EFFECT OF DUST DEPOSITION ON THE PERFORMANCE OF PHOTOVOLTAIC MODULES IN CITY OF TAXILA, PAKISTAN

by

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The air borne dust deposited on the surface of photovoltaic module influence the transmittance of solar radiations from the photovoltaic modules glazing surface. This experimental work aimed to investigate the effect of dust deposited on the surface of two different types of photovoltaic modules (monocrystalline silicon and polycrystalline silicon). Two modules of each type were used and one module from each pair was left exposed to natural atmosphere for three months of winter in Taxila, Pakistan. Systematic series of measurements were conducted for the time period of three months corresponding to the different dust densities. The difference between the output parameters of clean and dirty modules provided the information of percentage loss at different dust densities. The dust density deposited on the modules surface was 0.9867 mg/cm² at the end of the study. The results showed that dust deposition has strong impact on the performance of photovoltaic modules. The monocrystalline and polycrystalline modules showed about 20% and 16% decrease of average output power, respectively, compared to the clean modules of same type. It was found that the reduction of module efficiency ($\eta_{\rm clean} - \eta_{\rm dirty}$) in case of monocrystalline and polycrystalline module was 3.55% and 3.01%, respectively. Moreover the loss of output power and module efficiency in monocrystalline module was more compared to the polycrystalline module.

Keywords: *photovoltaic modules, effect of dust, efficiency reduction, outdoor evaluation*

Introduction

During the last few decades, the demand of non-conventional energy resources has increased to generate power (electricity) due to limited conventional resources (fossil fuels). Renewable energy is the best alternative of conventional energy resources for the production of clean energy. Among the renewable energy resources, solar energy is the permanent and abundant energy source.

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Photovoltaic (PV) module receives energy from Sun radiations and converts it directly into electricity. The performance of PV modules depends upon the geographical factors (longitude, latitude, and solar intensity), the environmental factors (temperature, wind, humidity, pollution, dust, rain, *etc.*) and the type of PV technology used. From the previous research, it can be found that PV modules have particular behavior in specific climates. Bashir *et al.* [1] investigated the performance of three commercially available PV modules in the winter conditions of Taxila, Pakistan. Monocrystalline PV module showed highest module efficiency. The output of PV modules showed great dependency on the solar irradiance and module temperature. Ali *et al.* [2] found that module efficiency for monocrystalline and polycrystalline modules in summer was 19.8% and 18.7% lower, respectively, compared to winter season in Taxila. Ulfat *et al.* [3] found that there are 3000-3300 annual sunshine hours in Pakistan. The most areas of Pakistan have about average of 7-8 daily sunshine hours [4]. So the solar energy is most suitable energy source for Pakistan.

Dust is major environmental factor which affect the module performance. Kaldellis *et al.* [5] investigated the effect of dust on PV modules and found that efficiency of PV module was decreased up to 0.4% as dust density increased to 0.09 mg/cm^2. Rajput and Sudhakar [6] studied the behavior of PV modules with dust deposited on their surfaces. Results showed that power and efficiency of module decreased up to 92% and 89%, respectively, compared to clean modules. Jiang *et al.* [7] investigated the impact of airborne dust deposition on the performance of PV module inside the laboratory under the controlled conditions in a test chamber. Dust was uniformly distributed on the panel surface with the help of a fan. It was concluded that efficiency of PV module reduced to 26% as mass of dust increased to 22 g/m^2. Adinoyi and Said [8] found the effect of dust on the performance of PV modules in Saudi Arabia. After the six month exposure to the natural environment, 50% reduction in power of PV modules was examined. Similarly Cabanillas and Munguia [9] found that with the increase of dust to 2.326 mg/cm^2 in 20 days, the reduction in power was 6% for crystalline silicon module and 13% for amorphous silicon module. Kumar *et al.* [10] determined the impact of dust on performance of PV modules by conducting experiment on 96 cm^2 photovoltaic panels with maximum power of 302 mW. It was found that the decrease of energy conversion efficiency was 10%, 16%, and 20% with increasing of the dust density 0.1 g, 0.2 g, 0.3 g, respectively. Mohamed and Hasan [11] examined the dust accumulation on the surface of four polycrystalline modules and found 50% decrease in the PV efficiency. An indoor study was conducted by Sulaiman *et al.* [12] to determine the influence of dust on the PV modules. The reduction of modules efficiency was 18.1% and 16.5% using mud and talcum, respectively. Benatiallah *et al.* [13] and Bouchalkha [14], also reported the decrease of module output power with increase of dust density on the surface of PV modules. From the previously mentioned literature, it can be conclude that dust deposition on the PV module surface has a major effect in the reduction of output power and it should not be neglected in module performance measurement.

