photovoltaic solar panels

These are amazing bits of kit – just face them into the sun and direct current electricity pours out of the wires. The main advantage of using solar panels rather than wind turbines is that they are passive and quiet, and so will not create a disturbance. The panels are so passive that you cannot see anything happening and the only indication of power production is the amp meter in the battery shed. This, of course, is ideal in urban areas.

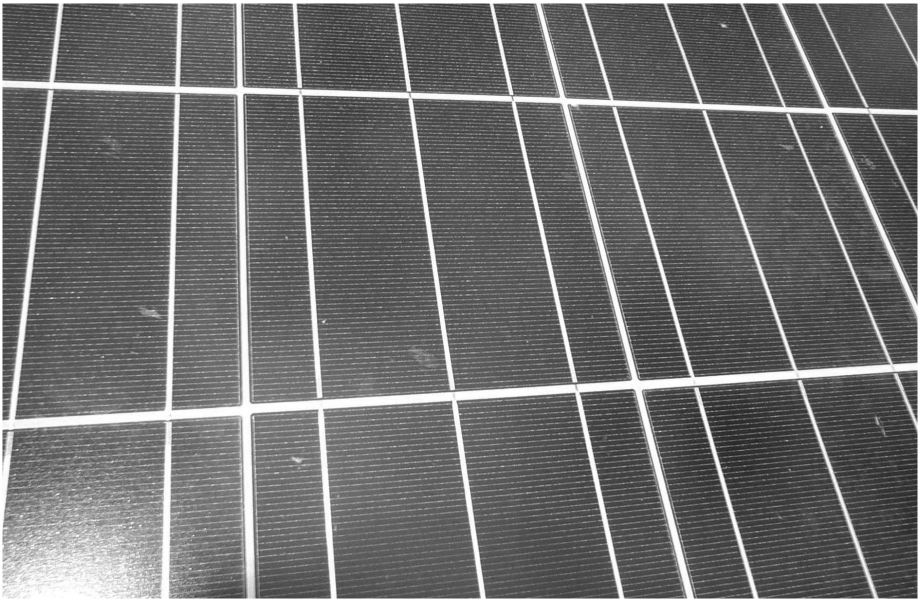

fig 19: solar panel

So how do they work? Well it's all down to electrons. In the *electricity* chapter, (page 109), I've described electricity as 'the flow of electrons through a conducting material'. Put simply, try to imagine that an electron is a fuzzy ball of potential energy smaller than the smallest thing. The next thing to contemplate is the photon, which for these purposes is the smallest part of a ray of sunshine and similar to an electron. Then you need to know that the solar panel is made up of two distinct electrical layers – front and back. The material the front layer is made of has molecules with a surplus electron that is easy to dislodge, and the material the rear layer is made of is accepting of spare electrons. A photon that has travelled from the sun, at 186,000 miles a second, enters the front layer of the panel, where it collides with one of the readily available electrons in the front layer material and displaces it. The displaced electron is then knocked into the layer of material at the back of the panel. This is similar to using a cannon shot in a game of billiards. This process continues all over the panel surface as long as the sun is shining, creating a flow of electrons and (because – as we know – electricity is the flow of electrons) electricity is produced.

panel materials

Solar panels are made up of a series of silicon photovoltaic wafers that individually produce about 0.5 volts of electricity. The wafers are built up in series until the correct open circuit voltage is achieved, which for a 12 volt system is about 21 volts. The voltage needs to be higher than battery voltage so that electricity will flow into the batteries – because voltage drives current. The other reason that the panel voltage has to be so high is to compensate for the fact that as the panel heats up in the sun the output voltage reduces slightly.

These wafers are made of pure silicon with added compounds to improve the electron flow. The silicon is essentially the same grade as that used in semi-conductors in the electronics industry. For more detailed information on panel construction and the manufacturing processes I recommend *Practical Photovoltaics* by Richard J Komp, *resources* (page 177).

There are three different types of silicon that are used as the photovoltaic material in solar panels, and there is much confusion as to which is the best. So let's try to clarify a few things, although you must understand that technological improvements are being made all the time and this information may be out of date quite quickly.

monocrystalline silicon

Wafers of monocrystalline silicon are made from slices of electronics-grade silicon taken from a single large crystal. The panels made from these wafers are currently the most efficient at producing electricity in direct sunlight – up to 18 per cent efficient – but unfortunately they are expensive and contain a large amount of 'embedded' energy. Embedded energy represents the energy required within the manufacturing process. Monocrystalline panels use the purest grade of silicon and the silicon blocks have to be gradually melted in a controlled environment to produce one large crystal. This means that a huge amount of energy is used in the preparation of the materials and not only are the panels expensive to produce in terms of energy but also financially, so you have to balance the overall cost of the panel against the potential extra output you would expect from it.

