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Modeling impact of environmental factors on photovoltaic array performance

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Abstract
It is represented in this paper that a methodology to model and quantify the impact of the three environmental factors, the ambient temperature, the incident irradiance and the wind speed, upon the performance of photovoltaic array operating under outdoor conditions. First, A simple correlation correlating operating temperature with the three environmental variables is validated for a range of wind speed studied, 2-8 ms^{-1}, and for irradiance values between 200 and 1000 Wm^{-2}. Root mean square error (RMSE) between modeled operating temperature and measured values is 1.19% and the mean bias error (MBE) is -0.09%. The environmental factors studied influence *I-V* curves, *P-V* curves, and maximum-power outputs of photovoltaic array. The cell-to-module-to-array mathematical model for photovoltaic panels is established in this paper and the method defined as segmented iteration is adopted to solve the *I-V* curve expression to relate model *I-V* curves. The model *I-V* curves and *P-V* curves are concluded to coincide well with measured data points. The RMSE between numerically calculated maximum-power outputs and experimentally measured ones is 0.2307%, while the MBE is 0.0183%. In addition, a multivariable non-linear regression equation is proposed to eliminate the difference between numerically calculated values and measured ones of maximum power outputs over the range of high ambient temperature and irradiance at noon and in the early afternoon. In conclusion, the proposed method is reasonably simple and accurate.

Keywords: Cell-to-module-to-array model for photovoltaic panels; Environmental factors; I-V curve; Maximum power output; Multivariable non-linear regression.

1. Introduction
Manufacturers of solar cells or modules typically provide data available only at one operating condition referred to as Standard Reporting Conditions (SRC) or Standard Test Conditions (STC, hereafter the subscript * is used to denote this condition), such as the open circuit voltage (V_{oc}^*), the short circuit current (I_{sc}^*), the current at maximum power (I_m^*), the voltage at maximum power (V_m^*), the temperature coefficients at open circuit voltage and short circuit current ($\beta_{V_{oc}}{}^*$ and $\alpha_{I_{sc}}{}^*$, respectively).The STC, However, is rarely encountered in actual operation and the PV arrays always operate over a wide variety of conditions so the environmental factors, the ambient temperature, incident irradiation flux and wind speed, play a central role in the performance of PV arrays.
Considerable efforts have been spent by a large amount of agencies and authors to study performance of photovoltaic cells, photovoltaic modules and arrays under actual outdoor operating conditions. Some

authors (D.L. King [1]) from Sandia National Laboratories calculated the current at five strategically located points throughout the current-voltage (I-V) curve to relate the outdoor I-V curve and modeled impact of factors including ambient temperature, incident solar irradiance, wind speed measured at standard 10-m height, back-surface module temperature, cell temperature inside module, and so forth. Although the results of the deviations obtained by them are considered to be quite small, its disadvantage lies in the large amount of input data it requires which is not easily to be tested. It is well documented that the operating temperature plays a key role in the output of a photovoltaic device. A scan of the relevant literature (Schott T [2], Servant JM [3], Eicker U. [4], Tiwari GN [5], E. Skoplaki [6] etc.). Produces dozens of correlations expressing the operating temperature as a function of pertinent weather variables. Nevertheless, most of the correlations usually include a reference state and the corresponding values of the pertinent variables. An equally large number of correlations expressing the temperature dependence of the PV module's electrical efficiency can also be retrieved [7]. Furthermore, lots of correlations can be found (Al-Sabounchi [8], Marion, B. [9] etc.). In this category expressing the module's maximum electrical power, which is just related to electrical efficiency. Most of these correlations, nevertheless, have not been validated by experimentally measured data yet.

In this paper, it is presented that a methodology to model the impact of environmental factors on I-V curves P-V curves, as well as maximum power outputs of PV array through numerical and regression method. The environmental factors discussed in this article include solar irradiance, wind velocity and ambient temperature. To balance the smoothness of I-V curves and the amount of calculation, a new method named segmented iteration is used to solve the I-V curve expression equation. The stepwise regression method is adopted to analyze the significance of the impact on PV array performance of the three environmental variables, while the experiment data is fitted by a multivariable non-linear regression equation in applying the non-linear multivariable regression method. From the mathematic point of view, the proposed approach is reasonably simple, and it is validated for the Donghua University PV power generation system. Furthermore, a simple correlation for the operating temperature of PV array is also validated. It is concluded that the model has a relatively high accuracy and can be applied to analyze the performance of the PV array under outdoor conditions.

2. Model and methodology

A cell is defined as the semiconductor device that converts sunlight into electricity. A module refers to a number of solar cells connected in series and in an array, modules are connected in both series and parallel. Hereafter, it is assumed that each cell in the photovoltaic array is identical, and if not it can be a fairly complex task to relate the I-V curve of a cell within the whole array. A cell-to-module-to-array model for PV panels taking the three environmental factors into consideration is presented in this article. After solving the *I-V* curve expression adopting a new iteration method defined as segmented iteration, the *I-V* curves as well as the *P-V* curves can be related to illustrate performance of PV array over a large range of ambient temperatures, irradiation flux, and wind speeds. Subsequently, a numerical model to calculate the maximum power output of PV arrays is proposed. By contrast, a non-linear multivariable regression expression is derived from experimentally measured data in applying multivariable non-linear regression method, which correlates maximum power output with the three environmental variables.

2.1 Mathematic model

2.1.1 The cell-to-module-to-array model for PV Panels

As depicted in Figure 1, solar cell model is traditionally presented by an equivalent circuit composed of a photon generated current I_L, a lumped series resistance R_s, an anti-parallel diode and a shunt resistance R_{sh}. The current I of the photovoltaic cell can be written using the classical single diode model as shown in Eq. (1) [10].

$$I = I_L - I_0\{exp[(V + IR_s)/V_T]\} - (V + IR_s)/R_{sh} \tag{1}$$

wherein, I_0 is the reverse saturation diode current corresponding to the diffusion and recombination of electrons and holes in the p and n sides; V is the solar cell voltage and V_T is the thermodynamic voltage. The voltage V_T equals $nk(T_c + 273.15)/e$ (it's recalled that for $n = 1$, $V_T \approx 25mV$ at 300 K and n is the ideality factor and $n > 1$).

