An Experimental Study of the Effect of Dust on Photovoltaic Power Generation Efficiency in a Tropical Climate

Yod Sukamongkol

Energy Engineering Program, Faculty of Engineering, Ramkhamhaeng University,
Ramkhamheang Rd., Huamark, Bangkapi, Bangkok, 10240, Thailand
Phone: +66 86 5625007 Email: yod_skm@yahoo.com

Abstract: This paper presents an experimental test along with procedures to investigate the effect of dust influences on the photovoltaic efficiency under the prevailing meteorological conditions in tropical climates. The reduction of the transmittance of solar radiation and electrical power generation due to the dust on a PV module has been measured. According to the observed results during a 30-day period, the dust accumulation reduces the glass cover transmittance from 89.8% to 74.9% and also results in the decrement of conversion efficiency from 4.78% to 4.07%. The comparisons between the experimental results and the simulated results used the same meteorological data as the experiment show that the predicted results simulated by the model agree satisfactorily with those observed from the experiments.

Keywords: Photovoltaic Module, Conversion Efficiency, Dust, Transmittance.

1. Introduction

Nowadays, solar energy is widely used in photovoltaic (PV) systems to generate electrical energy. Although there are many researches and developments in PV devices which are focused on studies of materials, components, designs and sizing of systems, the influence of the surroundings, especially the influence of dust, on the performance of PV modules has not been given much attention [1].

Dusts are solid particles of varying size from 1 µm to 1 mm which can be suspended temporarily in a gas. But they can settle down under gravity. The effect of dust on a PV module influences the efficiency of the PV module by decreasing the solar radiation incident on its surface. The transmittance of solar radiation through the dust varies from about 2% to 40% depending on the duration of dust accumulation, size and density of the dust particles, the air pollution level, season and location [2].

The main purpose of this study was to conduct an experimental test to investigate the PV's efficiency compared with a simulation model under the prevailing meteorological and operating conditions in our tropical climate. Performance indicators of the PV module which are the electrical energy generated by the clean module and the dust-coasted module are compared and discussed. The experimental test was done during the winter (November to December) in Ramkhamhaeng University, Bangkok, Thailand. The average dust particle size and density in the winter around the university's area were noted to be about 50-70 µm and 90-120 µg/m^3, respectively [3].

2. The Photovoltaic Module Model

A Photovoltaic cell is a device that can produce an electric current when the sunlight is incident on it. When the light hits the surface of the module, it may be reflected, transmitted or absorbed by the PV cell to converting photon energy to electrical energy. Photons give their energy to electrons based on the conservation of momentum and energy principles to produce the photovoltaic effect [4].

Normally, a PV system operates in the clamped voltage mode. The output voltage of the PV module is fixed at the system's operating voltage which is usually equal to the battery voltage. The output current of the PV array consisting of several PV modules can be expressed as [5]:

$$I_p = MI_l - MI_o \left[\exp\left(\frac{q\left(NV + \frac{I_p R_s N}{M} \right)}{NAkT_p} \right) - 1 \right] - \left[\frac{NV + \frac{I_p R_s N}{M}}{\frac{NR_{sh}}{M}} \right] \tag{1}$$

The reverse saturation current, I_o, is a small current flowing back through the PV arrays all the time. To estimate this current, an exponential expression which is a function of cell temperature is used.

$$I_0 = BT_p^3 \left[\exp\left(-\frac{E_{go}}{kT_p} \right) \right] \tag{2}$$

I_l depends on the incident radiation, G_i, on the module which can be expressed as [6]

$$I_l(G_i) = \left(\frac{G_i}{G_0} \right) I_l(G_0) \tag{3}$$

The conversion efficiency of the PV cell can be formulated as following:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_p \cdot V}{A_p \cdot G} \tag{4}$$

