CHARACTERIZATION OF THE ELECTRICAL OUTPUT OF FLAT-PLATE PHOTOVOLTAIC ARRAYS*

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ABSTRACT

The electric output of flat-plate photovoltaic arrays changes constantly, due primarily to changes in cell temperature and irradiance level. As a result, array loads such as direct-current to alternating-current power conditioners must be able to accommodate widely varying input levels while maintaining operation at or near the array maximum power point. The results of an extensive computer simulation study that was used to define the parameters necessary for the systematic design of array/power-conditioner interfaces are presented as normalized ratios of power-conditioner parameters to array parameters, to make the results universally applicable to a wide variety of system sizes, sites, and operating modes. The advantages of maximum power tracking and a technique for computing average annual power-conditioner efficiency are discussed.

INTRODUCTION

The electric output of photovoltaic (PV) arrays varies with irradiance level and temperature, and is unique in comparison with the current-voltage (I-V) characteristics of conventional electric-power generators. Figure 1 illustrates the typical I-V characteristic of a PV array and the way it varies with irradiance and temperature. The short-circuit current of an array is directly proportional to the irradiance level, and the maximum power voltage is linearly dependent on cell temperature.

To obtain maximum energy from the array, the array load must accommodate the site-specific and time-dependent changes in array output. Also, the maximum input ratings of the load must be compatible with the maximum levels that the array can deliver. This paper addresses a case where the load for the PV array is a power conditioner (PC) designed to convert the direct-current array output into alternating current, which is the form supplied by utilities.

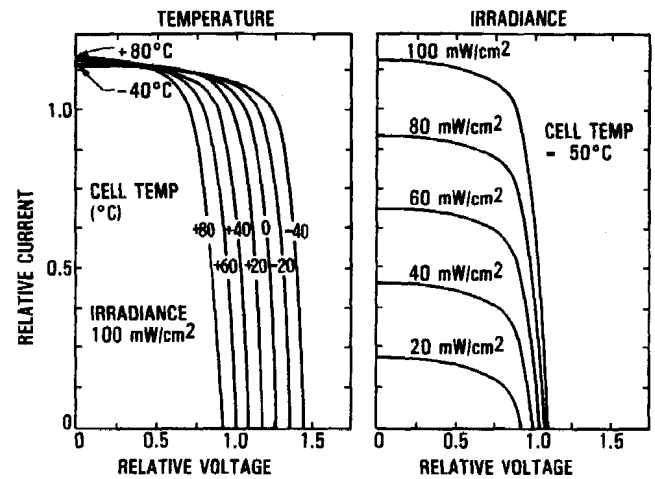

Figure 1. Influence of Irradiance Level and Cell Temperature on Array Current-Voltage Curve

Information is provided on PC operating parameters, power, current and voltage limits, and voltage tracking capabilities to assist a system designer in optimally matching an array and PC. The various PC variables are assessed in terms of expected annual energy output of the array/PC system. The analysis was performed for flat-plate arrays using the total irradiance on a fixed-tilt flat surface, as opposed to the direct-normal irradiance that would be used for tracking concentrator arrays. The details and results of the study are presented in (1).

GENERAL ANALYSIS APPROACH

To define the relationships between PV system performance and PC operational mode, it was necessary to simulate typical array performance for a

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variety of representative long-term operating conditions. This was done by using a computer to calculate hourly electric output for a period of 1 year at each of 26 sites in the United States. Hourly weather data were obtained by using SOLMET typical meteorological year (TMY) weather-data tapes containing historical measurements for a TMY at each site.

The hourly irradiance level on the array was derived from the SOLMET irradiance data by using an algorithm developed by T. Klucher, based on the work of B. Liu and R. Jordan (2). The array was assumed to be a flat, south-facing surface tilted up from the horizontal at an angle equal to the latitude of the site. The hourly cell temperature was then computed based on the irradiance level incident on the array, and the hourly ambient air temperature from the SOLMET data tape. For a detailed description of the algorithms, see (2).

