PHOTOVOLTAIC PERFORMANCE MEASUREMENT PRACTICE AND PROBLEMS

L.D. Runkle and R.G. Ross, Jr.
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

ABSTRACT

The function of solar cells, modules and arrays is to produce useful electrical energy. Because photovoltaic conversion efficiency is used to discriminate between competitive photovoltaic technologies as well as between alternate means of producing electrical energy, it is important that the means used to measure the performance of these devices be understood. This paper traces the evolution of photovoltaic performance measurement from its early application in space arrays to its present status in terrestrial applications. Although the discussion is generally addressed to the problem of measuring the power of flat plate modules and arrays, the technology of measuring the characteristics of cells provides the basis for much of the discussion. The problem of developing voluntary concensus performance measurement standards is also discussed and suggestions for enhancing their development are offered.

1. INTRODUCTION

The performance of photovoltaic solar cell modules is delineated by their current-voltage characteristic curve, Fig. 1. Aside from the intrinsic properties of the module itself, this characteristic is a function of three extrinsic variables; (1) the total irradiance reaching the module, (2) the spectral distribution of the irradiance and (3) the temperature of the module. In order to compare the performance of different modules, these three extrinsic variables must remain the same from sample to sample. It is apparent from Fig. 1 that the short-circuit current increases linearly with the intensity of the irradiance. Likewise, from Fig. 2 it can be observed that a temperature increase causes a decrease in voltage amounting to about 0.5% per 1°C. The effect of changing the spectral distribution of the irradiance is more subtle and is illustrated in Fig. 3 which displays relative power as a function of air mass (from Ross & Gonzalez, (1)). Air mass is a normalized parameter denoting

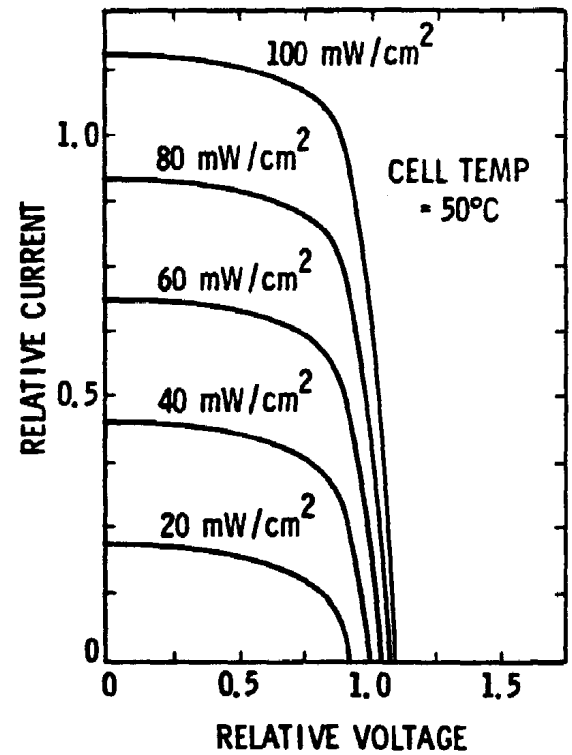

Fig. 1. Typical current-voltage characteristics of a solar cell module as a function of intensity.

the ratio of the path length traversed by the incident sun through the earth's atmosphere to the thickness of the atmosphere. It serves as a convenient measure of different solar spectral distributions ranging from the bluish sun of outer space (air mass zero or AM 0), to the white light of an overhead sun (AM 1), to the redish sun of afternoon (AM 6). To compare the performance of different modules, a common set of conditions is required; thus a level of irradiance must be specified, the spectral distribution or air mass of the irradiance defined, and a temperature selected.

To be presented at the ASES 1984 Annual Meeting,
Anaheim, California, June 5-9, 1984

