A COMPARISON AND VALIDATION OF TWO PHOTOVOLTAIC MODELS

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ABSTRACT

This paper describes a new one-diode equivalent photovoltaic (PV) model that has been implemented into the ESP-r simulation program. The validation of this model, as well as that of ESP-r's existing one-diode model, is also treated. Specifically, the PV arrays installed at a laboratory facility at CETC-Varennes are modelled using both models and the simulation results are compared to monitored data. The monitored data include the weather conditions at the site, the direct-current power generated by the PV modules and the temperature of the modules.

INTRODUCTION

The ESP-r simulation program is capable of modelling the energy and mass flows within building and plant systems that are combined and subjected to control laws (ESRU, 2002). The interested reader is referred to Clarke (2001) for a detailed treatment of ESP-r's theoretical basis.

The current-voltage (I-V) characteristic of a solar cell can be obtained by considering an equivalent circuit of the cell (Markvart, 1994). This is known as the equivalent one-diode circuit and is illustrated in Figure 1. The current source is the light-generated current, I_l, and the diode current, I_d, represents the resistance of the cell's junction to current flow (Markvart, 1994). The output current, I, is equal to the difference between the light-generated current and the diode current.

(Kelly, 1998) developed two models of photovoltaic (PV) systems within the ESP-r simulation program: a simple efficiency-based model and a one-diode equivalent model. The one-diode equivalent model uses the PV module's short circuit current and open-circuit voltage at standard testing conditions to calculate the solar cell's power output and does not consider the temperature-dependence of these two variables.

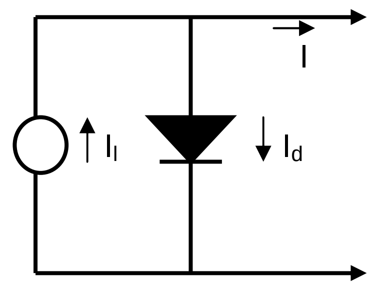

Figure 1. A one-diode equivalent circuit.

A cell's short-circuit current, I_{sc}, is defined as the current that passes through an external load when the voltage is equal to zero. A cell's open circuit voltage, Voc, is defined as the voltage when all the light-generated current passes through the diode, i.e. the current, I, is equal to zero. ESP-r's existing one-diode equivalent model also requires the input of an empirical coefficient which needs to be determined experimentally since it is not available from manufacturers' data.

(Thevenard, 2004 and 2005) reviewed ESP-r's PV models and PV models available in other building energy simulation programs and recommended that an alternate equivalent one-diode PV model be implemented in ESP-r. The new one-diode model takes into account the temperature-dependence of the short-circuit current and open-circuit voltage. In addition, the new one-diode model uses empirical coefficients that are commonly provided by manufacturers to describe the performance of their PV modules.

The objectives of this study are to: (1) validate the new one-diode equivalent PV model that has been implemented in ESP-r with monitored data; (2) validate the existing PV model in ESP-r developed by (Kelly, 1998) with monitored data and (3) compare the simulation results obtained using both of ESP-r's PV models.

MATHEMATICAL MODELS

The new one-diode equivalent model implemented in ESP-r is based on the WATSUN-PV model (Thevenard, 2004 and 2005). The WATSUN-PV model has an empirical basis and calculates the short circuit current, I_{sc}, and open-circuit voltage, V_{oc}, as follows:

$$I_{sc} = I_{sc,ref} \frac{E_{T,eff}}{E_{ref}} \left[1 + \alpha\left(T_c - T_{c,ref}\right)\right] \quad (1)$$

$$V_{oc} = V_{oc,ref} \left[1 - \gamma\left(T_c - T_{c,ref}\right)\right] \cdot \max\left(0{,}1 + \beta \ln\left(\frac{E_{T,eff}}{E_{ref}}\right)\right) \quad (2)$$

where

the subscript *ref* indicates reference conditions, $E_{T,eff}$ is the effective irradiance incident on the module (W/m^2), which includes the bean and diffuse components of solar radiation, taking into account the reflectance of the front surface of the module. Tc is the cell temperature (°C) and α, γ and β are empirical coefficients. The empirical coefficients in equations (1) and (2) are provided in the specifications for many PV modules, as are $I_{sc,ref}$ and $V_{oc,ref}$. Standard reference conditions are E_{ref} = 1000 W/m^2 and $T_{c,ref}$ = 25°C.

