GENERALIZED CAPACITY FACTORS FOR GRID-INTERTIE SOLAR PHOTOVOLTAIC SYSTEMS

J. M. GORDON and T. A. REDDY
Applied Solar Calculations Unit, Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus 84993 (Israel)
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Summary

We present a simple calculation and graphical procedure for direct determination of the annual capacity factor of no-storage grid-intertie photovoltaic systems. This is applicable to the principal solar collector types and to a wide range of climates. This method provides "translation equations" for predicting both instantaneous power output (under any specified test conditions) and long-term average power output of photovoltaic modules from instantaneous measurements. Such a procedure, which we validate for one site only, should enable a designer to make accurate preliminary assessments concerning the suitability of potential sites and solar collector types by simple analytic calculations or, equivalently, by reading points off the graphs presented herein.

1. Introduction

We consider the problem of the preliminary sizing and power output prediction for central no-storage utility-intertie photovoltaic (PV) systems. The designer typically requires an accurate estimate of the yearly average solar system output or, equivalently, the "capacity factor" $CF$ defined as

$$ CF = \frac{24 \text{ h day}^{-1} \text{ yearly average system power output}}{\text{Maximum power rating of system}} \quad (1) $$

Accurate calculation of the capacity factor is important not only because of the obvious value of the PV system as a fuel saver, but also because of the potential "capacity credit" of the PV system. By "capacity credit" we refer to the displacement of conventional generating capacity, at a fixed reliability level, as a consequence of installing the PV system [1].

One problem that arises is the ambiguity in specifying the maximum power rating of the solar system. Typically, one stipulates the incident solar radiation, the solar cell temperature or ambient temperature, and the wind speed as "standard" or "reference" conditions, and then measures the
output of the system at the point of maximum power. Measurement of module peak power is currently not a standard procedure and involves field measurement under uncontrolled conditions, followed by data extrapolation to the temperature and irradiance conditions which are more representative of those under which the solar system will operate [2 - 4].

However, different laboratories and manufacturers employ different “standard conditions”. Manufacturers' claims of module peak power may in fact be substantially different from actual peak power delivery, even for consistent standard conditions. Accordingly, it is recommended that before any calculation procedures of the type described in this paper be employed, the PV modules should be tested independently under well-defined standard conditions. In this way, possible discrepancies between manufacturers' claims and actual performance at peak power (denominator of eqn. (1)) can be avoided.

Furthermore, the PV modules may only rarely experience conditions close to the “standard conditions”, particularly since standard conditions often correspond to a solar radiation of 1 kW m\(^{-2}\) and a solar cell temperature of 28 °C. We will present “translation equations” that can convert measurements under any reasonable test conditions into performance predictions under other conditions and into yearly average power output or CF.

A second problem is that CF values are usually obtained via large-scale, time and money intensive computer simulations which require extensive climatic data bases. An accurate but short-hand method for estimating CF is hence a key objective.

2. Procedure

We first derive an expression for the instantaneous power output of a PV system, that depends on climatic variables and readily measurable solar cell characteristics only. We assume that losses due to sources such as power conditioning, dust, mismatching, degradation of the materials, wire losses, tracking errors (where applicable), power dissipation due to shading etc., are either small or can be accounted for separately on the basis of equipment specifications and field layout, and that PV systems are operated at maximum power point.

PV efficiency can be expressed in two equivalent forms [5, 6]. One expression relates to the empirical and verified observation that PV efficiency \( \eta \) decreases linearly with cell temperature \( T_C \):

\[
\eta = \eta_R \{ 1 - \beta (T_C - T_R) \}
\]

where \( \eta_R \) and \( T_R \) are the efficiency and PV temperature under reference or test conditions respectively, and \( \beta \) is the PV temperature coefficient. In principle, this expression pertains only to the PV module.

