Analysis of a Photovoltaic Installation

Module Rating

Photovoltaic modules are rated for power produced under an intensity of 1 kW/m^2 for *Air Mass 1.5* (AM1.5). AM1, or the "high noon", condition exists when the sun is directly overhead, and "air mass" is defined as the column of air, from the top of the atmosphere to the ground, through which the sunlight must pass. AM1.5 describes the more average situation when the sun is 60° above the southern horizon in the northern hemisphere, the condition for which the light must pass through a column of air 1.5 times the thickness of the AM1 air column. As sunlight passes through the atmosphere, absorption at some wavelengths and scattering occurs, so the spectrum changes with air mass. Since the *insolation*, or intensity of sunlight, at the top of the atmosphere has the value $S_\circ = 1360W/m^2$, the insolation at the surface of the earth at high noon on a clear summer day is about 1 kW/m^2.

If a module is rated at 10% efficiency, the generated power will be 100W/m^2 $\times$ the area of the module. Thus, if 5 kW total power is required at noon for AM1.5, one would need 50 m^2 of modules. The actual instantaneous AC power delivered to a home would be about 80 to 85 % of this power because there are losses in the inverter (for DC low voltage to AC 120 V conversion) and electrical connections.

What Solar Intensity Values Should Be Used?

The solar intensity striking a PV module depends upon the orientation of the flat module with respect to the surface of the earth, the angle of the sun above the southern horizon at noon (seasonal variation), the time of day and the weather. The orientation of the module, the angle of the sun above the horizon and the time of day can be combined to define the angle at which the light intersects the plane of the module, an angle which changes by the minute. Knowledge of this angle and the current weather condition would enable one to calculate the instantaneous power delivered by a module. However, this sort of calculation may not be the most useful.

Instead of designing a system based on a desired instantaneous power generated on a hypothetical sunny day, it is generally more logical to think about the *average solar energy* available at a particular location for each day of the year. This average is just a measured number which includes the weak, diffuse light on cloudy days as well as the bright, direct light on sunny days. There are three versions of this data: fixed orientation of the module; one-axis tracking of the sun; two-axis tracking of the sun. Two-axis tracking is expensive and requires maintenance. One-axis tracking is much cheaper and consists of a mechanism which is pointed south and tracks the seasonal variation in the position of the sun above the southern horizon on a daily or weekly basis. Usually, however, the module has a fixed orientation, with the angle above the horizon being chosen for the highest value of the yearly average intensity of light on the module.

In Corvallis the position of the sun above the southern horizon at noon varies from 21.5° at the winter solstice to 68.5° at the summer solstice. That is, at least when one can see the sun. A good choice for the orientation of the module is to have it point toward the south at an angle of 45° from straight up. This orientation is referred to as *at latitude*.

Tables and graphs of the average daily solar energy per square meter for modules oriented at latitude allows one to calculate how much energy a module will provide per day on the average for each day of the year. As an example, the average energy per day in April in Corvallis is about 1.5 kWhr/m^2/day.

PV Array and Cost

Once the appropriate insolation has been decided upon, the calculation of the size and cost of an array to meet some average daily electrical energy goal can be performed. For this analysis the insolation from the above section will be used, the module efficiency is assumed to be 10% and the inverter efficiency is 80% . The delivered electrical energy per square meter is then $1.5 \times 0.1 \times 0.8$ kWhr/m^2/day = 0.12 kWhr/m^2/day. This is enough to power two 60 W bulbs for one hour. To achieve delivered energy of 5 kWhr/day, 42.5 m^2 would be needed. Installed modules (Solarex) cost about \$1000/m^2, so the total cost is \$42,500.

This example installation would be useful only if there was a bi-directional grid connection or local storage (battery, capacitor, flywheel, H_2 generation). The charge-discharge cycle battery efficiency could be as low as 50%, so the cost per kWhr doubles. Capacitors and flywheels are much more efficient.

The cost for this energy, without local storage, is calculated by dividing the cost of installation by total energy delivered over the lifetime of the system. There are 7300 days in 20 years, so the installation cost must be divided by 7300. Thus, the cost of energy is \$5.82/5 kWhr = \$1.16/kWhr. We currently pay about \$0.07/kWhr here, but elsewhere in the US some pay \$0.21. This may seem to be too large a cost for renewable energy, but it is not a grim as it seems. The cost of electrical power from the power grid will certainly increase over the next 20 years, even in 2003 dollars. The \$1.16/kWhr cost is guaranteed for the next 20 years, and this cost estimate is on the high side. Photovoltaic modules may be available for \$500/m^2 or less. Some states offer tax incentives for homeowners, with California leading the way.

For two-axis tracking, the daily solar energy is about 3.5 kWhr/m^2/day, and the delivered power is about 0.28 kWhr/m^2/day. The cost per kWhr would now be only \$0.37. Including the capital cost of the tracking system and maintenance thereof would increase this substantially. The lowest cost per kWhr will be achieved using a single-axis tracking system.