polycrystalline silicon

Polycrystalline wafers are made from a block of metallurgical-grade silicon with a large crystal structure, but not from a single crystal. They are less energy intensive to produce than monocrystalline wafers and can be made from silicon stock that is slightly less pure. Recent improvements in wafer quality mean that they are almost as efficient as monocrystalline panels – up to 16 per cent efficient. As a lower grade material is used and it is a less energy-intensive manufacturing process these panels are slightly less efficient and less expensive than monocrystalline.

amorphous silicon

Amorphous panels look totally different from those made from crystalline materials as they are an even brown colour. They are also much cheaper to produce and are said to be more efficient at low light levels. However they have a poor yield for the same surface area – only 8 per cent – compared with the panels made from crystalline materials and suffer from light-induced degradation. In other words the output degrades noticeably over a short time, which could be less than a week, and accounts for the poor yield.

At the moment it seems to me that the best value panels, on the balance of cost over output, are those made from polycrystalline material but, as I say, things are bound to change rapidly.

orientation

The panels can either be fixed to face a specific direction – ideally due south – or they can be mounted on a frame that tracks the sun. The tracking mechanism moves the panel array from facing east in the morning to facing west in the evening.

As discussed in the *why and wherefore* chapter (page 13) the choice between tracking and static panels is down to the site, but there is also the added factor of system complexity to consider. The more complicated the system is, the greater the chance there is of something not working correctly. It is down to the individual to decide what's right for them. In the *research* chapter (page 151), however, one of the things monitored is the output of both fixed and tracking panels to provide information that will help in making your decision.

The panels work best when they are directly facing the sun, which is where the tracking improves overall output. In many urban situations the surrounding buildings and trees block the sun's rays for part of the day. This will affect the decision-making process for the orientation of the panels and whether tracking or static mounting is used. If the sun is blocked due south then it may be a good idea to orientate the panels either slightly west or east, or to get the best of both by using tracking. As a rule of thumb, tracking suitable for mounting two or three panels costs the same as an additional panel.

The tracking is more effective in summer than in winter because, in latitudes away from the equator, the sun is higher in the sky in summer and so moves a greater distance across the sky. This means that, without tracking, there is a greater part of the day when panels are not even facing in the general direction of the sun.

inclination angle

Another thing to be considered is the height the sun reaches in the sky in different seasons. Bear in mind that the seasonal variations between summer and winter occur just because the height of the sun above the horizon changes and affects the length of the days. As the height of the sun reduces towards winter the panel inclination needs to be changed so that the panel is facing directly towards the sun.

Fig 20 shows the height of the sun at noon on the shortest day in December where I live and, as you can see, it's not that high above the horizon. The panels are set on a steel pole about 2 metres high and the trees in the foreground are only saplings.

fig 20: shortest day sun height

The general consensus of opinion is that the panel angle at the summer solstice should be your latitude plus 15°, and at the winter solstice latitude minus 15°. You can, however, just check occasionally with a set square placed on the panel. If the inclination is right there should be no shadow, so you can use the set square to check and then adjust the inclination accordingly.

One side of the set square sits on the panel following the slope, and so the other part, normally the steel part, faces the sun. Any shadow either above or below the set square will indicate the way you should adjust the inclination so that there is no shadow visible on the sloping plane. You don't have to be fanatical about this but just keep an eye on it and adjust the angle every other month or so.

The method of angle adjustment is up to you if you make your own mounting frames (see fig 29), but a threaded bar with lock nuts or a steel strut with a series of holes and a lock nut will work well. The whole thing has to be shake proof, to resist wind damage, and simple to change.

This is totally irrelevant of course if your panels are roof mounted and the frame is at a fixed inclination