3. Effect of Dust on the Transmittance of the Glass Cover

Generally, the transmissivity, τ, is a measure of the ability of medium to transmit the light; the total transmissivity can be expressed as [7]

$$\tau = \frac{G_b}{G_a} \tag{5}$$

When dust is coated on the module's surface, it will block the sunlight passing through the glass cover onto the PV cell. This reduces the transmittance coefficient as well as the solar radiation. One of the earliest researches, Garg [8] found that after a glass sheet was exposed for 30 days, its transmittance was reduced from 90% to about 45% at the tilt angle 15° and to about 8% for angle 45°. He noted that the horizontal glass receives more dust than a vertical glass and he also defined the ratio of the transmittance of an uncleaned cover (τ_u) to that of the cleaned cover (τ_c) as the dust correction factor (DC). Next, Duffie and Beckman [9] reported that the influence of dust on the solar collector reduces the radiation intensity by 2% in dry climates whilst Al-Hasan et.al. [10] presented the effect of dirt on beam radiation and also estimated the transmittance coefficient

as a function of incident angle, the dust density, and the number of particles.

Recently, the influences of dust on the transparent cover of solar collectors were discussed by Hamdy K. et-al. [11] while Mastekbayeva et-al. [12] focused on the transmittance of a low density polyethylene (LDPE) glazing used commonly in solar collectors. Moreover, Mastekbayeva also developed the dust correction factor model for the uncleaned cover sheet inclined at 15° (DC_{15}) from the horizontal at Bangkok for a month which can be described by the following equation

$$DC_{15} = 0.0001 \cdot N_d^2 - 0.0082 \cdot N_d + 0.999, \ 0 \le N_d \le 30 \qquad (6)$$

In general, the dust correction factor can be applied to estimate the incident solar radiation, G_i, on the PV module by

$$G_i = (\tau\alpha)G \cdot DC \qquad (7)$$

4. Experimental Setup and Test Procedure for Model Validation

4.1 Experimental Setup

To ensure that the system simulation model discussed above is acceptable, the predicted results operating under the same meteorological and operating conditions as the experimental results must be compared.

The experimental system in this study consists of two 50 × 50 cm^2 glass sheets and two a-si 40W$_p$ PV modules with area 0.625 × 1.245 m^2. One glass sheet and one PV module of each pair were cleaned everyday while the others were left uncleaned to observe the transmittance and the conversion efficiencies due to the dust accumulation during the test. The panels were installed at the top of the LTB Building, Faculty of Engineering, Ramkhamhaeng University, Bangkok, Thailand, with a tilt angle of 15° facing to the south. The solar radiation above and below the cleaned and the uncleaned glass sheets were measured to calculate the transmittance of the glass. The electrical power generated by the PV modules was delivered to the resistance load to keep a constant output voltage.

4.2 Experimental Test Procedures

The experimental test on the system was conducted under the prevailing outdoor conditions for thirty consecutive days. The actual meteorological data observed during the experiment were used as input parameters for the simulation model. Pyranometers were used to measure the total solar irradiance falling above and below the surface of the glass sheet and on the PV modules. Ammeters and voltmeters measured the currents and voltages generated by the PV modules. An outdoor wind anemometer was used to measure the wind speed V_{wind} while the ambient temperatures, T_a, were measured by type-K (Copper-Constantine) thermocouple sensors. All these sensors were directly connected to the data-logger. The data-logger logged all the experimental data every ten seconds and stored the average values for every five minutes of data in the data storage.

5. Results and Discussions

The observed prevailing variations of the solar irradiance, G, and ambient temperature, T_a, of the first days are shown as a sample data in figure 1. These metrological data are used as the input of the simulation model.

The comparison between the corresponding values of PV generated electrical power, P_e, simulated by the model and those measured from the experiment are also shown in this figure. The fluctuations are caused by the prevailing variations of solar irradiance. The simulated generated power is reasonably close to the observed power except for some discrepancies at times of high solar irradiance. The variations of P_e may result from either the overestimation of the solar absorptivity of the solar cell or the underestimation of the heat convective coefficient between the module and the wind. Therefore, the predicted P_e is found to be higher than the actual value at high solar irradiance. These results are similar to those studied by Sukamongkol et-al. [5].

The solar radiation above and below the glass cover sheet are measured to determine the transmittance of solar radiation through the glass cover as defined in eq (5). The determined transmittances of the clean and uncleaned sheet are shown in figure 2. It is seen that the transmittance of the clean sheet was slightly variable around 90% while the transmittance of the uncleaned sheet was reduced from 89.8% to 74.9% after 30 days of exposure.

