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# EXPERIMENTAL EVALUATION OF A PHOTOVOLTAIC SIMULATION PROGRAM

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**Abstract**—A widely used photovoltaic (PV) simulation code, PVFORM, is evaluated in a grid-connected configuration against experimental data from a prototype demand-side management PV array. Taking advantage of the comprehensive array monitoring program, each of the key algorithms composing the simulation code is evaluated independently. PVFORM as a whole was not found to have any major flaws, but was found to overpredict actual power output due mostly to assuming ideal array sun-tracking performance and ideal maximum power point tracking.

## 1. INTRODUCTION

Having the capability of simulating photovoltaic (PV) systems of selected configurations is important not only for PV system designers, but also for utilities and agencies interested in evaluating the performance and usefulness of PVs in their service area.

There are two key elements to consider when dealing with PV simulations: (a) the data describing the solar resource; and (b) the transfer functions that convert the solar resource information into system output data. This study is chiefly concerned with the latter; however, we cannot stress enough that without adequate solar resource information (of either climatological or real time nature, depending on the intended use), the best simulation codes would be useless.

However, little attention has been given to date to their systematic field evaluation. PVFORM, the focus of this article, was developed at Sandia National Laboratories. It has been distributed to, and used by a large worldwide audience. Although this program does not address the spectral aspects that may be of relevance to some of the developing PV technologies (e.g., see[6]), PVFORM is considered to be a useful decision-making tool for most current PV applications.

This article evaluated PVFORM in a grid-connected configuration against experimental data obtained from a prototype 15.4 kW (DC) PV array located in New York state. Each of the key algorithms composing the simulation code are evaluated systematically and independently.

## 2. METHODS

### 2.1 *Experimental data*

The experimental data used for this evaluation were recorded between July 1990 and April 1991, during the first 10 months of the Niagara Mohawk Demand Side Management (DSM) PV Project located on the roof of the Division of Military and Naval Affairs building in Albany, New York[2,7].

The PV system has the following characteristics:

- *Modules:* Seventy polycrystalline ribbon silicon flat-plate panels (Mobil Solar Ra 180), totaling 15.4 kW (DC) for a collecting area of 151 $m^2$.
- *Structure:* Three passive one-axis trackers (Robbins Engineering) with horizontal N–S axis and horizontally mounted modules.
- *Inverter:* High efficiency 15-kW power conditioning unit (PCU) with maximum power point tracking (MPPT) capability (Omnion Series 3200).
- *Interconnect:* Grid-connected on the customer side of the meter (three-phase 480 V).

A data acquisition system samples over 50 sensors every 10 s and records 10-min averages. The subset of experimental data that pertains to the present study includes:

- Ambient Temperature, $T_a$
- Wind speed, $V$
- Global, direct and diffuse irradiance, $I_g$, $I_d$, $I_b$, using an ASRC-type rotating shadowband radiometer (RSR)[8].
- Plane of array irradiance on each tracking unit, $I_c$, including both silicon-based and thermopile sensors calibrated at Sandia National Laboratories[9].
- Panel operating temperature, $T_p$, in five points on each tracking unit.
- Slope, $S$, of each tracking unit.
- DC power at both the array and PCU terminals, $P_{DC}$.
- AC power fed onto the grid, $P_{AC}$.

### 2.2 *Step-by-step model validation*

The key processes of a photovoltaic simulation program such as PVFORM are listed below. Each main process may be subdivided in distinct calculation procedures.

1. Plane of array irradiance (POAI) modeling, including: solar/array geometry calculations and tilted irradiance conversion models.
2. Cell temperature, $T_c$, calculation, including: array specifications and cell temperature algorithm.
3. DC power calculation, including: nominal irradiance to DC conversion efficiency, efficiency deg-

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radation with temperature array mismatch, and line losses.

4. AC power calculations, including PCU transfer function.

The four main processes are sequential, that is, the input of one depends on the output of one or more of the preceding ones. In addition, the POAI and temperature calculation steps also rely for input on the solar resource data including:

1. Hourly global irradiance.
2. Hourly direct irradiance.
3. Ambient temperature.
4. Wind speed.

The flow chart in Fig. 1 graphically displays the relationship between the processes, their input, and their output.