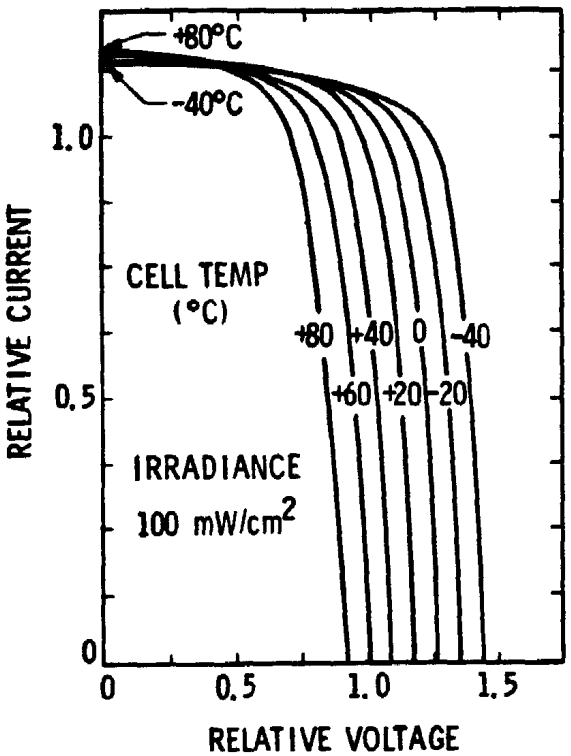

Fig. 2. Typical current-voltage characteristics of a solar cell module showing effects of temperature.

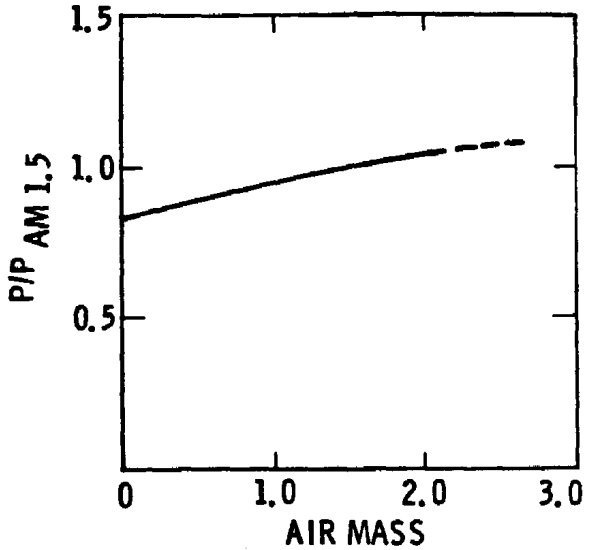

Fig. 3. Normalized power output as a function of air mass.

2. BACKGROUND

The first widespread use of large solar panels or arrays to power electrical equipment occurred in the various spacecraft programs, where the determination of the performance of solar cells and arrays in space was crucial because of the limitation imposed upon the size of the array by the lifting capability of the rockets that boosted the spacecraft into orbit. It was in this program that the techniques and procedures for making photovoltaic measurements were first developed. The intensity and spectral distribution of the irradiance in outer space was determined: then earthbound simulators and measuring techniques were developed to facilitate evaluation of the evolving solar cell technology and to proof test the spacecraft arrays. Everyday measurements of cells were facilitated by the use of calibrated reference cells, temperature controlled plates and steady-state lightsources simulating the AM 0 spectrum of space. The reference cells were calibrated on balloon flights that carried appropriate instrumentation to the edge of the earth's atmosphere.

Testing of the arrays was more difficult than testing cells. Cells could be put in fixtures, the temperature controlled, the intensity of the irradiance adjusted, the spectrum evaluated and the performance measurements thus obtained. For arrays there was only the sun, with the spectrum and intensity of the particular moment, and at a temperature depending not only on the ambient and the irradiation but on the wind as well. This led to hours of data taking at the mercy of the weather and laborious calculation or data processing to evaluate the anticipated performance of the solar panel in space.

The arduous process of sunlight testing coupled with electronic instrumentation advances led to the development of the large-area pulsed solar simulator (LAPSS). This device uses a xenon light source pulsed by a current discharged from a capacitor bank to irradiate the solar panel. During a part of the time that the light pulse is on, an electronic load sweeps the panel from no load to short circuit, and the voltage and current characteristics of the panel are sampled several hundred times. The pulse is about three milliseconds and the sweep takes about one millisecond. The intensity of the flash during the sweep is adjusted to be near 100 mW cm^{-2}. A calibrated reference cell is used to measure the effective AM 0 intensity at the sampling times, and the temperature of the panel is measured by a thermocouple. The sampled data is stored, then processed by a computer that normalizes the printout of the I-V curve to the selected intensity and temperature. The great virtue of this equipment is that the measurement is made in seconds, not hours. Further, the spectral distribution of the irradiance is known, the intensity is selected and the temperature of the module

or array is known and does not change during the course of data taking.

