THERMAL PERFORMANCE OF RESIDENTIAL PHOTOVOLTAIC ARRAYS

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ABSTRACT

Detailed thermal analyses of a diverse variety of residential photovoltaic (PV) arrays are used to develop a generic understanding of the thermal performance of different array mounting concepts. Eight residential-style buildings, which incorporate four different types of array mounting schemes on their roofs, served as testbeds for this study. Array rear-surface air cooling was determined to be the key design parameter, correlated with the observed operating-temperature differences of the various array types. Design information is presented to allow estimates of operating temperatures of array concepts of interest.

1. INTRODUCTION

Eight prototype PV residences, shown in Fig. 1, were designed and fabricated, and are now being tested at the Southwest Residential Experiment Station (SW RES), established by the New Mexico Solar Energy Institute (NMSEI) at Las Cruces, New Mexico (1). Five prototypes and one full-size PV residence are also undergoing testing at the Northeast Residential Experiment Station (NE RES) in Concord, Massachusetts (2). Both of these test sites and the current analysis effort are part of the U.S. Department of Energy's National Photovoltaics Program.

Fig. 1. Southwest residential experiment station

Preliminary test data from SW RES (3) indicate that unexpectedly large temperature differences exist among arrays of different designs (Fig. 2). Array temperature is an important design consideration, because the electrical power output of PV modules decreases with increasing cell temperature at a rate of approximately 0.5%/°C increment. More significantly, recent studies indicate that a PV module's lifetime may be strongly affected by the cell temperature, with a factor-of-2 decrease in array lifetime per 10°C increase in cell operating temperature (4).

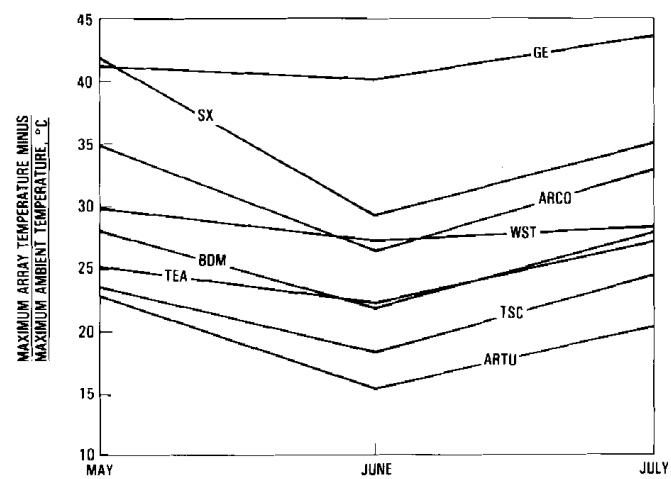

Fig. 2. Preliminary array temperature test results at southwest residential experiment station

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The Flat-Plate Solar Array Project (FSA) at the Jet Propulsion Laboratory (JPL) has sought to define design requirements, design analysis and test methods, and design approaches for flat-plate arrays and modules. This paper reports the results of a joint investigation by JPL and NMSEI to improve the understanding of the crucial factors affecting the operating temperature of residential PV arrays.

2. STUDY APPROACH

Although the operating temperature differences noted in Fig. 2 are dramatic, the key determining factors are masked by the large number of variable design parameters incorporated in the eight residential array types. For example, the eight prototype systems at the SW RES use six different module designs, eight different array mounting details, and array tilt angles ranging from 25 deg to 45 deg. The study objective was thus to systematically understand the role of these various design parameters and to determine their relative importance to array operating temperature.

The approach taken was first to develop a detailed transient thermal model of each array prototype, based on its measured geometry and module thermal-optical properties. Incident solar irradiance, sky radiation temperature, front- and rear-surface wind velocity and front- and rear-surface air temperature were input boundary conditions. A transient model using a 1-second time step was selected based on the needs of accurately accounting for the dynamic effects of wind cooling. The nodal models were assembled and solved using the large thermal analyzer computer program SINDA (5) together with experimental data for the front-surface environmental boundary conditions. Two sets of 5-minute-increment experimental measurements were used: one for June 10, 1982, and the other for September 23, 1982. Because data on rear-surface boundary conditions were not available, the computation strategy involved using the models to determine the rear-surface ventilation present in the eight array designs as required to yield the measured module cell temperatures throughout the two days.