Hourly electrical performance was derived by using a baseline I-V curve selected as representative of a present-day silicon-cell array. The I-V curve defined the normalized output of a typical array at standard reporting conditions (100 mW/cm^2, 25°C). The appropriate I-V curve for each hourly irradiance level and cell temperature was then derived.

Because the shape of solar-cell I-V curves varies somewhat for cells of different manufacture, and with different degrees of degradation with age, other I-V curves were also used to define the sensitivity of the simulation results to I-V curve shape. The shape, or squareness, of I-V curves is generally quantified by the parameter fill factor, which is defined as the ratio of maximum power to the product of open-circuit voltage and short-circuit current. Typical new arrays have fill factors averaging about 0.70, and ranging from 0.60 to 0.76. As an array ages its fill factor often decreases, reflecting degradation associated with increased series resistance. Fill factors ranging from 0.45 to 0.75 were used in the sensitivity studies.

To make the results as generally applicable as possible, the data are presented as normalized ratios of load characteristics to array characteristics at SOC (100 mW/cm^2, NOCT). Standard operating condtions (SOC) are a set of recognized reference conditions for rating PV arrays, and are different from peak rating conditions (100 mW/cm^2, 25°C) in that they use the nominal operating cell temperature (NOCT) for the chosen PV modules in the intended mounting configuration, instead of the fixed 25°C cell temperature that is selected for ease in laboratory measurements. Use of NOCT makes the results of this study generally independent of operating-temperature differences associated with modules and arrays with different thermal properties. Site-to-site, weather-related operating-temperature differences are included separately through the presentation of site-specific results.

The NOCT for any particular array is defined as the operating temperature of the cells in the intended mounting configuration with an incident irradiance level of 80 mW/cm^2, an air temperature of 20°C, a wind velocity of 1 m/s, and the array open-circuited. This set of conditions yields a temperature that accurately represents the average cell temperature in the field during periods of significant energy production (2). Roughly, 50% of the energy will be produced above and 50% below this temperature.

Typical values of NOCT for ground-mounted arrays range from 45 to 50°C, and for roof-mounted arrays from 60 to 70°C.

The I-V curve at SOC for an array of interest can be closely approximated from the I-V curve at peak rating conditions by subtracting a voltage offset (shifting the curve to the left, parallel to the voltage axis) by an amount equal to 0.5% of the maximum power voltage at 25°C times the temperature difference (NOCT - 25°C).

The majority of the results that follow are presented in terms of the current, voltage, or power produced by the array at its maximum power point at SOC.

MAXIMUM POWER TRACKING

Because the maximum power point of an array varies with time, maximum annual array energy can be obtained only by continual adjustment of the array operating voltage by the PC, using closed-loop feedback. The degree of voltage movement required to obtain most of the available energy is an important input to the design of such a system. This voltage window is most easily characterized by the center voltage in the window and the plus and minus percentage of movement, or tracking range from the center voltage.

Other options available for array operation include fixed-voltage operation and periodic adjustment of the operating voltage based on a pilot solar cell.

The question that must be answered regarding maximum power tracking is whether the additional expense above fixed-voltage operation is worth the gain in energy. The approach used in the study was to determine the performance advantage of an ideal maximum power tracker over fixed-voltage operation. An ideal tracker is assumed to continuously track the array's maximum power point with no error. Figure 2 provides a plot of the fraction of annual energy obtained for operation at a fixed voltage compared to ideal maximum power tracking for five sites. The annual energy fraction is plotted as a function of the ratio of PC fixed-operating voltage to the voltage at the array maximum power point at SOC. The curves indicate that nearly all (98%) of the electrical energy from a PV array can be obtained by using a properly selected fixed-operating voltage. A 5% error in the selection of this fixed-operating voltage will increase the energy losses to about 4%.

