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A Macroscopic Approach - Performance of Crystalline Silicon Photovoltaic Modules

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Theoretical and experimental investigations of the thermal and electrical performance of crystalline silicon photovoltaic modules have been carried out. Based on the basic diode model, a macroscopic model describing the performance of crystalline silicon photovoltaic modules has been developed. The simulation model was validated by the test data for three different PV modules. The parameters in the model can be obtained by Newtonian iteration scheme if limited test data are known. The maximum power output and the efficiency of crystalline silicon photovoltaic modules can be found easily and accurately. It is convenient to use this new macroscopic model to describe the thermal and electrical behavior of crystalline silicon PV modules, providing a new tool for researchers and engineers.

Keywords: *Photovoltaics, PV Module, Crystalline Silicon, Electrical Performance*

Introduction

With the fast development of photovoltaic technology for the past thirty years and increasing pressures from environmental protection and energy conservation nowadays, solar energy application for electricity generation is regarded as a potential renewable energy resource for the new century. It might become a major option to supply electrical energy in the future [1]. The foundation of photovoltaic technology, i.e. the photovoltaic effect, was found more than 150 years ago. However, development of this photovoltaic technology is not as rapid as imagined, because the basic mechanism of photovoltaic effect is mainly concerned with microelectronics. This paper intends to investigate the thermal and electrical performance of crystalline silicon photovoltaic modules (one of the popular PV modules on market) from macroscopic view for engineering uses.

The research history of electric effect of photovoltaics or solar cells can be traced back to one hundreds years ago. The primitive solar cell, as reported by Fahrenbrush and Bube [2], was discovered by Becquerel, when he illuminated an electrode in an electrolyte solution and found a photovoltage. Several decades late, in 1877, Adams and Day observed a similar effect in solid selenium material. Around 1914 saw the development of the selenium solar cell and its wide use in photographic exposure meters. The selenium solar cell was found to have about one percent efficiency in direct sunlight converting into DC electricity. However, it was in 1954 the crystalline silicon p-n junction solar cell was demonstrated by Chapin [3] and Reynolds [4]. Chapin and his coworkers obtained approximately 6 percent efficiency of direct solar radiation when they used a photocell to deliver power from the sun. This result was promising since at that time the greatest overall efficiency was about 1 percent, obtained by using thermal-electric junctions to convert solar radiation into electrical power. Reynolds et al. also reported a 6 percent efficiency for a copper sulfide/cadmium sulfide cell. These collective works opened a new era for modern semiconductors.

Shockley and Queisser [5] found that an upper theoretical limit exists for the efficiency of p-n junction solar energy converters, due to the principle of detailed balance, which requires that the only recombination mechanism of hole electron pairs is radiative. The study of Staebler and Wronski [6] indicated that the photo conductivity and dark conductivity of some samples of hydrogenated silicon (a-Si:H) is decreased when exposed to light for a long time. Yamaguchi et al. [7] has used electron beam induced and capacitance-voltage method to study the variations of minority carrier diffusion length and carrier concentration in irradiated InP single crystals. They found that a high carrier concentration p-InP with a higher carrier concentration substrate has superior radiation resistance because a high carrier concentration p-InP substrate has lower concentration damage. Hamker reported that dopant and band gap gradient are useful in increasing the efficiency of AlGaAs/GaAs heteroface solar cells. Large electric fields opposing the flow of holes toward the junction in the emitter of p-n devices are not necessarily detrimental when surface recombination velocities are low. Greenbaum et al. reported that exposure to concentrated sunlight of single silicon point-constant solar cells causes a degradation in their efficiency. Through effort from scientists for decades, current generation of solar cells has been largely improved with the converting efficiency of about 30 percent in the lab [8]. The popular crystalline silicon PV modules on market have an energy efficiency of about 15%.

In order to optimize PV system design and reduce the uncertainty in the predicted performance, it is of great importance to propose a physical model for engineering applications. Previously, Shockley and Quelsser developed the standard diode equations for current density versus voltage in a p-n junction solar cell. Hoval [9] modified the solar cell model by introducing an ideality factor n. A constant fill factor solar cell model has been provided by Jones [10], in which it is assumed that the fill factor is not varied during the operation of the PV systems. Based on experimental data, a new macroscopic model is introduced in this paper. It can be used to predict the performance of crystalline PV modules if limited test data are available. It intends to develop this model for engineering applications. In this model, the short circuit current and the open circuit voltage are normalized.

Performance Tests

Three different PV modules were tested under a solar simulator – 3-phase Arrays for PV module tests. The PV arrays has 96 Halogen lamps with 75 W for each lamp. The solar radiation density can be changed from below 100 W/m² to 1400 W/m². As the number of the lamps is large and the diffuse angle of the light is quite high the solar radiation flux on PV modules is quite uniform. Figure 1 shows the test set-up principle. PV module is located in an enclosure which is air-conditioned through an air-conditioning system. PV cell temperature can be maintained at a steady state temperature in the range of 15-80 °C. A variable external resistant load is connected in the I-V Test Box. The current and voltage applied to the load can be recorded through a data logger. The I-V curves under any solar radiation and PV cell temperature can be measured.