The WATSUN-PV model assumes that the maximum power point voltage, V_{mp}, and the maximum power point current, I_{mp}, vary proportionately with the short-circuit current and open circuit voltage and therefore the maximum power, P_{mp} is given by equation (3):

$$P_{mp} = I_{mp,ref} \cdot V_{mp,ref} \left(\frac{I_{sc} \cdot V_{oc}}{I_{sc,ref} \cdot V_{oc,ref}}\right) \quad (3)$$

The parameters $I_{mp,ref}$ and $V_{mp,ref}$ are available from manufacturers' specifications.

In this study, the PV modules operate at maximum power point and therefore equations (1) – (3) are the only equations used by the WATSUN-PV model to calculate the power output of the modules.

ESP-r's existing one-diode equivalent model does not consider the temperature-dependence of the short-circuit current and open-circuit voltage; rather, the short-circuit current and open-circuit voltage at reference conditions are used to calculate the power output of the PV module. In addition, this model requires an empirical constant whose value varies with the characteristics of the PV material. This empirical constant is not available from manufacturers' data, but rather is to be found by laboratory testing.

In ESP-r, the PV module surface is represented as a multi-layered construction consisting of several material layers. Each layer is represented with one or more nodes. One node within the surface is identified as a special material node; this node represents the location of the PV cells within the module. The cell temperature Tc is determined by considering the energy balance of the special material node. It should be noted that the solar radiation absorbed by the special material node is reduced by the power generated from the node.

MONITORED DATA

The monitored data for two PV arrays installed at a laboratory facility at CETC-Varennes are used in this study.

The PV modules installed at CETC-Varennes are multicrystalline silicon modules from AstroPower (model APC 5103). Each module has a rated maximum power of 48W at reference conditions (1000 W/m^2, 25°C and air mass 1.5). The characteristics of the modules are provided in Table 1. Each of the two arrays is made up of several modules connected in series and parallel and rack mounted on the building roof at an angle of 45°. Both arrays face south. The characteristics of each array (identified as A and B) are provided in Table 2

The following data are collected at CETC-Varennes:

- voltage (V) of high tension sections of arrays (each array is separated into a high tension section and a low tension section);
- voltage (V) of low tension sections of arrays;
- current (A) of high tension sections of arrays;
- low current (A) of arrays A;
- DC power (W) generated by arrays (input to DC-AC converter);
- AC power (W) delivered by arrays (output from DC-AC converter);
- temperature (°C) of arrays (sensors are placed at the center of each high- and low- tension section of each array);
- global irradiance on the horizontal (W/m^2);
- direct irradiance on the horizontal (W/m^2);

- diffuse irradiance on the horizontal (W/m^2);
- total irradiance (W/m^2) at 45°;
- ambient temperature (°C);
- relative humidity (%);
- wind speed (km/h) and
- wind direction (degrees clockwise from north).

Table 1. Description of PV modules

Module length (mm)	959.5
Module width (mm)	395.0
Number of cells in series	36
Number of cells in parallel	1
$V_{oc,ref}$ (V)	20.37
$I_{sc,ref}$ (A)	3.02
$V_{mp,ref}$ (V)	15.32
$I_{mp,ref}$ (A)	2.7

Table 2. PV array characteristics

	Array A	Array B
Number of modules	140	112
Area (m^2)	56.0	44.8

The data are recorded every 15 seconds. For this analysis, the recorded data are averaged over 15-minute intervals for four representative days: June 27 (2005) represents a hot summer day; January 21 (2005) represents a cold winter day; July 9 (2005) represents a cloudy summer day and July 2 (2005) represents a sunny summer day.