Table 1 summarizes the findings for 12 representative sites selected from the 26 analyzed. It can be seen that the optimum fixed voltage ranges

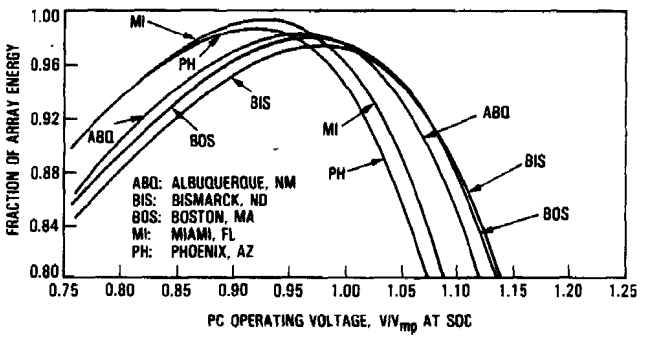

Figure 2. Fraction of Available Annual Array Energy Obtained versus Power-Conditioner Fixed-Operating Voltage

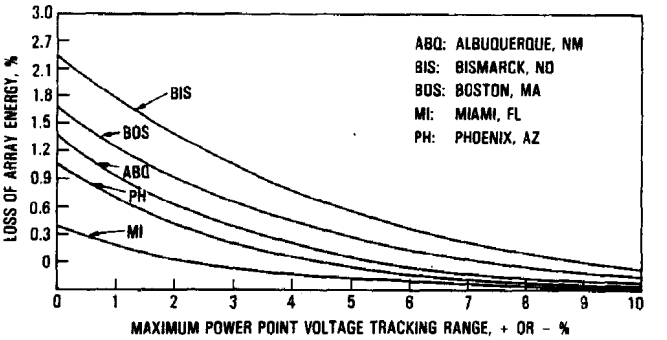

Figure 3. Percentage Loss in Available Annual Array Energy versus Power-Conditioner Voltage Tracking Range Half Width, Expressed as a Percentage of Optimum Center Voltage

Table 1. Simulation Results for Fixed-Voltage Power Conditioner

Site	Optimum Operating Voltage, V_{op}/V_{mp} at SOC	Loss in Energy, %
Albuquerque, NM	0.96	1.7
Bismarck, ND	0.97	2.5
Boston, MA	0.97	2.0
Brownsville, TX	0.92	0.8
Caribou, ME	1.00	2.2
Charleston, SC	0.95	1.1
Fort Worth, TX	0.93	1.5
Fresno, CA	0.94	1.3
Miami, FL	0.93	0.7
Omaha, NB	0.96	2.1
Phoenix, AZ	0.92	1.4
Seattle, WA	0.97	1.4

from about 92% of the array voltage for hot climates, such as that of Phoenix, AZ, to 100% of the array voltage for colder climates, such as that of Caribou, ME. Additionally, it can be seen that the fraction of available annual energy that is lost by fixed-voltage system ranges from 0.7 to 2.5%, with few sites over 2%.

To define the requirements for a maximum-power-tracking PC, the hourly computer simulations were used to develop data on the optimum center voltage and the fraction of the available energy that is obtained as a function of the voltage tracking range. The optimum center voltage turns out to be nominally the same as the optimum fixed voltage presented in Table 1. Figure 3 illustrates the percentage loss in available annual array energy for five representative sites as a function of the tracking range half width (stated as a percentage of the optimum center voltage).

From the above discussion, it follows that the add-on cost for a maximum power tracker should be less than the value of the annual energy lost using fixed-voltage operation. Because actual trackers may oscillate about the maximum power point due to instantaneous changes in solar irradiance, the value of the energy lost by this spurious operational characteristic must be added to the cost of providing the tracker. A study performed by G. Hart, et al., at the MIT Lincoln Laboratory indicates that such energy losses may severely limit the worth of some maximum power trackers (3).