Three different modules made of mono-crystalline silicon were tested

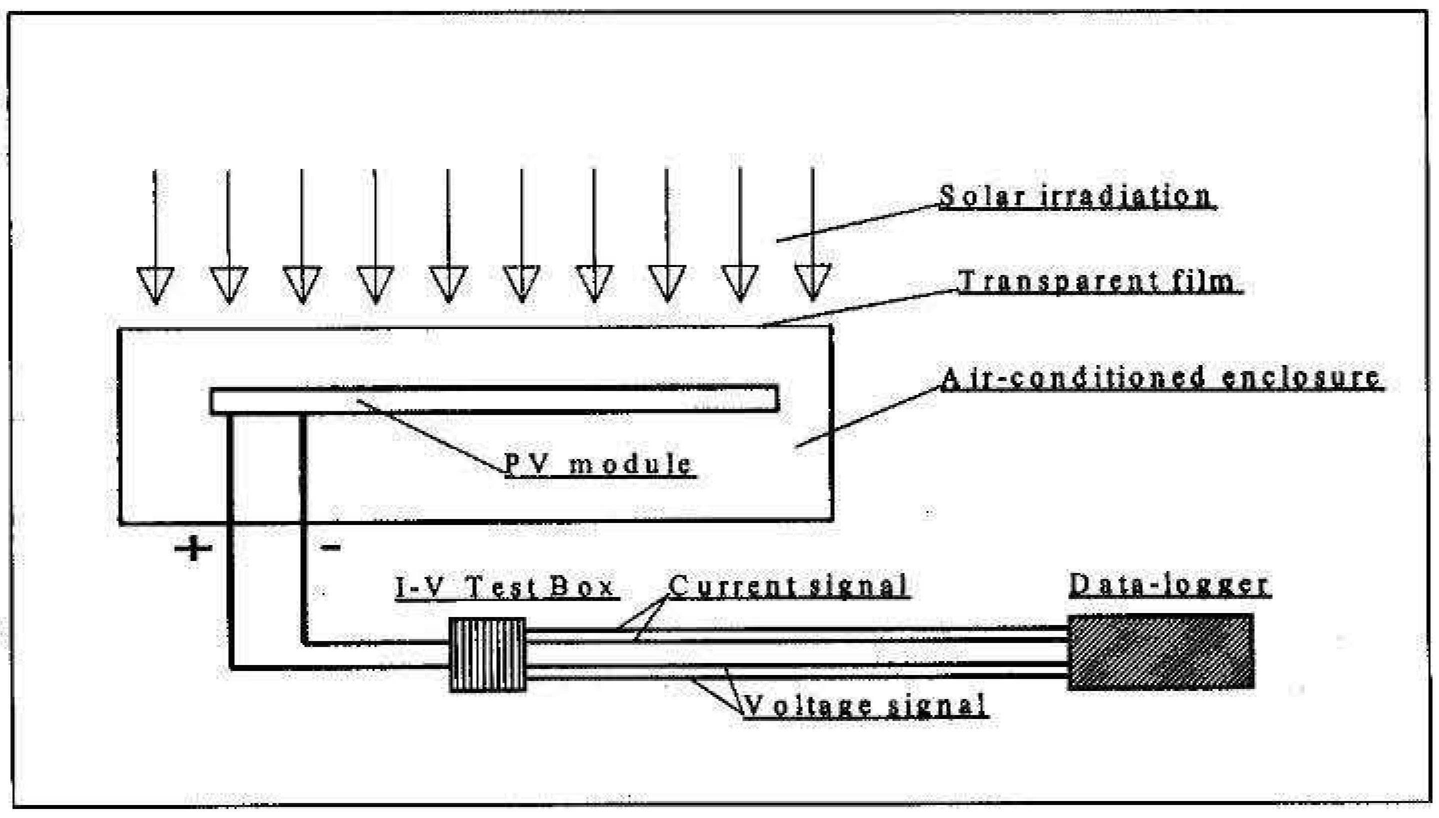

Figure 1 – I-V Characteristics Test Set-Up

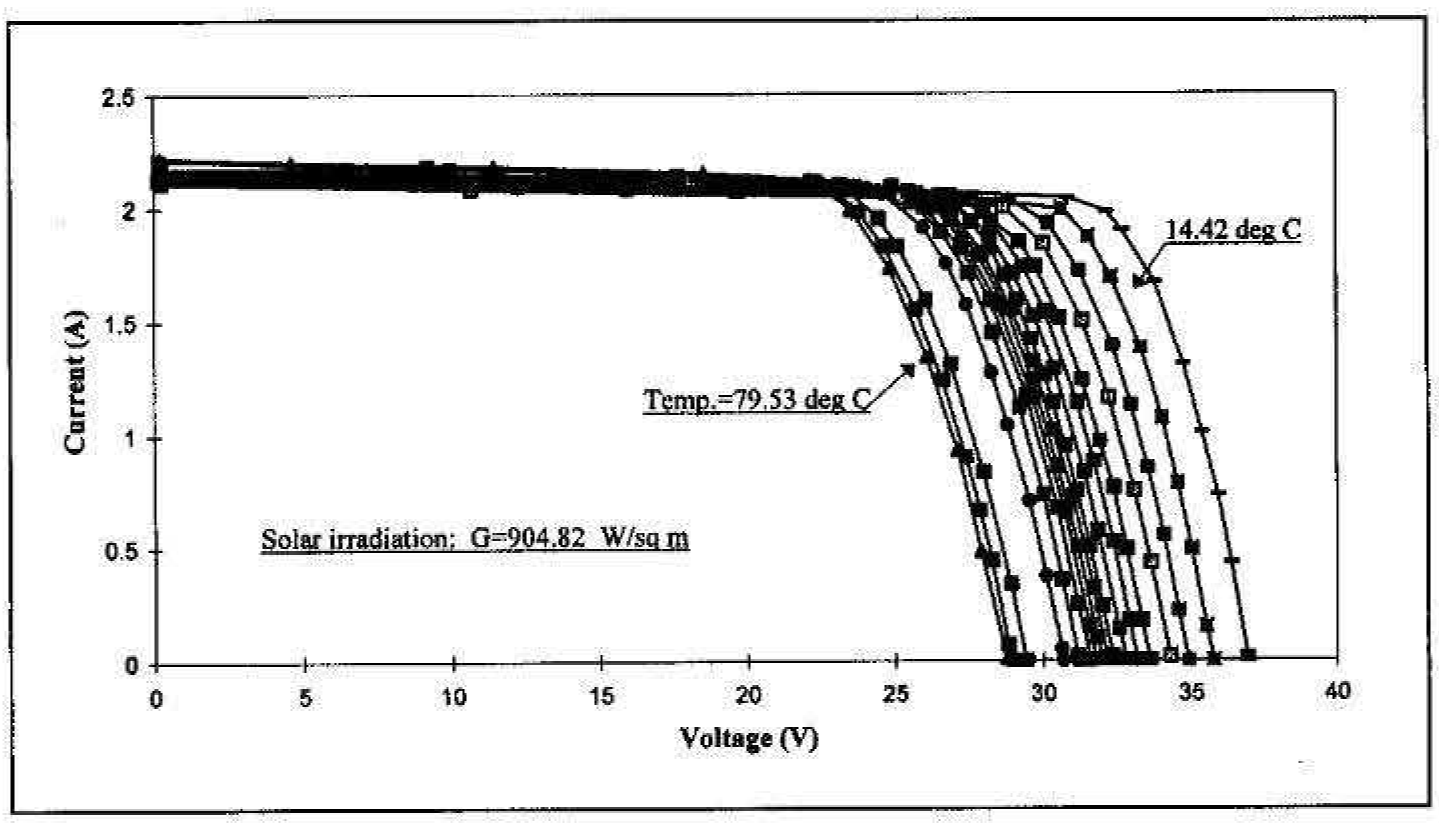

Figure 2 – Test Results of I-V Curves of PV Module A

PV Modules	Height (mm)	Width (mm)	Area (m^2)	Design parameters V_{oc}(V)	I_{is}	P_m(W)
A	920	527	0.485	32.0	2.2	60
B	478	238	0.114	19.0	0.8	12
C	1280	357	0.457	22.0	2.5	50