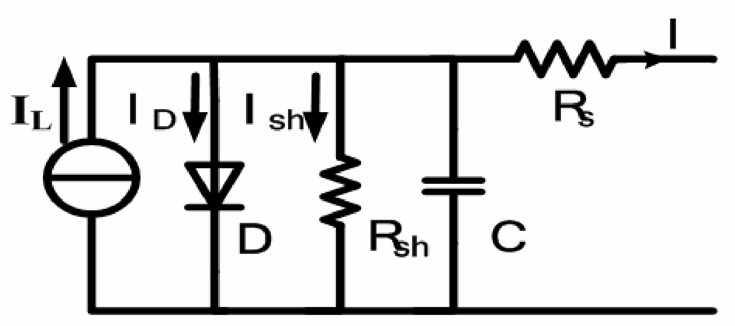

Figure 1. Equivalent circuit for photovoltaic cell

Eq. (1) cannot be used directly to obtain the required predictions, because some parameters, I_L and I_0 in particular, cannot be established from the usually available information provided by the manufacturers. This difficulty is effectively overcome when the following assumptions, which are generally valid for c-Si PV cells and modules, are made: the effect of parallel resistance is negligible; the photo-generated current and the short-circuit current are equal; $exp((V+IR_s)/V_T >> 1$ under all working conditions [11].
The following expression for the open-circuit voltage can be led to based on the above assumptions and with I=0.

$$V_{oc} = V_T \, ln(I_{sc} / I_0) \quad (2)$$

Whence

$$I_o = I_{sc} \, exp(-V_{oc} / V_T) \quad (3)$$

Substituting Eq. (3) into Eq. (1), Eq. (4) can be obtained:

$$I = I_{sc} \{ 1 - exp[(V - V_{oc} + IR_s) / V_T] \} \quad (4)$$

Now, for the prediction of the I –V curves of a PV generator operating on arbitrary conditions of irradiance, temperature, and wind speed, a good balance between simplicity and exactness is obtained through the following additional assumptions.
Firstly, the short-circuit current of a solar cell depends exclusively and linearly on the irradiance. That is,

$$I_{sc}(G) = (I_{sc}^* / G^*) G_T \quad (5)$$

where G_T is the irradiance or solar rad'n flux on module plane.

Secondly, the open-circuit voltage of a solar cell is dependent on the temperature of the solar cells T_c and irradiation flux G_T . Hence,

$$\begin{aligned} V_{oc}(T_c) &= [V_{oc} * + (T_c - T_c^*) dV_{oc} / dT_c] \, [1 + \rho_{oc} \, ln(G_T / G_{oc}) ln(G_T / G^*)] \\ &= V_{oc} * + \beta (T_c - T_c^*) [1 + \rho_{oc} \, ln(G_T / G_{oc}) ln(G_T / G^*)] \end{aligned} \quad (6)$$

where the voltage temperature coefficient, $\beta = dV_{oc} / dT_c$ is negative. ρ_{oc} and G_{oc} are empirically adjusted parameters. Values of $\rho_{oc} = -0.04$ and $G_{oc} = G^*$ that are adopted in this paper have proven adequate for many silicon PV modules.

Thirdly, the series resistance is a property of the solar cells, unaffected by the operating conditions and can be calculated by

$$\begin{cases} R_s = R_s^* = r_s^* V_{oc}^* / I_{sc}^* \\ r_s^* = 1 - FF^* / FF_0^* \\ FF^* = \dfrac{V_m^* I_m^*}{V_{oc}^* I_{sc}^*} = \dfrac{P_m^*}{V_{oc}^* I_{sc}^*} \\ FF_0^* = \dfrac{v_{oc}^* - \ln(v_{oc}^* + 0.72)}{v_{oc}^* + 1} \\ v_{oc}^* = V_{oc}^* / V_T^* \end{cases} \tag{7}$$

where I_{sc}^* is the short circuit current in STC (A); V_{oc}^* refers to the cell open circuit voltage in STC (V); r_s is the normalized cell series resistance; FF^* is the cell fill factor in STC; υ_{oc} is the normalized open circuit cell voltage.

Lastly, the operating temperature of the solar cell is affected by environmental factors, ambient temperature, irradiance, wind speed and can be demonstrated by the following correlation that is worked out by E. Skoplaki [12].

$$T_c = T_a + (0.32/(8.91 + 2.0V_f))G_T(V_f > 0) \tag{8}$$

In which T_a is the ambient temperature($^\circ C$), while V_f refers to the free-stream wind speed in the windward side of the PV array measured by a mast-mounted anemometer just well above the PV array(ms^{-1}). G_T denotes the irradiance, or solar radiation flux, on module plane(Wm^{-2}).

This simple correlation indicated in Eq. (8) correlates the PV cell operating temperature with the three basic environmental variables and can be applied for wind speed $> 0ms^{-1}$.

If the local or near the PV array wind speed is easier to measure, the following modified correlation is useful.

$$T_c = T_a + (0.25/(5.7 + 3.8V_w))G_T(V_w > 0) \tag{9}$$

wherein V_w is loosely used to denote local or near the PV array wind velocity (ms^{-1}). This correlation is proved to be valid for the Donghua photovoltaic power generation system which is depicted in the Section 3.

