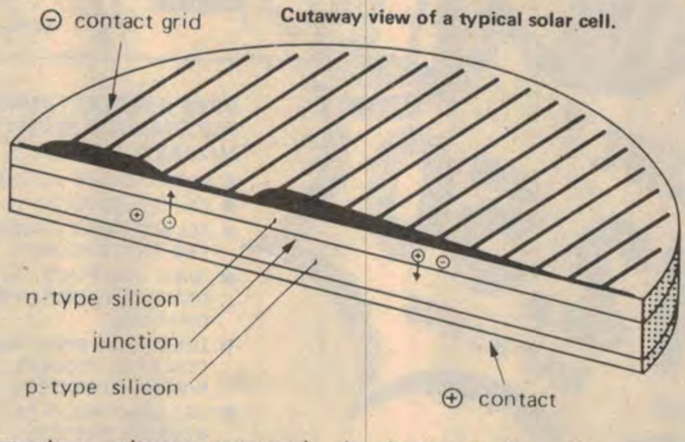
If the cell is now irradiated with light, electron-hole pairs will be generated in the junction region, separated by the field associated with V_B, the holes being forced to the p-side and the electrons to the n-side. i.e.: they move across the junction. Consequently, the barrier potential will fall considerably, to say 0.1 V!

However, the p-contact will then be at a potential 0.6 V above that of the n-contact. Now, you can measure this! With sufficient irradiation, electrons charge across the junction from the p-region to the n-region — via a load and round again if you want the solar cell to do work.

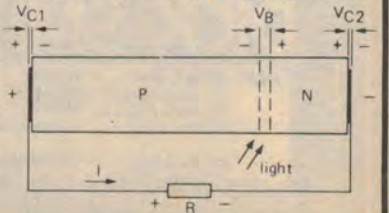
Thus, convential current flow will be from the p-contact (which becomes the positive terminal) to the n-contact via a load. The maximum current obtainable is approximately proportional to the level of irradiance and the area of the cell.

Conversion efficiency of solar cells ranges between 8% and 15%, typically 10-12%, under a standard solar irradiance of 1 kW/m^2 (100 mW/cm^2). It is limited by three main factors: firstly, only part of the Sun's available spectrum is used: second, the absorbed photons have an unused excess of energy and lastly, some of the electron-hole pairs created are lost through recombination.

Cutaway view of a typical solar cell.



Representation of a solar cell showing the contact and barrier potentials. V_B falls considerably when light falls on the junction.



A solar cell 'piece' from Sensor Technology, type C202, used in projects in this issue.

provided with a sturdy, cast aluminium frame at the rear which serves as a heat dissipator for the array.

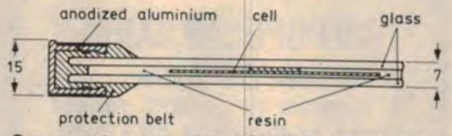
High temperatures on a solar cell panel have to be avoided, otherwise damage may result. Although individual cells can withstand quite high temperatures before they suffer structural damage, the resin potting compound cannot. Excessive heat induces strains in the resin, causing it to tear away from the surface of the cell, leaving a gap, and decomposition of the resin due to excessive temperatures can cause discolouration. The results of these two effects combine to attenuate the light falling on the cell, decreasing its efficiency.

It is important that solar panels are used within the Safe Operating Area Limits (SOAR) given in manufacturers' data. Most panels are designed so that, when used singly – for charging a storage battery, for example – they cannot be damaged. Series and parallel connection requires care to avoid excessive dissipation in particular cells. Notes on avoiding problems are given a little later in the article.

Load considerations

Operating solar cell arrays into a fixed load resistance is not ideal since, at different levels of insolation, the output voltage and current will vary and thus the maximum power output point varies. Thus, the optimum load resistance should be different for different levels of insolation. If a secondary battery (an accumulator – such as a lead-acid or nickel-cadmium type) is used as a load, this problem is largely overcome.

As an example, let's examine the characteristics of a typical solar panel – the Philips BPX47A, Figure 3. It delivers a maximum power output of almost 10 watts at a peak insolation of 1 kW/m^2 into a load resistance of 20 ohms. At half that insolation level (500 W/m^2), power in a 20 ohm load would only be 2.9 watts. For a 12 volt accumulator (see the 'battery load line'), power delivered to the battery at peak insolation would be a little under 10 watts, but at 500 W/m^2 insolation it would be 4.8 watts.



