Renewable Electric Energy Systems : Solar and Wind Principles

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Abstract – this brief describes the principles and sizing of solar and wind electric generation for household-size systems.

I. Introduction

Electricity is generally produced from fossil fuel sources which include coal, gas and oil. These fossil fuel sources have two key issues : firstly the resources are limited and secondly the use of these fuels produce greenhouse gas emissions. Due to this there has been strong interest in examining renewable energy sources for generating electric power. The two most convenient for household applications are solar and wind.

A. Energy Consumption and Economics

The first step in designing a renewable energy system for a household is determining the required amount of energy it must deliver. The energy E used by an electric appliance is its power consumption P multiplied by the time t it is used. Electrical energy is normally measured in kW.hr :

$$E(\text{kW.hr}) = P\ (\text{kW}) \times t\ (\text{hr}) \qquad (1)$$

Consider a 100 W incandescent light bulb being used six hours per day. Its energy consumption is 0.1 kW x 6 hours/day = 0.6 kW.hr/day. In Adelaide the electricity price is roughly $0.20/kW.hr and so it costs :

0.6 kW.hr/day × $0.20/kW.hr = $0.12/day

to run the light bulb. This corresponds to about $40 per year. Note compact fluorescent lights use roughly only one-fifth of the power to produce the same amount of light.

The amount of energy used by a household can be estimated by performing the calculation shown in (1) for all electrical appliances used [1,2]. Typical households use of the order of 5 to 20 kW.hr per day. The largest component of this is usually heating and cooling such as air-conditioners. Other major components include refrigerators and lighting.

B. Stand-alone and Grid-connected Systems

There are two main types of renewable energy power systems. *Stand-alone* systems are used in remote areas where access to the power grid is either expensive or not available. Electrical energy is generated from the renewable energy source and is used to power the desired loads. Batteries are normally used to store excess energy and act as a reservoir of energy when the power demand exceeds the available supply. The sizing of the battery needs to take into account that there may be several days of cloudy weather or little wind.

Grid-connected systems are used when the household is already supplied by electricity from the power grid. Here no batteries are required as the energy generated by the renewable energy source is fed directly back into the power grid using a *grid-connected inverter*. Grid-connected systems reduce the household's electricity bill. If the generated energy exceeds that used, the electricity bill will become "negative".

II. Solar Energy Systems

A. Solar Energy Calculations

Under "full sunshine" conditions (when the sun is directly overhead) the peak *irradiance* (power in sunlight) is approximately 1000W/m^2. Solar cells can convert the power in sunlight into electric power with an efficiency of approximately 5-20% depending on the type of solar cell. The peak power from a solar panel is given by :

$$P_{PK} = 1000\text{W/m}^2 \times Area \times efficiency \quad \text{W} \qquad (2)$$

The intensity of sunlight varies during the day but the total amount of solar energy is called the *irradiation* and can be represented by the number of equivalent *peak sun hours* t_{EQ} per day. For a solar panel with a peak power rating of P_{PK}, the total energy produced per day is then given as :

$$E = P_{PK} \times t_{EQ} \quad \text{kW.hr} \qquad (3)$$

The number of peak sun hours depends on the latitude, time of year and the amount of cloud cover. Contour plots of peak sun hours in South Australia in mid-summer and mid-winter are shown in Fig. 1. Note that the amount of solar energy available in winter is several times smaller than in summer. The Australian Bureau of Meteorology (BOM) website [6] provides irradiation data for most of its weather stations.

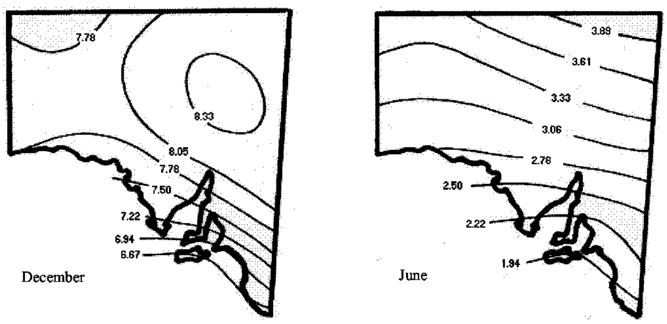

Fig. 1. Average peak sun hours per day for South Australia during mid-summer and mid-winter for a horizontally-oriented solar panel, from [2].

The results shown in Fig. 1 assume a horizontally-oriented solar panel. Significantly more power can be obtained by orienting the panel due north and tilting it to face the sun. The amount of improvement is more in winter than summer due to the lower angle of the sun. Solar arrays normally used a fixed *tilt angle* and its choice is a trade-off between optimising the summer and winter output. Fig. 2 shows the output power improvement for a solar panel tilted at the same angle as the latitude as a function of the time of year.

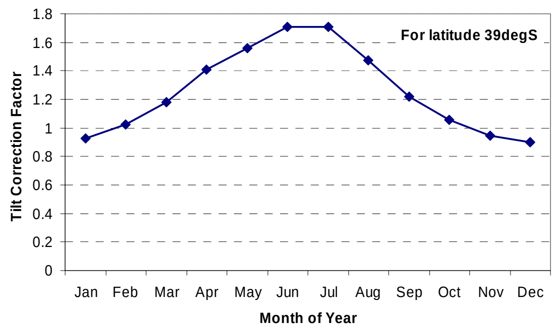

Fig. 2. Approximate tilt correction factor to convert peak sun hours for a horizontal solar panel to one tilted at the latitude, for a latitude of 39°S [4].

Table 1 gives some initial guidance on selection of the tilt angle based on the variation of the energy usage (*load*) during the year.