Once the rear-surface cooling was fully characterized, the effects of the various array mounting design parameters were isolated by incorporating a common module design and array tilt angle (30 deg) into each of the eight computer models.

3. PROTOTYPE ARRAY CONSTRUCTION DETAILS

The prototype residential PV systems of SW RES include all four generic types of array mounting arrangements: rack, direct, standoff and integral.

The rack array is designed like a ground-mounted array to support the array at an appropriate tilt angle above a flat roof. This type of array is used in the TEA system (6).

The General Electric Co. (GE) and ARCO Solar, Inc. (ASI) systems both use direct-mounted arrays, which lie directly on the roofing felt and replace the conventional roofing material. The GE system's array (7) is composed of 375 GE "shingle" modules. There is a 5-cm (2-in.) air space between the plywood deck and the subroof insulation, which is composed of a layer of 3-mm (1/8 in.) untempered Masonite and two layers of R-11 fiberglass batting. The ASI system's PV array uses prototype "batten and seam" (ARCO RES ASI 15-2200) residential modules (8).

Three prototype systems, the BDM, ARTU, and Solarex Corp. arrays, use standoff-mounted designs, where the array is mounted parallel to, but above, the roof's conventional weather seal. The BDM array (9) is integrated into the trapezoidally sloped portion of the prototype's roof. The ARTU array is divided into three 2.59 x 7.32 m (8.5 x 24 ft) subarrays. In the Solarex prototype system (10), the array is a monolithic large-area design with its bottom vent protected from the ambient wind. The Solarex modules use polycrystalline silicon cells that have a lower conversion efficiency than the other types of cells involved in this demonstration project.

The WST system (11) and the TriSolar (TSC) system (12) use integral-mounted arrays in which the modules serve as the roof weather seal and structure. The rear surfaces of their modules are exposed to the attic interior.

4. THERMAL ANALYSES

Using the study approach outlined above, detailed transient thermal models were developed for each of the array prototypes, and simulation runs were made using the measured data for June 10 and September 23, 1982. The measured environmental parameters included: (1) ambient temperature, (2) irradiance levels on the tilted roofs, (3) local wind speed, and (4) local wind direction. The array rear-surface heat transfer was deduced by forcing the computed solar array cell temperatures to match the measured values. A substantial effort was made to insure consistency between the models and reasonableness of the physical parameter values. The accuracy of field measurements was checked carefully and the external wind

cooling model was refined to a high degree. See (13) for a description of the detailed process of calibration and transient simulation.

In the simulation results, rear-side heat transfer was found to be the key parameter responsible for the dramatic variation in array temperatures and thus required special attention. Three prominent characteristics of rear-side cooling were identified:

1) Substantial local cooling exists near inlet air vent openings at the array's rear surface. The temperature of this air approximates that of outside ambient conditions, and velocities may be enhanced or diminished by the extent to which the vent catches external wind.

2) Average cooling of the array rear surface is controlled by the average attic air temperature associated with perfectly mixed air. This temperature is a function of the inlet air temperature, the air exchange rate, and the thermal energy being added to the air from the array.

3) Enhanced rear-surface cooling is achieved if the average attic air convectively cools the array with a modest velocity.

Within the computer model, it was found most convenient to model the condition of average rear-surface cooling by an air ventilation factor set equal to the air exchange rate per unit area of array ($m^3/h\text{-}m^2$). This factor was subsequently found to be approximately proportional to the ratio R_a of the rear-surface air vent area to the array area. Conditions near inlet vents or with modest rear-surface wind velocities were modeled with special model additions.

Details of the modeling results are presented below for each of the four array types.

