

Fitting solar panels

There are many types of solar panels and regulators, but which might constitute the most effective set-up for your boat? David Berry investigates

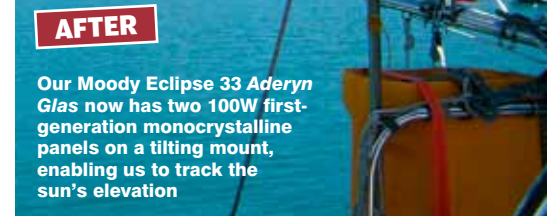
The odd thing about solar panels is that performance is not particularly improving as time passes and new technologies are developed. There are now three generations of solar panel technology, but the focus of development has always been expressed in 'cost per watt' terms – and that is not helpful for sailors.

The chances are that if you have solar panels on your boat – or, for that matter, perched on the roof of your house – they are going to be first-generation silicon-based technology, either mono- or polycrystalline, where an expensive crystal of silicon is mechanically sawn into thin slices, a process requiring high temperatures and demanding techniques. Second-generation panels are the amorphous types, but their efficiency is nowhere near as good as the first-generation panels. They use thinner films of the active substance and easier manufacturing techniques, so they are cheaper to make.

The upcoming third generation is the polymer (organic) panel which uses roll-to-roll printing techniques akin to printing newspapers: these will be cheaper still when they get to market.

So what's holding back consumers from embracing the improving cost per watt as we move through these generations? Three things. Firstly, as each new generation of available solar panels (as opposed to the exotic ones destined for NASA and so on) matures, it is obvious that the conversion efficiency is lower than the previous generation.

Conversion efficiency is the measure of electrical output for given solar input. For any given physical size of panel under test conditions, the first generation would provide an output of around 20% to 25% of the energy



LEFT We originally had five 15W second-generation amorphous panels in the same area

illuminating it (the insolation), the amorphous panels a lot less than that at maybe 11% to 13%, and the new organic technology a measly (though improving) 8% max. In practice, on our boats, we don't even achieve these figures. Cost per watt falls as we move up the generations, but so too does the conversion efficiency.

Secondly, unlike the energy companies who can cover vast acres of ground with solar farms, we sailors usually have a limited space in which we can plant our panels. To us the cost per watt is not a ruling parameter, it's watt per unit area – and this gets worse with each new generation. Therefore we still need to buy first-generation silicon panels.

Lastly, there's the question of useful life. First-generation panels are good for at least 10 years after which the output drifts slowly away,

while the new polymer panels have a much shorter lifetime, sometimes as little as a year. The polymers used in their construction are actually degraded by UV, so they need replacing much more frequently.

The proponents of the new polymer technology point out that manufacture and disposal of the new panels is a benign process since they contain no toxins nor materials that are difficult to break down in the environment: and if this is important to you then you may look to the new polymer panels as planet-savers. For me, however, the first-generation panel provides a robustly efficient way of capturing the sun's energy and will probably do so until the scientists find a way of improving the polymer panel's conversion efficiency and useful life.

If you want to learn more there's an excellent online course in organic

solar panels run by the Technical University of Denmark, accessible in English through Coursera (www.coursera.org).

Three generations of cell technology

Like a battery, a solar panel is made up of cells wired together to produce the required output voltage. Each solar cell, whatever its technology, is constructed from a number of layers mounted on a transparent substrate which provides the mechanical strength.

At the heart of any cell is the active semiconductor layer. This is bounded on each side by particle transport layers and electrodes. The electrode on the substrate side is also transparent to allow light through to hit the active layer.

When a photon (a quantum of light energy) enters the active layer it dislodges an electron from



an atom of semiconductor and the electron flows in the electrical circuit to which the panel is attached. Hit the panel with enough photons and the current becomes large enough to be useful. Inspired by massively abundant free solar energy – hugely more abundant than wind energy – researchers have been trying to reduce the cost per watt of solar cells.

Cheaper panels

Cells and panels are characterised by efficiency, defined as the electrical output (at the MPP or maximum power point) divided by the solar input power.

If we take dimensionally similar examples of each generation of panel and test them by insulating them with 100W of sunlight we may find that, using the efficiencies quoted previously, the first generation rigid silicon cell would give us a maximum of about 20W of electrical output. Generation 2, the amorphous type, would give us 11W and the new kid on the block only about 8W. To put these results in context, the maximum theoretical physical limit for conversion efficiency (known as the Shockley-Queisser limit) is 33%, and while this can in principle be increased by mounting more active layers in a stack – each transmitting and accepting a different part of the spectrum – the ultimate efficiency is nailed by physics at 86%. The NREL chart (Figure 1, above) shows the current position.