Since experimental measurements are available at most sequential steps of the simulation, we are in a position to proceed with a step-by-step evaluation of the PVFORM program by replacing, in turn, each simulated value by a measured value and gauging the impact on intermediate and final calculations.

Each step requires a modification and recompiling of PVFORM. The steps are numbered so as to be consistent with the list of processes presented earlier.

*Step* 1.1. in this step, we ran PVFORM "as is," that is, in the configuration that had been made available by Sandia National Laboratories. The input data fed to the program were the four hourly meteorological quantities measured at the site: $T_a$, $V$, $I_g$, and $I_b$. For practical reasons, PVFORM was slightly modified to run in local standard time rather than in solar time. We selected the north–south horizontal axis/horizontal panel tracking option in the program's menu, since this configuration came the closest to describing the prototype array. Most other options in PVFORM's menu were set to their default value, with the exception of ground albedo estimated here at 0.15, and the PCU DC–AC nominal efficiency.

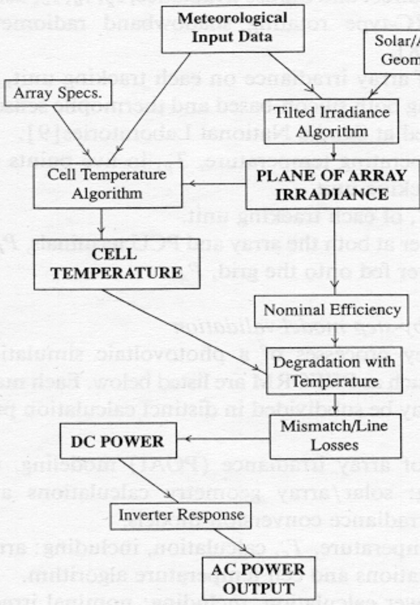

Fig. 1. PVFORM data flowchart.

*Step* 1.2. in this step, we accounted for the actual geometry of the array. We modified PVFORM to include the exact azimuth of the tracking axis and to account for the 50° limit slope of the trackers. (For structural reasons the roof-mounted arrays were aligned about 10° west of south.)

*Step* 1.3. This step was designed to gauge the impact of nonideal passive tracking on the simulation output. The measured array slope was substituted for the computed, ideally tracking, slope.

*Step* 1.4. After fully accounting for the array's specifications, the next source of uncertainty is the slope irradiance algorithm. PVFORM Version 3.3 uses the model of Perez *et al.*[5]to compute POAI. For this step, we replaced the modeled POAI by the measured POAI (average of five radiometers mounted on the three trackers). Note that a small degree of error persists in the estimation of the total solar energy impinging on the modules, since the array is composed of three independent passive trackers which do not track the sun identically at all times.

*Step* 2. Once POAI is fully known, the next unknown is cell temperature. At this stage we replaced the temperature modeled by the Fuentes algorithm[4]with the average temperature measured on the back of five modules. As above, a slight degree of uncertainty remains because of the three independent trackers.

*Step* 3.1. We replaced PVFORM's default coefficient for efficiency degradation with temperature by the value that had been provided to us by the module manufacturer.

*Step* 3.2. Here, we replaced PVFORM's default line and mismatch losses by the value determined experimentally during the array acceptance testing program: during clear and stable conditions, the system had been found to deliver about 4% less DC output at the inverter's entrance than would have been expected from its rating, after accounting for temperature degradation only.

*Step* 4.1. At this stage we replaced the simulated DC power at the inverter by its measured value, while keeping the default inverter response curve.

*Step* 4.2. Finally, we replaced the default inverter curve by the actual response which had been determined experimentally.

## 3. RESULTS

For each step of the analysis, we present below a comparison between PVFORM's simulated and measured AC power output and/or comparison between key intermediate calculations and measurements.

*Step* 1.1. Figs. 2 and 3 illustrate the performance achieved when running PVFORM "as is" in calculating POAI, operating temperature, DC power, and AC power, respectively. A substantial positive bias (+6%) was found in the simulation of POAI and the short-term RMS prediction error approached 20%. This translates into a +11% bias and 22% RMSE for the predicted DC output and +13% bias and 24% RMSE for the predicted AC output. A small positive bias (+1°C) was found for the predicted panel temperature, with a dispersion (RMSE) on the order of 3.5°C.