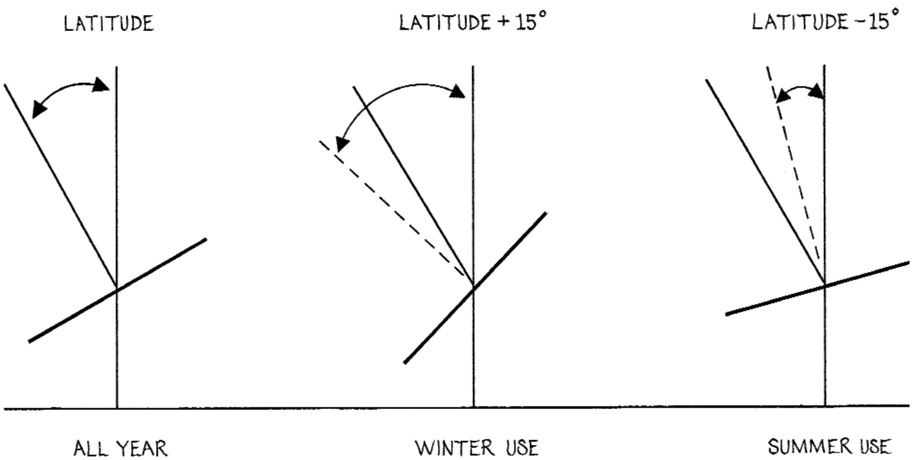

fig 21: panel inclination seasonal change

The main difference in the power of the sun between mid-summer and mid-winter is not the variation in the distance away from the sun, which is negligible. It is in fact the distance that the light has to pass through the atmosphere which acts as a filter. When the sun is near the horizon then the sun's rays have to pass through at least 300 per cent more atmosphere and all the dust and muck that it holds. This is illustrated in fig 22.

roof mounting

If you mount panels on your roof then you will be effectively reducing the possible output of the panels. It is rare that roofs face exactly the right direction and have the correct average pitch (angle). It means that you have to accept what the roof dictates unless you have a flat roof, but then there are problems with walking on flat roofs and possible degradation of the waterproof surface.

There is another problem that may not be apparent until everything is in place – namely pigeons and seagulls and the fact that they like to perch on things and leave traces of their presence in the form of a sticky, white mess. This only seems to happen if the panel provides a good perching point, so if the panels are mounted low down the roof the perching attractiveness is reduced and so is the mess. Even so it is still beneficial to have easy access to clean the panels regularly to ensure even output.

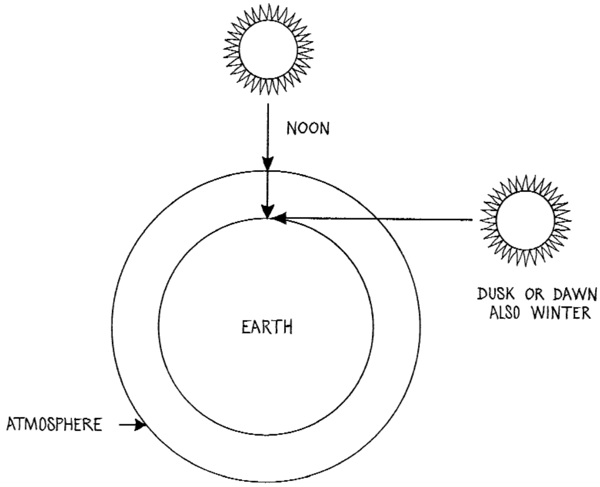

fig 22: the sun and the atmosphere

shade and muck

A slight amount of shade on one corner of a panel will dramatically affect the electrical output. That's just the way it is because the individual wafers within the panel are connected in series, see the *electricity*

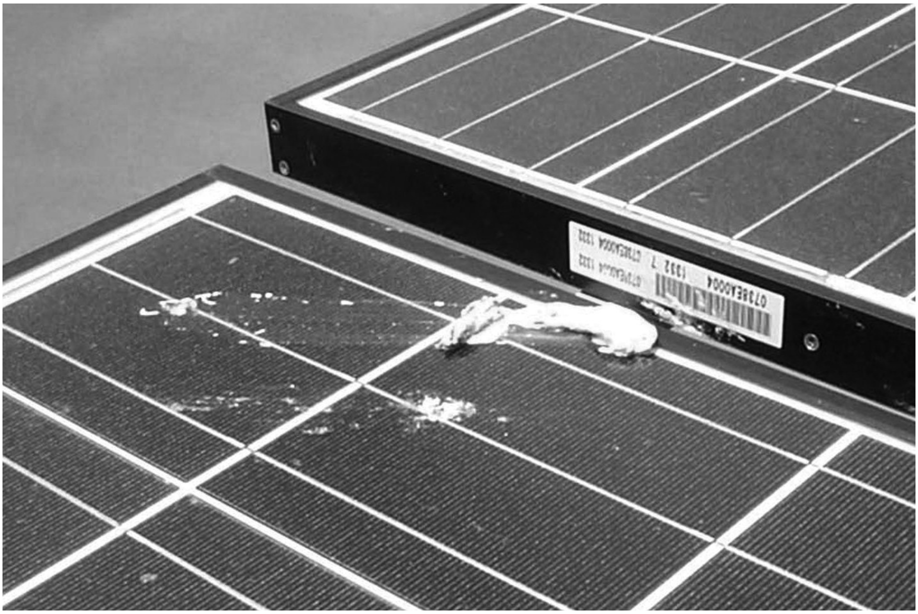

fig 23: mucky solar panel

chapter (page 109), and so the shading of one wafer blocks the output of all the rest in that series. This is the same with general muck, dust, snow, and bird mess.

output

With wind turbines the output is constantly varying up and down with the fluctuations in the wind speed. With solar panels the variations of the light intensity are more gradual and less frequent, sometimes to the point where you think the amp meter has got stuck. The panels seem to give much more power than an similar-sized turbine.

