Renewable Energy for a Small Cruising Boat

1 References

Sources of information are:

Reference A	Boat Owner's Mechanical & Electrical Manual, Third Edition, Nigel Calder
Reference B	Department of Climate Change Wind speed database, http://www.decc.gov.uk/en/windspeed/default.aspx
Reference C	Marlec Data Sheet for Rutland 914i Wind Generator, http://midsummerenergy.co.uk/pdfs/Rutland914idatasheet.pdf
Reference D	GB-Sol Semi-flexible 70W Solar Panel, http://midsummerenergy.co.uk/buy/semi-flexible-solar-panels/gbsol70.html
Reference E	European Insolation Levels, http://www.apricus.com/html/insolation_levels_europe.htm
Reference F	Maximum Power Point Tracking (MPPT) regulators http://midsummerenergy.co.uk/solar-panel-information/Technical/MaximumPowerPointTracker
Reference G	Effect of Ambient Temperature on Solar Panels http://www.reuk.co.uk/Effect-of-Temperature-on-Solar-Panels.htm
Reference H	Practical Sailor's Wind Generator Test http://www.naviclub.com/Test_comparatif_eoliennes_marine.pdf
Reference I	Watts in the Wind, Yachting Monthly, October 2010. Re-print from: http://marinedirectory.ybw.com/reprints/results1.jsp
Reference J	Photovoltaic Graphical Information System http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php
Reference K	Fridge & freezer Calculations http://www.swingcat.co.uk/what/fridge_freezer_calcs.xlsx

2 Introduction

This article is a technical note documenting the deliberations behind an electrical system installed in my 10m sailing catamaran called Swing Cat. The general principle behind the design is that the energy consumed should come entirely from renewable sources. The deliberations are applicable to any small cruising boat, not just a catamaran.

This paper analyses energy derived from panels of photovoltaic cells (i.e. solar panels) and wind generators. It looks at energy requirements and balances production of energy against its consumption. It also looks at energy storage. Finally, it describes the components of the system installed. In a future version of this article, feedback on actual performance will be given.

3 Solar Power

A suitable solar panel for a yacht is a semi-flexible 70W panel (Reference D). This can be fixed to gently curving decks and may be walked upon. This means that in full overhead sun at the equator this panel will deliver 70W – this is the “standard sun”. One can look up figures for “insolation” anywhere in the world. For London, we have an average insolation of 2.61 hours per day; i.e. we have the equivalent of 2.61 hours of standard sun per day[1].

Using the same panel one could expect 2.61h*70W=183Wh/day. Divide by 12, for a 12V system, and this gives 15.3 Ah per day. More in the summer and less in the winter.

3.1 Losses in a PV Charging System

The actual power delivered to the battery can be a lot less than the peak power advertised for a solar panel. This section will discuss three phenomena responsible:

- the effect of battery voltage on panel power output;
- the effect on power output of the temperature of the solar panel in direct sun;
- inefficiencies in the system.

3.1.1 The Effect of Battery Voltage

With either no regulator or conventional regulators, inserted between the solar panel and the battery, the actual battery voltage determines the solar panel voltage – see Figure 1. The peak power from a panel is measured at a point where the product of current (I amps) and voltage (V volts) is a maximum – this is shown in Figure 1. At all other points on the *I-V* curve of a particular solar panel, the I*V product[2] is less – i.e. one is getting less power from the solar panel than this maximum. Inspecting Figure 1, if the battery voltage ranges between 10V & 15V, the power delivered by the panel ranges from approximately 40W to 58W, compared with the 69W (3.75*18.4) maximum.

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[1] Insolation is also quoted in kW/m^2 or kWh/m^2; since the equatorial sun at midday will also deliver power of $1kW/m^2$ or, in an hour, the energy of $1kWh/m^2$, the numbers are the same - e.g in London the average energy delivered per day is 2.61 kWh/m^2.

[2] The power output from a solar panel, P = I * V, where Pis measured in watts, I in amps and V in volts.