The other form simply states that all absorbed solar radiation that is not converted into electricity must be dissipated as heat:
\[ \eta = \eta_n - U(v) \frac{(T_C - T_a)}{I} \]  

(3)

where \( \eta_n \) is the module optical efficiency; \( U(v) \) is the linearized module heat loss coefficient as a function of wind speed \( v \); \( I \) is the incident insolation flux including incidence-angle modifier losses and \( T_a \) is the ambient temperature. All tests are conducted with normally incident solar radiation. Eliminating cell temperature \( T_C \) from eqns. (2) and (3), and using the approximation that \( (\eta_R \beta I/U) \approx 1 \), we obtain

\[ \eta \approx \eta_R (a_1 - a_2 T_a - a_3 I) \]  

(4)

with

\[ a_1 = 1 + \beta T_R \quad a_2 = \beta \quad a_3 = \beta \frac{(\eta_n - \eta_R)}{U(v)} \]

The instantaneous PV power output per unit area \( P \) is then

\[ P = \eta_R ((a_1 - a_2 T_a) I - a_3 I^2) \]  

(5)

Equations (2) - (5) indicate that \( T_C \) and \( P \) should not be parametrized arbitrarily in terms of climatic variables and PV characteristics, but rather that they assume specific functional forms. Furthermore, we can now express instantaneous PV power output per unit area \( P \), under any specified operating conditions, relative to PV power output under standard or test conditions \( P_{\text{test}} \) from the following “translation equation”:

\[ \frac{P}{P_{\text{test}}} = \frac{I[a_1 - a_2 T_a - a_3 I]}{I_{\text{test}}[a_1 - a_2 T_{a_{\text{test}}} - a_3 I_{\text{test}}]} \]  

(6)

where the PV system is tested under standard or test conditions of solar radiation \( I_{\text{test}} \), ambient temperature \( T_{a_{\text{test}}} \) and wind speed \( v_{\text{test}} \). This gives us a performance prediction procedure for instantaneous power output.

Towards calculating long-term average power output, we now average eqn. (5) over all hours of the year and take advantage of a combination of the facts that hourly solar radiation is weakly correlated to both ambient temperature and wind speed, and that the terms in which these cross-correlations occur are small [7], to obtain for the yearly average power output per unit area \( \langle P \rangle \)

\[ \langle P \rangle \approx \eta_R \langle I \rangle \left(a_1 - a_2 \langle T_a \rangle - a_3 \frac{\langle I^2 \rangle}{\langle I \rangle} \right) \]  

(7)

where \( \langle T_a \rangle \) is the yearly average daytime ambient temperature, \( \langle I \rangle \) is the yearly average collectible solar flux, and \( a_3 \) is evaluated at the yearly average daytime wind speed. From eqn. (7), we have our second “translation equation” for the CF relative to the CF under standard or test conditions:
$\text{CF} =$ 

$$\frac{\langle I \rangle (a_1 - a_2(T_a) - a_3X)}{I(\text{test})[a_1 - a_2(T_a(\text{test})) - a_3\langle v(\text{test}) \rangle]I(\text{test})}$$

(8)

where

$$X = \frac{\langle I^2 \rangle}{\langle I \rangle}$$

The calculations delineated above imply a proposed PV test procedure wherein PV temperature $T_C$ would not have to be measured. That is to say, a non-intrusive test could be envisioned where, by measuring $P$ under varying $I$, $T_a$ and $v$, a linear regression calculation would yield the effective PV parameters of eqn. (4), i.e., $\eta_R a_1$, $\eta_R a_2$ and $\eta_R a_3$ (where $\eta_R a_3$ could also be treated as a linear function of $v$ when greater accuracy is required). These three PV parameters could then be used in eqns. (5) - (6) and (7) - (8) for the prediction of instantaneous and long-term performance respectively. (It should be noted that in eqns. (6) and (8) the parameter $\eta_R$ does not appear because it enters as a proportionality constant in both numerator and denominator and hence cancels.)

Equation (8) shows that the problem of predicting CF accurately is reduced to the calculation of two factors: (1) yearly average collectible solar flux $\langle I \rangle$ and (2) a “correction factor” which depends only on readily measurable (or manufacturer-provided) PV parameters and the radiation statistic $X$. The magnitudes of the PV module parameters described by eqn. (4) are such that the factor $\langle I \rangle$ is the dominant contributor to the CF (compared with the “correction factor” noted above). Since $\langle I \rangle$ is governed by site meteorology, concentration ratio and tracking mode only, the CF should have a weak sensitivity to the specific PV material, e.g. crystalline silicon, polycrystalline silicon, other semiconductor materials etc. Two PV modules can however have identical CFs with vastly different instantaneous and yearly average power outputs.