Rack Mount:

The TEA rack-mounted array supports the PV modules at a 26-deg tilt angle, with the lower module edge about six inches above the flat roof of the model residence. The backs of the modules are only slightly isolated from the ambient air, by a highly porous decorative lath screen.

The interaction between a rack-mounted array and the local wind is complicated, since boundary-layer thickness may vary significantly over the array. Array temperature gradients in excess of 15°C were measured, with the highest cell temperature at the array center and the lowest value at the lower edge near the opening between the array and the flat rooftop.

The cell temperature is strongly affected by the local rear-surface air movement. Near the edges of a large rack-mounted array the local rear-surface air speed, U, may vary from about the level of the ambient front-surface wind speed, V, to, in some cases, several times that wind speed. For instance, the wind may accelerate to three or four times its speed as the air volume squeezes through a small opening such as the narrow gap between the lower array edge and the flat rooftop in the TEA design. In contrast, the local rear-surface air speed in the center of the array may be nearly zero.

Figure 3 illustrates the cell-temperature variation as a function of V and U. For instance, under the set of reference conditions of an irradiance of 100 mW/cm^2, ambient temperature of 30°C, local rear-surface air speed of 0, and front-surface wind speed of 2 m/s, the cell temperature at the center of a large, rack-mounted array would be around 60°C. The cell temperatures for the side and upper edges, where the U value approximates V, would be 54°C. The cell temperatures at the lower edge of the rack-mounted array would be between 46°C and 49°C, with U as high as 3V to 4V.

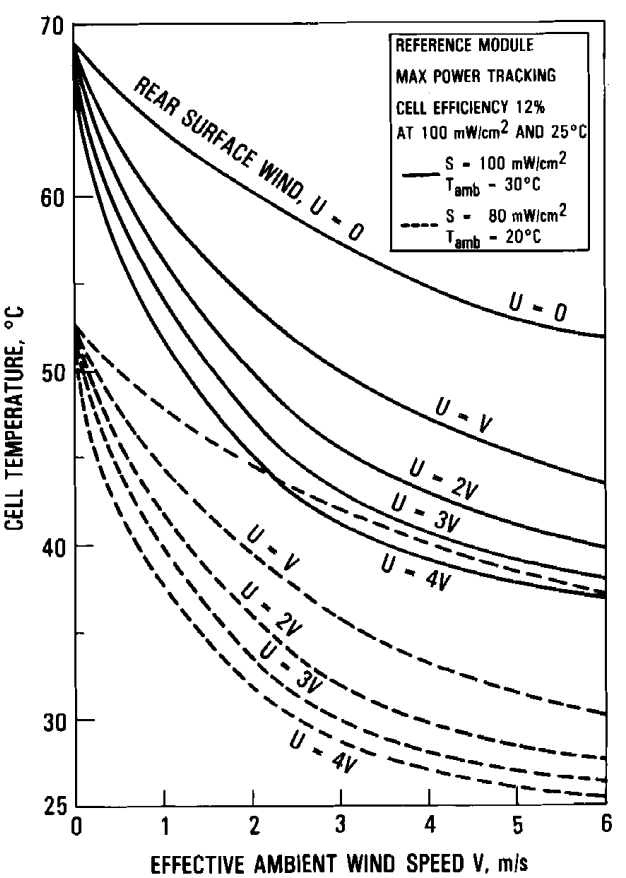

Fig. 3. Effect of front- and rear-surface wind distributions on cell-temperature levels of rack-mounted arrays

Direct Mount:

In contrast with the open-back configuration of the rack mount, the modules in a direct mount are attached directly to the sloped roof's plywood surface with no rear-surface air gap. As a result, a direct-mount array has a high cell operating temperature because the rear surface is isolated from the cooling of ambient air flow.

Fig. 4 shows the cell-temperature levels for direct-mounted arrays. Operating a direct-mounted array with back-surface insulation results in a temperature level that is equal to the maximum temperature at which the array can operate, and a temperature level that is independent of the attic temperature. On the other hand, if the roof sheeting is exposed to the attic (without additional thermal insulation), the cell temperature for a direct-mounted array can be significantly affected by the attic's ventilation rate.