SIMULATION INPUTS

Hourly weather files for the four representative days were created from the monitored data in the format required by ESP-r. The solar radiation data specified in the weather files are the direct normal irradiance and diffuse horizontal irradiance per hour.

The characteristics provided in Tables 1 and 2, obtained from CETC-Varennes, are used to describe the PV arrays in ESP-r, for both the WATSUN-PV model and Kelly's PV model. The empirical coefficients required by the WATSUN-PV model, provided in Table 3, have been determined by (Thevenard, 1999) experimentally. Specificially, (Thevenard, 1999) measured I-V curves for various temperature and insolation conditions and used non-linear curve-fitting algorithms to determine the module parameters (short-circuit current, open-circuit voltage, maximum power point current and voltage) and empirical coefficients. Although for this analysis, the module parameters and empirical coefficients required by the WATSUN-PV model were obtained from experimental data, since the latter were available, the module parameters and empirical coefficients required by the model are available from manufacturers' specifications.

Table 3. Empirical coefficients required by WATSUN-PV model for modules A and B (Thevenard, 1999).

	Array A	Array B
α (/°C)	-8.310E-05	-8.267E-06
γ (/°C)	0.00355	0.00344
β	0.0054	0.0681

Since the laboratory test data were not available to determine the empirical constant required by Kelly's PV model, the default value (σ = 10) is used for the simulations.

The implementation of the WATSUN-PV model in ESP-r allows the miscellaneous power losses from the PV modules due to uncertainty in the module ratings, ageing, soil and dirt, mismatch, snow, blocking diodes and wiring to be considered. However, these factors are ignored in the simulations reported here.

The construction of the arrays is assumed to be typical of PV installations: 2 mm of clear glass, 1 mm ethylene vinyl acetate (EVA), 1 mm Silicum, 1 mm EVA and 2 mm clear glass. The overall U-value of the PV module used in the simulations is 5.27 W/ m^2°C.

Each PV array is modelled in ESP-r as a thin zone; the zone is made up of one surface which represents the PV modules, with the remaining surfaces defined as an aluminium layer representing the array's aluminium frame. The interior convection coefficient for the PV module surface is set to a high value (10 W/m^2°C), as is the zone's infiltration rate, and no casual gains are defined in the zones.

Simulations are carried out for the four representative days using 15-minute time-steps.

SIMULATION RESULTS

Figures 2 to 5 compare the DC power produced by array A, as predicted by the WATSUN-PV and (Kelly,

1998) models, to the actual power produced for the four representative days considered in this study.