TABLE 1. SELECTION OF TILT ANGLE FOR SOLAR CELLS [1]

Seasonal Load Variation	Latitudes 5° to 25°	Latitudes 25° to 45°
no load change with season	Lat to Lat +5°	Lat +5° to Lat +10°
maximise winter power	Lat +5° to Lat +15°	Lat +10° to Lat +20°
maximise summer power	Lat -5° to Lat +5°	Lat to Lat +10°

Other important effects which should be taken into account when calculating the expected energy output of a solar energy system include :

- *panel orientation* : max. output energy is obtained when the panel faces due north, there is a significant loss of power if the panel faces east or west [3];
- *solar panel effects* : solar cell power output drops with cell temperature at roughly 0.5%/°C, also without regular cleaning, accumulated dust on the solar panel can cause a drop of output of up to 10%;
- *shading* : shadows across even a small part of a solar panel can significantly reduce the output of the panel;
- *efficiency of batteries and inverters* : battery efficiency is typically 80 to 90% and inverter efficiencies are typically 85 to 95% [2];

B. Solar Cell Economics

Ref. [2] gives some indicative pricing information :

- solar panels : $8 to $12 per peak watt;
- 1600W stand-alone solar system including batteries : $30,000 to $35,000 ($18 to $22 per peak watt)
- 1600W grid-connected solar system : $20,000 to $25,000 ($12 to $16 per peak watt)

The cost per peak watt is likely to increase for lower power systems as some cost components such as installation and metering do not scale linearly with system size.

There are a number of Australian government incentive schemes [5] to encourage the use of solar power including :

- photovoltaic electricity rebate program : $8/W for domestic PV systems greater than 450 W up to 1,000 W, maximum rebate is $8,000;
- remote area generation programs to improve the provision of electricity in these area.

III. WIND ENERGY SYSTEMS

A. Principles of Wind Energy Systems

The output power of a wind turbine with blades of diameter D in a wind of velocity v is given by :

$$P(\mathrm{W}) = 0.5 c_p \left(\pi D^2 \big/ 4 \right) \rho_A v^3 \qquad (4)$$

where ρ_A is the density of air = 1.225 kg/m^3 and c_p is the wind turbine co-efficient of performance. This latter term represents how efficient the turbine is at converting the power in the wind into useful output power. It has a maximum ideal value of 60%. In practice, values of 30 to 45% are common.

The Bureau of Meteorology website [6] provides average wind speed information at some of its weather stations in the form of the *wind run*, which is the distance the wind moves over 24 hours past the weather station, see Fig. 3. The average wind speed is the wind run divided by 24 hours. Note that wind speeds at a given location are sensitive to the local terrain and may differ substantially from a nearby monitoring station. The wind speed is also sensitive to the height above the ground. The BOM data is normally taken at a height of 10m which matches the height of most small wind turbines.

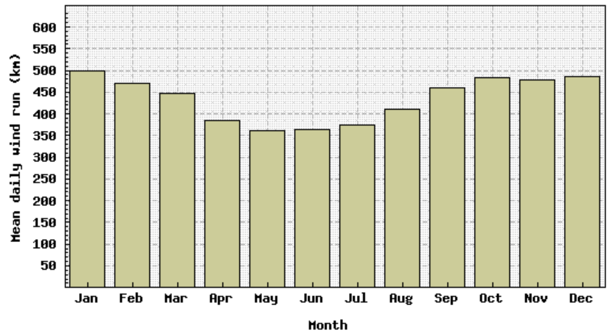

Fig. 3. Example of daily wind run data from the BOM for Woomera, SA.

Using the average wind speed in (4) will generally significantly underestimate the actual energy generated, typically by a factor of about two. This is because of the natural variation of wind speeds combined with the fact that the output power of the wind turbine is proportional to the cube of the wind speed. For more information see [3].

A rough method for estimating the annual energy output from a wind turbine of diameter D in metres, with rated power P_R in kW, in winds with a standard wind speed distribution (*Rayleigh* distribution) of average speed of v in m/s is [3] :

$$\text{energy (kWhr/yr)} = 8760 \cdot P_R(\text{kW}) \left[0.087 v - \frac{P_R(\text{kW})}{\left[D(\text{m})\right]^2} \right] \qquad (5)$$

Example costs for two small (200W and 900W) stand-alone wind turbines (just the generator and tower, not including batteries) were in the range $6 to $9/peak watt. Note that there are Australian government incentive schemes which apply to small wind power systems, particularly if they are in remote areas, see [5].

IV. REFERENCES

[1] Australian Standard, AS 4509.2—2002, “Stand-alone power systems, Part 2: System design guidelines.”

[2] South Australian Government, “Solar Electricity,” available from http://www.dtei.sa.gov.au/__data/assets/pdf_file/0017/15623/0203a.pdf, accessed 13 May 2008.

[3] G.M. Masters, “Renewable and Efficient Electric Power Systems,” John Wiley, 2004.

[4] A. Rockett and R.W. Scott, “Evaluation of the Potential for Photovoltaic Power Generation in Illinois,” available from http://www.sws.uiuc.edu/pubdoc/IEM/ISWSIEM2006-05.pdf, accessed 14 May 2008.

[5] http://www.dtei.sa.gov.au/energy/rebates_and_grants.html, accessed 14 May 2008.

[6] Australian Bureau of Meterology climate data, http://www.bom.gov.au/climate/averages/, accessed 14 May 2008.

A WORD FOR TODAY

As you do not know what is the way of the wind, or how the bones grow in the womb of her who is with child, so you do not know the works of God who made all things.

Ecclesiastes 12:5