*Step* 1.2. Accounting for the exact geometry of the array resulted in a reduction of the POAI prediction bias from +6% to an acceptable +2.5%, while the RMSE was cut to 14% (see Fig. 4). At the AC output level, the positive bias was reduced to about +9% while the dispersion was reduced to 19%.

*Step* 1.3. Fully accounting for the operation of the passive tracker reversed the bias (−2.5%) and resulted in a considerable improvement of the plane of array irradiance short-term error that was cut down to 7% (see Fig. 5). For the AC output prediction the positive bias was reduced to +4.5% and the RMSE to 12%. (Note that some of the difference in scatter between POAI and AC prediction results from the fact that we compared the measured and modeled POAI of one fully characterized tracking unit, whereas AC output is a function of three tracking units which do not have identical slopes at all times.)

It is interesting to remark that the bias and RMS errors achieved for POAI prediction are only slightly higher than for ideal model test conditions[5] despite: (a) the use of an estimated albedo to describe the complex roof/surroundings reflective properties; and (b) the utilization of rotating shadowband radiometer data as input to the slope model. This last result would speak favorably for the utilization of such instruments as an effective resource assessment tool for solar energy applications.

*Step* 1.4. Replacing modeled POAI with measured POAI resulted in a slightly reduced scatter for DC and AC power prediction. However, this step also led to an increased positive bias for both components, respectively, +5.5 and +7% for the DC and AC power calculations. This is because the slight negative bias of the modeled POAI made up for some of the positive bias in the power calculations.

This step also allowed us to single out the panel temperature algorithm by removing all sources of imprecision from its input. The Fuentes algorithm was found to perform well, exhibiting no bias and a dispersion on the order of only 2°C. (see Fig. 6).

*Step* 2. Replacing modeled with measured temperature did not result in any noticeable performance change for the AC and DC prediction. This confirms our favorable assessment of the Fuentes model.

*Step* 3.1. Using manufacturer-supplied rather than default coefficients for efficiency degradation with temperature did not result in any appreciable change in simulation performance.

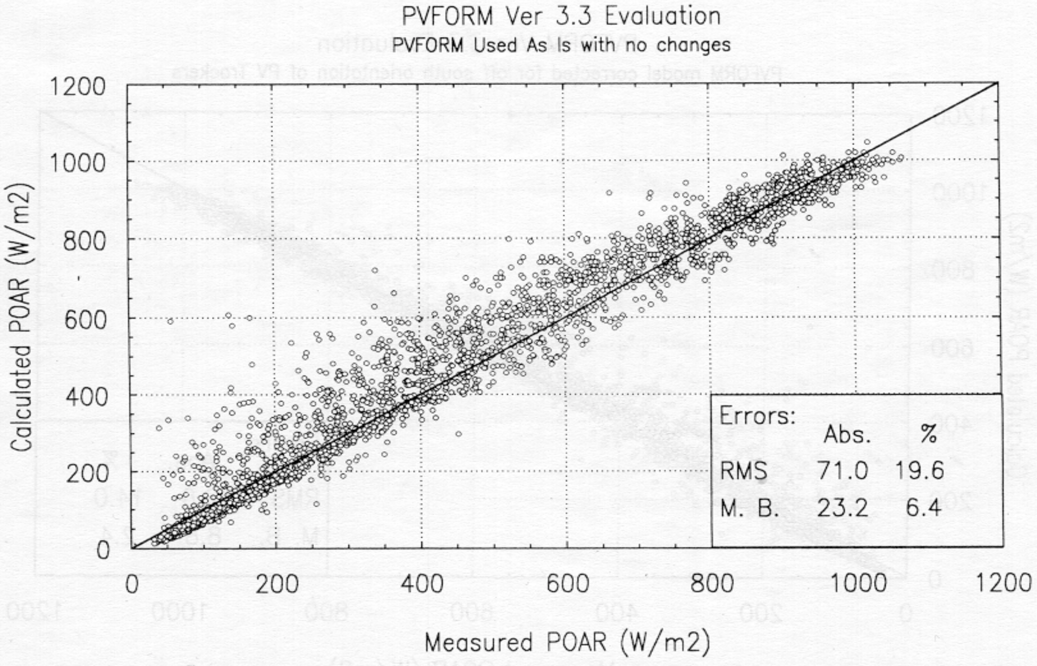

Fig. 2. Unmodified PVFORM plane of array irradiance prediction (POAR).