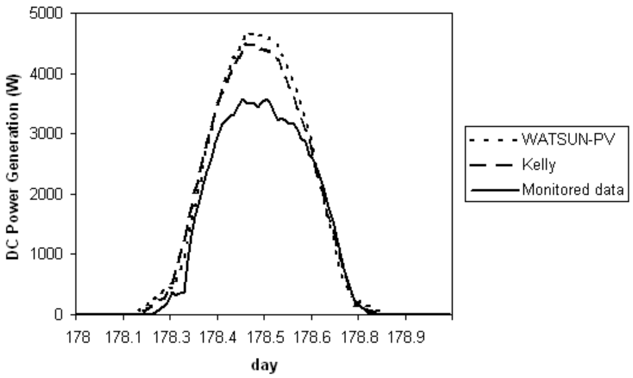

Figure 2. DC Power generation of Array A on June 27

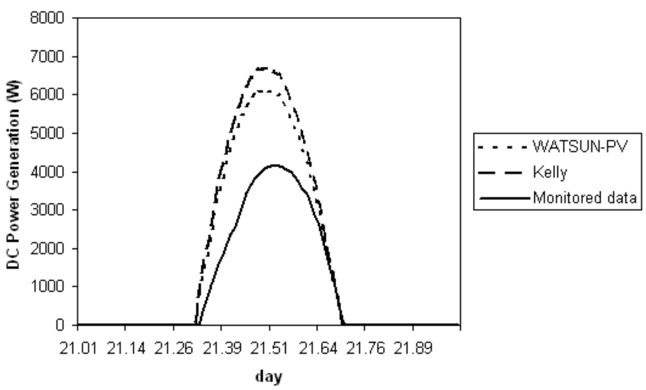

Figure 3. DC Power generation of Array A on January 21

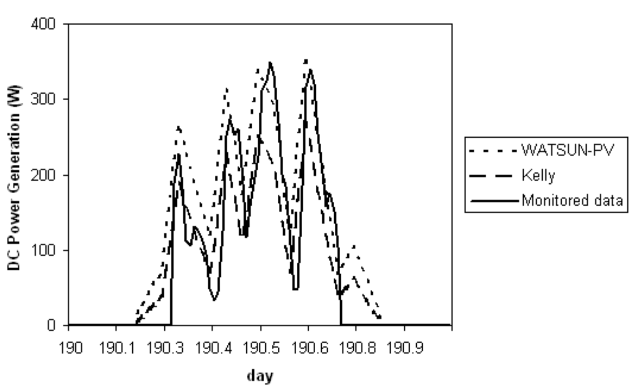

Figure 4. DC Power generation of Array A on July 9

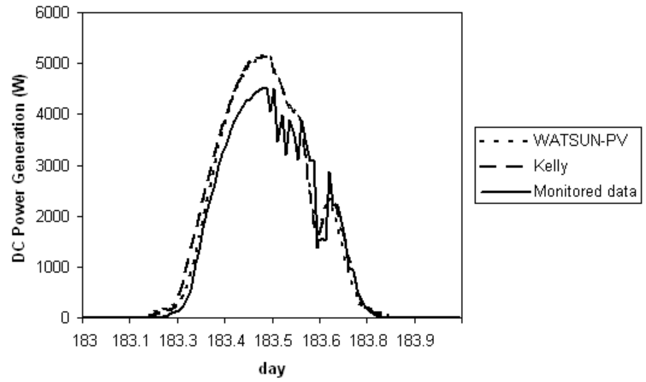

Figure 5. DC Power generation of Array A on July 2

Figures 2-5 suggest that both of ESP-r's PV models correctly predict the shape of the power generation-versus-time curve. However, both models tend to over-predict the power generated by the PV arrays at mid-day, particularly on the sunny days (June 27, January 21 and July 2). The results of the WATSUN-PV model and Kelly model are similar but the latter model seems to over-predict the power generation to a lesser degree on the sunny days. The power predictions for Array B, not presented, are similar to those of Array A.

Figures 6-9 provide the surface temperatures of PV array A, the measured average temperatures of array A (average of measurements taken at two different locations on the array) and the outdoor temperatures for the four representative days considered in this study. It should be noted that both of ESP-r's PV models use the same algorithm to determine the temperatures of the array surfaces.