If the voltages mentioned in the panel material section (page 60) seem confusing then I'm not surprised, and here is the explanation. My panels are rated at 130 watts with a nominal 12 volt output, but they peak at 17.6 volts, and have an open circuit voltage of 21 volts. On top of that the maximum rated current is 7.39 amps, which means that, in theory, I should only get the rated output of the panels if the battery bank is at an impossible to maintain and potentially damaging 17.6 volts. The calculation to illustrate this is 17.6 volts x 7.39 amps = 130 watts, see the *electricity* chapter (page 109).

Having said all that the reality is somewhat different and my panels actually produce 8 amps or slightly more on bright days. The most important factor to explain this is again that voltage drives current and, if your batteries are well charged then there is effectively less load for the panels to feed and so the panel output is reduced until you use some power from the batteries, and the battery voltage reduces from charging voltage to nominal battery voltage.

series parallel connections

Panels are manufactured with different voltages but most commonly they are 12 or 24 volts. If you have a 12 volt system you would, of course, use 12 volt panels. With a 24 volt system you could use either two 12 volt panels in series or one 24 volt panel. If you then want to increase the output of the system by adding further panels you effectively build another set (array) of panels and wire them in parallel with the first set.

Fig 24 (page 68) illustrates this as follows:

A shows 2 x 12V panels wired in parallel. In this format the voltage remains the same as for a single panel but the available current is doubled.

Output: 2 x 8.3A x 12V = 200W

B shows the 2 x 12V panels wired in series so the voltage is doubled (to 24V) and the current remains the same. This gives twice the amount of power whilst keeping the current down.

Output: 8.3A x 24V = 200w

C shows 4 x 12V panels wired in series and then parallel thus doubling the capacity of B. This keeps the voltage at 24V and increases the current with the addition of 2 more panels.

Output: 2 x 8.3 x 24V = 400W

D shows 4 panels but they are wired in series to increase the voltage. The overall wattage is the same as in C.

Output: 8.3 x 48V = 400W

Some years ago I was confused about the difference between nominal panel voltage and maximum panel voltage. This came about when I was thinking about what panels to use for a 110 volt battery system. Should I use nine panels (9x12 volt = 108 volt) or eight panels (8x14 volt = 112 volt)? So, in the spirit of home mechanics, I did an experiment to see what happens to output as you move away from nominal voltage.

I set up a series of 2 volt battery cells in excess of 14 volts in all, and so was able to change the battery voltage by moving the positive panel wire either up or down the pack, using 10, 12, or 14 volts. I wired a panel across 12 volts and got, let's say, 6 amp output. When I put the panel across 10 volts of battery the output amps remained the same but there was less power in watts. When I then added a cell to get 14 volts the current went down. This proved to me that 12 volt nominal really meant 12 volt nominal even though peak voltage on load is 17 volts, and the peak volts are there to drive current.

panel mounting

The panels are mounted on a steel or timber framework made, or bought, for the size and number of panels you intend to fit. If there is any chance that you might expand the system then it is a good idea to install a frame that is larger than the initial requirement.