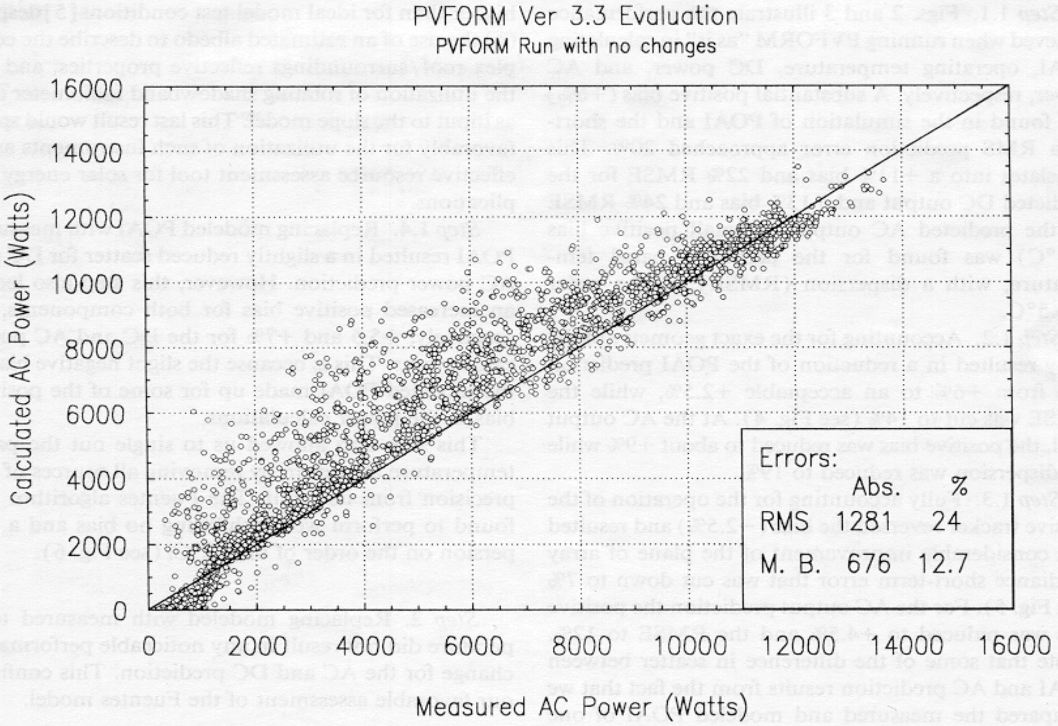

Fig. 3. Unmodified PVFORM AC power prediction.

*Step* 3.2. When using non–default line and mismatch loss coefficients, we were able to reduce the model bias for DC and AC power prediction to, respectively, +4% and +5.2%, while the RMSE errors remained practically unchanged, respectively, of the order of 10% and 12% (Fig. 7).

The level of dispersion and the positive bias found at this stage, when all input-related uncertainty from