Another consideration in the trade-off between fixed-voltage and maximum power tracking is the potential affect of array degradation with time. As an array degrades the fill factor decreases and causes the optimum operating voltage to decrease also. If the fixed-operating voltage is updated periodically, this voltage decrease has no effect; however, if it is not updated, the annual energy losses will increase as the fixed voltage becomes too high for the degraded array. Table 2 provides the shift in the optimum operating voltage for three initial fill factors of 0.75, 0.70 and 0.65.

Figure 4 expands on this analysis by displaying the annual energy loss caused by array power degradation for two PC operational modes, maximum power tracking and fixed-voltage operation. Also shown, by the dotted line, is the energy loss with updated fixed-voltage operation where the operating voltage is always adjusted to match the array degradation.

An important observation from Figure 4 is that the annual energy output of an array degrades about 1.4 times faster than its power rating at SOC, even with an ideal maximum power tracker. This has significant economic implications relative to the worth of heavily degraded systems or, more correctly, to the worth of arrays with poor fill factors, such as might be expected with some thin-film cells.

All life-cycle economic analyses that we are familiar with have incorrectly assumed that the fraction loss in annual energy from a degraded array is equal to the power degradation. The accelerated rate of energy degradation reflects the fact that the electrical efficiency of low-fill-factor arrays drops considerably with decreasing irradiance level. Since the mean irradiance level in an annual energy sense is 70 to 80 mW/cm^2, the power rating of 100 mW/cm^2 overpredicts the energy performance of

Table 2. Shift in Optimum Operating Voltage With Array Fill-Factor Degradation

Actual Fill Factor	Optimum Operating Voltage / Initial Optimum Operating Voltage		
0.75	1.00	—	—
0.70	0.95	1.00	—
0.65	0.91	0.96	1.00
0.60	0.89	0.93	0.97
0.55	0.86	0.90	0.94
0.50	0.84	0.88	0.92
0.45	0.82	0.86	0.90

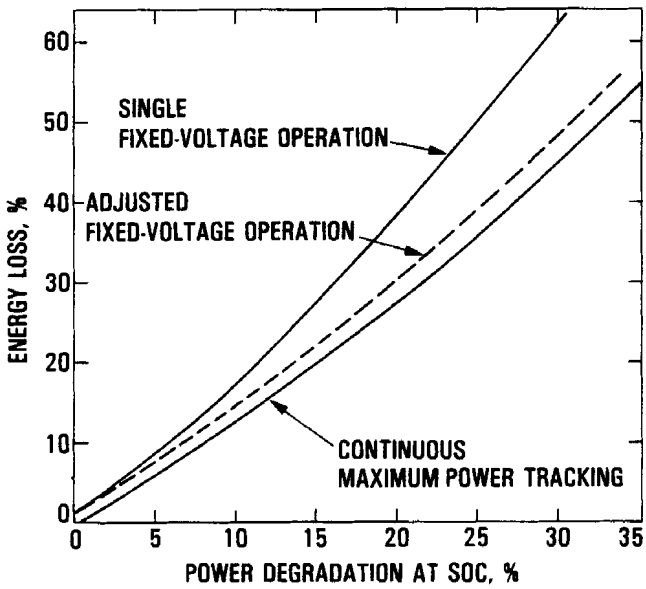

Figure 4. Annual Array Energy Loss versus Power Degradation as a Function of Power-Conditioner Voltage Operation Mode

low-fill-factor arrays. For a discussion of this topic, see (2).

POWER-CONDITIONER EXTREME LIMITS

Another important PC design issue is the maximum power, current, and voltage that the PC must withstand. Three key considerations are evident:

(1) The amount of energy that is lost during times when the array output exceeds PC operating limits and energy is rejected.

(2) The protection strategy to be used when the maximum limits are exceeded.

(3) The absolute maximum levels to be expected if survival limits are a consideration.