Table 1 – Specifications of the PV Modules

under different incident solar radiation and cell temperatures. The specifications of the three modules are given in Table 1. Figure 2 shows the experimental results for PV module A, measured under a solar intensity of G = 904.82 W/m² for different cell temperatures. It is found that the open circuit voltage is decreased as a result of cell temperature increase, despite of the independence between the short circuit current and the cell temperature. It indicates that the first order derivative of the open circuit voltage with respect to the cell temperature is negative. The Auger effect and the recombination velocity and the diffusion of minority carrier in the p-n junction are slightly dependent on the cell temperature. The normalized current and voltage are shown in Figure 3 for different cell temperatures. All the curves overlap, which shows that there exists a single function which is able to represent the relationship between the two variables. It is reasonable to develop a theoretical model to describe the characteristics of non-dimensional I–V curves which forms the basis for a macroscopic model of PV modules.

The corresponding power outputs for different cell temperatures are shown in Figure 4. The maximum power points for different cell temperatures are clearly shown, which can be approximated as a linear relationship for different incident solar irradiance as shown in Figure 5 [11].

The Simulation Model

With respect to the basic diode model of solar cells, the equivalent circuit is shown in Figure 6. It is shown that the photo-generated current I_L dominated by the solar irradiation causes the transport of minority carrier

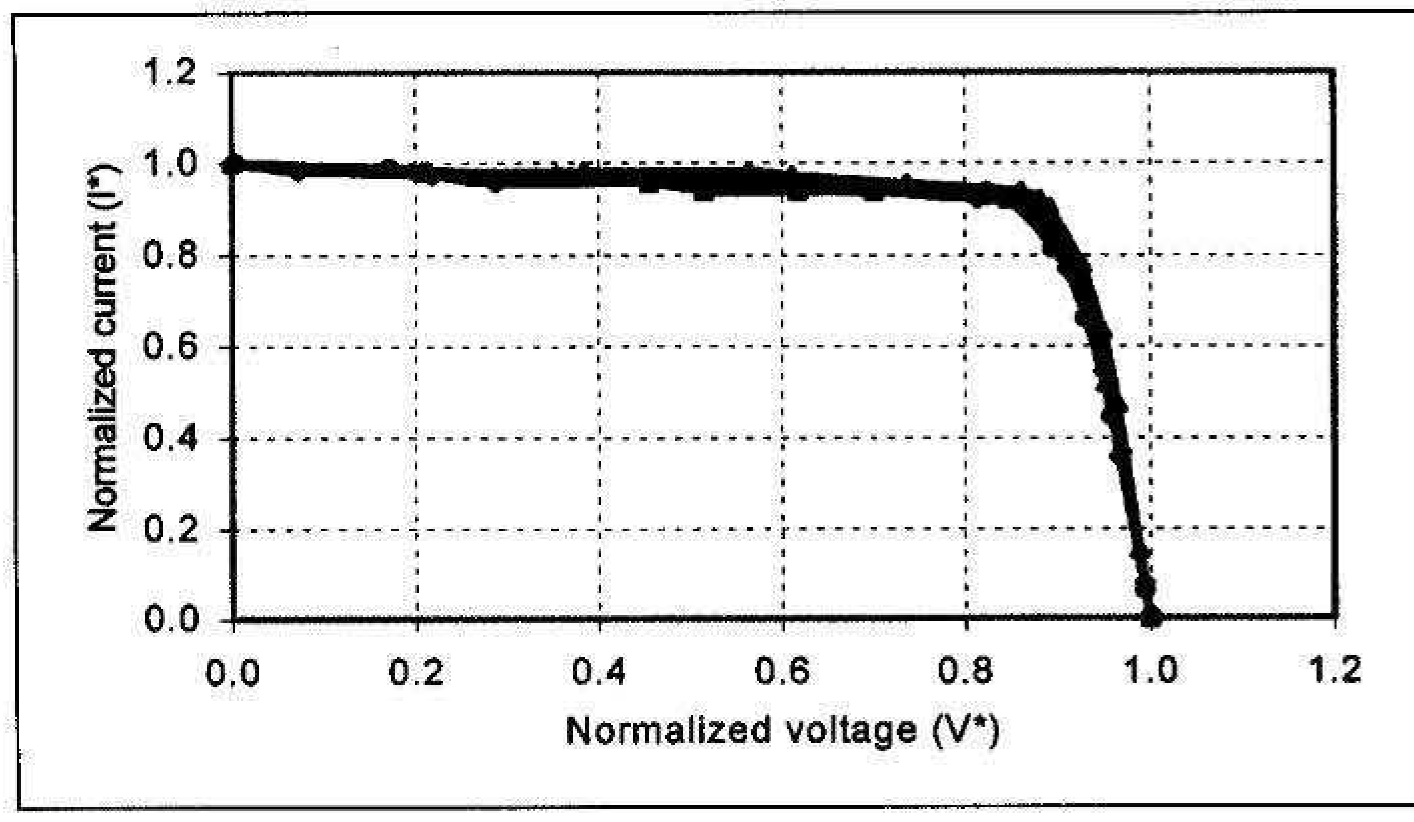

Figure 3 – Normalized Current and Voltage for Different Cell Temperatures for Module A