Substitution of Eqs. (5), (6), (8) into Eq. (4) leads to the following *I-V* curve expression equation.

$$\begin{cases} I_G = (I_{sc}^*/G^*)\cdot G_T - (I_{sc}^*/G^*)\cdot G_T \cdot \\ \quad \exp\{300\cdot[V_G - (V_{oc}^* + \beta(T_c - T_c^*))(1 - 0.04\ln^2(G_T/G^*)) + R_s I_G]/[0.025(T_c + 273.15)]\} \\ T_c = T_a + (0.25/(5.7 + 3.8V_w))G_T(V_w > 0) \end{cases} \tag{10}$$

As for PV modules which consist of N_c solar cells connected in series the above-mentioned equitation can be rewritten as follow:

$$\begin{cases} I_G = (I_{sc}^*/G^*)\cdot G_T - (I_{sc}^*/G^*)\cdot G_T \cdot \\ \quad \exp\{300\cdot[V_G / N_c - (V_{oc}^* + \beta(T_c - T_c^*))(1 - 0.04\ln^2(G_T/G^*)) + R_s I_G]/[0.025(T_c + 273.15)]\} \\ T_c = T_a + (0.25/(5.7 + 3.8V_w))G_T(V_w > 0) \end{cases} \tag{11}$$

When it comes to PV array in which there are N_s PV modules in series and N_p ones in parallel, the *I-V* curve expression is:

$$\begin{cases} I_G = N_p(I_{sc}^*/G^*)\cdot G_T - N_p\cdot(I_{sc}^*/G^*)\cdot G_T\cdot \\ exp\{300\cdot[V_G/V_G/(N_cN_s)-(V_{oc}^*+\beta(T_c-T_c^*))(1-0.04\ln^2(G_T/G^*))+R_sI_G/N_p]/[0.025(T_c+273.15)]\} \\ T_c = T_a+(0.25/(5.7+3.8V_w))G_T(V_f>0) \end{cases} \quad (12)$$

2.1.2 The maximum power output for PV array

This first selected numerical model detailed hereafter approximates the cell current (I_m) and the cell voltage (V_m) at the maximum power point from both cell short circuit current (I_{sc}) and open circuit voltage V_{oc} using the expressions shown below [13].

$$\begin{cases} V_m = V_{oc}[1-(b/\upsilon_{oc})\ln a - r_s(1-a^{-b})] \\ I_m = I_{sc}(1-a^{-b}) \\ P_m = V_m I_m \end{cases} \quad (13)$$

where

$$\begin{cases} r_s = R_s/(V_{oc}/I_{sc}) \\ a = \upsilon_{oc}+1-2\upsilon_{oc}r_s \\ b = a/(a+1) \end{cases} \quad (14)$$

This set of expressions is valid for $\upsilon_{oc} < 15$ and $r_s < 0.4$, and I_{sc} and V_{oc} are determined by Eq. (5) and Eq. (6), respectively. For PV array, the maximum power output is calculated by

$$P_{mar} = N_c N_s N_p P_m \quad (15)$$

By comparison with the first model, the experiment data is fitted by a multivariable non-linear regression equation in applying the non-linear multivariable regression method. The following expression is presented to determine the maximum power output in the operating conditions using the parameters Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, m_1, m_2 and m [14].

$$P_{mar} = Q_1G_T + Q_2T_a + Q_3[\ln(G_T)]^m + Q_4T_a[\ln(G_T)]^m + Q_5G_T\exp(m_1+m_2V_w) + Q_6G_T[\ln(G_T)]^m\exp(m_1+m_2V_w) \quad (16)$$

In this paper, it's demonstrated that the results obtained from Eq. (16) improve the ones given by Eq.(13).

2.2 Methodology

The expressions stated by Eq. (12) can be inconvenient to use in the sense that *I* is implicit (it appears on both sides of the equation), theoretically making it necessary to solve the equation iteratively. In order to relate the whole *I-V* curve, the method defined as segmented iteration is used. By this method, the whole *I-V* curve is divided into three segments, i.e. $V < 0.8V_{oc}$, $0.8V_{oc} \le V \le 0.95V_{oc}$ and $V > 0.95V_{oc}$. I_G is substituted for $0.99I_{SCG}$ on the first step to solve this equation iteratively and then the value of the current corresponding to a given voltage can be attained after certain amount of iteration. To relate the *I-V* curve smoothly, and meanwhile insure the accuracy, it is proved valid in this paper that for $V < 0.8V_{oc}$, 20 values of current corresponding to 20 points of voltage that is divided equally need to calculate. Similarly, 50 points need to calculated for $0.8V_{oc} \le V \le 0.95V_{oc}$ and 20 points for $V > 0.95V_{oc}$.

When the modeled values of the maximum power output are compared to measured ones, the parameters root mean square error (RMSE) and mean bias error (MBE) as depicted below, have been used to calculate errors. The RMSE provide information on the variation of the modeled values from measured ones, while MBE supplies the average deviation of the modeled values from the measured ones [15]. The RMES and MBE derived from measured versus modeled parameters have been analyzed in this paper.

$$RMSE(EP_m) = 100 \bullet \sqrt{\sum_{i=1}^{N}(P_{mdi} - P_{mei})^2 \Big/ N} \Bigg/ \frac{1}{N}\sum_{I=1}^{N} P_{mei} \tag{17}$$

$$MBE(EP_m) = 100 \bullet \sqrt{\sum_{i=1}^{N}(P_{mdi} - P_{mei}) \Big/ N} \Bigg/ \frac{1}{N}\sum_{I=1}^{N} P_{mei} \tag{18}$$

where P_{mdi} denotes the *ith* modeled value of the maximum power (W); P_{mei} is the *ith* measured value of the maximum power (*W*); N is the number of modeled or measured values.
The methodology of stepwise regression is adopted to analyze the significance level of the impact of the three environmental variables G_T , T_a , V_w as well as module temperature T_c on the maximum power output of PV array. The algorithm of the stepwise regression can be illustrated as below: the above-mentioned four variables are introduced one after another into a linear mathematic model; each time a new variable is introduced, the *F*-test of the former selected ones is carried out individually; as a result, the formerly introduced variables must be excluded if it becomes no longer significant due to the introduction of the latter ones. This process is repeated until neither significant independent variable is included into the regression equation nor insignificant one is excluded from the equation.
The highly accurate expression for PV array maximum power output shown as Eq. (16) is derived by the means of the non-linear multivariable regression method through SPSS, renowned as excellent data analysis software.