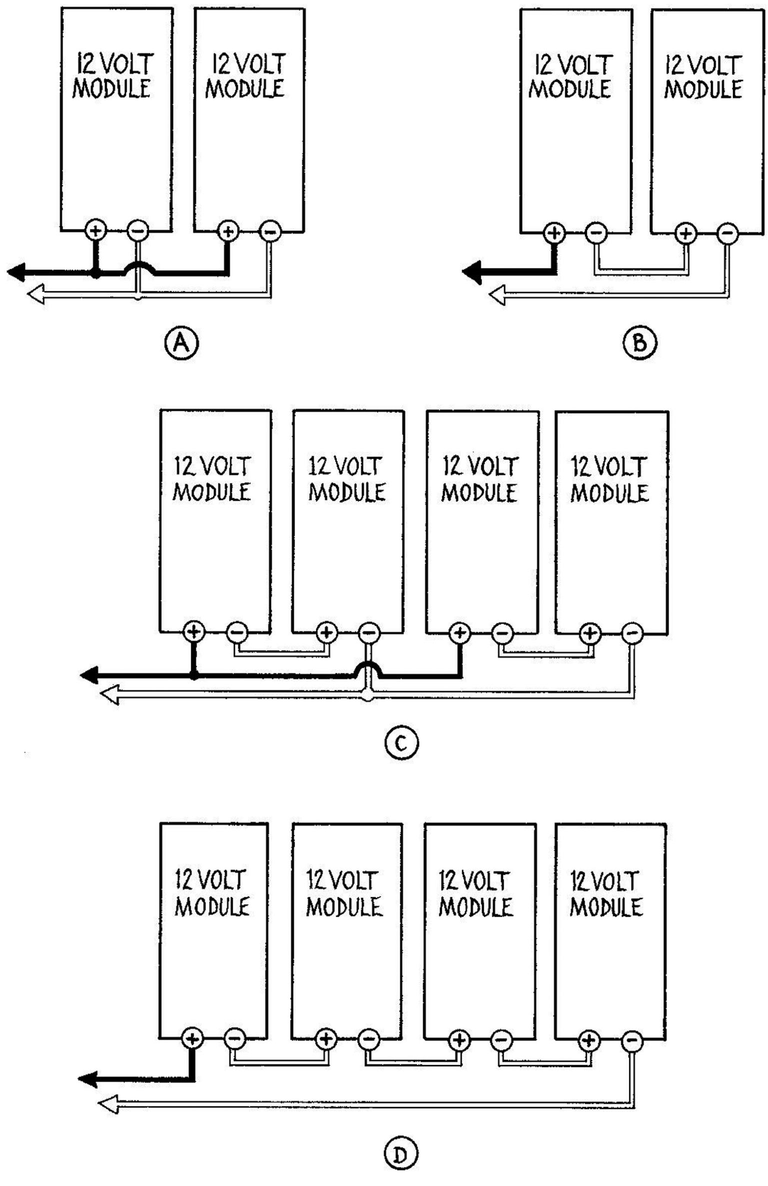

fig 24: panel series parallel connections

The panel frames can be mounted on:

- the ground supported by legs that give the right inclination
- a pole which raises the panels above any low-level shadow
- a roof
- a frame mounted on a wall

ground-mounted frames

The panel frame needs to be slightly off the ground to prevent shade from grasses and low-lying vegetation. This also reduces the possibility of damage from lawnmowers and the like. The frames need to be anchored well into the ground to prevent wind damage and easy theft. This can be achieved by weights or footings.

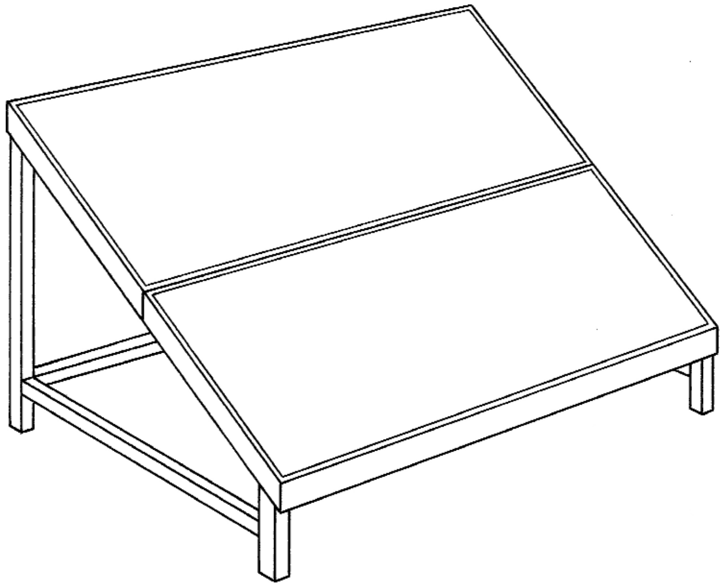

fig 25: ground mounted solar array

pole-mounted frames

This method needs a sturdy steel pole of about 15 cm diameter mounted in a good footing. You don't want the pole to come loose in high winds or rot out after a few years. The pole raises the panels above shade from shrubs and bushes, and also keeps it away from the kids. In the past I have drilled a hole about 2 metres deep in the ground with a post-hole borer and just dropped the pole into it. The success of this approach depends on the soil type, but it helps to weld bits of angle iron at right angles to the pole just below ground level. When these are buried they prevent the pole from turning in the ground in high winds and also help to stop it rocking. Any rocking will easily make the hole larger and create a nuisance.

fig 26: pole mounted solar array

The advantage of the pole-mounting system is that it is easy to add a pivot to allow for the change of panel inclination from winter to summer. You will notice in fig 27 that the pole has had four pieces of angle iron welded on to make the top section square. This gives a square shoulder for the array frame to sit against. There is more about this design in the making your own tracker section (page 73).

fig 27: angle adjustment mechanism for pole-mounted system

roof-mounted frames

Roof mounting can be tricky depending on the roof covering. The most important thing is that the fixings have to be secure and attached to the main roof timbers or steel work. If there are no structural timbers in the place where you want to mount the panel then you have to add some, in the same way as carpenters add timber into a stud wall to pick up hand basins, cupboards and the like. Tile and slate roofs are the most difficult to work on, and what you have, in effect, are galvanised steel or aluminium straps that slide up between the tiles and attach to the timbers. Fitting them can be a bit tricky if you have not done this sort of thing before. Working on roofs can be dangerous so always use scaffolding with handrails and correct boarding.