Current and Power Limits

A key consideration in the selection of current and power limits is the cost of accepting higher levels compared with the energy lost, or downtime suffered when over-limit conditions are encountered. Peak irradiance levels of up to 130 mW/cm^2 are obtained routinely, and it is expected that reflection augmentation resulting from white surfaces including snow will lead to even higher values (up to 150 mW/cm^2). Two basic strategies were considered for managing these over-limit situations. One strategy, called the total rejection strategy, is the discontinuation of power acceptance from the array by the PC. The second strategy, called the partial rejection strategy, involves reducing the current and/or power levels so that the limits are not exceeded during array operation. This can be achieved by changing the array operating point on the I-V curve or by using a shunt. To assess these two options, the energy loss was calculated for each strategy as a function of PC current and power levels. Table 3 provides the power and current limits required to obtain 99 and 99.9% of the energy for both strategies.

Table 3. Power-Conditioner Current Limit Required to Obtain 99% and 99.9% of Available Annual Energy with Partial and Total Rejection Strategies

Site	PC Current Limit / Array I_{mp} at SOC			
	99%		99.9%	
	Partial	Total	Partial	Total
Albuquerque, NM	1.06	1.19	1.17	1.20
Bismarck, ND	0.95	1.07	1.05	1.10
Boston, MA	0.89	1.04	1.01	1.09
Brownsville, TX	0.92	1.04	1.03	1.05
Caribou, ME	0.94	1.09	1.08	1.10
Charleston, SC	0.90	1.04	1.01	1.08
Fort Worth, TX	0.94	1.05	1.04	1.10
Fresno, CA	0.98	1.05	1.04	1.05
Miami, FL	0.86	1.02	0.97	1.05
Omaha, NB	0.95	1.09	1.08	1.26
Phoenix, AZ	1.00	1.06	1.05	1.16
Seattle, WA	0.88	0.95	0.95	0.96

It can be seen that for the same energy performance, a PC using a total rejection strategy must accommodate current levels about 15% higher than one using a partial rejection strategy.

Voltage Limits

Voltage limits must also be considered in the PC design, particularly during startup when the array may be at its maximum open-circuit voltage. Worst-case open-circuit voltages are associated generally with low temperatures and high irradiance levels, such as might be encountered during a bright, cold winter day with snow on the ground. The following three approaches were used to estimate likely maximum open-circuit voltages.

First approach: The hourly combination of incident irradiance and calculated cell temperature

(based on incident irradiance and ambient air temperature) that led to the maximum open-circuit voltage data was noted. This voltage represents the worst-case thermal-equilibrium condition existing on the SOLMET TMY data tape. Because this condition does not reflect the easily foreseeable case where the sun suddenly appears from behind an obstruction and shines on a cold array, it is considered a lower-bound estimate of the maximum open-circuit voltages.

Second and third approaches: The lowest ambient temperature as recorded in the TMY data tape and that recorded in a weather atlas (4) were both assumed as the solar-cell temperatures. Both of these cell temperatures were then combined with a 100 mW/cm^2 irradiance level to determine the array open-circuit voltage in these conditions. Since the simultaneous occurrence of such conditions is unlikely, these determinations of open-circuit voltage can be viewed as upper limits in the former case for the selected TMY year, and in the latter case as a true upper-bound value because of the inclusion of long-term weather extremes.

Table 4 summarizes the results from the three estimation techniques. Because the upper-bound estimates are only about 12% higher than the lower-bound estimates, they serve as a useful basis for estimating the worst-case voltages for any site without an excessive penalty for conservatism.

ARRAY POWER DISTRIBUTION

An additional aspect of long-term array performance that is important to the design of array loading systems is the fraction of annual energy generated at various power levels. Because PC efficiency typically varies with output power level, calculation of average efficiency of total annual energy losses requires data on the fraction of annual energy input to the PC as a function of power level.