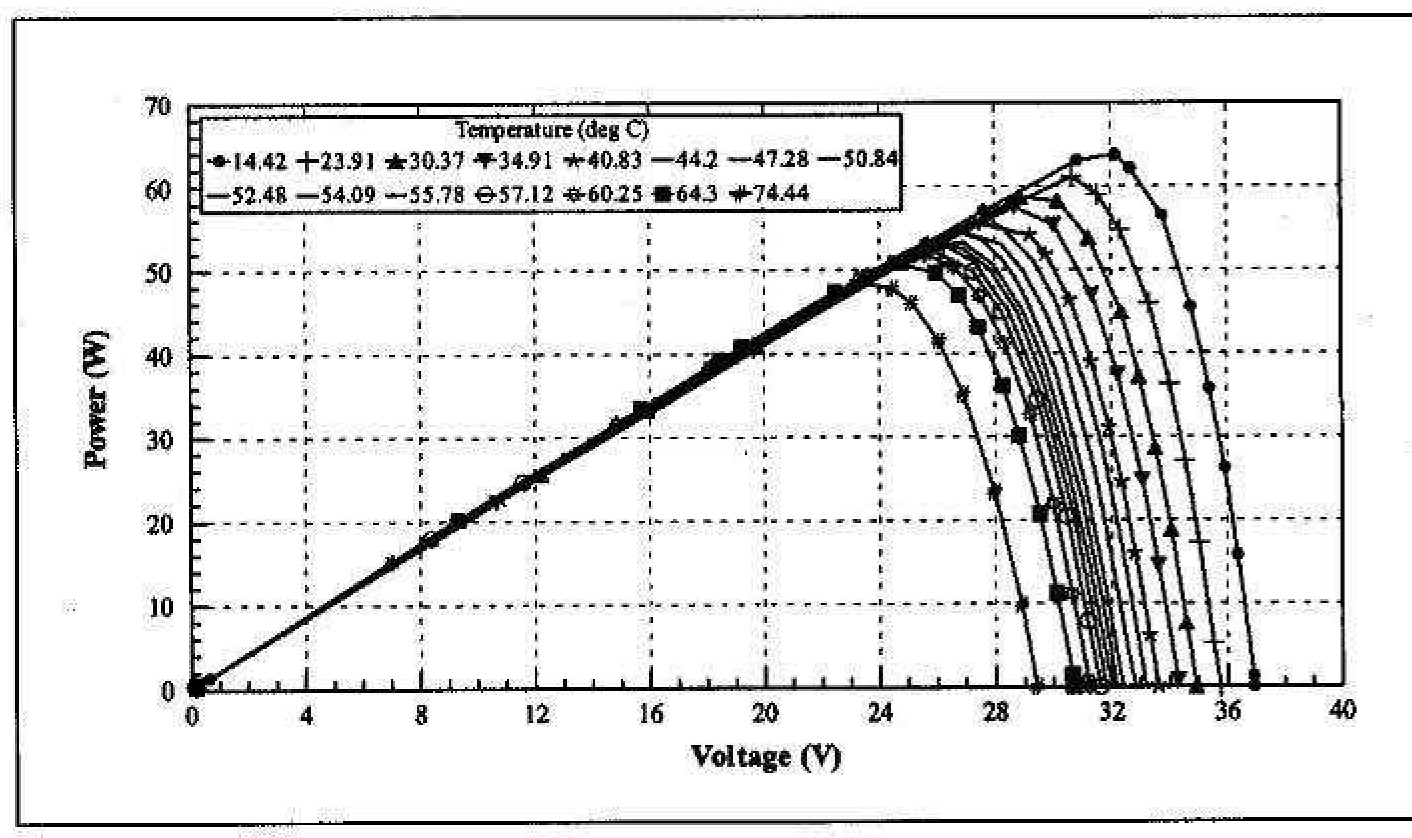

Figure 4 – Power Output from PV Module A

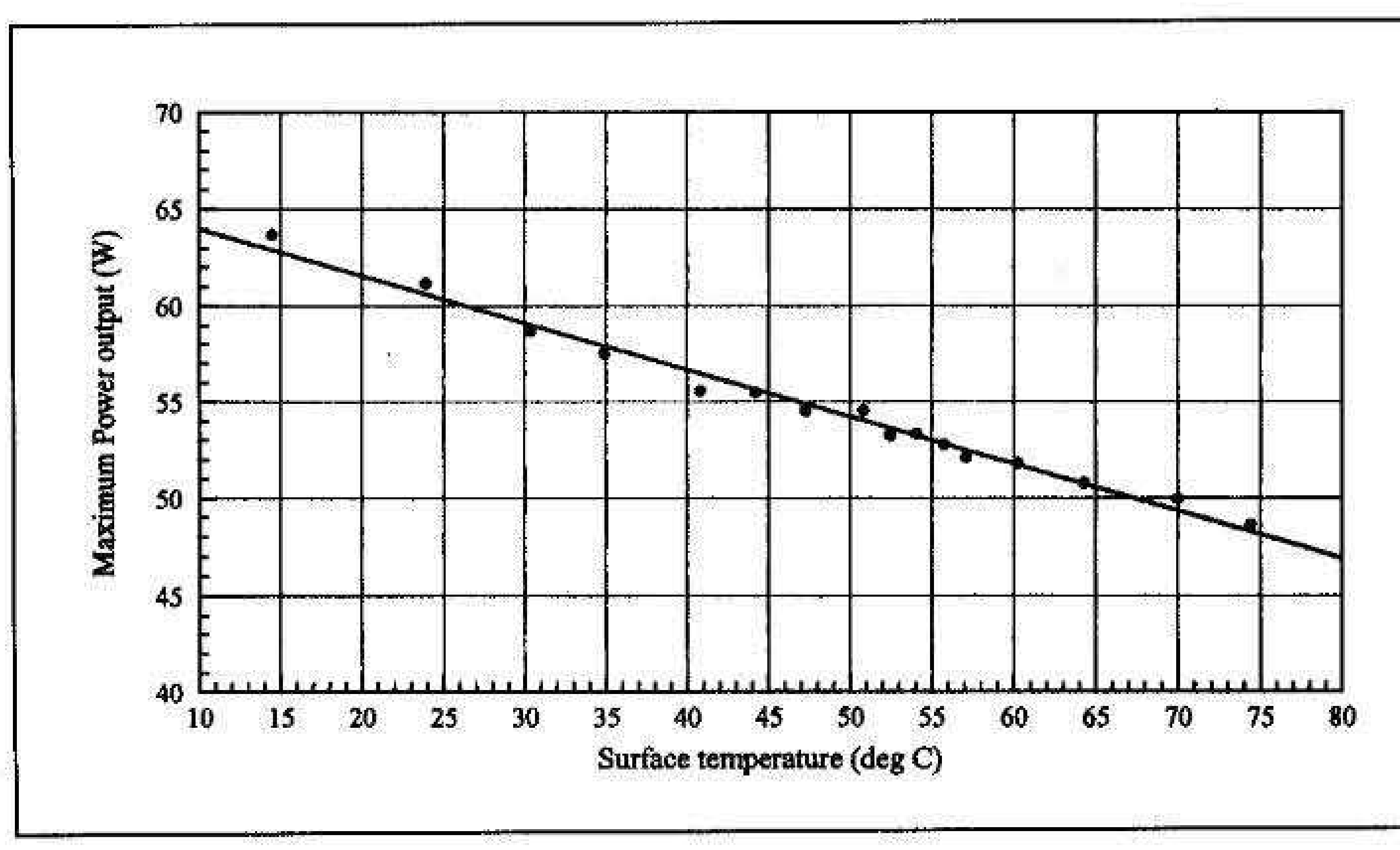

Figure 5 – Maximum Power Output vs PV Surface Temperature for PV Module A

in the p-n junction of the diode, and perform the output current and voltage for an external load at the terminal of the PV system. The additional series and parallel internal cell resistances are denoted by R_s and R_sh respectively. It is assumed that the current in the diode is dominated by the minority-carrier diffusion at each edge of the depletion regions, and by combining the transport equations with the one-dimensional continuity equations. The relationship of current-voltage of the PV module can be represented by:

$$I = I_L - I_s \{Exp [q(V + R_s I)/nkT_{cell}] - 1\} - (V + R_s I)/R_{sh} \quad (1)$$

where I_s is the diode saturation current. q is the electron charge(e), accompanied with an ideality factor n and Boltzmann's constant k. The diode saturation current can be written as [12]:

$$I_s = Aq [(D_p p_{no}/L_p) + (D_n n_{po}/L_n)] \quad (2)$$

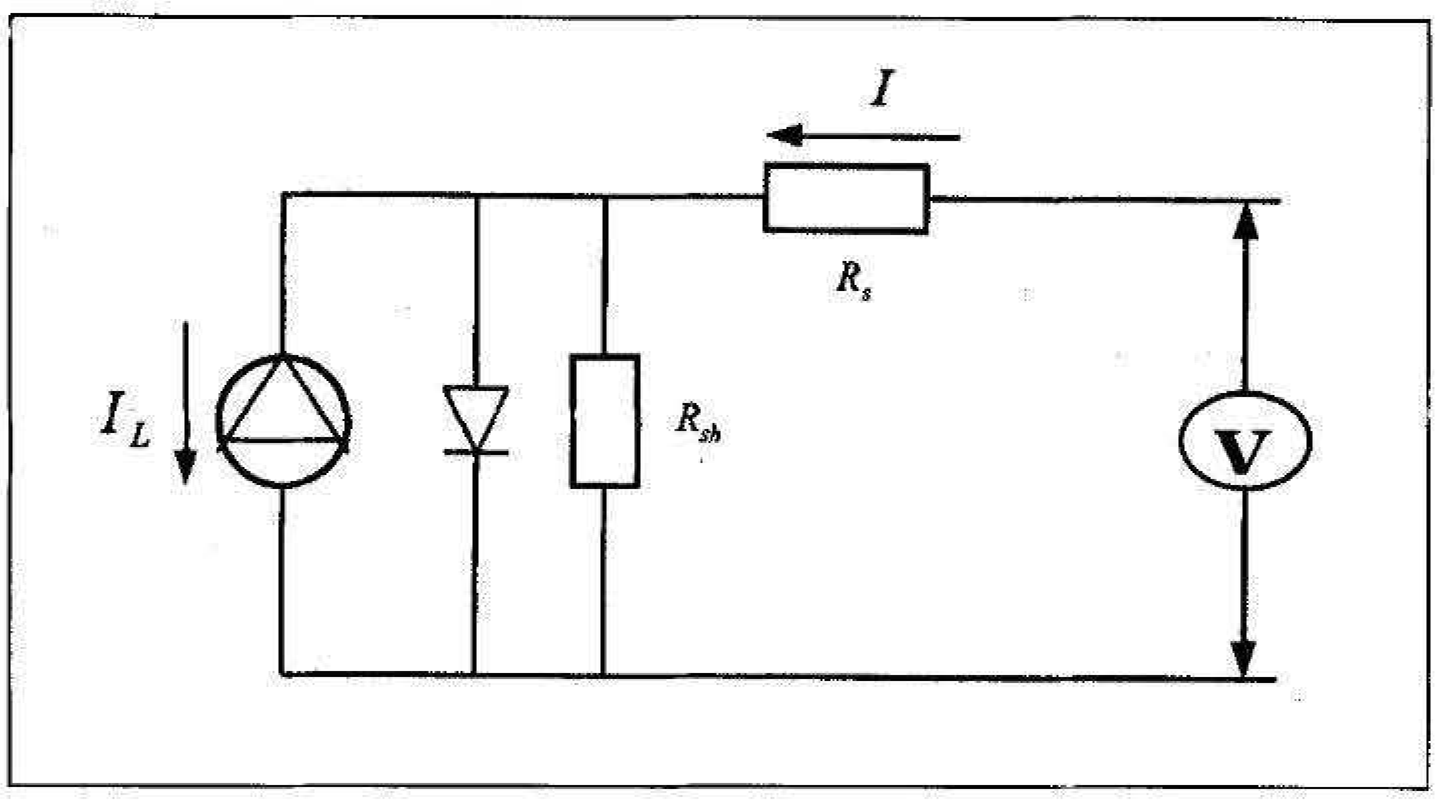

Figure 6 – Circuit Representation of a Solar Cell System

D_p is the diffusion coefficient for holes in the n region; D_n is the diffusion coefficient for electrons in the p region; P_{no} is the equilibrium concentration of holes in the n region; n_{po} is the equilibrium concentration of electrons in the p region; A is the total area; L_p and L_n are the diffusion lengths of holes and electrons, respectively.