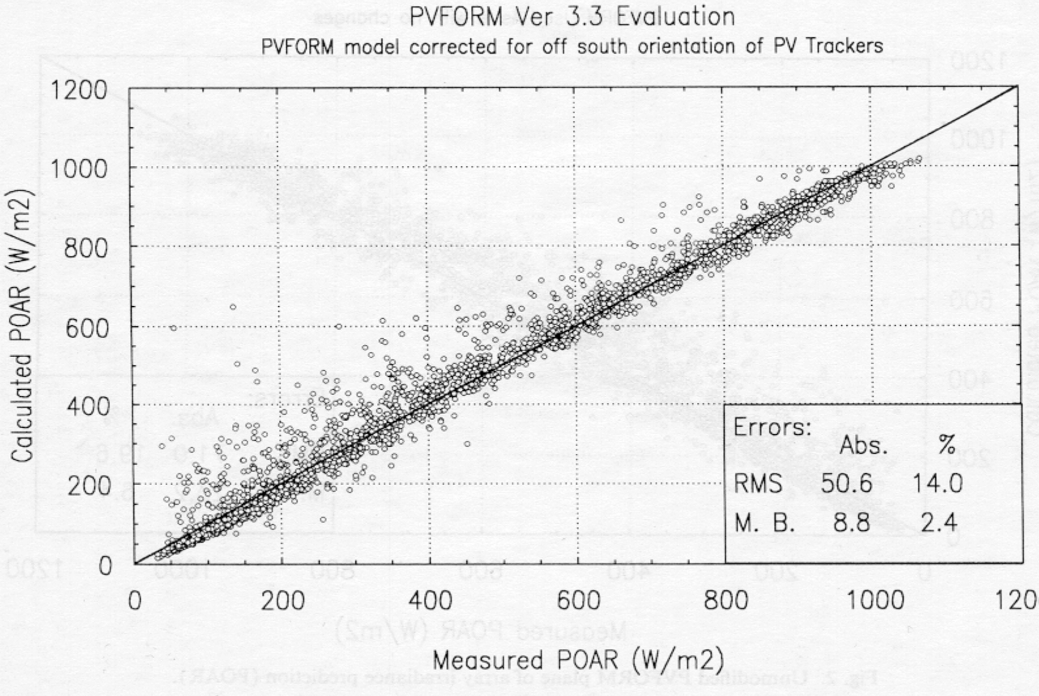

Fig. 4. Plane of array irradiance prediction using exact array geometry.

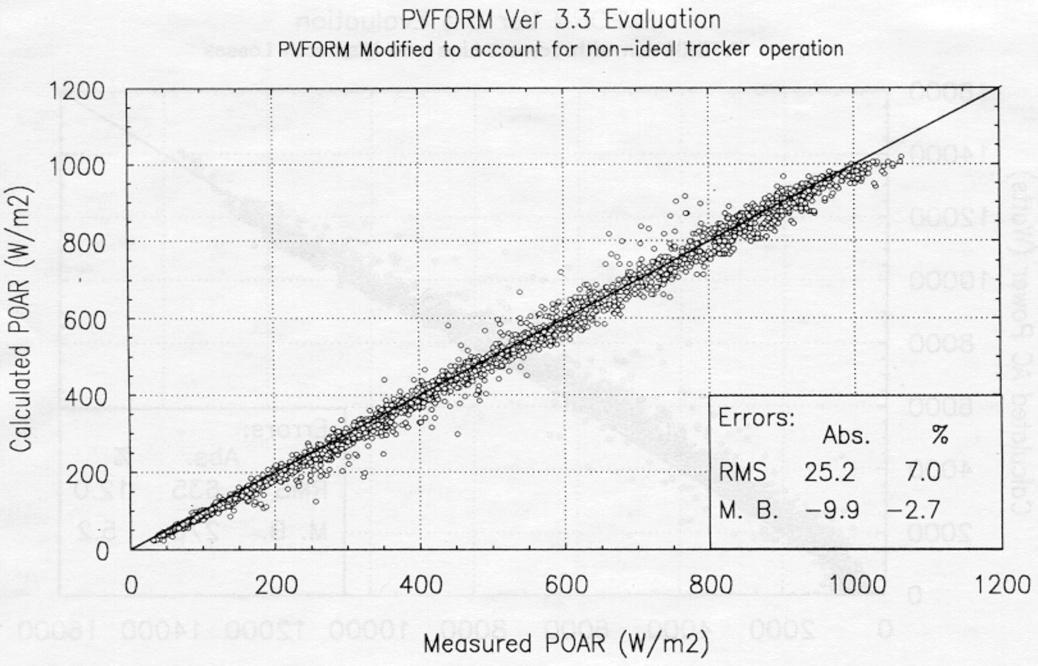

Fig. 5. Plane of array irradiance prediction accounting for the operation of the passive tracking.