Standoff Mount:

With the standoff mount, the module is mounted parallel to, but separated from, the roof weather-seal surface by an air gap of typically 7 to 15 cm (3 to 6 in.).

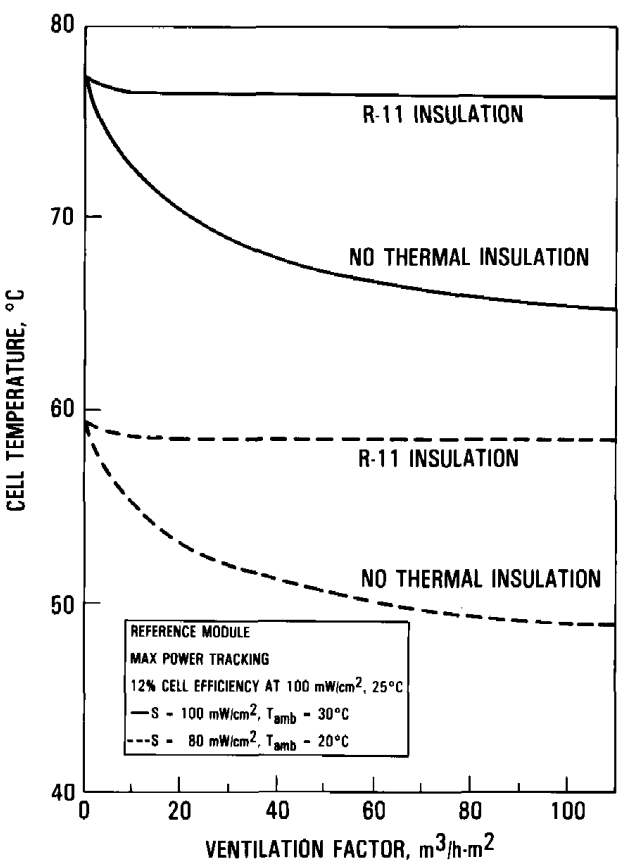

Fig. 4. Cell-temperature levels for direct-mounted arrays

Two different analytical models were used for standoff-mounted systems: one for the main array body and one for the modules near the vent inlet opening. Qualitatively speaking, the local rear-surface air speed and air temperature are near the ambient values for modules near the inlet vent. The thermal behavior of these modules is dominated by these inlet air conditions. Under the selected reference conditions (100 mW/cm^2, 2 m/s, 30°C) the temperature of these vent-dominated modules will be around 53°C, as shown in Fig. 3.

For the main array body, the cell temperature and the air temperature at the space underneath the array are governed by the ventilation at the array's rear surface. This ventilation is a complex function of the area of the array, the opening area of the air channels, and the standoff height. As a first approximation, the specific ventilation factor can be estimated as a linear function of the vent-array area ratio R_a. The values of R_a vary significantly among the three standoff-array designs. Assuming an effective rear-surface air speed of 0.25 m/s, the computed ventilation factors for the BDM system (R_a = 0.115), the ARTU system (R_a = 0.02), and the Solarex system (R_a = 0.0083) are 103.0, 18.0, and 7.5 m^3/h-m^2, respectively. These values correlate reasonably well with the ventilation factors deduced from the transient simulations: a specific ventilation factor of 50 to 100 m^3/h-m^2 for the BDM system, of about 20 m^3/h-m^2 for the ARTU system, and of 5 to 10 m^3/h-m^2 for the Solarex system.

Figure 5 shows the cell-temperature levels for standoff-mounted arrays. For the selected reference boundary conditions (100 mW/cm^2, 2 m/s, and 30°C, as above), the cell temperature may range from 71°C for a monolithic array with a narrow air channel and an R_a of 0.005, to a value of 56°C for a BDM-type arrangement with an R_a of about 0.1. The BDM system effectively reduces the average cell temperature by breaking its large array into a number of separate smaller arrays, thus reducing the effective array area and increasing rear-side cooling.