This figure also present the values of the predicted results of the dust correction factor in comparison with the factors determined from observed data. The results show that the model predicted values are fairly close to the experimental data with the same pattern decreasing from 1.00 to 0.84. These results agree with those observed by Mastekbayeva et al. [12].

Figure 3 shows the daily data of the observed total global radiation and the comparison between the total electrically generated power simulated by model and the measured power. The total solar radiation values are in the range of 17.5 – 21.5 MJ/m^2. For the clean module, the fluctuations of generated power, which vary from 0.68 to 0.83 MJ, are directly caused by the prevailing variations of solar irradiance. For the uncleaned module, the dust accumulation on the surface of the module
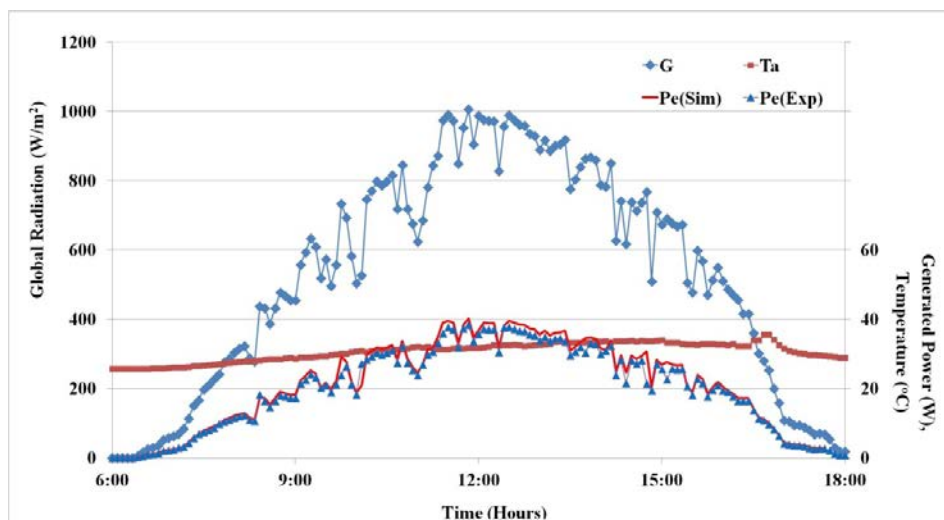

Figure 1. Variation of Metrological Data and the Predicted and Observed Variations of Generated Power.

reduces the solar radiation transmittance that leads to the reduction of generated power by the PV module. With the same solar radiation input, the simulation model predicted the reduction curve of generated power with the same pattern fluctuations as those of the clean one. The differences between the values of generated power by the clean and uncleaned modules are 0.03, 0.07 and 0.11 MJ for 7, 15 and 30 days of exposure, respectively. It is clearly shown in the graph that the simulated and observed results are good agreement with each other.

The conversion efficiencies of the clean PV module between 4.78 % to 4.92% and the decrement of the uncleaned module efficiencies from 4.78% to 4.07% are presented in figure 4. This figure also displays the conversion efficiency reduction curve of the PV module. It is seen that more exposure days make more efficiency reduction due to the presence of more dust settled on the module's surface. Both the predicted and the measured results show that the efficiency reduction rises from 0.2% on the first day up to 4.98% on the seventh day. Similarly, it continually increases from 4.98% to 9.63% and almost 15% on the fifteenth and thirtieth days, respectively. Therefore, it can be concluded that fairly good agreement can be achieved between the predicted results and those observed from the experiment.
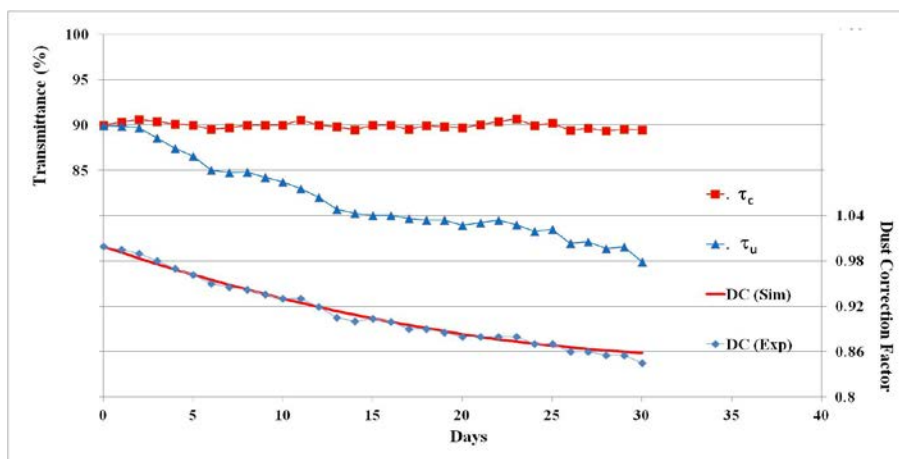