From the macroscopic point of view, the saturation current can be measured through experiments. It is linked to the series and shunt resistance in the circuit. If the shunt resistance is neglected as reported by Flood [13], there might have led into a obvious mistake in the derivation of the expression for short circuit current. Thus, the effect of series resistance is neglected in this paper. Equation (1) becomes:

$$I = I_L - I_s\,[\mathrm{Exp}\,(qV/nkT_{cell}) - 1] - V/R_{sh} \qquad (3)$$

The output power of the device is simply written as:

$$P = IV = V\,\{\,I_L - I_s\,[\mathrm{Exp}\,(qV/nkT_{cell}) - 1] - V/R_{sh}\} \qquad (4)$$

Under short circuit condition, V = 0 and equation (3) becomes:

$$I_{SC} = I_L \qquad (5)$$

Actually under one sun condition, I_{SC} is essentially equal to I_L for low value of R_S. It is dominated by the incident solar radiation. From equation (1), the open circuit voltage is the solution of

$$I_{SC} = I_s\,[\mathrm{Exp}\,(qV_{oc}/nkT_{cell}) - 1] - V_{oc}/R_{sh} \qquad (6)$$

where I_L has again been approximated by I_{SC}. Regarding I_{SC} and V_{oc} to be the scale of current and voltage for normalization, the normalized relationship becomes

$$I^* = 1 - I_s^*\,[\mathrm{Exp}\,(qV_{oc}V^*/nkT_{cell}) - 1] - V_{oc}V^*/R_{sh} \qquad (7)$$

and the open circuit voltage V_{oc} can be expressed by

$$0 = 1 - I_s^*\,[\mathrm{Exp}\,(qV_{oc}/nkT_{cell}) - 1] - V_{oc}/R_{sh} \qquad (8)$$

The maximum output power P_{max} is evaluated when $\partial P/\partial V = 0$, i.e.

$$I + V\frac{\partial I}{\partial V} = 0 \qquad (9)$$

The above equation can be solved by Newtonian iteration. The final solution of iteration is denoted by V_{max} under which the PV module gives the maximum output. The substitution of V_{max} into equation (3) gives the relevant current I_{max}. Since the fill factor FF is defined by

$$FF = P_{max}/I_{SC}V_{oc} \qquad (10)$$

it can be represented by normalized variables:

$$FF = I^*_{max}V^*_{max} \qquad (11)$$

In order to find the parameters in equation (3), a conjugate gradient approach [14] [15] is used to minimize the objective function defined as

$$f\left(I^*_s,\ \frac{qV_{oc}}{nkT_{cell}},\ \frac{V_{oc}}{R_{sh}}\right) = \sum_1^M (I^* - I^*_m)^2 \qquad (12)$$

where M is the number of points of measured data; I^* and I^*_m are the normalized current listed and the current expressed by equation (7).

Validation Results

The experimental data are used to find the parameters in equation (7). The regression results are listed in Table 2.

Module	Equation	I_{max}	V_{max}	FF
A	$I^* = 1 - 3.378 \times 10^{-8}\,[\mathrm{Exp}(17.18V^*) - 1] - 3.25 \times 10^{-2}V^*$	0.91	0.83	0.76
B	$I^* = 1 - 9.314 \times 10^{-8}\,[\mathrm{Exp}(16.01V^*) - 1] - 15.11 \times 10^{-2}V^*$	0.83	0.82	0.68
C	$I^* = 1 - 3.685 \times 10^{-6}\,[\mathrm{Exp}(17.10V^*) - 1] - 2.179 \times 10^{-2}V^*$	0.91	0.84	0.77

Table 2 – Regression Results for the Three Modules

The normalized current and voltage for maximum output power of the PV modules are calculated by Newtonian iteration with an accuracy of $\varepsilon = 10^{-5}$ in terms of the above expression. One of the expressions is shown graphically in Figure 7 compared with test results marked by bullets. The above expressions fit the experimental curve with a r.m.s. deviation less than 5 percent.