Integral-Mount:

With an integral-mount array the modules replace the roof structural surface and weather seal, and interface directly with the interior attic air. As with a standoff-mounted array, the temperature of an integrally mounted array is very sensitive to the degree of rear-surface ventilation as measured by the ventilation factor or vent-array area ratio R_a. For an integral-mounted system, R_a is simply the ratio of the attic vent area to the array area.

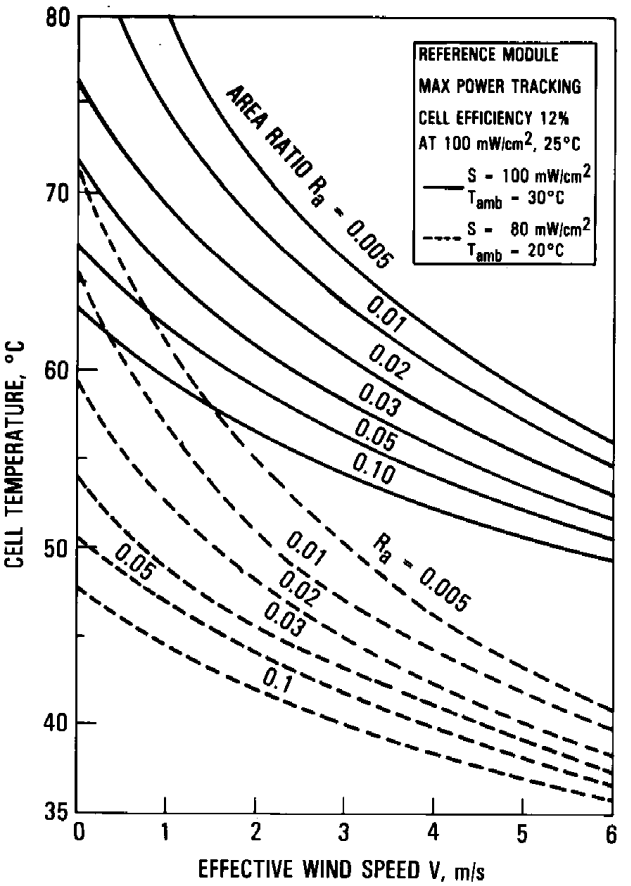

Fig. 5. Cell-temperature levels for residential arrays with various rear-surface vent-array area ratios R_a

The two integral-mounted arrays can be characterized by specific ventilation factors ranging between 5 and 10 $m^3/h\text{-}m^2$ for the WST system and 20 to 30 $m^3/h\text{-}m^2$ for the TSC system. The vent size for the WST and TSC prototypes are 7.7 and 16.8 ft^2, respectively, and the array surface areas are 810 ft^2 and 624 ft^2, respectively. Corresponding R_a values are 0.0095 and 0.027, respectively. Again, the correlation between the ventilation factor and the R_a ratio is approximately linear.

Temperature results for integrally mounted arrays are similar to those of standoff-mounted arrays with equal R_a values, and can be determined from Fig. 5.

5. RELATIONSHIP WITH MODULE NOCT

As a qualitative design guideline, the average temperature of the various residential array designs can be correlated with the mounting features and the module NOCT values. The module's NOCT value is its operating temperature in a fully exposed-back, ground-mounted array under standard conditions of 80 mW/cm^2 irradiance, 20°C air temperature and 1 m/s wind velocity. Under these same conditions, the temperature of a residential array whose back-surface cooling is inhibited may reach 10°C to 15°C above the module's NOCT. Arrays falling into this category include direct-mounted arrays with back insulation, integral-mounted arrays with small air vents, and monolithic standoff-mounted arrays with low air-channel height.

A moderate array temperature, around 5°C to 10°C above the NOCT values, requires some back-surface cooling. Examples in this category include direct-mounted arrays with the roof deck uninsulated and exposed to a well-ventilated attic, integral-mounted arrays with medium-sized vents, and large, monolithic standoff-mounted arrays with a modest standoff height.