For dust effects, the type of dust is an important factor. Some researchers reported the effect of natural pollutants like wind induced soiling while other used artificial dust for laboratory experiments. El-Sobokshy and Hussein [15] used five kinds of dust having different properties. Three of them were limestone particulates with different classes and the other two were cement and carbon particulates. The effect of particle size was investigated and found that fine particulate dust has a greater impact on performance of PV panels than coarser particles. Kaldellis *et al.* [16] analyzed the dust effect on the performance of PV systems in Athens, Greece. The effect of dust was studied using three different pollutants, red soil, limestone, and carbonaceous fly-ash particles. It was found that there was a 6% reduction on PV performance with carbonaceous fly-ash, 10% with limestone, and 19% with red soil. Al-Hasan [17], Goossens and Van Kerschaever [18] used sand and soil dust particles as pollutant, respectively.

Present study investigates the effect of dust on the performance of PV modules in Taxila, Pakistan. Due to the fact that Taxila is surrounded by the cement industries, the effect of dust on PV modules cannot be ignored.

Methodology and experimental set-up

The effect of dust was investigated by using four commercially available photovoltaic modules of two different types, two monocrystalline (c-Si) and two polycrystalline (p-Si) silicon modules. The panels were placed on the roof top of Mechanical Engineering Department, UET Taxila (Latitude 33.74 N and 72.83 E) on a rack facing towards south with a fixed tilt angle of 50°, fig. 1.

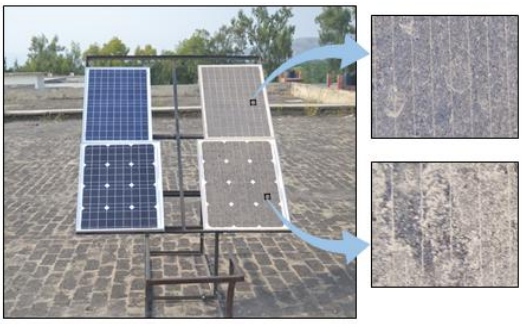

Figure 1. The PV modules used in the study with dust deposited on dirty modules surfaces after 11 weeks

The manufacturer rated power of each module was 42 W. The manufacturer rated values of modules are shown in tab. 1. During the study, one module of each type was remained in outdoor atmosphere for three months to accumulate dust naturally on the panel surface (these modules are named as *dirty* modules). The effect of dust was determined by comparing the output parameters of clean and dirty modules. The density of dust was measured by weighing the dust deposited on the glass sheet placed near to the panels using digital weight balance. The difference between weight before and after the dust deposited on sheet provided the information about dust density deposited on the area of panel. To avoid the dew factor at night, the set-up was covered by a shade (1 m above the panels) with all sides open which was removed during day time. The voltage and current of each module were measured simultaneously with the help of *I-V* and *P-V* curves. Two digital multimeters (Fluke 179, true RMS, accuracy: +1% for DC current and + 0.09% for the DC volt) along the variable resistance (100 W) were