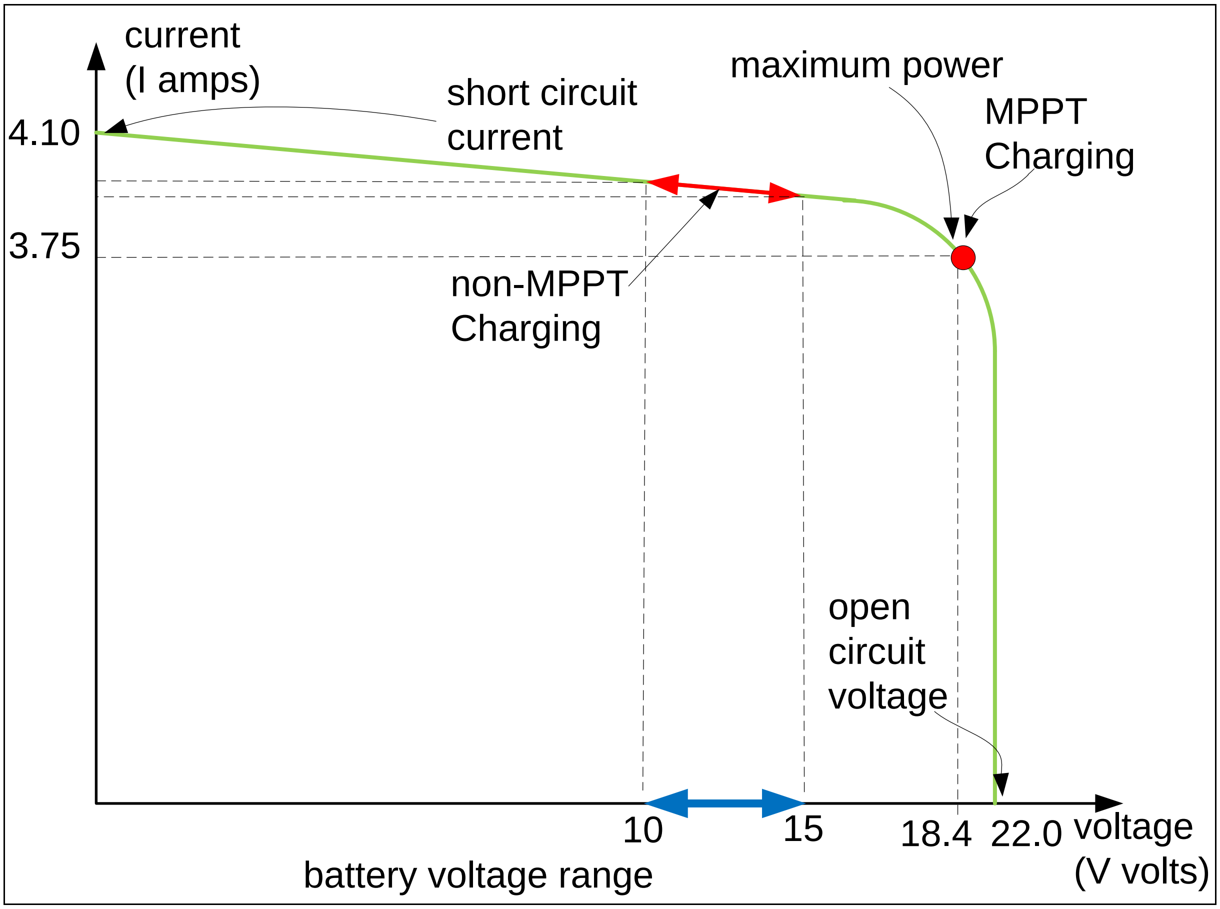

Figure 1: I-V Curve for a 70W Solar Panel (Reference C)

However, there is a newer type of regulator technology called Maximum Power Point Tracking (MPPT). These convert the DC from the panel at its rated voltage (say 19V) to AC and then rectifies it to DC again at the battery voltage. With this technology one gets a maximum power delivered of the rated power output minus about 5%.

3.1.2 The Effect of Temperature

The peak power output quoted for a panel is measured at an ambient temperature of 20^{0}C with the panel at a temperature of 25^{0}C. The panel is at a higher temperature because it is in direct sunlight and absorbs heat from the sun. Above these temperatures, panels become less efficient and this effect is slightly worse in panels made from amorphous silicon than those made from monocrystalline silicon.

What sort of efficiency loss are we talking about? Reference G describes an experiment to find out. Up until a panel temperature of 42^{0}C there was very little drop in power output. Above this temperature the power output declined by about 1% for every 1^{0}C rise in temperature. By the time the panel temperature reached the sort of temperature it would experience in Dubai (75^{0}C) the power output had dropped by almost 40%. In the much cooler climes of the UK, this is not a problem!