3. Validation

3.1 Experiment system

The experimental data used to validate the model detailed above is acquired from the monitoring system for the photovoltaic power generating system of Donghua University, which is funded by the National Golden Sun Demonstration project of China. Figure 2 illustrates the structure of the experiment system, which is composed of PV panels on the roof, inverters, control cabinets, datalogger and the monitoring PC. The photovoltaic module parameters in the Donghua University System are listed in Table1.

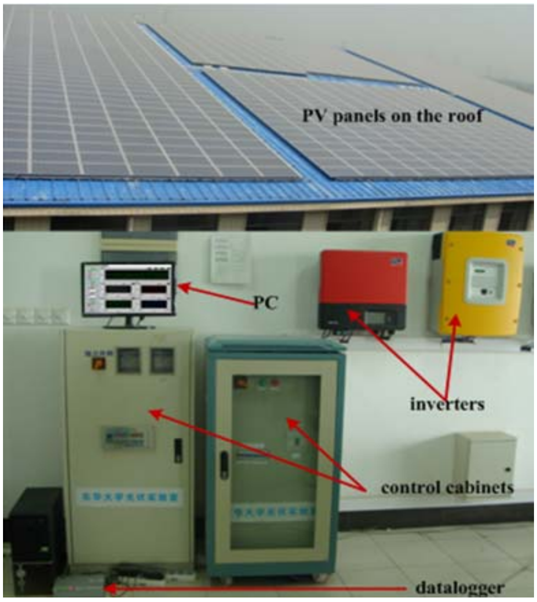

Figure 2. Donghua University PV power generation system

Table 1. The solar cell parameters in the Donghua University system

Item	V_m^* (V)	I_m^* (A)	V_{oc}^* (V)	I_{sc}^* (A)	β ($mV \cdot ^\circ C^{-1}$)	N_c	N_s	N_p
Value	0.4861	4.86	0.6028	5.2	-2.0694	72	10	3

3.2 Validation results and discussion

3.2.1 The correlation for the operating temperature

The operating temperature plays an important role in the photovoltaic conversion process. The cited correlation described in Eq. (9) ignores free-convection, which is small for all wind speeds, and irradiation, which is important only at wind speed $< 1ms^{-1}$ and therefore should be used for wind speeds $\geq 1ms^{-1}$. From the bar diagram exhibited as Figure 3, the number of days of wind force of Grade 3-4 (it should be noted the wind speed of Grade 3 is 3.4-5.4 ms^{-1} and Grade 4 is 5.5-7.9 ms^{-1}) reaches 432 during the period from Jan.1st, 2011to Mar.1st, 2013, and thus, the correlation can be applied to PV array exposed to Shanghai outdoor climate situations. The comparison of measured operating temperature values with the modeled ones calculated according to Eq. (9) is displayed in Figure 4, and as it can be seen, the modeled values are in great agreement with the ones measured in the range of high irradiation, albeit slightly lower over the range of low irradiance, which is resulted from the omitted free-convection. However, it should be noted that the RMSE is 1.19% and the MBE is -0.09%. Therefore, it can be concluded that the correlation is valid for a range of wind speed studied, i.e. 2-8 ms^{-1}, and for irradiance values between 200 and 1000 Wm^{-2}. So the correlation balances between reasonable simplification and accuracy.

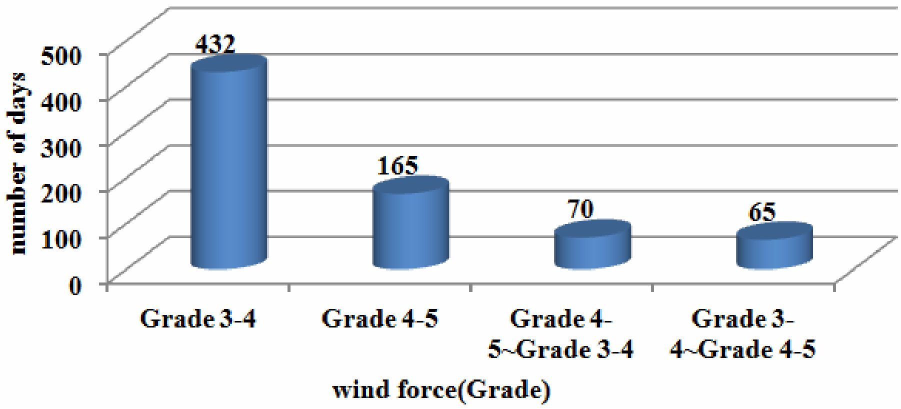

Figure 3. Bar diagram of wind force of Shanghai from Jan. 1st, 2011to Mar. 1st, 2013