Table 1. Characteristic specifications and measured values of photovoltaic modules

	c-Si		p-Si	
The PV modules dimensions				
Module dimen. (mm × mm)	690 × 540		690 ×455	
Cell dimen. (mm × mm)	156 × 52		156 × 45	
No. of cells (in series)	12		4 × 9	
Total cells area (m²)	0.292		0.2527	
Rated values at STC	Clean	Dirty	Clean	Dirty
Max power, P_{max} [W]	42.31	42.29	41.89	41.89
Max current, I_{max} [A]	2.31	2.33	2.55	2.46
Max voltage, V_{max} [V]	18.38	18.21	18.16	18.23
Short circuit current, I_{sc} [A]	2.69	2.7	2.32	2.33
Open circuit voltage, V_{oc} [V]	23.07	22.97	22.84	22.83
Temp. coeff. of I_{sc} [%°C^{-1}]	0.06	0.06	0.06	0.06
Temp. coeff. of V_{oc} [%°C^{-1}]	–0.38	–0.38	–0.36	–0.36
Temp. coeff. of P_M [%°C^{-1}]	–0.47	–0.47	–0.5	–0.5
Average measured values of 11 weeks				
Avg. global solar Irradiance [Wm^{-2}]	774.7	774.7	774.7	774.7
Avg. module power [W]	27.39	21.99	25.51	21.79
Avg. module efficiency [%]	12.07	9.59	13.05	11.2

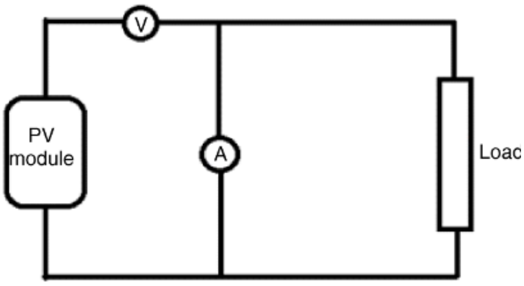

Figure 2. Schematic diagram of the circuit

used for this purpose as described by [19]. The schematic diagram of circuit is shown in fig. 2. The maximum power was calculated using measured maximum current and maximum voltage:

$$P_{\max} = I_{\max} \cdot V_{\max} \tag{1}$$

The pyranometer was used to measure the global solar irradiance having sensitivity 11.346 μV/Wm^{-2} and spectral range of 280-3000 nm, connected to the solar radiation monitoring system which records and store the reading after every minute. Following relation was used for the calculation of module efficiency:

$$\eta_{\text{module}} = \frac{P_{\max}}{GA} \tag{2}$$

$$\% \text{ reduction in output power} = \frac{P_{\text{clean}} - P_{\text{dirty}}}{P_{\text{clean}}} 100 \tag{3}$$

$$\% \text{ reduction in module efficiency} = \frac{\eta_{\text{clean}} - \eta_{\text{dirty}}}{\eta_{\text{clean}}} 100 \tag{4}$$

The data was recorded for twice in a week (mostly sunny days) for three months (11 consecutive weeks) at 9 a. m., 12 a. m., and 3 p. m. The dust effect was investigated by measuring the module parameters after the direct atmospheric exposure.

A sample of air borne dust was collected and tested using hydrometer method to find the composition of dust at Soil Test Laboratory of University of Engineering and Technology, Taxila. There was 32% fine sand (diameter > 0.06 mm), 60% silt (diameter 0.06 – 0.002 mm), and 8% clay (diameter < 0.002 mm).

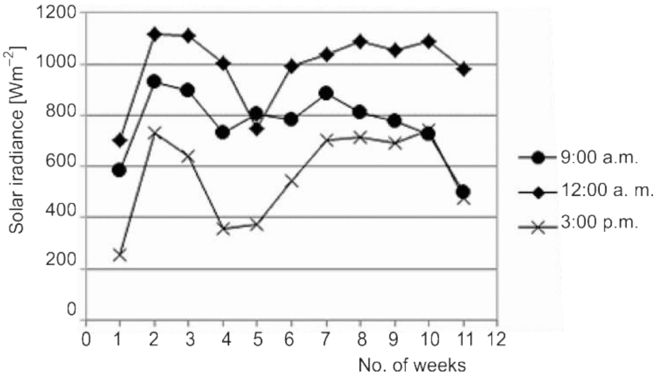

Figure 3. Weekly average solar irradiance at 9:00 a. m. 12:00 a. m., and 3:00 p. m.