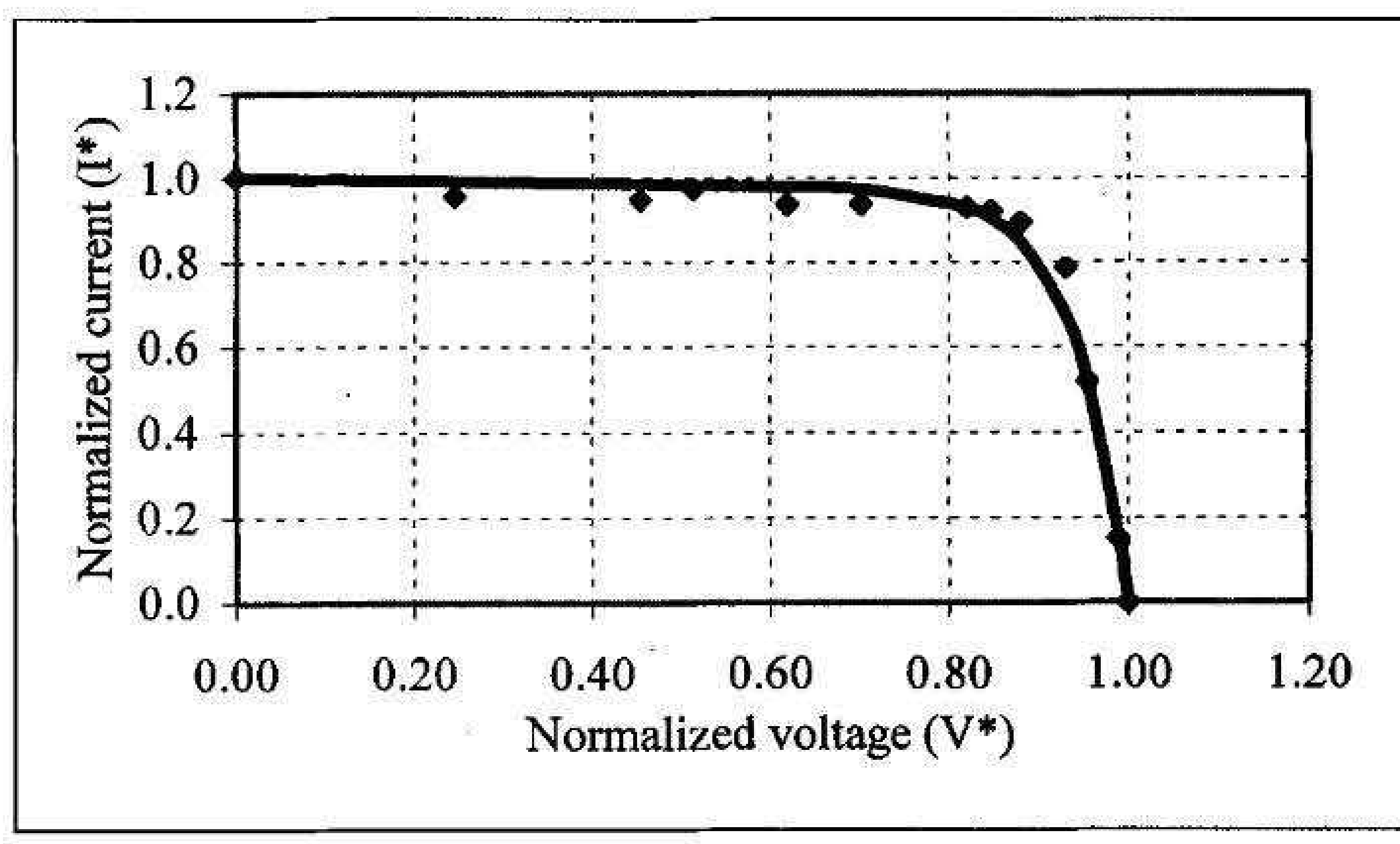

Figure 7 – Comparison between Regression and Test Results for Module A

It is found that an increase of solar irradiation causes a drop of fill factor, but not for a lift of saturation current. However, the short circuit current may be changed under different incident intensity of solar radiation. Observation finds that the open circuit voltage changes with the cell temperature and solar irradiation. Assuming that T_o and G_o are the referred cell temperature and solar irradiation, the maximum power output of the PV module can be written as:

$$P_{max} = I_{max}V_{max} = FF \times I_{sc}V_{oc} = FF \times I_{sc}\,(T_o)V_{oc}\,(T_o,\ G_o)(1+\delta_I)(1+\delta_v) \qquad (13)$$

where $\delta_I = a_1\delta G^* + a_2\delta G^{*2}$ (14)

and

$$\delta_v = b_1\delta G^* + b_2\delta G^{*2} + c_1\delta T^* + c_2\delta T^{*2} \qquad (15)$$

where $\delta G^* = (G - G_0)/G_0$ and $\delta T^* = (T_{cell} - T_0)/T_0$ are respectively the non-dimensional difference of solar irradiation and cell temperature. If $T_0 = 293.2\text{K}$ and $G_0 = 575.0\ \text{W/m}^2$, the regression for the empirical coefficients in term of the experimental data gives the results shown in Table 4. The r.m.s. deviation is less than 3.5 percent. The efficiency of a PV module becomes:

$$\eta = \eta_0 (1 + \delta_I)(1 + \delta_V) \quad (16)$$

where η_0 is the efficiency under reference conditions, given by

$$\eta_0 = \frac{FF \times I_{sc}(T_0) V_{oc}(T_0, G_0)}{AG_0} \quad (17)$$

where A is the area of the PV module.

Comparisons between the efficiency calculated by equation (16) and that of measurement are shown in Figure 8. It shows that the efficiency predicted by the model achieves good agreement with measured results. Module B is found to have the highest energy efficiency, and module A is in the middle, while module C gives the lowest one. There exists a trend that efficiency becomes lower as cell temperature increases. It shows that the effect of cell temperature on the efficiency is greater for stronger solar irradiation.

a_1	a_2	b_1	b_2	c_1	c_2
0.984	4.67×10^{-2}	5.69×10^{-2}	0	-1.13	0.524

Table 4 – Regression Results for δ_I and δ_V

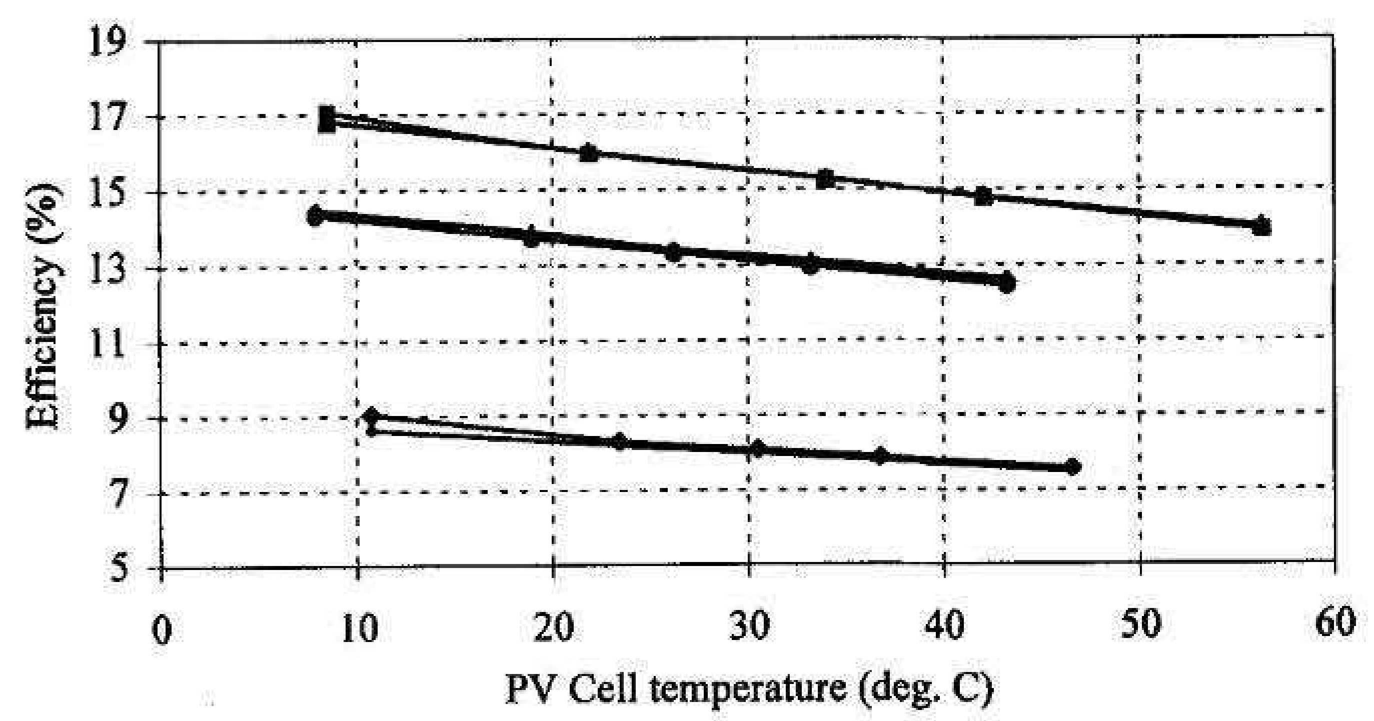

Figure 8 – Comparisons between Simulation and Test Results for the Three PV Modules

For constant solar irradiance, the relationship between the maximum power output and cell temperature can be approximated by a linear function:

$$P_{max} = a + b \times T_{ce} \quad (18)$$

The regression results are shown in Table 5 for the three PV modules. For PV module A, the gradient is 12% and 18.5% for PV module C, which mean that the reduction of power output is 0.12-0.18 W per degree C of PV cell temperature increase.