If the array's back surface receives ample ventilation, the average array temperature may be reduced to the NOCT level. Such arrays include rack-mounted systems, standoff-mounted systems with large separations and integral-mounted systems with large attic vents. Table 1 summarizes these results.

Table 1. Difference between array operating temperatures and NOCT

Degrees Above NOCT	Mounting Arrangement
10 to 15	• Direct mounted with back insulated • Stand-off mount with low channel height • Integral mount with small vent
5 to 10	• Direct mounted, exposed to ventilated attic • Stand-off mount, high channel • Integral mount, medium-sized vent
-5 to +5	• Rack mounted • Integral mounted with large vent • Stand-off mounted high channel and large separation between subarrays

6. SUMMARY

The most significant design parameter that governs the relative thermal performance of different PV residential arrays is the degree of rear-surface cooling. In particular, direct-mounted arrays with insulated rear surfaces should be avoided. In the case of the integral mount, the experimental data recommend the use of large attic vents that provide a relatively large vent-array area ratio and ample air cooling to the array back surface. The standoff-mounted array's thermal behavior also is sensitive to the vent-array area ratio. A large area ratio can be obtained through a large standoff height and/or a small effective array area. This can be made possible by dividing the array into several subarrays separated

from one another. The large temperature gradient that characterizes the rack-mounted arrays is somewhat of a surprise. The use of increased intermodule spacing should minimize the gradient and reduce the average temperature.

The results obtained in the present investigation provide useful design information for different mounting features. However, correlations between many design parameters and ventilation characteristics are empirical and still include significant uncertainties. Basic research activities are underway to improve the quantitative correlation between the ventilation factors and such design features as the separation distance between subarrays, standoff height and vent size.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

(1) Establishment and Operation of the Southwest Residential Experiment Station, DOE/ET/20279-213, August 1982.

(2) Mahoney, P.C., and Hart, G.W., "June 1982 System Performance, Northeast Residential Experimental Station," Massachusetts Institute of Technology Energy Laboratory, October 1982.

(3) Schaefer, J.F., Wabrek, R., and Ranade, S., "SW RES Status," Photovoltaic Residential Project: Second Project Integration Meeting, August 19-20, 1982, Las Cruces, New Mexico, Sandia Laboratories, Albuquerque, New Mexico, August 1982.

(4) Otth, D., and Ross, R.G., "Assessing Photovoltaic Module Degradation and Lifetime for Long Term Environmental Tests," Proceedings of the Institute of Environmental Science, 1983 Annual Technical Meeting, Los Angeles, California, April 19-21, 1983. pp. 121-126.

(5) Smith, J.P., SINDA User's Manual, Report No. 14690-H001-RO-00, Systems Group, TRW Co., 1971.

(6) Design and Fabrication of a Prototype System for Photovoltaic Residences in the Southwest: Total Environmental Action, Inc., Final Report, DOE/ET/20279-209, June 1982.

(7) Mehalick, E.M., Design and Fabrication of a Prototype System for Photovoltaic Residences in the Southwest, DOE/ET/20279-193, April 1983.

(8) Yenamandra, R., and Schuetz, ARCO Solar Final Report: Fabrication of a Prototype System for Residences in the Southwest, DOE/ET/20279-238, December 1982.

(9) BDM Corporation Final Report: Design and Fabrication of a Prototype System for Photovoltaic Residences in the Southwest, DOE/ET/20279-225, August 1982.

(10) Gibson, R., Solarex Final Report: Design and Fabrication of a Prototype System for a Photovoltaic Residence in the Southwest, DOE/ET/20279-235, November 1982.

(11) Pittman, P.F., and Dresseler, R.T., Westinghouse Final Report: Design and Fabrication of a Prototype System for Photovoltaic Residences in the Southwest, DOE/ET/20279-236, December 1982.

(12) Millner, A., TriSolar Final Report: Design and Fabrication of a Prototype System for Photovoltaic Residences in the Southwest United States, DOE/ET/20279-218, August 1982.

(13) Wen, L., and Wabrek, R.M., "A Preliminary Thermal Investigation of Residential Photovoltaic Applications," in preparation, 1984.