It should be noted that eqn. (8) permits evaluation of the long-term average CF, independent of the arbitrary choice of “standard conditions”, just as eqn. (6) accomplishes the same objective for instantaneous power output. Sensitivity calculations using eqn. (8) with actual climatic data and PV module parameters show that the contribution of the $X$ term may be small, but can be far from negligible, in extreme cases reaching 20% of the CF. We therefore treat this contribution in detail below.

3. Generalized radiation statistics and results

Figures 1 - 4 present $\langle I \rangle$, in kW m$^{-2}$, as a 24 h day$^{-1}$ average, for the principal solar collector types, as a function of yearly average clearness index (ratio of horizontal global to horizontal extraterrestrial radiation) $\langle K \rangle$ and latitude. These figures are based on the empirical correlations of ref. 8, which in turn are based on Typical Meteorological Year data for the 26 U.S. SOLMET stations.
Fig. 1. Yearly average collectible solar flux \( \langle I \rangle \) in kW m\(^{-2} \), vs. yearly average clearness index at three different latitudes for stationary flat-plate collectors in polar mount (tilt equal to latitude), with no shading, based on ref. 8.

Fig. 2. As in Fig. 1, but for stationary CPC (non-imaging concentrator) with a concentration ratio of 1.5, an acceptance half angle of 35°, in polar mount, with no shading.

In ref. 8, the yearly collectible energy \( q \), in GJ m\(^{-2} \), is parametrized as a quadratic function of the radiation threshold \( I \), in kW m\(^{-2} \):

\[
q(I) = q_0 - q_1 I + q_2 I^2
\]  

(9)
where the positive coefficients $q_0$, $q_1$ and $q_2$ are simple functions of (a) climate, (b) latitude, (c) collector type and (d) tracking mode. The 24 h day$^{-1}$ average solar flux $\langle I \rangle$ is then simply

$$\langle I \rangle (\text{kW m}^{-2}) = 0.03171q_0 (\text{GJ m}^{-2})$$  \hspace{1cm} (10)
Figures 5 - 8 present our calculation of $X = \langle I^2 \rangle / \langle I \rangle$, in kilowatts per square metre for the same cases as those treated in Figs. 1 - 4, this calculation being based on the observation in ref. 9 that $\langle I^2 \rangle$ is simply proportional to the area under the plot of the yearly collectible energy vs. radiation threshold. Specifically,

$$X(\text{kW m}^{-2}) = \frac{\langle I^2 \rangle}{\langle I \rangle} = \frac{2}{q_0} \int_{0}^{I_{\text{max}}} (q_0 - q_1 I + q_2 I^2) \, dI$$

$$= 2I_{\text{max}} \left(1 - \frac{q_1 I_{\text{max}}}{2q_0} + \frac{q_2 I_{\text{max}}^2}{3q_0}\right)$$

(11)

where $I_{\text{max}}$ is either the smaller root of

$$q_0 - q_1 I_{\text{max}} + q_2 I_{\text{max}}^2 = 0$$

(12)

or, if eqn. (12) has no real roots,

$$I_{\text{max}} = \frac{q_1}{2q_2}$$

(13)

Hence by combining measured or manufacturer-supplied PV parameters with readily calculable radiation values or, equivalently, points that can be read off the graphs of Figs. 1 - 8, the designer can determine accurately the CF for a proposed PV system in a specific location.

Fig. 5. Yearly average radiation statistic $X = \langle I^2 \rangle / \langle I \rangle$, in kW m$^{-2}$, vs. yearly average clearness index, for the collector type of Fig. 1.
4. Qualifications

Several qualifying remarks are in order at this point. Firstly, our proposed method ignores the possibility that PV efficiency can depend sensitively on the spectral content of incident solar radiation which changes with diffuse fraction and air mass. Although this is not found to be problematic for crystalline and polycrystalline PVs, it may be a significant factor for amorphous silicon PVs [10 - 12]. However the magnitude of this effect for amorphous silicon PVs remains to be established conclusively.
Secondly, eqn. (4) for PV efficiency becomes rather inaccurate at very low solar flux levels \(I < 200 \text{ W m}^{-2}\), where efficiency decreases significantly with decreasing irradiance [13]. However, because this inaccuracy in our method is weighted by only the lowest solar flux values, the error introduced in yearly average CF is negligible [10, 13].