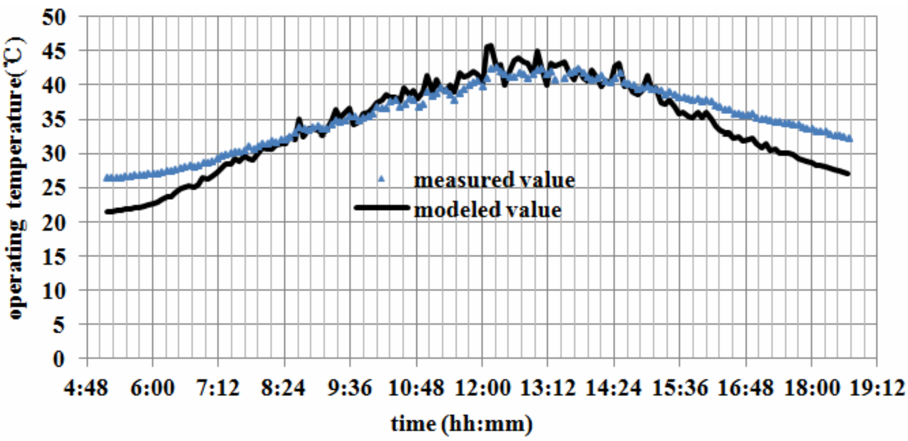

Figure 4. Comparison of measured with the modeled operating temperature values

3.2.2 The I-V and P-V curves for PV array

Primary, it can be argued that model detailed in the Section 2 is at the price of neglect listed as follows: The effects of the parallel resistance and the influence of the cell temperature in the short-circuit current. The influence of the parallel resistance is, to a great extent, compensated here, by the particular way of estimating the series resistance of a PV module, which assures that the maximum power of the modeled curve coincides exactly with that corresponding to the real one. Because of this, the accuracy of the

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model tends to be good around the maximum-power operation point, that is, just on the voltage region of interest. For points far away from the maximum-power operation point, the error is a little large, but it doesn't change the overall trend of the *I-V* and *P-V* curves.

The short-circuit current tends to increase slightly with increasing temperature. This can be attributed, in part, to increased light absorption, since semiconductor band gaps generally decrease with temperature, and, in part, to increased diffusion lengths of the minority carriers. For a solar cell operating at 70 $^{\circ}C$, nonetheless, only 0.13% of I_{SC} is increased, as a result of which, ignoring this dependence has no practical effects, in all the cases.

The solid lines in Figures 5-7 show the modeled *I-V* curves and *P-V* curves, while the scattered points depict the measured values. The modeled curves are shown to agree well with the experiment data as shown in Figures 5-7, which exhibiting how the three environmental factors affect the outdoor characteristics of PV array. Looking further into Figures 5 and 6, it can be concluded that the outdoor *I-V* curves and *P-V* curves change steadily for the range of ambient temperature, i.e. 15-35 $^{\circ}C$ and for irradiance values between 200 and 1000 Wm^{-2}, while after further analysis of Figure 7, it can be found that the influence of wind speed on *I-V* curves of PV array gets weak as the wind speed increases from 2 ms^{-1} to 6 ms^{-1}.

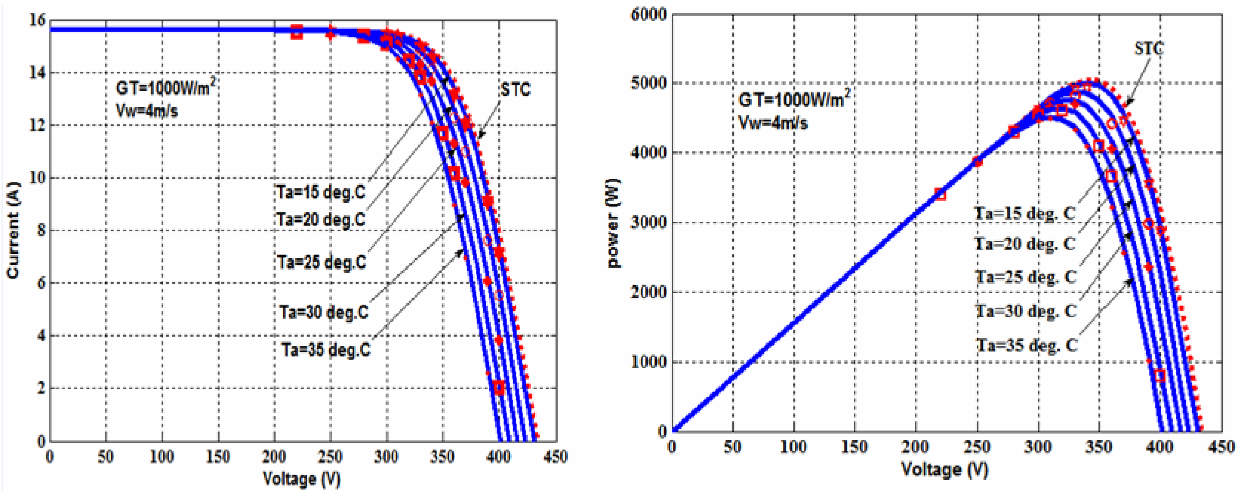

Figure 5. I-V curves (left) and P-V cures (right) for PV array versus experiment data (scattered points) at different ambient temperatures

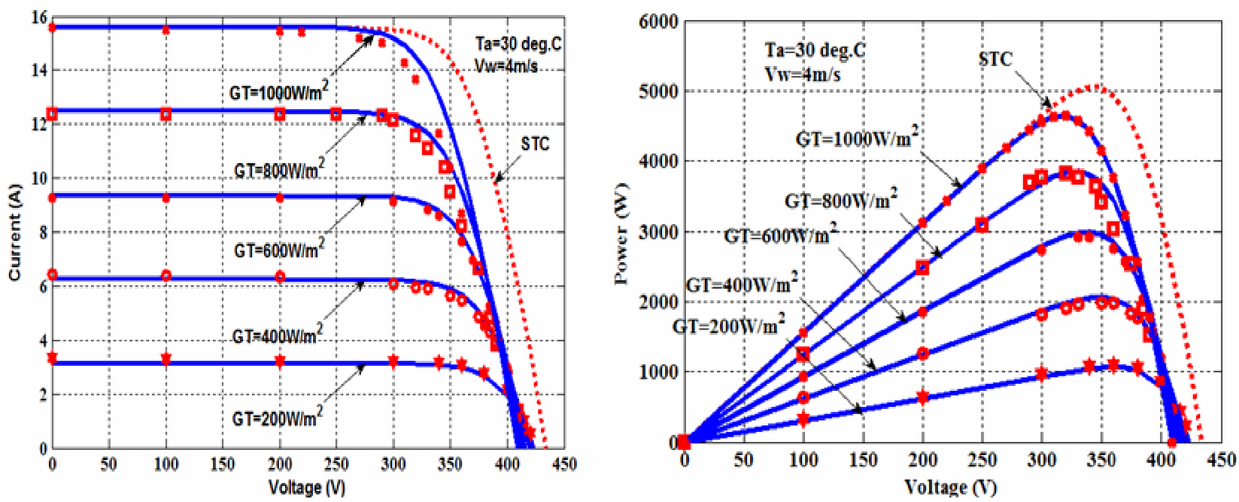

Figure 6. I-V curves (left) and P-V curves (right) for PV array versus experiment data (scattered points) at different irradiance