3.1.3 PV Charging System Inefficiencies

In a practical system there are a number of inefficiencies due to a number of factors. Since we are interested in the power delivered **by** the batteries, not even the power put into them, we do need to allow for them. The most important of these losses are due to:

- charging and discharging the batteries (see Section 6.1) ~ 10%;
- heat and voltage drops in the MPPT regulator ~ 5%;
- voltage drops in wiring connecting the solar panels ot the batteries, via the regulator ~ 1 to 3%.

We are assuming here that the battery voltage effect and any losses due to elevated solar panel temperatures are minimal because we are using an MPPT regulator and the climate is temperate. But, to be on the safe side let's assume total losses of about 20%.

3.2 Actual Power Delivered by a PV System

I earlier gave a simple calculation which suggested one could expect, from a 70W panel, about 183 Wh per day if one lived in London. I then argued for system losses of, say, 20%, which brings the energy output down to 146 Wh.

For comparison, there is a European Commission website (Reference J), which uses the Photovoltaic Geographical Information System (PVGIS) database of solar radiation for anywhere in Europe or Africa, to calculate the energy provided by any size solar panel at any angle of inclination. The energy estimates given take into account losses due to the temperature of the panel being above the 25^0 at which it is rated, losses due to reflections and system losses.

There are 2 databases: an old version PVGIS-3 and a new, more accurate one, based upon satellite data (PVGIS-CMSAF). Using the latter, for London, suggests an average daily energy of 187 Wh – see Figure 2. This may seem close to the 183 Wh calculated earlier but the figure of 187 is after losses while the figure of 183 is before losses.

Also, this is at an optimum inclination of 38^0. Using the database one can vary inclination and change other variables. For example, if the 70W panel is mounted horizontally, the power output drops to 159 Wh. Even modest angles of inclination bring big benefits: at 10^0 the output is 172 Wh, at 20^0 181 Wh.

Taking the figures for a horizontal panel, the best month is June with 290 Wh (24 Ah) and the worst December with 30 Wh (2.5 Ah).

Performance of Grid-connected PV

NOTE: before using these calculations for anything serious, you should read [this]

PVGIS estimates of solar electricity generation

Location: 51°30'29" North, 0°7'40" West, Elevation: 16 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Nominal power of the PV system: 0.1 kW (crystalline silicon)
Estimated losses due to temperature: 7.6% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 2.8%
Other losses (cables, inverter etc.): 14.0%
Combined PV system losses: 22.8%

Fixed system: inclination=38°, orientation=0° (Optimum at given orientation)				
Month	E_d	E_m	H_d	H_m
Jan	0.08	2.49	1.39	43.1
Feb	0.12	3.23	2.03	56.8
Mar	0.19	5.86	3.38	105
Apr	0.26	7.84	4.81	144
May	0.27	8.44	5.15	160
Jun	0.28	8.41	5.35	161
Jul	0.27	8.35	5.18	161
Aug	0.24	7.43	4.60	143
Sep	0.21	6.41	3.99	120
Oct	0.15	4.69	2.75	85.2
Nov	0.10	2.97	1.74	52.1
Dec	0.07	2.15	1.20	37.1
Yearly average	**0.187**	**5.69**	**3.47**	**106**
Total for year		**68.3**		**1270**

E_d: Average daily electricity production from the given system (kWh)
E_m: Average monthly electricity production from the given system (kWh)
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)
H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

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Figure 2: PV Performance Example for a 70W Panel in London[3]

[3] The nominal power of the PV System is given as 100W, but 70W is used in the calculation.

4 Wind Power

A particular wind turbine will generate power proportional to wind speed and independent of battery voltage (unlike solar panels). The bigger the blade length, the more power is generated. The fewer blades a wind turbine has, the more efficient it is and the faster the blades turn; however more blades give higher mechanical torque. At low wind speeds the extra torque is quite useful since it can lead to a lower cut-in speed – i.e the wind speed at which the generator starts to deliver power to the battery.