Construction of the BPX47A solar panel

For this reason, solar panels are manufactured with the correct number of cells to charge a (nominal) 12 V storage battery (34 in the BPX47A). The solar cells are able to work at near-optimum efficiency and the storage batteries can provide peak demands of the power-consuming equipment and bridge overcast periods and night time when the panel receives little or no energy.

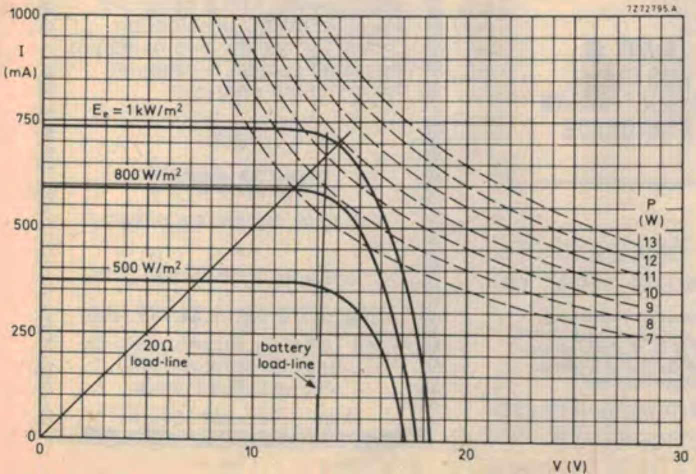
Series connection of solar cells

Any number of solar cells may be connected in series to give a desired output voltage. There are however, some points to remember. If all but one of the cells are in shadow, the irradiated cell will not be able to overcome the barrier potentials of the shadowed cells (since all their barrier potentials are in series) and no current will flow. Taking that a little further, sufficient cells in a solar array must receive irradiation so that the barrier potentials of the remaining cells can be overcome. In the extreme case, what happens when only one cell in an array does not receive sufficient irradiation? The irradiated cells will then force a current through it and the cell will develop a *reverse* voltage across it and thus dissipate power. The actual dissipation will depend on the amount of shadowing. If the irradiance to shadowed cell increases, the power dissipated will *increase* as more current will be able to flow through it, but until the cell can produce the same current as the others – by receiving the same irradiation – it will remain reverse-biased.

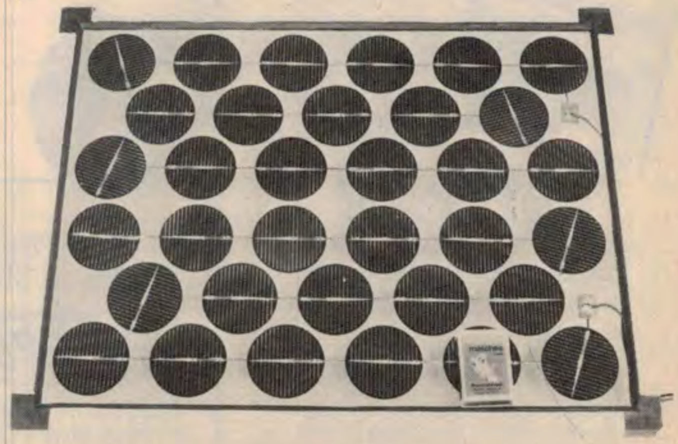
The maximum dissipation of a cell is limited by its area. As a guide, the dissipation should be less than the maximum power received at an insolation of 1 kW/m^2. For example, the area of one cell in the Philips BPX47A is 26 cm^2 and thus the maximum dissipation is 2.6 W. For the Sensor Tech. C200 (characteristics given in Figure 1), which has an area of 20 cm^2, maximum dissipation is 2.0 W.

An effective way of limiting the dissipation is to place a protection diode across each cell to short out any reverse voltage across the cell. This is a rather expensive solution and is unnecessary if the cells are used to charge a battery as the constant voltage characteristic of the battery will limit the maximum voltage which can be developed across any one cell. This is another reason why solar panels are designed to feed a storage battery. If however, several panels are connected in series a protection diode must be connected across each panel to limit the maximum reverse voltage. ▶

Figure 3. **Characteristics of Philips' BPX47A solar panel.**



Philips' BPX47A solar panel (matchbox for size comparison.)