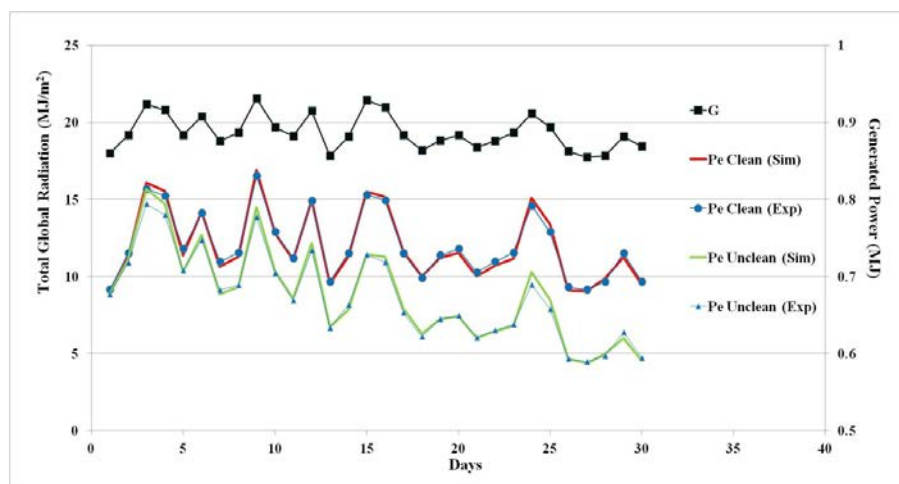**Figure 2.** Predicted and Observed Variations of Transmittance and Dust Correction Factor.

Figure 3. Variation of Daily Total Global Radiation Data and the Predicted and Observed Variations of Generated Power.
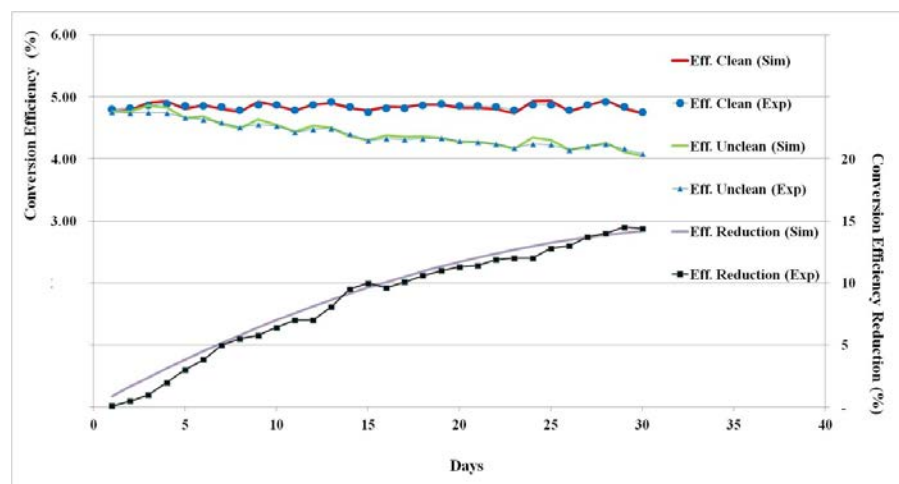

Figure 4. Predicted and Observed Variations of Conversion Efficiency and Conversion Efficiency Reduction.