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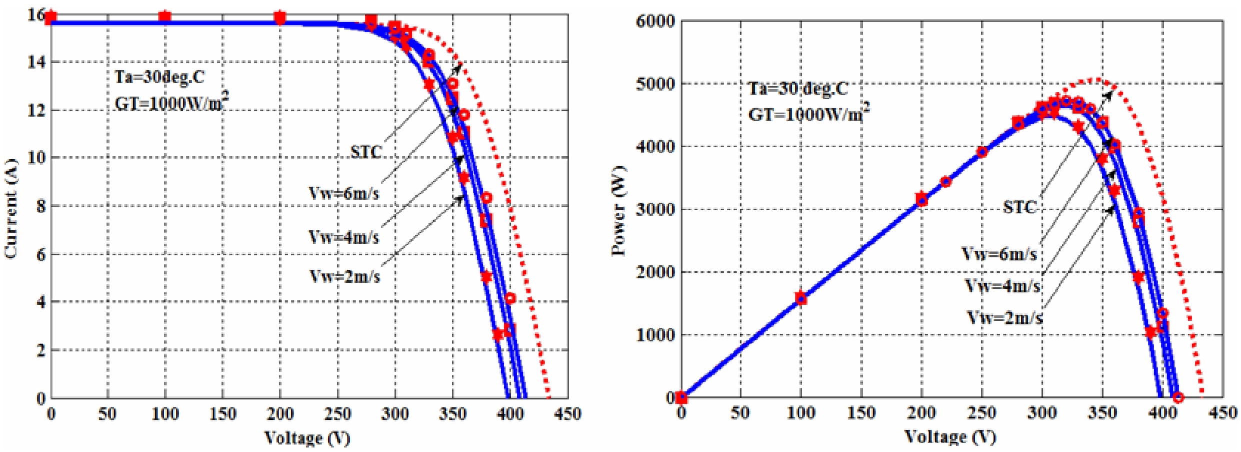

Figure 7. I-V curves (left) and P-V curves (right) for PV array versus experiment data (scattered points) at different wind speeds

3.2.3 The maximum power output

First of all, it should be realized that the maximum power point tracking errors caused by the inverter is ignored in this paper. Figure 8 is drawn to compare experiment power outputs with the values calculated by Eqs. (13) to (15), and the modeled values are higher than the measured ones in general, as a result of the real complicated outdoor operating conditions, including humidity, spectral effects and dust accumulation on photovoltaic array plane [16] in addition to the basic three factors discussed in this paper. Figure 8 reveals consistency between the modeled values and the measured ones in the morning (6 a.m. to 11 a.m.) and in the late afternoon (3:30 p.m. to 6:30 p.m.), notwithstanding the main difference found for the noon and the early afternoon. However, the RMSE is 0.2307%, while the MBE is 0.0183%. Whence, the modeled described by Eqs. (13) to (15) has relatively high accuracy. Figure 9 shows modeled versus measured maximum power outputs at different ambient temperatures. It can be figured out that the main difference is found for high ambient temperature. Furthermore, the maximum power outputs are dependent parabolic on the ambient temperatures. It's obvious that it increases rapidly with the increasing ambient temperature in the morning and decreases, less rapidly yet, with the decreasing ambient temperature in the afternoon. Figure 10 depicts modeled versus measured maximum power outputs at different irradiance and it can be seen that the maximum power outputs are dependent linearly on the incident solar irradiation on the array plane. Figure 11 illustrates modeled versus measured maximum power outputs at different wind speeds. From Figure 11, it is doubtful whether the wind speed plays a significant or direct role on the maximum power outputs.

Subsequently, since a large amount of experiment data is available, the experiment data is fitted by a linear regression equation adopting the stepwise regression methodology detailedly represented in Section 2 to find out whether the wind speed impacts on the maximum power outputs significantly. The results attained for the linear regression equation of P_m enumerated in Table 2. As shown in Table 2, none of the three basic environmental factors, ambient temperature T_a, incident irradiation flux G_T, and wind speed V_w, is excluded from the regression equation, whereas the linear equation is apparently in low accuracy. A multivariable non-linear regression equation derived through multivariable non-linear regression method is demonstrated to improve the accuracy in the following part of this paper.

As to fit and validate the multivariable non-linear expression equation, Eq.(16), the experimentally measured data is divided into two sets. The data set used to fit the Eq. (16) is named hereafter the fitting data set, while the remaining measured data is called the validation data set. Table 3 provides the result found for fitting Eq.(16). Figure 12 shows statistics from the validation data set when regression predicted and measured maximum power outputs are compared. As is shown, the regression predicted values agree better to the measured values compared with the modeled values calculated by Eqs. (13) to (15), resulting from the main difference occurred at noon and early afternoon is eliminated. The RMSE is 0.1711%, and meanwhile the MBE is -0.0063%. It can be seen from Figure 13 that the regression predicted values in far more excellent accordance with experiment ones over the full range of ambient temperatures in comparison with Figure 9. Similarly, the information presented in Figure 14 illustrates the greater consistency between regression predicted values of P_m and measured ones when it is made a comparison with Figure 11. The relatively good linear dependence of P_m on the solar irradiation flux is sacrificed for the above-mentioned better consensus, which is displayed in Figure 15. However, it should be argued that the deviation is within acceptance. In all, the regression multivariable non-linear expression quantifying the influence on the maximum power output of three environmental factors has a high accuracy and is applicable to analyze.