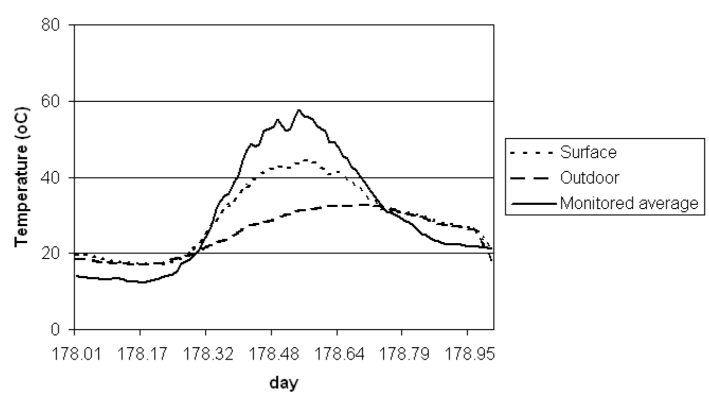

Figure 6. Temperatures of Array A on June 27

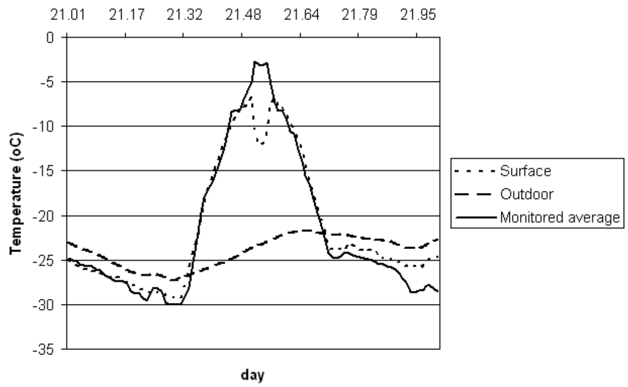

Figure 7. Temperatures of Array A on January 21

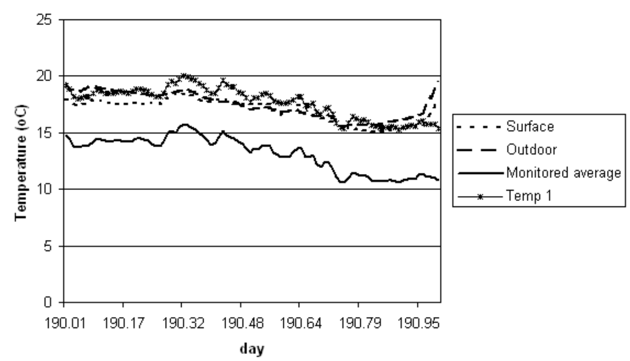

Figure 8. Temperatures of Array A on July 9

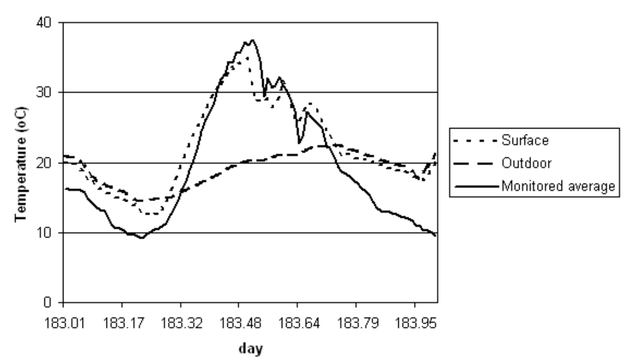

Figure 9. Temperatures of Array A on July 2

On the sunny summer days (June 27 and July 2), the surface temperatures of the array predicted by ESP-r during the night are close to the outdoor temperatures, as one would expect. On the cold, sunny day (January 21), the surface temperatures predicted by ESP-r are close to the average monitored temperatures except at mid-day. On the cloudy, summer day (July 9), the predicted surface temperatures are approximately 5°C higher than the average monitored temperatures. However, the predicted surface temperatures are close to the one of the monitored temperature readings (shown as 'Temp 1' in Figure 8), suggesting that there may be some errors in the temperature measurements and the average of the two monitored temperatures may not be representative of the array temperature. It is not expected that the small differences between the predicted surface temperatures and the monitored temperatures will significantly impact the predictions of the power generated by the array.

ANALYSIS

In order to identify the possible sources of the discrepancies between the predicted and actual DC power generation of the PV arrays, simulations of the arrays were carried out in TRNSYS (SEL, 2004). The solar radiation data input to TRNSYS includes the global horizontal irradiance and diffuse horizontal irradiance per hour. In order to correctly compare the TRNSYS and ESP-r simulation results, the same solar radiation is input to ESP-r, that is the global horizontal irradiance and diffuse horizontal irradiance per hour (previous ESP-r simulation results were obtained using the direct normal irradiance and diffuse horizontal irradiance per hour). The PV model in TRNSYS is based on a one-diode equivalent electrical circuit and the concept of nominal operating cell temperature (NOCT).