5. Conclusion

It can be concluded from the experimental validation results that the simulation model developed is able to predict the performance of clean and uncleaned PV modules within acceptable limits of accuracy. In fact, the discrepancies which appeared in the predictions of the generated power can be minimized if the estimated values of the solar absorptivity of the module and the heat convective coefficient between the wind and the PV module are more precisely pre-determined. Next, the dust accumulation results in the reduction of the transmittance from 89.8% to 74.9% leads to the decrement of dust correction factor from 1.00 to 0.84 after 30 days of exposure. With this consideration, the conversion efficiency reduction curve of PV module rises up to 4.98%, 9.63% and 14.63% on the seventh, fifteenth and thirtieth days, respectively. These efficiency reductions lead to the lower PV power generation. Therefore, it is recommended that the PV modules in an operating PV system should be cleaned from time to time to keep the high power generation with high PV conversion efficiency. Finally, the author suggests that the further study should include a longer time including outdoor conditions of each season, a variety of locations, different types of PV module and tilted angles of the module installation.

6. Nomenclature

A = diode ideality factor, A_p = module area (m^2), B = PV material constant, E_{go} = band gap energy at 0 K (1.16eV for silicon), G = solar radiation (W/m^2), G_a = solar radiation above the medium (W/m^2), G_b = solar radiation below the medium (W/m^2), G_0 = reference solar radiation (1kW/m^2 at AM1.5), I_p = output current of panel (A), I_l = light generated current per module (A), $I_l(G_0)$ = light generated current at G_0 (A), I_o = reverse saturation current per module (A), M = number of module strings in parallel, N = number of modules in each series string, N_d = number of exposure days V = terminal voltage (V), R_s = diode series resistance per module (ohms), R_{sh} = diode shunt resistance per module (ohms), T_p = cell temperature (K), q = electric charge, k = the Boltzmann constant (1.38x10^{-23} J/K) and α = absorbance

Reference

[1] Mekhilefa S, Saidurb R, Kamalisarvestanib M, Effect of dust, humidity and air velocity on efficiency of photovoltaic cells, *Renewable and Sustainable Energy Reviews*, 16 (2012) 2920-2925.

[2] Hegazy AA, Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors, *Renewable Energy* 22 (2001) 525-540

[3] Premanoch P, A Study of Noise Pollution and Total Suspended Particulate Levels in Ramkhamhaeng University (Huamark), *Ramkhamhaeng Research Journal of Science and Technology* 13 (2010) 27-37

[4] Neamen D, *An Introduction to Semiconductior Devices* (2006) McGraw Hill, USA.

[5] Sukamongkol Y, Chungpaibulpatana S, Ongsakul WA, Simulation Model for Predicting the Performance of a Solar Photovoltaic System with Alternating Current Loads, *Renewable Energy* 27 (2002) 237-258.

[6] Messenger RA, Ventre J, *Photovoltaic system engineering* (2004) CRC.

[7] Incropera FP, DeWitt DP, Bergman TL, Lavine AS, *Fundamental Heat and Mass Transfer* (2007) 6th ed., *John Wiley&Sons.*

[8] Garg HP, Effect of dirt on transparent covers in flat-plate solar energy collectors, *Solar Energy* 15 (1974) 299-302.

[9] Duffie JA, Beckman WA, *Solar Engineering of Thermal Processes* (2013) John Wiley & Sons, 4nd Ed., USA.

[10] Al-Hasan AY, A new correlation for direct beam solar radiation received by photovoltaic panel with sand dust accumulated on its surface, *Solar Energy* 63 (1998) 323-333.

[11] Hamdy KE, Ahmed EG, Hamid RH, El-Hussainy F, Effect of dust on the transparent cover of solar collectors, *Energy Conversion and Management*, 47 (2006) 3192–3203.

[12] Mastekbayeva GA, Kumar S, Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate, *Solar Energy* 68 (2000) 135-141.