So there's still a bit to go: 33% would be a useful increase to us, but don't hold your breath because the academic drive is to produce cheaper panels measured in through-life cost and cost per watt. This is fine if you don't mind renewing cheap panels after a year of insolation – and have unlimited space.

But the space issue is insurmountable on a boat. When I bought my first panels for *Adey*

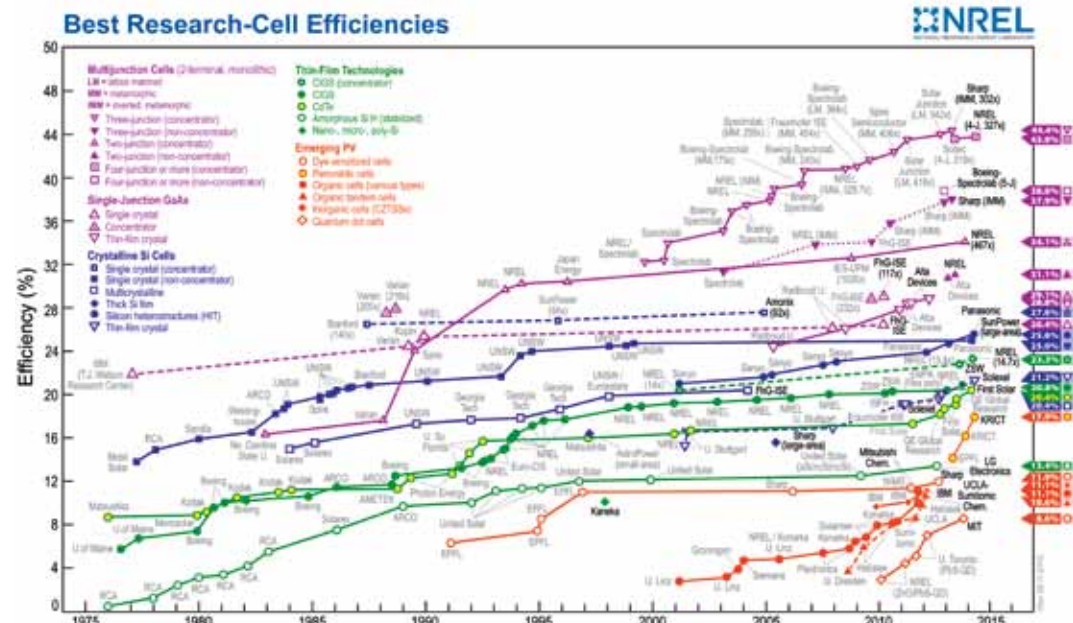


FIGURE 1: The US National Renewable Energy Laboratory keeps abreast of developments in solar panel design and publishes this table online at www.nrel.gov/ncpv/images/efficiency_chart.jpg. The new generation panels are represented by the wiggly bit at bottom right: notice how quickly their efficiencies are improving

Glas I bought second-generation amorphous types and covered the purpose-built bridge on her stern with five 15W panels. Later I discovered that the output wasn't going to be enough for our needs so I replaced them with first-generation monocrystalline panels: two 100W panels occupied the same area. Roughly speaking, for any given power output amorphous panels need twice the space of crystalline, and polymer panels twice the space of amorphous. So for boat owners, a high conversion efficiency means more watts in a given space: and at present this means we have to go on fitting first-generation silicon panels.

But what do the numbers mean? If you buy a 100W panel, can you expect to get 100W from it?

Nothing is ever that simple! Panels are characterised under strict conditions. The 100W number means that when the panel is insulated under a normal sunlight spectrum at a flux of 1,000W/m², filtered by a particular atmospheric path length (AM1.5) and at a temperature of 25°C (all this is called 'one sun'), the panel will output 100W at its maximum power point.

So, can you get 100W in practice? Yes you can: it's not unusual to receive that level of insolation, or more, hitting the ground at solar noon. If you want to estimate the amount of insolation falling on your panels wherever you are in the world,

you can use one of the web-based calculators available to help, like that

provided by the European Commission Joint Research Centre (JRC) at <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#>.