Figures 10-13 compare the predicted DC power generation of array A by (1) the WATSUN-PV model when the solar radiation data are defined using the direct normal irradiance and diffuse horizontal irradiance (WATSUN-PV:DR label), (2) the WATSUN-PV model when the solar radiation data are defined using the global horizontal irradiance and diffuse horizontal irradiance (WATSUN-PV:Glob label), (3) the TRNSYS PV model and (4) the actual DC power generation measured by the data acquisition system. The DC power generation predicted for array B is similar to that of array A and therefore not presented in this study.

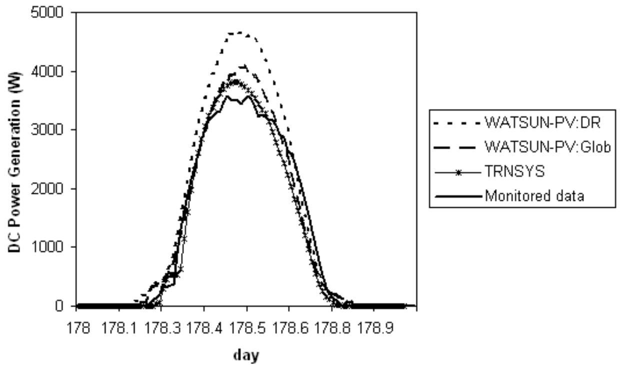

Figure 10. DC Power generation of Array A on June 27

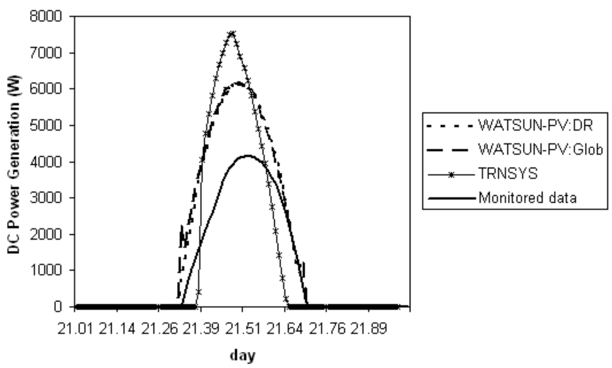

Figure 11. DC Power generation of Array A on January 21

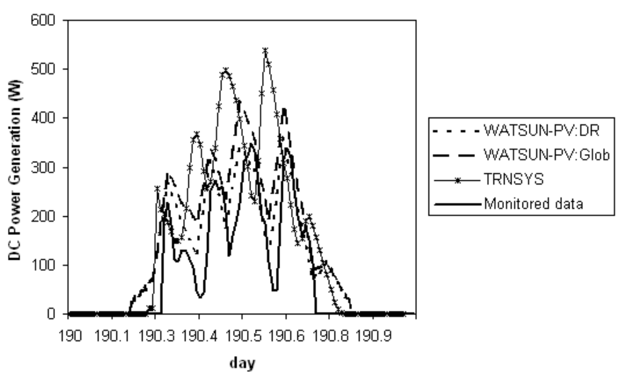

Figure 12. DC Power generation of Array A on July 9

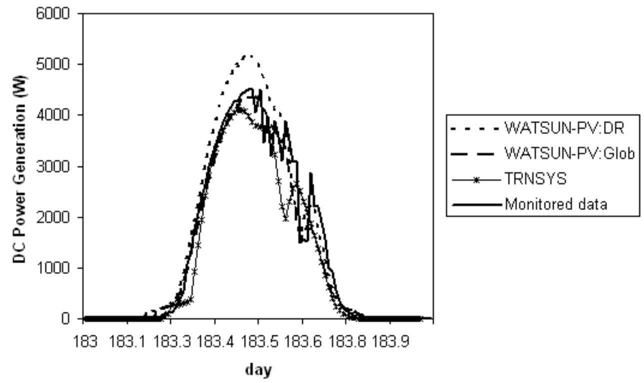

Figure 13. DC Power generation of Array A on July 2

On the two warm sunny days (June 27 and July 2), the WATSUN-PV model more accurately predicts the DC power generated by array A when the global horizontal irradiance and diffuse horizontal irradiance are specified in the weather file. On these days, the WATSUN-PV simulation results agree with the TRNSYS simulation results and the monitored data. On the cold winter day (January 21) and the cloudy summer day (July 9), the DC power generation predicted by TRNSYS does not agree with the monitored data and no difference is seen in the WATSUN-PV results whether the direct normal irradiance or global horizontal irradiance is used to specify the solar radiation data in ESP-r.

Since there is no pattern to the disagreement between the measured values and the different simulation results, a comparison of the measured versus predicted total irradiance on the tilted array is carried out next. Figures 14-17 present the total irradiance on the tilted array A for the four representative days as predicted by ESP-r (using either the direct normal irradiance or global horizontal irradiance in the weather file) and TRNSYS and measured by the pyranometer at CETC-Varennes.