From the above, a 2-blade large diameter turbine would seem the best choice for average and high wind speeds. However, the blade tip could be moving very fast and generate a lot of noise. Generally speaking, the broader the blade, and the broader the tip, the quieter the turbine. On the other hand, if one is interested in useful power at low wind speeds and quiet operation, one could choose a turbine with many blades.

Manufacturers naturally advertise power outputs from their products at fairly high wind speeds; e.g. 140W at 11 m/s. Well, 11 m/s[4] is actually the top end of Force 5 or the bottom end of Force 6. It is not my idea of a nice quiet evening to be anchored, moored or alongside with 22 Knots of wind howling through the rigging, although if that were the case I might derive some compensating satisfaction from the fact that my batteries were getting a good seeing to.

Yachts spend most of their time in sheltered conditions, not anchored off Portland Bill. A nice sheltered location is my home town of Malmesbury – a long way from the sea. Consulting the Department of Climate Change's wind speed database (Reference B), the average wind speed is a more modest 4.8 m/s – i.e. Force 3. By the sea, it will surely be higher? Yes, but not by much; a location at random for a property on the water's edge at Falmouth harbour has an average windspeed of 5.4m/s, which is still Force 3.

If we assume an average wind speed of 5m/s we will get, for the excellent Rutland 914i, generated power of 247 kWh/year (see Reference C and its graph reproduced in Figure 3). From this we can expect (247*1000)/(12*365)=56 Ah a day. This is not to be sneezed at.

[4] 1 m/s = 1.94 knots.

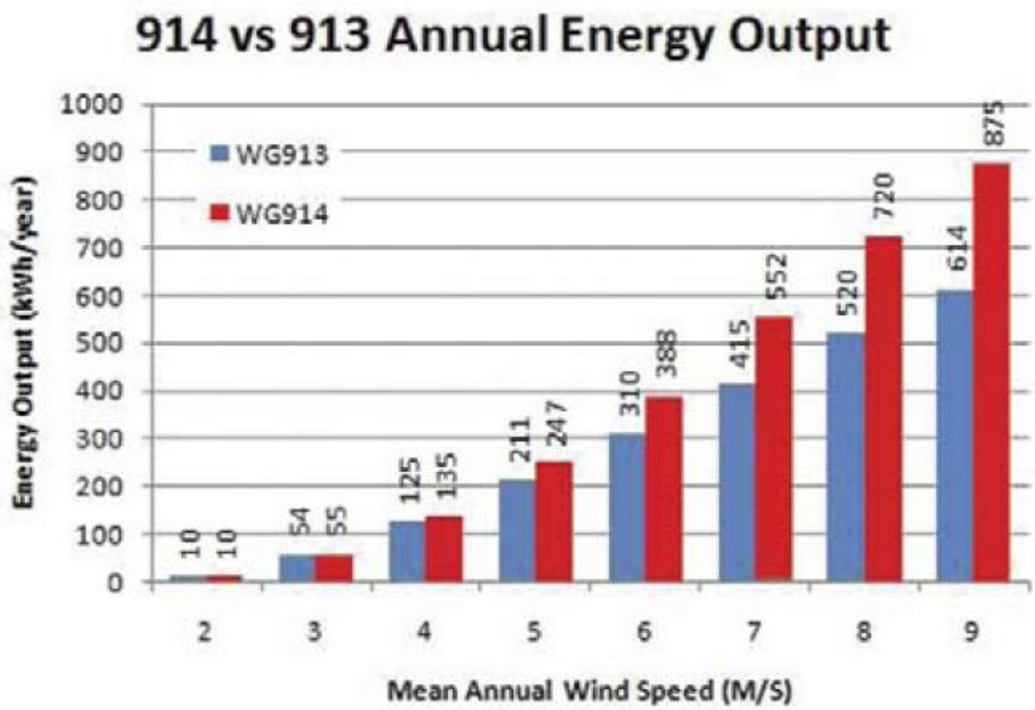

Figure 3: Power Output from Rutland Wind Generators

Is this amount of power output realistic. In **Error! Reference source not found.**, Yachting Monthly tested 16 wind turbines costing £318 to £1880; they give indications of the power each unit is likely to generate over the year given their own estimates of likely wind speeds throughout the year – see Table 1. They estimated the Rutland 913 (the 914i was not available for the test) would give an average of 44 Ah per day; using the same calculation as before, with the 913 figure for 5m/s given in Figure 3, (211*1000)/(12*365)=48 Ah per day – this is in quite close agreement with YM.