Parallel connection

If cells are connected in parallel to supply a higher current the voltage across each cell will obviously be the same. However if one cell receives less insolation than the others, the shadowed cell will be biased into its forward region and current will be forced through it from the other cells receiving full insolation.

In the worst case one cell in a parallel-connected array will be shadowed and the rest will receive full light. All the energy from the irradiated cells will be dissipated in the shadowed cell and it will heat up. For this reason individual cells should not be connected in parallel.

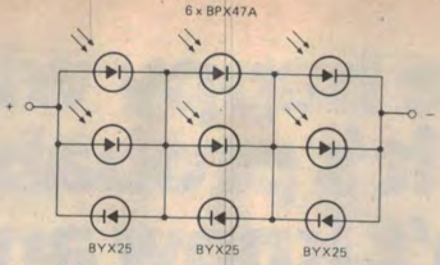


Figure 4. **Matrix connection of a solar panel to improve output. The BYX25s serve as protection diodes.**

When solar panels, or chains of series-connected cells are connected in parallel, the dissipation in a shadowed panel will be equally divided between each of its cells. In the case of the BPX47A panel with 34 cells in series the temperature rise is limited to such an extent that up to 12 panels can be safely connected in parallel.

Solar panels in series and parallel

For higher voltages and higher currents a number of solar panels can be connected in a series-parallel combination. To limit the dissipation in any panel a matrix is used as shown. With the Philips BPX47A panel, for example, the matrix must be three series by two parallel. Protection diodes are still required across each panel to limit the dissipation in individual cells; Figure 4 shows how. ●

We are indebted to Ampex Electronics and Philips for assistance with this article.

EXPERIMENTING WITH SOLAR CELLS

There are a number of interesting and instructive little experiments you can perform with solar cells. There are a number of small hobby-type electric motors around which require only 100 mA, or less, which run quite happily from 1½ V. Four Sensor Tech, C202 cell pieces or Dick Smith Z-4820 cells, connected in series, will power one of these motors. Why not convert a small battery-driven toy?

Electroplating, especially when doing it with precious metals, works best with low current density, long period operation. This method gives a beautifully smooth finish. A solar plater set-up is illustrated in the accompanying diagram.

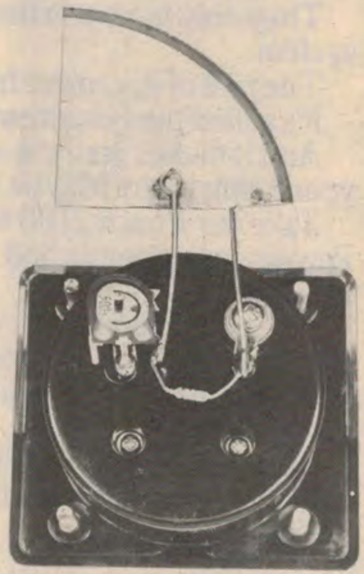
The wirewound pot is adjusted to give 5-10 mA of current for small items, three to five times that for larger items, and the process allowed to run for three or four hours or longer, depending on the results you want. There's plenty of room for experiment here.

Copper plating is quite easy, and probably simplest to start out with as the ingredients are readily obtainable. The plating solution is copper sulphate and a large piece of copper wire (sanded until it's bright) will serve as the anode. Don't use a metal plating bath — remember!

Another interesting device to experiment with is a sun (or light) intensity meter. The circuit and construction details are shown here. We mounted all the bits on the terminals of a small 1 mA meter. The solar cell we used was a single Sensor Tech. C202. The device works as follows: When driving a low resistance load, the current through the load is pretty well directly proportional to the insolation (energy falling on the cell), the voltage output varying only over a small range.
To use it, hold the device at arm's length and turn your back to the sun. Angle the unit to peak the current reading. Calibrate it by adjusting the trim pot to get a full scale reading on a bright, cloudless summer day. Full scale then represents something close to 100 mW/cm^2 insolation. The scale is fairly linear.

Solar cells make excellent photosensors and may be used in such applications as light-operated relays, photodensitometers, receiver for a light-beam communicator etc, etc.

Front view of the sun intensity meter we made as an experiment. The cell we used is a Sensor Tech. C202, quarter of a C200.



Rear view of the sun intensity meter showing how the cell was mounted on two pieces of 18 gauge tinned copper wire.