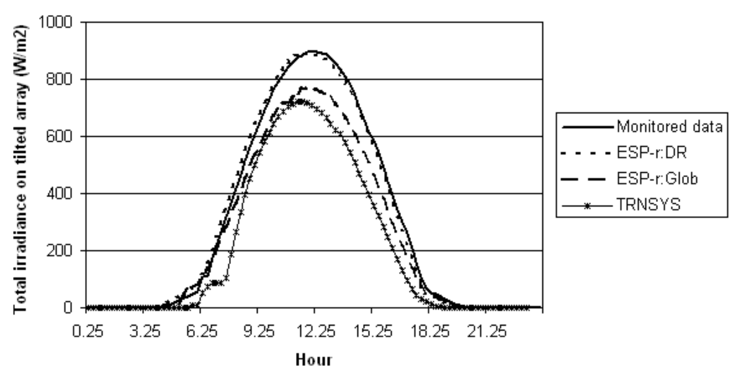

Figure 14. Total irradiance on Array A on June 27

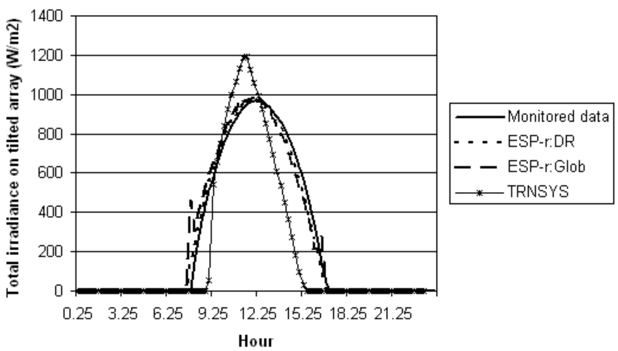

Figure 15. Total irradiance on Array A on January 21

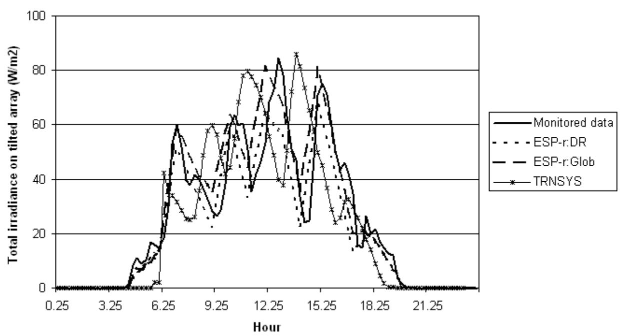

Figure 16. Total irradiance on Array A on July 9

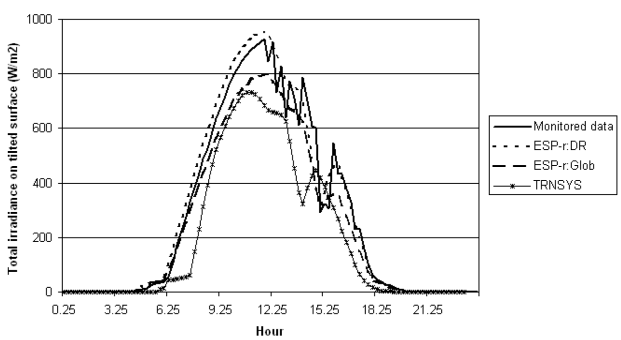

Figure 17. Total irradiance on Array A on July 2

On the sunny summer days (June 27 and July 2), the irradiance on the tilted array predicted by TRNSYS is lower than the measured irradiance. This is also the case in ESP-r when the global horizontal irradiance, versus the direct normal irradiance, is specified in the weather file. In ESP-r, the predicted irradiance agrees with the monitored data when the direct normal irradiance is specified. This pattern is not reflected in the results for the cold sunny winter day (January 21) or for the cloudy summer day (July 9). The question arises whether there are errors with the monitored data since the irradiance on the tilted surface that is calculated by ESP-r should be the same whether the direct normal or the global horizontal irradiance is specified in the weather file; this is the case for the cold winter day and for the cloudy summer day but not for the sunny summer days.

The results of this study are inconclusive and further work is required to validate the PV models within ESP-r. Specifically, a verification of the monitored data used in this study is required and/or another set of monitored data should be used in future validation work. In addition, a verification of ESP-r's source code with respect to the calculation of the irradiance on a tilted surface should be carried out.

CONCLUSION

This study is a first attempt to validate the new one-diode equivalent model, based on the WATSUN-PV model, that has been implemented in ESP-r and the existing one-diode equivalent model, developed by (Kelly, 1998).

The simulation results using (Kelly, 1998)'s PV model are comparable to the simulation results obtained using the WATSUN-PV model, when comparing the simulation results with monitored data. Both of ESP-r's one-diode equivalent PV models correctly predict the shape of the power-versus-time curve for the four representative days considered in this study. However, the ESP-r models over-predict the amount of DC power generated at mid-day, especially on the sunny days.