The array shown in fig 28 comprises nine panels, each 120 watts at 24 volts giving an installed capacity of 1080 watts. There are three other panels on a separate roof. Both arrays will give 10 kilowatt hours of power on a bright, sunny day. The day I visited it was very overcast with a thick blanket of cloud covering the sun and the system was producing about 100 watts, perhaps 1 kilowatt hour for the whole day.

fig 28: roof-mounted solar array

wall-mounted frames

The mounting frames have to be mounted very securely to the wall, so just a few screws is not adequate to withstand the wind pressure in a gale. The anchor bolts have to be well into the brickwork and the wall itself has to be in good condition. If you are fixing to a timber building then the fixings must be attached to the timber frame not just to the wall cladding. The panel frame, by its very nature, has to sit the panels at an angle to the wall, with the bottom further out from the wall than the top. Because of this it is possible to build mountings that allow for seasonal inclination adjustment.

making your own tracker

A mate of mine developed this tracking system a number of years ago and it seems to work well enough. The idea is to use a pole-mounting system as seen in fig 27, which is part of a tracked system. The frame that holds the panels is mounted on bearings, and the bearings are mounted on a sub-frame that is bolted to the pole as described in the pole-mounted frames section (page 69). The pole has four pieces of angle iron welded on to it to make the top section square. This gives a square shoulder for the sub-frame to sit against. A bolt goes through the sub-frame and the top of the pole to act as a pivot and to tighten things up. A threaded stainless steel bar then acts as the adjustment mechanism, using locking nuts.

The bearings are just standard self-aligning, foot-mounted plumber blocks available at any engineering suppliers. The bearings are mounted on the sub-frame, the angle of which is adjusted during the year. This arrangement forms what is called in astronomy circles an ‘equatorial mount’, meaning that if a telescope were mounted on this frame it would be able to follow a specific star – as long as it was driven at the right speed. The upshot of using this system is that as the sun travels across the sky in what looks like a curve to us, the mount enables the panels to follow that curve.

It’s the drive he uses that’s both interesting and relatively simple. The panel-mounting frame is driven by a heavy-duty screw jack, as used for moving satellite dishes to tune into various satellite positions. The screw jack is an electric ram, like a hydraulic ram found on heavy machinery but driven by electricity. Mine are set so that in the morning they are fully extended and in the evening they are closed up; they have about 60 cm of movement, but you can get various lengths, see *resources* (page 177). These are driven by any DC voltage up to 36 volts; for my system 12 volt is used because the whole tracking system is driven from a 12 volt tapping off the main battery bank. This is fitted with a fuse to protect the timers and the screw jack motor in case of damage.