Thirdly, we have used an equation for solar cell performance towards predicting the performance of PV modules, arrays and systems. This treatment should be adequate provided losses due to factors such as solar cell mismatch, power dissipation due to shading, line losses and the like are small or can be treated as constant corrective terms.

Fourthly, the empirical correlations for yearly collectible energy [8], which form the basis for our calculations, are strictly accurate for U.S. climates only. Furthermore, these correlations apply to specific, albeit rather common, collector orientations and tracking modes. For example, general yearly collectible energy correlations are not yet available for tracking flat plates (non-concentrators) or for tracking low-concentration collectors (e.g. reflector-enhanced flat plates).

In addition, the correlations were parametrized for one value of ground cover ratio (ratio of net collector area to gross land area) only, which does not allow for studies on sensitivity to field layout. However, once such correlations are forthcoming, they can be incorporated easily into our calculation procedure.

Fifthly, although our procedure has been presented based on yearly collectible energy correlations, this method is equally applicable to any time scale, for example, on a monthly basis. Shorter time scales than a year may be of interest in cases where the seasonal dependence of power output is important. However, one then requires correlations for collectible energy on the appropriate time scale.
5. Partial validation and conclusions

We compare our predictions with the experimental results of the three-year PV monitoring program of Pacific Gas and Electric Co. (PG & E) on 26 flat-plate and concentrating PV modules [13]. The four parameters with which we characterize a PV module (eqn. (4)) were determined for each monitored system from the PG & E PV module test data [13]. Capacity factors are expressed relative to PG & E "standard conditions" of $I_{\text{(test)}} = 1 \text{ kW m}^{-2}$ for flat plates and $0.85 \text{ kW m}^{-2}$ for concentrators, $T_{\text{a(test)}} = 20 ^\circ C$ and $v_{\text{(test)}} = 1.8 \text{ m s}^{-1}$. The test site had approximately $\langle T_{\text{a}} \rangle = 16.7 ^\circ C$ and $\langle K \rangle = 0.61$.

A comparison of our predicted values with experimentally measured values is presented in Table 1, which shows satisfactory agreement. (Comparisons with the results for tracking flat plates are not presented since the corresponding empirical correlations for yearly collectible energy have not yet been developed.) The systematic overprediction of 5% in CF for concentrators, while being within experimental uncertainty, could be due to small tracking errors and/or dust accumulation, or errors in the empirical correlations used in our method. Similarly, the larger variance in CF among the fixed flat plates and among the concentrators, for the predicted CF, as opposed to the experimental CF, is not significant since this variance is smaller than experimental uncertainty.

The results in Table 1 bear out the point made in Section 2 that CF is dominated by site meteorology, concentration ratio and tracking mode only, as opposed to the specific PV module materials. In other words, for the one site considered in Table 1, flat-plate PV modules of different materials and production processes have roughly the same CF, both as measured experimentally and as predicted theoretically. The same observation pertains to the high-concentration-ratio PV modules. (The large differences in concentration ratio here are not significant because the concentration ratio is

<table>
<thead>
<tr>
<th>Collector type</th>
<th>PV module manufacturer</th>
<th>Annual capacity factor (experimental) [13]</th>
<th>Annual capacity factor (predicted)</th>
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<tbody>
<tr>
<td>Fixed flat plates</td>
<td>Solarex</td>
<td>0.235</td>
<td>0.228</td>
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<td>Mobil Solar</td>
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<td></td>
<td>Varian (1000 X)</td>
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<td>0.288</td>
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</table>
sufficiently large in each case for the accepted radiation to be essentially all beam.)

Two sets of simple but powerful graphs based on yearly average radiation statistics provide accurate and extremely rapid estimates of CF values for the principal PV collector types over a wide range of climates. Our results can handle any arbitrary standard test conditions, and can serve as a valuable tool in the planning, site location and performance prediction of utility-intertie, no-storage PV systems. The agreement between theory and experiment, as presented in Table 1, is for one site only, and hence should be viewed as partial validation.

References