Wind speed			**Duration**
Knots	**Force**	**m/s**	**%**
0-8	0-3	0-4.12	40
8-14	3-4	4.1-7.2	35
14-20	4-5	7.2-10.3	20
Above 34	8	17.5	1-2

Table 1: Distribution of Wind Speeds During Year

5 Power Consumption

An attempt at estimating the power consumption of a small cruising yacht can be seen in Figure 4. Distinctions are made between summer and winter, being at anchor and passage making. The main current drains are the fridge and freezer – they are calculated using the spreadsheet at Reference K using average ambient temperatures of 35^{0}C in the summer and 10^{0}C in the winter; note that despite the very much lower winter temperature, the combined power consumption only halves.

		Summer				Winter			
Equipment	current	on the hook		passage making		on the hook		passage making	
	Amp	hours	Ah	hours	Ah	hours	Ah	hours	Ah
anchor light	0.2	8	2	0	0	8	2	0	0
autopilot	1.0	0	0	20	20	0	0	20	20
cabin fan	1.0	4	4	0	0	0	0	0	0
LED cabin lights	1.0	4	4	2	2	6	6	2	2
CD player	1.0	2	2	2	2	3	3	2	2
TV	1.8	2	4	2	4	3	6	2	4
DVD	0.4	2	1	2	1	3	1	2	1
GPS	0.5	0	0	24	12	0	0	24	12
echo sounder	0.3	0	0	4	1	0	0	4	1
lap top	5.0	2	10	2	10	3	15	2	10
VHF	1.0	0	0	24	24	0	0	24	24
radar	0.8	0	0	2	2	0	0	4	3
fridge	0.5	24	13	24	13	7	4	7	4
freezer	1.3	24	32	24	32	17	23	17	23
LED nav lights	0.6	0	0	8	5	0	0	10	6
log	0.1	0	0	24	2	0	0	24	2
totals			71		129		59		113

Figure 4: Daily Power Consumption Figures for a Cruising Yacht

6 <u>Size of Battery Bank</u>

From the daily power consumption estimates shown in Figure 4, it is possible to work out the size of the battery bank. The authorities I have consulted reckon on between 2.5 and 4 times the average daily load. However, the lower end (i.e. a battery bank of size 250Ah), assumes daily charging from an alternator or a generator. If one aims to be reliant solely on renewable energy, one has to cater for a few consecutive dull and windless days – therefore a figure at the top end of this range is appropriate.

6.1 Charging & Discharging Losses

You will never get out what you put in. The charging process will produce waste heat and the faster the rate of charge or discharge the greater the inefficiency, as well as the shorter the battery life. To limit the losses in the battery it is always best to keep them as cool as possible and, in this context, the larger the battery bank the better. As a rule of thumb: allow 10% for losses caused simply by charging and discharging the battery.

6.2 Battery bank Chosen

For these reasons given above, I have gone for a battery bank of 500Ah comprised of 4 125Ah Elecsol, deep-cycle, lead acid, Leisure batteries. At a weight of 28.5kg each, this will slow down Swing cat somewhat, but will make the electrical system more robust.

7 Matching Power Generation to Power Consumption

A system of 6 solar panels and one wind generator gives the approximate power generation capability shown in Figure 5. Approximate because:

- the panels are likely to develop less power than shown because some are bound to be shadowed at any one time;
- the power from the wind generator is shown as being the same in summer and winter, it is likely to be lower in the former and higher in the latter;

	# units	description	summer	winter	**summer**	**winter**
			Ah		**Ah**	
solar	6	70W panels	24	2.5	**144**	**15**
wind	1	Rutland 914i	56	56	**56**	**56**
losses @ 10%					**-20**	**-7.1**
				totals	**180**	**63.9**

Figure 5: Likely Power from Sun and Wind on Swing Cat (in the UK)

Comparing Figure 4 and Figure 5, one can conclude that the power generation capabilities are likely to be more than adequate for the summer but likely to be less than adequate for the winter. This is due to the power from solar panels dropping by between 90% between the best month (June) and the worst (December), while the power consumption requirements only halve.

However, sailing in a UK winter is likely to be rare and more time will be spent in marinas on shore power than in the summer.