the power calculation model has been removed, would indicate that the program lacks one key transfer function that would account for conversion efficiency variations with incoming sunlight, probably traceable to the ability of the PCU to maximum power track. By using an irradiance-to-DC power efficiency that is a function of temperature only, PVFORM tends to overpredict both DC and AC output. As can be seen in Fig. 7, prediction is unbiased at the high end, which typically represents clear stable conditions; however,

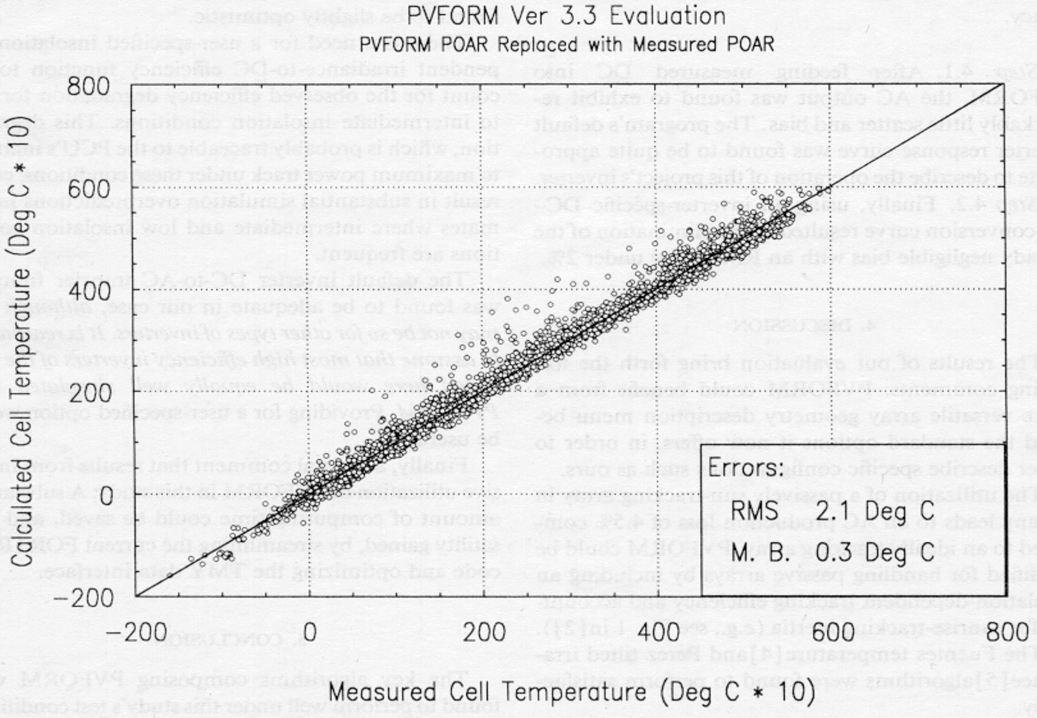

Fig. 6. Performance of Fuentes cell temperature prediction algorithm.