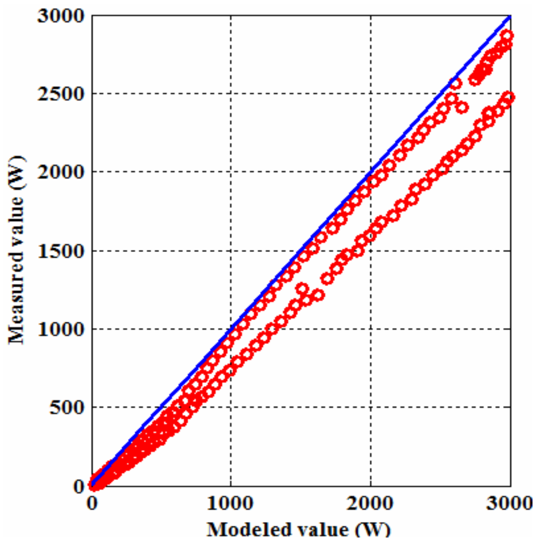

Figure 8. Scattering plot for $\mathbf{P_m}$ calculated by Eqs.(13) to (15) versus measured values

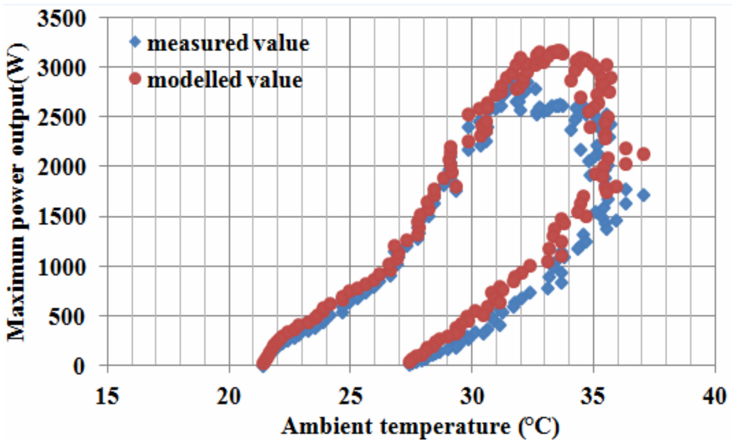

Figure 9. Modeled versus measured maximum power outputs at different ambient temperatures

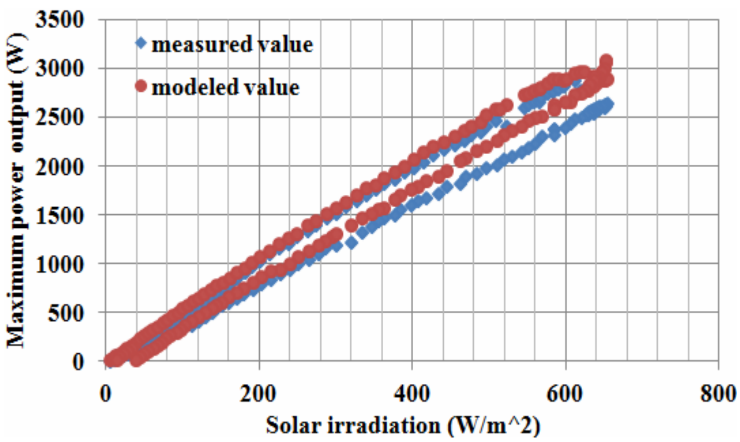

Figure 10. Modeled versus measuredmaximum power outputs at different irradiance

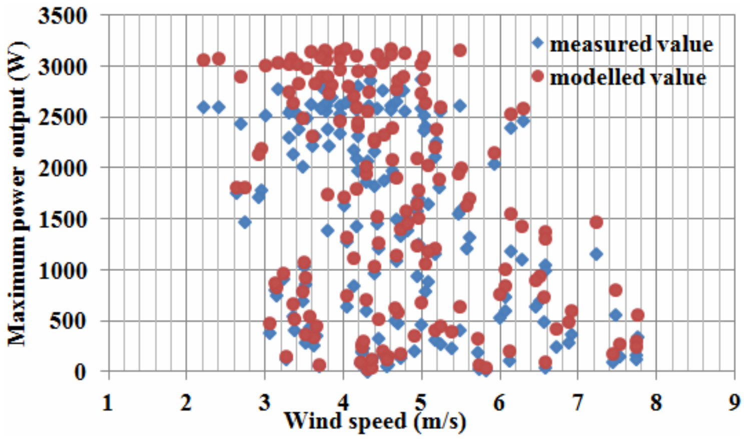

Figure 11. Modeled versus measured maximum power outputs at different wind speeds

Table 2. The results attained for the linear equation of P_m using stepwise regression

Item	Constant	G_T	T_a	V_w	T_c
Coefficients	1789.658	5.273	43.459	109.481	-113.425
Std. Error	117.851	0.103	9.638	8.824	11.442
t value of t test	15.186	51.020	-11.768	12.408	3.798
P	0.000	0.000	0.000	0.000	0.000

Table 3. The parameters obtained for multivariable non-linear equation of P_m

Item	Q_1	Q_2	Q_3	Q_4	Q_5
Value	-205.2810	-1.8060	6.5030	11.7230	0.0001
Item	Q_6	m_1	m_2	m	R^2
Value	-0.3160	2.8910	0.0020	3.1400	0.9250