For more on this see 'Solar Panels: Everything you need to know', PBO Summer 2011, or visit www.pbo.co.uk/solarpanels

Maximum power point

It's about time I tried to explain MPP. Power, measured in watts, is the product of volts and amps. A solar cell will have an output voltage determined by the active material at its heart. A solar panel made from a number of cells will equally have a maximum voltage it can produce, depending on how the cells are wired together: this is the open-circuit voltage V_{OC} , the voltage you measure when the panel is not attached to anything. It needs to be greater than the load (battery) you attach it to for a current to flow, and a nominal 12V panel may have a V_{OC} of 20V or more.

Once you connect the panel to a load the voltage will fall to a value determined by the load or state of the battery, for example. If we charge a

battery with enough sun hitting the panel to make 1A flow into the battery, the power from the panel will be something like 13V x 1A = 13W.

But this is not the most power that can be generated by that panel under those conditions. If, without changing the insolation, you had a knob which could turn up the voltage and a meter that read power you'd find that there would be a peak value of power at a voltage somewhere close to 80% of the V_{OC} .

In fact the current would reduce, but be more than compensated for by the increase of voltage up to some point; and this point would give the maximum power for that panel under those conditions – the maximum power point or MPP.

So what does all this tell us? It says that if the output voltage from the panel can be held at a point higher than the default to which it wants to fall, then more power can be drawn from the panel; and this must be a good thing. Figure 2 is an example of a curve indicating a notional 12V 200W panel and showing its MPP.

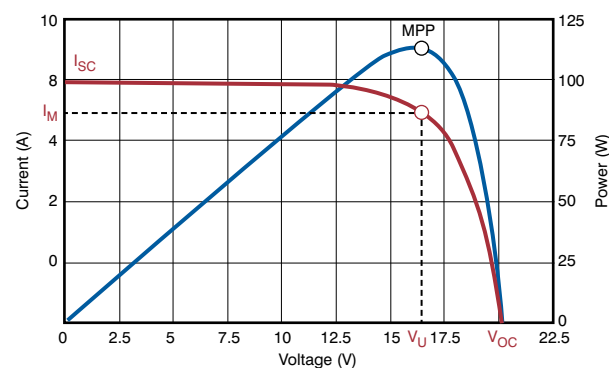


FIGURE 2: Notional panel performance curves showing the MPP. The curves show I-V (red line) and P-V (blue line). The crest of the blue line makes it easy to see the MPP voltage. The max voltage in a standard PWM regulator would be 14V (x-axis), and the power at 14V is about 100W. The MPPT regulator can drive the input up to the MPP voltage of about 16V so the power output increases to 112W – a 12% increase in power

So what can we do to improve the output?

It's a given that you need a controller. I mention this just in case someone is contemplating installing solar panels for the first time and thinks they can wire panels directly into the battery. You can't: the voltage may fry the batteries and perhaps even your boat.

There are quite cheap controllers out there, and any reputable manufacturer will offer a range.

Sooner or later the power you derive from your panels may not be sufficient for your needs. This can be seasonal, as in autumn the daily insolation is much less than in the summer; it can be geographical, as you may be changing latitude; it can be lifetime-related as your panels get older; or just that you're living up to the available energy and then find you need more.

Panels will also give better output if they are cool: one manufacturer of hybrid boats finds he gets an advantage using power to drive forced air cooling of his 1.5kW array of first-generation panels.

In PBO Summer 2011 I suggested it would always be more efficient to spend money on slightly larger panels rather than fancy controllers, and this is still my recommendation if you're starting from scratch: but if, like me, every sensible part of your boat has the optimum panel on it, and you've taken the time to

Installing the Victron 75/15

The Victron 75/15 has six high-current screw connectors, only four of which are of interest to us. Unless you only have a small requirement for current it's unlikely that the load connectors will be of interest to you.

The connectors are clearly marked with input from the solar panel array and output to the battery: installing is simply a matter of making the right connections then mounting the case using the four available mounting holes. As always, include a fuse: or, better still, use high-current capacity wire to reduce the cabling loss (I use high-current speaker cable) and



The Victron 75/15 installed alongside my battery box

include a fuse: or, better still, a voltage-sensitive breaker between the regulator and the battery.

One interesting aspect of the Victron is that it can accept inputs up to 75V, which means that panels can be arranged in series rather than parallel.

For example, you can link two 12V panels in series to deliver 24V into the regulator. Why would you do that? Because cabling losses are proportional to the square of the current, so if you have a long run of small cross-section cable you would lose less power by going for the higher voltage solution.