Figure 9 gives the computed relative energy efficiency of PV module A from the simulation model within the normal range of solar cell tempeature and solar irradiance.

Module	a	B	R	Solar irradiance (W/m^2)
A	66.42	-0.244	0.993	904.82
B	18.82	-0.083	0.985	980.20
C	44.57	-0.190	0.998	1022.21

Table 5 – Regression Results of Maximum Power vs Module Surface Temperature

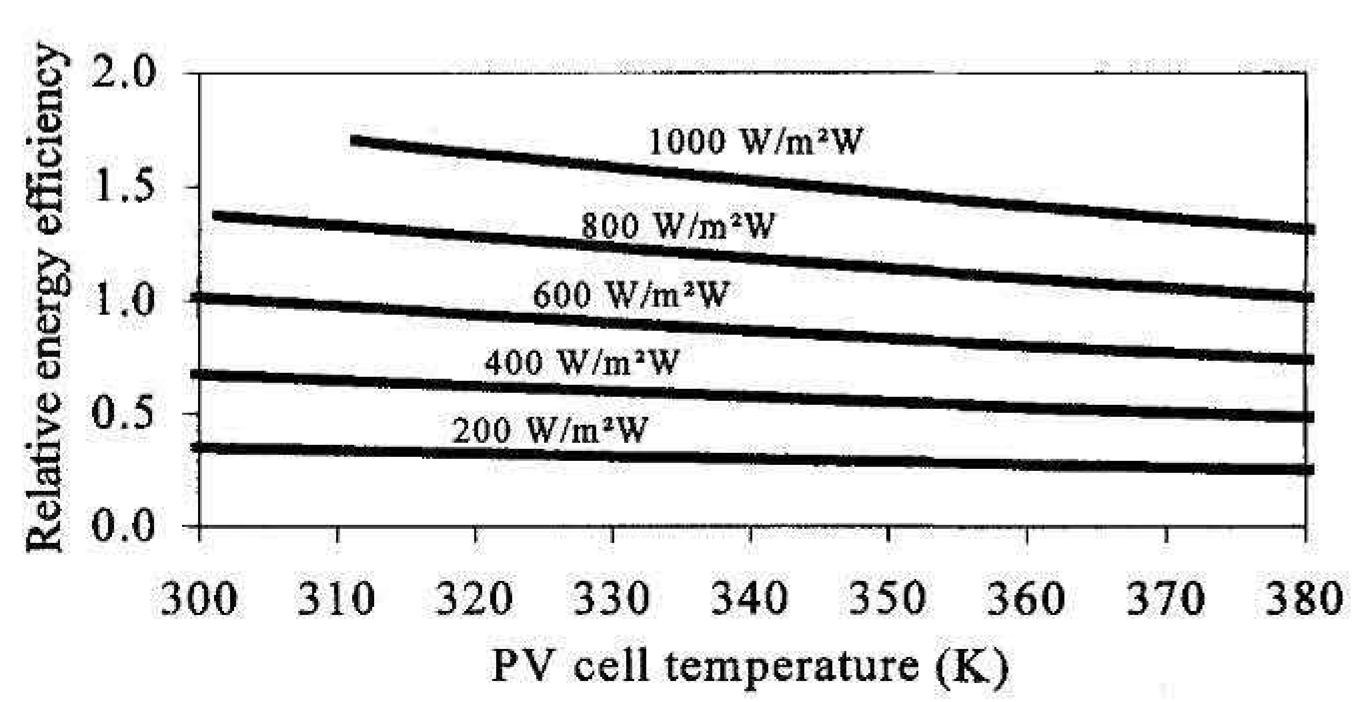

Figure 9 – Simulated Energy Efficiency vs PV Cell Temperature and Solar Irradiance

Conclusions

A macroscopic model has been developed to describe the performance of crystalline silicon PV modules. The parameters in the model can be obtained by limited experimental data. The model can be used to find the thermal and electrical characteristics for any solar cell temperature and solar irradiance. It is convenient for engineering application.

A simple expression with normalized parameters for energy efficiency is proposed. The non-dimensional differences of solar incident and cell temperature are used to represent the relevant variation of short circuit current and open circuit voltage duo to changes in environmental conditions.

A linear relationship has been found between the maximum power output from PV modules and PV cell temperature when incident solar irradiance is constant. It shows that for a temperature increase of 10°C the maximum power output reduces by 5% at a module temperature of 80°C when the solar irradiance is 904.82 W/m^2. That's the reason that research on thermal regulation on building-integrated photovoltaics is important for energy efficiency improvement of crystalline silicon PV module claddings.

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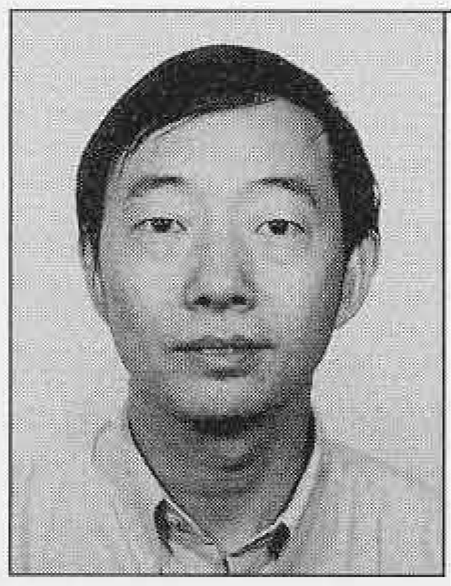

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