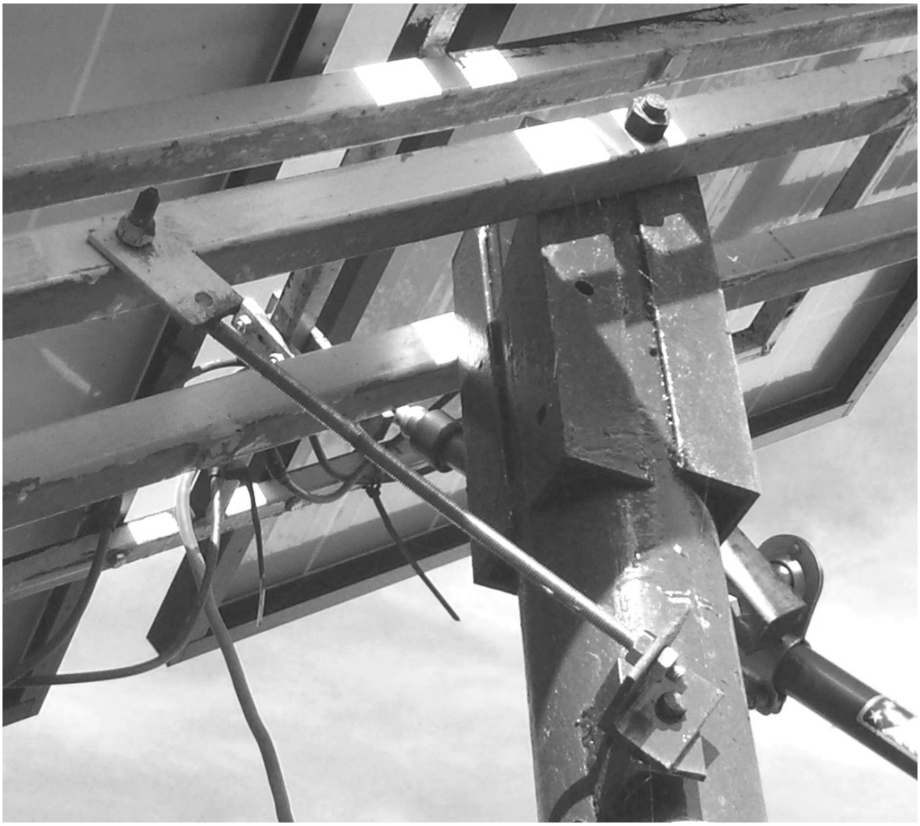

fig 29: panel pivot and angle adjustment

I may need to explain the idea of a 'tapping off' from a battery bank to get a different voltage and how to do it. The battery bank is made up of a series of cells, usually 2 volts each. Starting from one end of the pack (either end will do, but we will use the positive) the voltage between the end connection and the first-inter cell connection is 2 volts. Between the end and the second inter-cell connection there are 4 volts and so the voltage progresses as you measure between more cell connections. A 12 volt tapping off the main battery bank is obtained by connecting the tracking circuitry between the positive end terminal of the pack and the connection between cells 6 and 7. This gives a negative connection to complete the circuit. It's not a good idea to take a large amount of current out of these tappings, as this will create an imbalance in the battery by discharging some cells more than others, but to run small bits of supplementary circuitry it's fine.

fig 30: panel sub-frame and bearings

The panel does not track the sun, but what it does do is track the time and where the sun should be even if there is heavy cloud.

This means that when there is a break in the cloud the panels are already facing the sun and not tracking towards it. Time tracking uses a simple adjustable timer where you can adjust the duration of time on and the duration of time off. I use the mark 3 adjustable-interval timer from Maplin Electronics; see *resources* (page 177). In this case the timer powers the screw jack motor for 15 seconds and then switches off for 20 minutes when another 15 second pulse occurs.

In addition there is a separate system for returning the panel array back to facing east to start again the next morning. This is provided by a forward and reverse relay that is controlled by another timer and enables the screw jack to go backwards. This reversing timer is in actual fact a standard household 24-hour plug-in timer that is run off the inverter and switches on at 10 a.m., switching the relay on, and off at 9 p.m., switching the relay off. For more detail of the wiring of a reversing relay see the *system components* chapter under the relay section fig 2 (page 30).

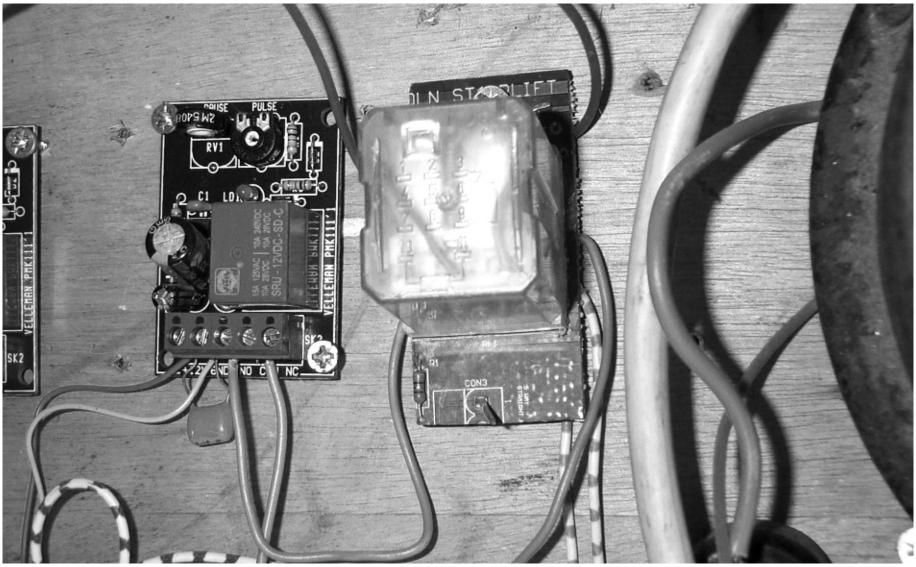

fig 31: timer and reversing relay

So let's talk the sequence through from sunrise. The first thing to note is that the pulse timer is running all the time (24/7). The panel array is facing east and prevented from moving by the limit switches within the screw jack until about 10 a.m., at which point the 24-hour timer switches on and switches the reversing relay to forwards. At the next 'on' pulse from the tracking timer, the screw jack moves the array slightly to keep up with the sun. The tracking timer keeps moving the array forward until about 4 p.m. when the array is facing southwest. At this point the timer keeps sending regular pulses but there is no more movement (because of the screw jack limit switches) until 9 p.m. when the 24-hour timer switches off and the reversing relay goes into reverse and so the panel slowly moves back to facing east where it is stopped yet again by the limit switches until 10 a.m. when it starts to move forward again.