The current will always be capped at 15A. However, you can also increase the array output by increasing the voltage in this way up to the maximum power that the controller can handle.

eliminate shading, and provided a tilting arrangement to allow you to track the sun as it arcs across the sky, then your options are limited. In fact, about the only thing you can do is buy an MPPT controller.

Luckily MPPT controllers are much cheaper now than they were when I wrote the original piece: for example, you can now get a Victron Energy 15A MPPT controller (model 75/15) for less than £100. This unit has a maximum current

capacity of 15A and a maximum input voltage of 75V. I bought a Victron at £90 (www.victronenergy.com), and this became my experimental control against which I could compare the cheaper units.

A quick look at either eBay or Amazon will reveal that there are other MPPT controllers out there that are even cheaper than the Victron. And, since the Victron has features you can't use (interface to a computer and load control, to

name two) it would seem reasonable to expect that a device with less features would cost around the £30-£40 that these websites offer.

I consequently bought an MPPT controller for £40 from Amazon. On eBay you can also buy controllers that purport to be MPPT types for a ridiculously low cost so I spent £6 on one of those too, just for fun. To see the test results turn the page...

Anatomy of a controller

The job of a controller is to regulate the amount of power coming from the solar panels and going into a battery so that the battery does not overcharge and/or overheat.

There are a number of ways of achieving this control. Perhaps the simplest practical solution is to use an on-off regulator which will disconnect the source panels when the battery voltage reaches a set point, but this is very unsophisticated and I'm not even sure you can buy such simple devices any more.

Next up would be a PWM type. Pulse width modulation is the name given to a train of pulses where the ratio between the on and off pulse time – the duty cycle – changes to deliver less power as the optimum battery voltage is approached. When the battery charge is low the PWM controller gets close to a simple series regulator and is quite

efficient because the battery can accept all the power available because of its low charge.

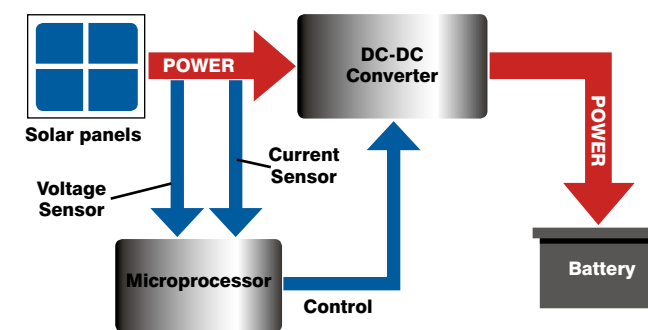
When the battery charge state increases the PWM feature kicks in, allowing the battery to recover a little during each off period and thus squeezes more power in.

Many PWM types are available and most offer three-stage charging to optimise the charge, and are claimed to increase battery life as a result of reduced stress during the charging cycle.

MPPT controllers

The most complex and expensive controller is the MPPT type, which actively seeks to find and transfer the maximum power from the panel to the battery.

The whole thing is controlled by a microprocessor which runs a computer program based on one of perhaps a dozen possible control algorithms, the most popular being 'perturb and observe'. All the hardware is



A block diagram of an MPPT controller

under the control of the program, including the all-important control of the voltage input.

The program measures the input current and voltage then changes the voltage and observes whether that results in more or less power (by multiplying together current and voltage).

If the result is more power then it changes the voltage again in the same direction: if less, then it changes the voltage in the opposite direction and recalculates. Controllers are

designed to carry out this analysis many times per second.

A very important feature of the MPPT controller is a DC-DC converter, which is an extremely efficient way of converting the input power to output power. It's no good tracking the maximum power at input if the power is then thrown away as heat in a poorly-designed transfer stage.

One disadvantage of MPPT controllers is their size, as they require large power components in their makeup.

Controller tests and results

To coax more energy out of my existing solar panel setup I needed a new MPPT regulator to replace my SunSaver 20A PWM device.

I was curious to find whether I would actually get the additional 10% or so extra power that manufacturers claim, and also whether the cheap units I'd found were any good.

I set up the tests to compare the SunSaver and the MPPT types side by side in as near identical conditions as possible. In the event I ended up with only two regulators to compare, the SunSaver and the Victron, but the results were still illuminating.

The tests were run over three days in August with *Aderyn Glas* tied to the quayside in Gouvia Marina on Corfu. The sky was consistently clear and blue, allowing a comparison of devices to be made over the period. Solar noon was 13:45 for each of the days and a test was timed to run one side or other of noon, so if one device was tested for an hour before noon the other device was tested for an hour after to give as similar sky conditions as possible.