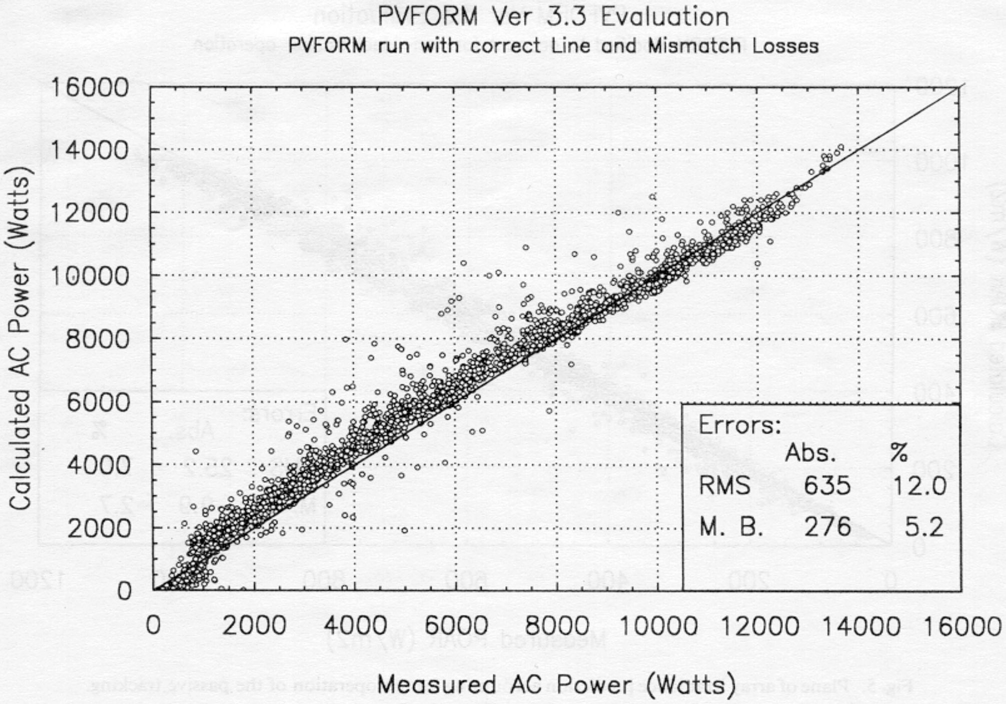

Fig. 7. AC power prediction accounting for actual line loss and mismatch coefficients.

for low to intermediate conditions, PVFORM overpredicts the system's yield. This could be easily corrected by adding a "DC efficiency curve" to account for the PCU's impact on irradiance conversion efficiency.

*Step* 4.1. After feeding measured DC into PVFORM, the AC output was found to exhibit remarkably little scatter and bias. The program's default inverter response curve was found to be quite appropriate to describe the operation of this project's inverter.

*Step* 4.2. Finally, using an inverter-specific DC–AC conversion curve resulted in the elimination of the already negligible bias with an RMS error under 2%.

## 4. DISCUSSION

The results of our evaluation bring forth the following comments: PVFORM could benefit from a more versatile array geometry description menu beyond the standard options it now offers, in order to better describe specific configurations such as ours.

The utilization of a passively sun-tracking array in Albany leads to an AC production loss of 4.5% compared to an ideally tracking array. PVFORM could be modified for handling passive arrays by including an insolation-dependent tracking efficiency and accounting for sunrise-tracking inertia (e.g., see Fig. 1 in [2]).

The Fuentes temperature [4] and Perez tilted irradiance [5] algorithms were found to perform satisfactorily.

Default temperature degradation coefficients for crystalline silicon were found to be fully applicable to Mobil Solar's ribbon silicon modules.

PVFORM's default line and mismatch losses were found to be slightly optimistic.

There is a need for a user-specified insolation-dependent irradiance-to-DC efficiency function to account for the observed efficiency degradation for low to intermediate insolation conditions. This degradation, which is probably traceable to the PCU's inability to maximum power track under these conditions, could result in substantial simulation overpredictions in climates where intermediate and low insolation conditions are frequent.

The default inverter DC-to-AC transfer function was found to be adequate in our case, *although this may not be so for other types of inverters. It is reasonable to assume that most high efficiency inverters of the type tested here would be equally well simulated with PVFORM.* Providing for a user-specified option would be useful.

Finally, a general comment that results from intensive utilization of PVFORM in this study: A substantial amount of computing time could be saved, and versatility gained, by streamlining the current FORTRAN code and optimizing the TMY data interface.

## 5. CONCLUSION

The key algorithms composing PVFORM were found to perform well under this study's test conditions.

The program as a whole was not found to have any major flaws, but was found to overpredict actual power output (+9%) by assuming both ideal maximum power point tracking and ideal array tracking performance, each accounting for about half of the overprediction. Hence, for a fixed or ideally tracking PV system, the overprediction from PVFORM due to maximum powerpoint tracking assumption should be on the order 4% to 5%.

Straightforward modifications of PVFORM to account for these effects, along with a more versatile array specification user interface and a general streamlining of the code to increase its computer efficiency would be advisable to increase the effectiveness and usefulness of this decision-making tool.

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