The hourly simulation results for the 26 sites were used to construct plots of the annual energy generated at various relative power levels. A typical plot of power output versus time for a period of one day will assist in understanding the data presentation format. Such a plot, illustrated on the left in Figure 5, can be modified by rearranging the hourly intervals in order of decreasing power-output level. Figure 6 is the result of performing the same operation on the hourly computer simulation results for an entire year for Albuquerque; the area under the curve is the annual energy output (integral of power over time) and the area under any two power levels is the energy generated during operation between these levels.

Table 5 tabulates the fraction of annual energy generated within each of six power intervals for each of 12 sites. The fractions serve as useful weighting factors for the determination of an

Table 4. Maximum Open-Circuit Voltage for 12 Sites (NOCT = 50°C)

Site	Maximum V_{oc} V_{mp} at SOC: Lower-Bound, TMY[a]	Upper-Bound, TMY	Upper-Bound, Atlas
Albuquerque, NM	1.49	1.69	1.74
Bismarck, ND	1.57	1.79	1.83
Boston, MA	1.52	1.69	1.69
Brownsville, TX	1.43	1.57	1.57
Caribou, ME	1.57	1.79	1.82
Charleston, SC	1.46	1.64	1.65
Fort Worth, TX	1.46	1.66	1.67
Fresno, CA	1.44	1.61	1.61
Miami, FL	1.40	1.56	1.56
Omaha, NB	1.58	1.75	1.75
Phoenix, AZ	1.43	1.61	1.61
Seattle, WA	1.49	1.64	1.64

[a]Start-up voltage for 99.9% of available annual energy

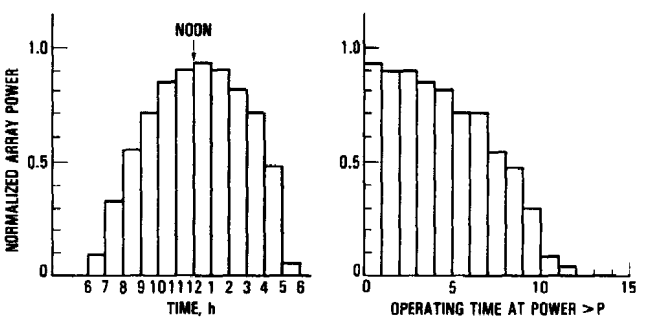

Figure 5. Illustration of the Construction Principle Behind a Plot of Normalized Power versus Operating Time With the Time Intervals Ordered According to Decreasing Power Level

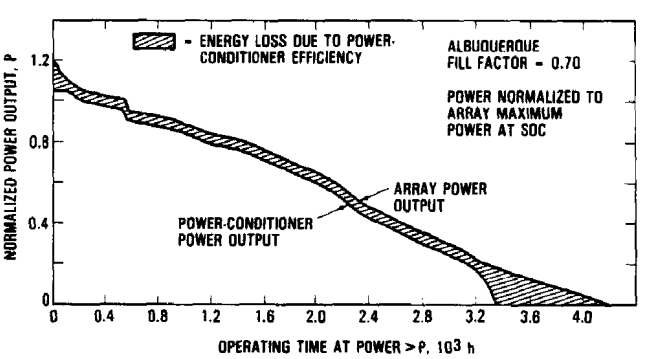

Figure 6. Effect of Typical Photovoltaic Efficiency on Annual Array Power Production

Table 5. Fraction of Annual Array Energy Available in Various Relative Power Intervals