3. TERRESTRIAL MEASUREMENTS

Although the measuring equipment of the space program is directly applicable to making measurements of terrestrial modules, some accommodation was required since the spectrum of the irradiance at the surface of the earth is modified by the atmosphere and depends upon such things as the length of the path the light takes in traversing the atmosphere (the air mass), the water vapor encountered and the turbidity.

In response to the need for definition of both a standard reference spectrum and a measurement procedure, an ad hoc committee of photovoltaic specialists met in 1976. An interim standard for performance measurement was formulated and reported in NASA Document 73702 which set the standard irradiance level at 100 mW cm^{-2}, defined the standard spectrum as that of direct normal sunlight at AM 1.5 and certain water vapor and turbidity, and adopted 28° C as the standard temperature (2). The procedure also adopted the concept of the reference cell as the standard means of measuring the effective AM 1.5 irradiance level of illumination sources which do not have a standard AM 1.5 spectral distribution. The reference cell, of known dimensions and fabricated of the same photovoltaic material as was used in the module to be measured, had to be calibrated against a precision pyrheliometer under sunlight conditions closely approximating those associated with the AM 1.5 reference spectrum. The turbidity and the water vapor content were to be determined by a sun photometer.

This process could only be carried out when the proper atmospheric conditions and sun position occurred. As a result, the calibration was often long and actually impossible in some regions. The virtue of such a reference cell was that it could be used with any reasonable light source to establish the AM 1.5 irradiance to which the module under test was being exposed. Since both the reference cell and the module were made of the same photovoltaic material they respond to the light in the same way. The drawback, of course, is that each module tested requires a matching reference cell.

For about ten years, this interim standard has provided a basis for uniform performance measurements and comparisons. Recently, with the planning and installation of larger photovoltaic power systems, attention has been directed to annual energy production as a more realistic measure of the worth of a solar cell module than peak power measured at arbitrary conditions such as those appearing in the interim standard. The peak power does not necessarily correlate well with annual energy at all locations at which photovoltaic arrays might be used. In fact the claim is made that modules produced by one process may be unfairly discriminated against by measuring at the 100 mW cm^{-2}, AM 1.5 conditions defined.

4. ISSUES

The issues that must be resolved in order to standardize performance measurements for terrestrial applications continue to focus on the selection of the irradiance level, the spectral distribution of the irradiance, and the temperature.

Irradiance-level Issues

Although short-circuit current is a highly linear function of irradiance over a wide range of levels, maximum power is only modestly linear with irradiance. At irradiance levels below 40 mW cm^{-2}, module power becomes quite sensitive to the shape of the module I-V curve. At low irradiance levels, high series resistance leads to proportionately increased power (lower I^2R losses) whereas a low shunt resistance (high current leakage) leads to proportionately lower power under the same conditions. Because an important amount of annual electrical energy is generated at irradiance levels below 40 mW cm^{-2}, there is a valid argument for measuring modules at an irradiance level closer to the annual average than at 100 mW cm^{-2} so as to properly include these low-irradiance-level power trends.

Another problem involves the determination of the ultimate arbiter of the validity of the measurements. Naturally one assumes that the National Bureau of Standards is that authority. In actuality, the NBS has absolved itself of the responsibility for making precise measurements of the irradiance of the sun, and this chore has devolved upon a group of dedicated independent concerned organizations and people who meet annually to make intercomparison measurements, and establish a standard irradiated watt. Each year representatives of concerned national laboratories, certain industry participants, representatives from foreign national labs and others gather at New River, Arizona, with their cavity radiometers to conduct a series of intercomparison measurements to establish a basis for the irradiance of the sun. Once in five years this takes place at the World Radiation Center in Davos, Switzerland. These instruments are then the standards against which the pyrheliometers and pyranometers are calibrated. Reference cells may then be calibrated against the pyrheliometers.

Solar Spectrum Issues

The present practice of using a direct normal AM 1.5 spectrum to measure flat-plate photovoltaic modules as defined by NASA Document 73702 is widely disputed by those who forsee the future use of amorphous silicon and other more blue-sensitive materials. They insist, with justification, that a bluer spectrum, which more properly recognizes the important contribution from blue-sky diffuse radiation should be used. The ASTM has adopted standards which define both of these spectra at AM 1.5. Standard E 891-82, "Terrestrial Direct Normal Solar Spectral Irradiance Tables for Air-Mass 1.5", is based upon work by Bird and Hulstrom (3) at SERI and has superceded the spectrum published in NASA 73702 as the standard. Likewise, E 892-82, "Terrestrial Solar Spectral Irradiance Tables at Air-Mass 1.5 for a 37 degree Tilted Surface", provides a standard for a "global" solar spectrum.