Throughout the tests the panels were held horizontal with neither azimuth or elevation adjustments. Care was taken to ensure there was no shading as the Earth rotated.

I had wanted to compare the measured results with the theoretical ones from the online JRC calculator but this turned out to



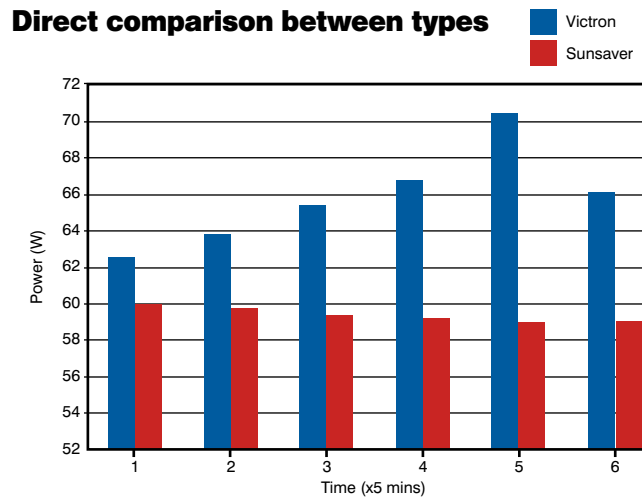
ABOVE All ready for testing. Nearest is the SunSaver 20, then MPPT30 and Victron 75/15. The data logger recorded power on the input of the regulator. **BELOW** The leads from the solar panel were fed through an ammeter to the unit under test. The voltage on both input and output was taken with a digital multimeter and the output current with a second digital multimeter. Readings were taken every five minutes



be impossible and, due to failure and unsuitability of the other two units I'd acquired, I had to be content with testing the MPPT Victron using the PWM SunSaver as a baseline.

The greatest problem was trying to achieve a consistent load, and the battery had to be driven down to the same starting voltage for each test by burning lights and other high-current devices. However, this process would not guarantee the same starting conditions since the batteries would show some natural recovery after such a drain. Input and output voltage and current (relative to the

Direct comparison between types



A direct comparison between the SunSaver PWM and Victron MPPT regulators. Power at the output of the regulator

TIME	VICTRON	SUNSAVER	DIFFERENCE	PERCENT
35	62.59	59.96	2.62	4.37
40	63.89	59.78	4.11	6.87
45	65.33	59.36	5.97	10.05
50	66.79	59.22	7.57	12.78
55	70.52	59.04	11.48	19.44
60	66.03	59.04	6.99	11.85
Average	65.86	59.40		10.87
Sum	395.14	356.40		10.87

The tabulated power results show the advantage the MPPT type has of being able to actively seek the best power point solution compared to the steady state output of the PWM device. The average margin of about 11% is probably misleading when taken over such a short period, and may actually have improved if the test had continued

regulator under test) was recorded at five-minute intervals. Each test lasted one hour, but there was a clear settling period at the start of each test which was ignored in the final data analysis – over a long term this would have little effect on

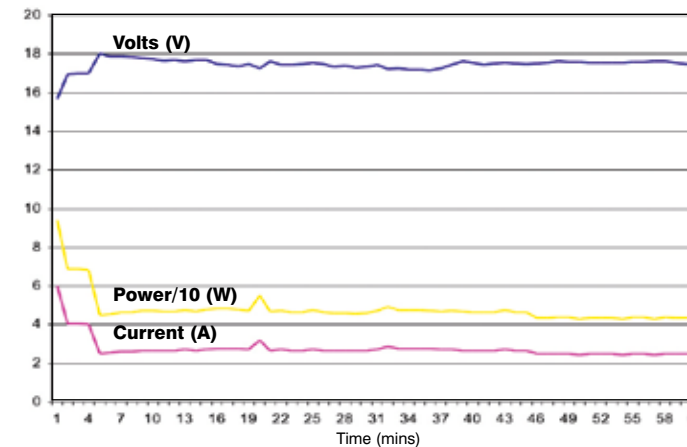
the energy produced.