SITE	ARRAY RELATIVE POWER INTERVAL 0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2
ALBUQUERQUE, NM	0.0343	0.0782	0.1040	0.2133	0.3693	0.2010
BISMARCK, ND	0.0750	0.1363	0.1442	0.2435	0.3277	0.0739
BOSTON, MA	0.0907	0.1383	0.1965	0.2840	0.2741	0.0163
BROWNSVILLE, TX	0.0572	0.1393	0.2025	0.3967	0.1905	0.0138
CARIBOU, ME	0.0779	0.1734	0.1754	0.2511	0.2542	0.0689
CHARLESTON, SC	0.0541	0.1512	0.1996	0.3749	0.2043	0.0158
FORT WORTH, TX	0.0590	0.1185	0.1642	0.3184	0.2995	0.0403
FRESNO, CA	0.0446	0.0990	0.1213	0.2721	0.4098	0.0533
MIAMI, FL	0.0508	0.1554	0.2382	0.4448	0.1073	0.0035
OMAHA, NB	0.0682	0.1282	0.1426	0.2723	0.3119	0.0767
PHOENIX, AZ	0.0339	0.0679	0.1275	0.3091	0.3821	0.0596
SEATTLE, WA	0.1302	0.1603	0.1847	0.2524	0.2692	0.0032
AVERAGE	0.0647	0.1305	0.1667	0.3027	0.2833	0.0522
CUM. VALUE OF AVERAGES	0.0647	0.1952	0.3619	0.6646	0.9479	1.0000

average PC efficiency, which is defined as the annual energy output to the load divided by the annual energy input to the PC.

Mathematically, this definition can be expressed as:

$$\eta_{ave} = \frac{\int P_{out}\, dt}{\int P_{in}\, dt} = \frac{\int \eta(P_{in}) P_{in}\, dt}{\int P_{in}\, dt} \qquad (1)$$

where

P_{in} = input power to PC

P_{out} = output power to PC

$\eta(P_{in})$ = efficiency expressed as a function of P_{in}

If we approximate the integrals with summations over N distinct power intervals (P1 through PN), we obtain:

$$\eta_{ave} = \frac{\left[\left(\sum_{P=P1}^{PN} \eta_P E_P\right) - P_{SB} T_{SB}\right]}{\sum_{P=P1}^{PN} E_P} \qquad (2)$$

where

E_P = annual PC input energy at array power interval, P

P_{SB} = standby PC power consumption per hour

T_{SB} = hours per year for which PC has no output power, but draws standby power

η_P = PC efficiency at array power level, P

Figure 7 illustrates a typical PC efficiency curve presented as a function of the array output-power rating. Note that these curves are often presented as a function of PC output-power rating. In this case, the curve must be translated to a curve giving efficiency as a function of PC input power and then to a function of array output power at SOC.

Figure 6 also illustrates the energy losses resulting from PC operation and rated power and current limits and their effect on PC efficiency. During array operation in the middle of the power region, the loss in energy due to the PC losses determines the PC efficiency. The bottom end of the relative-power scale is dominated by the array threshold power level for operation of the PC. The PC efficiency at the upper end of the relative-power scale is determined by the PC power and current limits. If the PC is sized so that its limits are close to the upper range of the array operating values, the efficiency over most of the PC operating range will increase; however there will be reduction in efficiency at the upper end to a value below the maximum efficiency. If the PC is oversized, the efficiency may be increased at the upper level, but it will be lower throughout the rest of operating range. The determining factor is the amount of margin the PC has in the amount of power and current it can withstand beyond its rating.

The average annual efficiency for the PC represented in Figure 6 was determined by taking the product of the average efficiency in each of 12 relative-power intervals and the fraction of annual array energy produced in each interval along with standby losses. Table 6 provides an abbreviated set of results for Albuquerque. As can be seen from this Table, and with the type of efficiency curve represented by Figure 7, undersizing the PC will increase average annual efficiency.