It is instructive to observe the difference in calculated short circuit current developed in a variety of cells when "exposed" to these two different spectra. These variations - shown in Table 1 for six different single crystal silicon reference cells, selected to represent the gamut of response characteristics available - reveal a small effect, from -0.4% to +1.4%, when global is compared with direct. The poly-crystalline cell included in the sample is seen to perform similarly to its single crystal (Cz) companions.

Table 1. CELL RESPONSE TO DIFFERENT SPECTRA.

Cell Number	Cell Mat.	Short Circuit Current $mA/mW/cm^2$		Change %
		Direct Spectrum	Global Spectrum	
MS 431	Cz- Si	1.349	1.360	+0.8
GQ 420	Cz- Si	1.087	1.082	-0.4
RS-425	Cz- Si	1.205	1.221	+1.3
SS-1440	Cz- Si	1.325	1.337	+0.9
US-417	Cz- Si	0.939	0.937	-0.2
YB-451	Poly Si	0.990	1.004	+1.4
UR-489	Cz- Si	1.013	1.028	+1.4
Exp.	a - Si	0.048	0.054	12.0

On the other hand, calculations run on an experimental sample of amorphous-silicon (a-Si) cells show that the ASTM global spectrum results in a 12% higher short circuit current than that obtained using the ASTM direct normal spectrum. This sample was characterized by the manufacturer as mediocre, and not as responsive in the blue region as could be expected from better material.

Since a global spectrum is what is seen by all flat-plate arrays, it would appear to be appropriate to adopt that spectrum for performance measurements. However, before this can be done, revised reference cell calibration procedures must be developed and demonstrated.

Temperature Issues

Recognizing that the ambient temperature varies from site to site as well as diurnally for any one site, points up the difficulty in selecting a temperature to use as a standard in measuring module performance. However, temperature compensations are less contentious than spectral and irradiance level considerations and can be applied with acceptable ease. Formulae have been developed to calculate P_{max} at a second temperature from measurements made at a first temperature. These rely upon a knowledge of the short circuit current, the open circuit voltage and the series resistance dependencies on temperature. As pointed out earlier, the NASA document specified that 28°C was the temperature at which the measurements were to be made. Shortly later another temperature was defined to more realistically represent operating conditions. This is called the nominal operating cell temperature, or NOCT, and is defined as the actual cell temperature when the solar module is irradiated at 80 mW cm^{-2} in an ambient air temperature of 20°C, and at a wind velocity of 1 m s^{-1}. These conditions, designed to reflect an annual average operating temperature, usually result in a value of approximately 48°C depending upon the thermal design of the module. Given the fact that the maximum power produced by a module decreases by about 0.5% for each degree Celsius that the temperature increases, the useful power at NOCT is approximately 10% less than that measured at 28°C.

STATUS

At the present time, the standards committees of the American Society for Testing Materials (ASTM) and the Institute of Electrical and Electronic Engineers (IEEE) are working on a family of standards applicable to the measurement of the performance of solar cells and modules, the International Electrotechnical Commission (IEC) has formally convened Technical Committee 82 to address photovoltaic standardization, and at least two propositions have surfaced which address the rationalization of module power ratings to annual energy.

ASTM Committee E-44 has been set up to develop standards on Solar Energy Conversion and comprises fourteen subcommittees, one of which is Subcommittee 44.09 - Photovoltaic

Electric Power Systems. At the present time 44.09 has ten standards in preparation. Two standards were issued in 1983 and a third has been approved for issue. Standard E 948-83, "Standard Methods for Testing the Electrical Performance of Non-Concentrator Terrestrial Photovoltaic Cells Using Reference Cells" is a step toward replacing the NASA document. However, the standard on module testing and a number of other documents in preparation must be issued in order to completely define the measurement procedure.

The IEEE activity, in contrast to that of ASTM, is generally focused on the larger elements of the system such as arrays, power conditioning and storage as well as the total system itself. No photovoltaic standards have been issued by the IEEE to date; however, the several subcommittees are actively striving to bring standards into being.