A distinct difficulty was apparent recording the PWM SunSaver voltages since even under high-throughput conditions the PWM feature was, surprisingly, still operating. This meant that the input

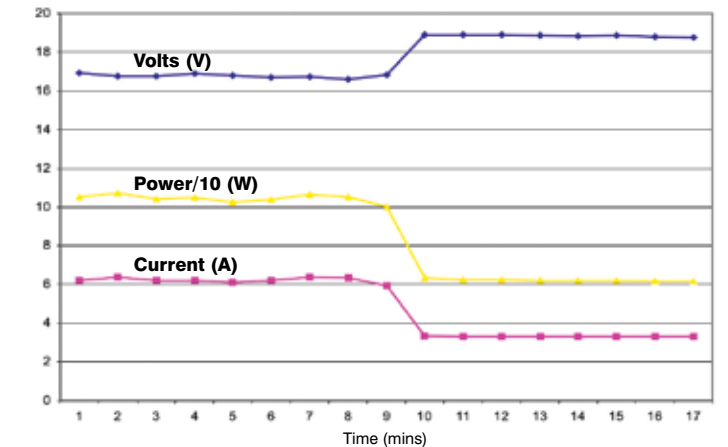
voltage was held at V_{OC} for a period equivalent to the PWM off-pulse, and this tended to skew the result.

The panel V_{OC} was 19.69V, so 80% of V_{OC} was 15.75V – the notional MPP. The air temperature was 30°C and the battery voltage 11.6V. Apart

from battery charging, the only other load was the notebook data recorder which consumed a steady 2A. Although it made no difference to a horizontal panel installation, for the record the stern of the boat was oriented to 025° true.



The input power curve for the Victron run over a one-hour period. The sustained high voltage results in the energy accumulated over this period of 47Wh



This is a good example of the MPPT regulator doing its job. As shade hits the panels it seeks a new maximum power solution, achieved by winding the voltage up to 19V (input parameters from the data logger)

Also-rans in the MPPT regulator market

I had a look at the MPPT30 Solar Controller which, at roughly £30, seemed an attractive buy. When it arrived I took the cover off and soon realised that whatever it was, it was unlikely to give an efficient conversion of energy since it didn't have the substantial inductive components that a 20A DC-DC converter would have.

In short, whereas the Victron is a weighty beast the MPPT30 Solar Controller is not. I verified that it had a microprocessor

(without a processor, tracking is impossible), but I was disappointed with the quality of the internal components and assembly standard.

Nevertheless I decided to include it in the tests, having ensured I had some over-voltage protection in case it failed. In the event it lasted about 30 seconds before indicating a fault condition.

Despite everything I could think of I couldn't clear the condition and get a set of data from the device.



The MPPT30 Solar Controller on the left is available all over the internet but is best left there, in my opinion. I didn't even test the CMPT02 Solar Charge Controller on the right. It may be a useful regulator – internally it seemed better constructed than the MPPT30 – but the small size, lack of DC-DC converter components and lack of a microprocessor clearly indicated it was not an MPPT type

Conclusions and recommendations

1 The JRC website calculator is a good starting point for discovering the likely energy you can capture in your chosen location, and will help you decide what your solar panel installation should look like. Use real-sky data, which includes the average cloud cover for your chosen location and time.

2 Only first-generation silicon panel technology, either mono- or polycrystalline, has sufficient power to area ratio (W/m^2) to provide the energy we need in the space we have available on a boat.

3 To maximise the energy, the single most important factor is to mount the panels on a tilting mount in a position that cannot be shaded by the mast, sails, flags, ropes etc. The tilting mount can give up to a third more

energy over the course of a summer day compared to a horizontal mount, and twice as much in winter.

4 Do a hard-nosed assessment of your energy requirements and be pessimistic about the energy you can get from your installation. Over-estimate the requirement and under-estimate the supply – at some point you will use all the energy you are getting.

5 Unfortunately I was not able to compare measured results with the theoretical results from the JRC calculator. This was probably due to difficulties in controlling the load. Theory predicted about 150W and the most I saw was 70W. However, comparative testing was possible and clearly showed a margin for the MPPT-

type regulator of better than 10%.

6 A PWM-type regulator such as the SunSaver 20 is fine for most situations, and in conditions of bright sunlight and high-current throughput is only about 10% lower in performance than the MPPT type.

7 However, to get the absolute maximum from your installation, especially in the more marginal dawn, dusk, cloudy and wintry conditions, consider an MPPT controller. In those conditions, it's claimed an MPPT type can deliver perhaps 30% more power than the PWM type.

■ My thanks to Johannes Boonstra at Victron Energy for answering queries and clarifying some points for me.