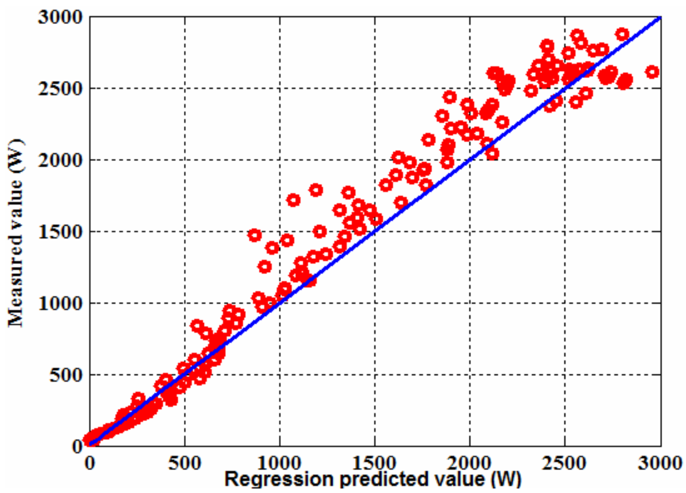

Figure 12. Scattering plot for results of multivariable non-linear regression of P_m

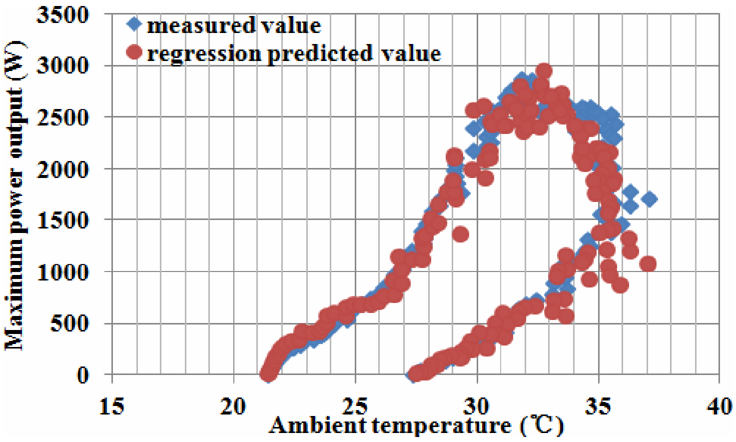

Figure 13. Regression predicted versus measured maximum power outputs at different ambient temperatures

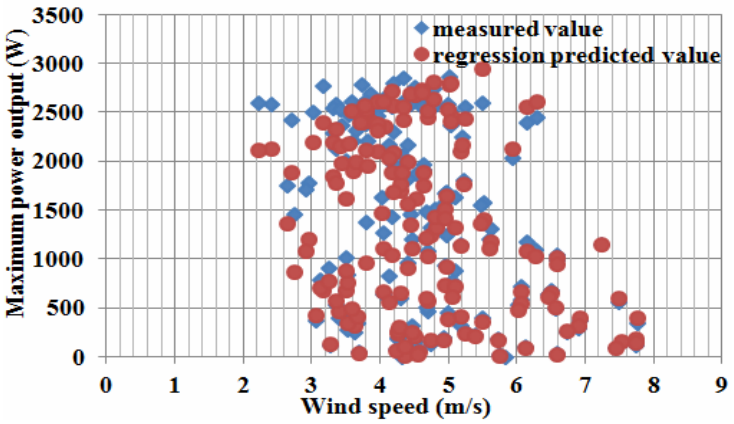

Figure 14. Regression predicted versus measured maximum power outputs at different wind speeds

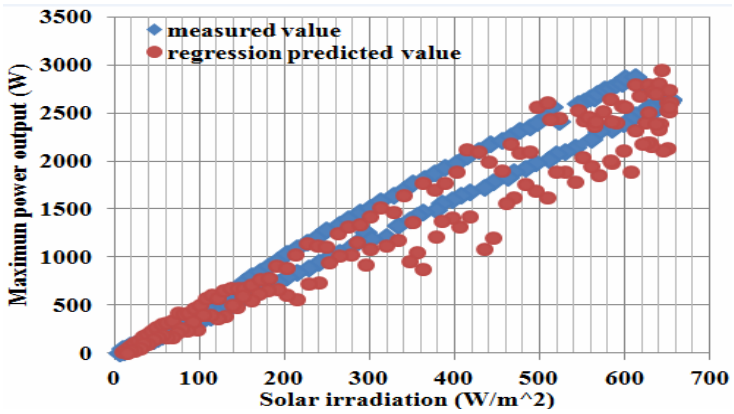

Figure 15. Regression predicted versus measured maximum power outputs at different irradiance

4. Conclusion

It is presented that both numerical and regression models of the influence on the photovoltaic array outdoor performance of three basic environmental variables, the ambient temperature, the incident irradiance and wind velocity. It is well documented that operating temperature plays a crucial role in the performance of PV array. A simple correlation correlating operating temperature with the three environmental factors is validated for a range of wind speed studied, i.e. 2-8 ms^{-1}, and for irradiance values between 200 and 1000 Wm^{-2}. RMSE between modeled operating temperature and measured values is 1.19% and the MBE is -0.09%. The environmental factors studied in this paper impact upon *I-V* curves, *P-V* curves, and maximum-power outputs of PV array operating under outdoor situations. The cell-to-module-to-array mathematical model for photovoltaic panels is established in this paper and the method defined as segmented iteration is adapted to solve the *I-V* curve expression to relate model *I-V* curves. The model *I-V* curves and *P-V* curves are concluded to coincide well with measured data points. The RMSE between numerically calculated maximum-power outputs and experimentally measured ones is 0.2307%, while the MBE is 0.0183%. The exact coincides can be found for lower ambient temperature and irradiance in the morning and in the late afternoon, notwithstanding main difference found for high ambient temperature and irradiance at noon and in the early afternoon. To eliminate this difference, a multivariable non-linear regression equation is proposed, which is proved to have a better accuracy of RMSE, 0.1711%, and MBE, -0.0063%.

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