In an effort to address the problem of establishing ratings that are related to annual energy, at least two propositions have been put forth. Charles Gay (4) of ARCO has proposed what is termed an AM/PM rating. It features the selection of a "standard day" with irradiance level, temperature and spectrum based on an analysis of worldwide conditions, followed by adjustment to site-specific conditions, which may or may not be less cumbersome than an adjustment from the present peak conditions. Gonzalez and Ross (5) at JPL have suggested a somewhat simpler adjustment based on fine tuning NOCT ratings using temperature and fill factor of modules. Such schemes as those proposed must be simple to be useful, given the variation in annual solar energy input to a device.

All in all, progress in developing standards appears to be painfully slow. This slowness is attributed to a number of factors. The consensus process, which requires that producers, users and unbiased third parties agree, is by itself an arduous negotiation. Often technical information is needed before a proper decision can be made, and there are some who contend that the photovoltaic area is too young to have standards applied. Frequently there is a lack of corporate support for participation in the activity, which requires travel and time that is often regarded as nonproductive.

One of the forces that should be driving the United States to more aggressive standardization activities is the international interest in photovoltaic standards. The IEC is actively considering a number of European standards as candidates for international adoption. The U.S. has been woefully weak in its ability to propose standards for international consideration. As a signatory of the General Agreement on Trade and Tariffs, the U.S. has agreed that standards adopted by international organizations are the medium of international trade. Therefore, our standards must be in harmony with the internationally adopted standards. This becomes important in a number of areas, including trade with developing countries that should be an important market for us.

The timely adoption of consensus performance measurement standards was the subject of a recent study by a JPL task force which interviewed numerous individuals representing manufacturers, users and national laboratories. No report has been issued to date, however preliminary results indicate that there is agreement at the working level of the need for standards, that the problems impeding the development of standards are acknowledged and that there is, a need for continuing government presence in the development of PV measurement standards.

Of particular concern is the fact that support by the U.S. government of photovoltaic standards activities is eroding. Although in the past, the DOE has supported substantial standards-related activities within the National Laboratories and funded the position of the Secretariat of Technical Committee 82 of the IEC, continued support is in jeopardy. This is in sharp contrast to the position taken by the European governments which support these efforts actively. Since standards exist for the purpose of facilitating commerce both national and international, it was felt that they are a proper and important concern of the government. Recommended ways in which the DOE could enhance the development of standards included: a) encourage participation in standards work, b) continue to provide financial assistance to the societies and groups who organize the standards work, particularly in the international arena, c) make available resources at the national laboratories to answer technical questions that pose a dilemma to the standards committees, and d) provide travel funds so that technically competent people from small businesses and consumer advocates can contribute to the standardization process.

6. CONCLUDING REMARKS

The photovoltaic performance measurement practice is subject to confusion because of the absence of relevant voluntary consensus standards. The technology for making measurements is understood; however, the selection of the conditions under which measurements should be made is an impediment. This selection must be made in order to provide a common basis of comparison between modules. It must be made with the understanding that the actual energy

produced in any one year will depend upon the geographical location as well as the variation of the energy input from its average. A consensus standard defining the conditions is needed so that the measurements can be made.

7. ACKNOWLEDGEMENTS

This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, and sponsored by the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

L.D. Runkle is Reliability and Engineering Sciences Deputy Manager, Flat-Plate Solar Array Project, and Supervisor Photovoltaic Operations Group and R.G. Ross, Jr. is Reliability and Engineering Sciences Manager, Flat-Plate Solar Array Project, and Supervisor, Photovoltaic Engineering Group.

8. REFERENCES

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

2. Brandhorst, H.W., Jr., et. al., "Terrestrial Photovoltaic Measurement Procedures", Lewis Research Center,Cleveland, Ohio, June 1977, ERDA/NASA/1022-77/16, NASA TM 73702.

3. Bird, R.E., Hulstrom, R.L. "Terrestrial Solar Spectral Data Sets," Solar Energy Research Institute, TR-642-1149, Golden, CO.3.

4. Gay, C.F., Rumberg, J.E., and Wilson, J.N., "AM/PM: All-day Module Performance Measurement," Sixteenth IEEE Photovoltaics Specialists Conference - 1982, pp. 1041-1046.

5. Gonzalez, C.C., and Ross, R.G. Jr., "Energy Predictions Using NOCT-Based Photovoltaic Reference Conditions," Progress in Solar Energy, American Solar Energy Society, 1983, Boulder, CO, pp. 935-940.