The temperatures of the arrays predicted by the models are within an acceptable range of difference with the monitored data. It is not expected that resolving the differences between the predicted and actual temperatures will impact the predicted power generation significantly.

The PV arrays were modelled with the TRNSYS software in order to identify any possible sources of error with ESP-r's PV models. The results of the TRNSYS simulations for the sunny summer days agree well with the monitored data and with the results of the WATSUN-PV model when the global horizontal irradiance, versus the direct normal irradiance, is used to specify the solar radiation data in ESP-r. On the cold winter day and cloudy summer day, neither ESP-r nor TRNSYS predicted the power generation of the PV arrays very well.

The total irradiance on the tilted array predicted by ESP-r and TRNSYS is less than the monitored data on the sunny summer days when the global horizontal, versus the direct normal, irradiance is used to specify the solar radiation data.

The comparisons between the predicted and actual DC power generation of the PV arrays are inconsistent for the four representative days considered in this study. Since the comparisons of the predicted and actual array temperatures and surface irradiances are also inconsistent, the validity of ESP-r's PV models is inconclusive. It is recommended that further validation of ESP-r's PV models be carried out in the future. In particular, it is recommended that the monitored data used in this study be verified and/or that another set of monitored data be used for future work.

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NOMENCLATURE

I	Current	{Amps}
V	Voltage	{Volts}
T	Temperature	{°C}
E	Irradiance	{W/m^2}
P	Power	{Watts}
α	Temperature coefficient of I_{sc}	{°C^{-1}}
β	Temperature coefficient of V_{oc}	{°C^{-1}}
γ	Irradiance coefficient of V_{oc}	
σ	Empirical coefficient used by (Kelly, 1998)	

Subscripts

ref	Reference
sc	Short-circuit
oc	Open-circuit
eff	Effective
c	Cell
mp	Maximum power-point