So, to round things up we can say that photovoltaic solar panels produce power when the sun is shining, and that the amount of power produced varies with the weather, from day to day, and from season to season. The actual output expected or attained varies also from site to site and so the mounting position on the property is very important – and identifying the optimum position for the panels can take days of observation and discussion. The attainable outputs are covered in the research chapter and graphs are produced to give an idea of the changes occurring during the year.

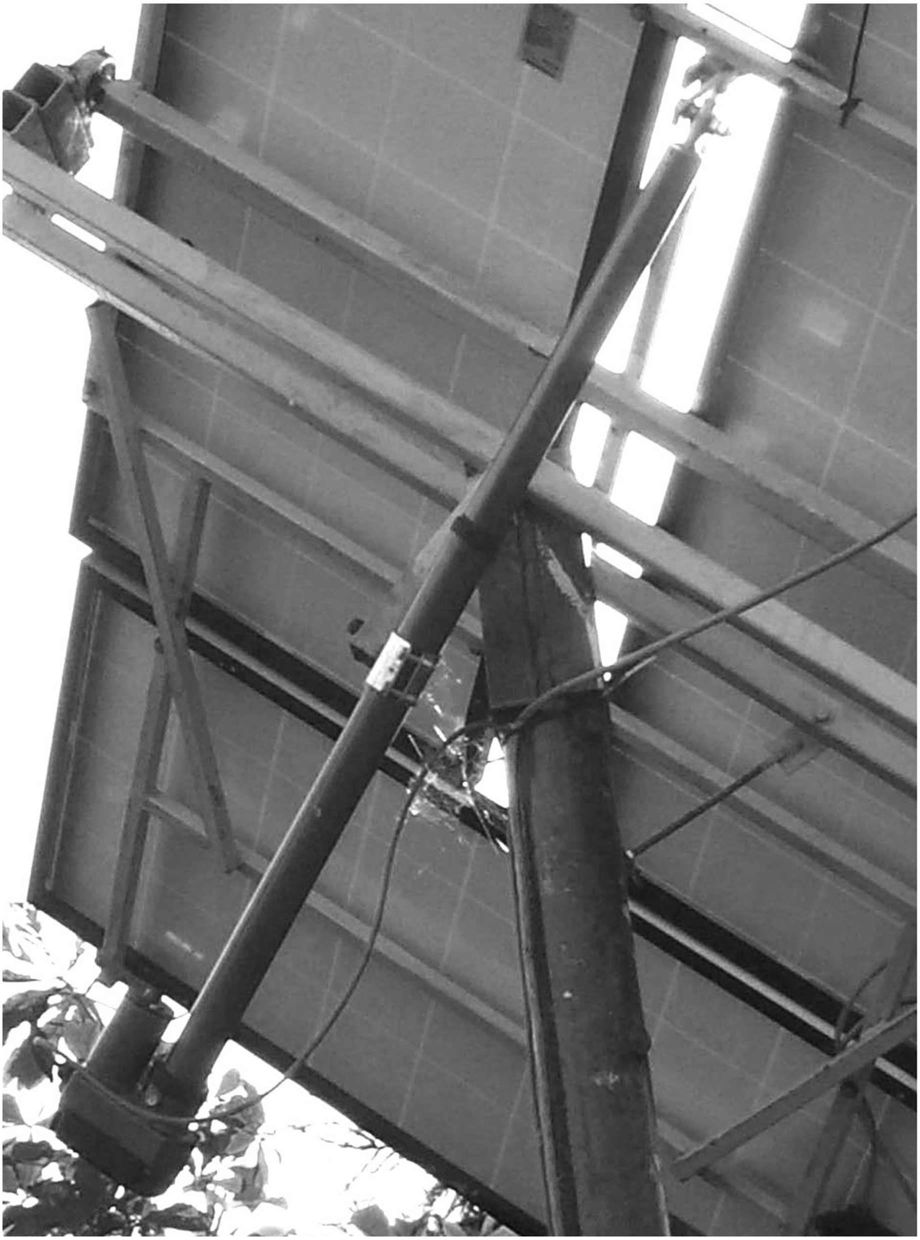

fig 32: screw jack and panel in the early morning position