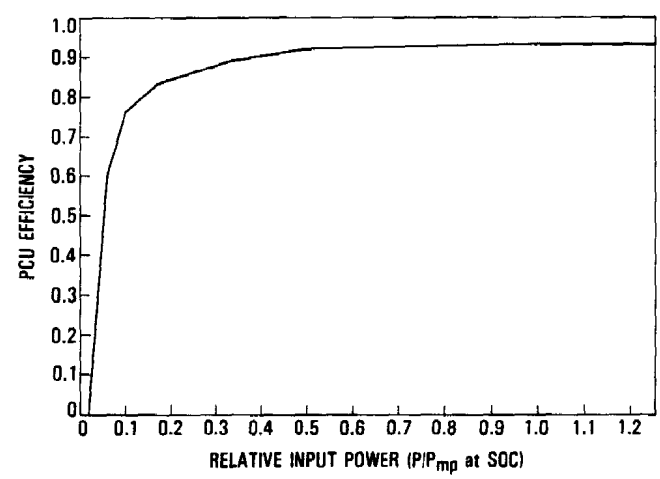

Figure 7. Power-Conditioner Efficiency as a Function of Array Output (PC Input) Power

Table 6. Example Average Annual Efficiency Calculation for Albuquerque, New Mexico

Relative Power Interval	Annual Energy Fraction (E_p/E_y)	Average PC Efficiency in Power Interval, P		
		R = 0.9	R = 1.0	R = 1.1
0.0-0.2	0.0343	0.610	0.590	0.570
0.2-0.4	0.0782	0.883	0.875	0.869
0.4-0.6	0.1040	0.917	0.914	0.908
0.6-0.8	0.2133	0.923	0.921	0.920
0.8-1.0	0.3693	0.925	0.925	0.925
1.0-1.2	0.2010	0.927	0.926	0.926
Standby Power Consumption (Neg. Value)		0.022	0.024	0.026
		Average Annual Efficiency, %		
Full Maximum Power Tracking		88.8	88.4	88.0
Fixed-Voltage Operation		87.3	86.9	86.5

Note: R is the ratio of PC full-output-power rating (divided by PC efficiency at PC full-power rating) to array maximum power at SOC.

CONCLUSIONS

Based on an ideal maximum power tracker the increase in allowable cost to obtain maximum power tracking (over fixed-voltage operation) is limited to about 2% of the annual energy value. The increase in cost due to energy lost by a real tracker over an ideal one must be subtracted from this 2% value.

A potential advantage to the use of maximum power-tracking results when an array degrades. Under fixed-voltage operation, the optimum voltage shifts and, if this is not accounted for, additional energy losses above that resulting from the degradation itself may occur.

The analyses on power and current limits indicate that a PC whose limits are about 20% higher than maximum-power SOC values will capture all available annual energy over all sites considered. It appears that the nominal oversizing can be accomplished without seriously jeopardizing overall efficiency. However, this is an important point to consider in selecting a PC because the analyses to obtain average annual efficiency indicate that greater efficiency is obtained by choosing a PC with a smaller rating.

An important note highlighted by this study is the importance of I-V curve shape (fill factor) in determining annual array energy performance. As an array ages and its I-V curve degrades, its energy performance decreases 1.4 times faster than its power performance. This is also true for arrays with poor initial I-V curve shape, such as some utilizing emerging thin-film cells.

REFERENCES

1. Gonzalez, C.C., Hill, G.M., and Ross, R.G., Jr., Electrical Interface Characteristics of Flat-Plate Photovoltaic Arrays, JPL Document No. 5101-202, Jet Propulsion Laboratory, Pasadena, California (in press).

2. Ross, R.G., Jr., and Gonzalez, C.C., "Reference Conditions for Reporting Terrestrial Photovoltaic Performance," Proceedings of the 1980 Annual Meeting of AS/ISES at Phoenix, Arizona, pp. 1091-1097, June 1980.

3. Progress Report 20 (for the Period November 1981 to April 1982), and Proceedings of the 20th Project Integration Meeting, pp. 460-466, JPL Document No. 5101-209, Jet Propulsion Laboratory, Pasadena, California, August 1982.

4. Climates of the States: Vols. 1 and 2, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Water Information Center, Inc., Port Washington, New York, 1974.