Results and discussion

The air borne dust deposited on the surface of PV module influence the transmittance of solar radiations from the PV modules glazing surface. The result is the significant decrease of output power and module conversion efficiency. Figure 3 shows the average weekly solar irradiance for the duration of this study. Most of the selected days (2 per week) were sunny over the 11 weeks. Table 2 compares the average monthly irradiance at 9 a. m., 12 a. m., and 3 p. m. with the already reported average irradiance for these months [20]. A good comparison can be seen.

Table 2. Comparison of measured average global normal solar irradiance with Akhter *et al*. [20]

Average global normal solar irradiance [Wm^{-2}] of clear sky days measured in this study									
	November			December			January		
Time	09:00 a. m.	12:00 a. m.	03:00 p. m.	09:00 a. m.	12:00 a. m.	03:00 p. m.	09:00 a. m.	12:00 a. m.	03:00 p. m.
Average measured values	756.17	984.25	595.13	819.5	967.13	583.5	667.17	1004.05	636.5
Akhter *et al*. [20]	788	890	779	697	842	736	730	941	819

Effect of dust on the output power of PV modules

The output power of PV modules varies linearly with the solar irradiance [19]. Over the period of study, the output power of modules decreased continuously due to dust accumulation. As the dust layer on the surface of PV module became thicker, the loss of module output power and efficiency became higher. The density of dust accumulated on the surface of the panels was 0.9867 mg/cm^2 after 11 weeks of environmental exposure. Figure 4 shows the module efficiency of each pair of modules at outdoor conditions before the start of the experimentation. It can be seen that difference of module efficiency between the modules of same type is very small (<1%).

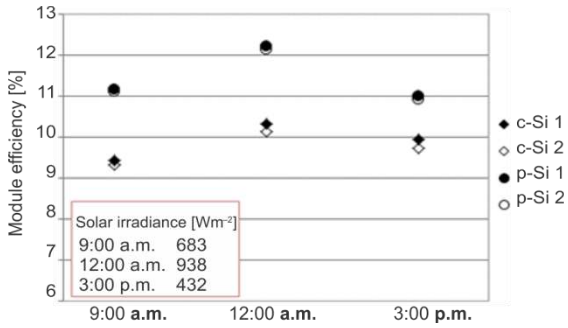

Figure 4. Module efficiency of modules at outdoor conditions before the start of the experimentation

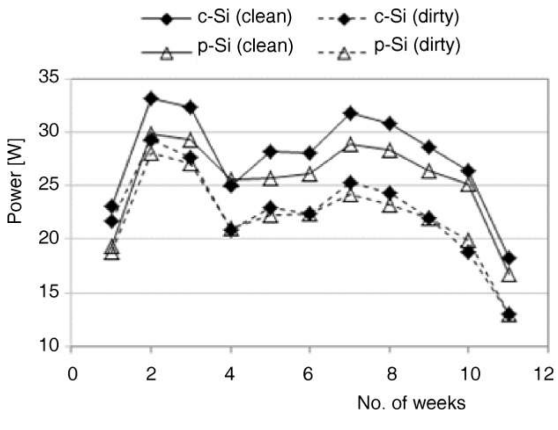

Figure 5. Variation of weekly average output power of c-Si and p-Si modules at 9 a. m.

Figure 5 shows the variation of weekly average output power of the clean and dirty PV modules at 9 a. m. Initially, after one week, both the modules (clean and dirty) have shown a small difference in the output power (about 5% for c-Si and 3% for p-Si modules). With the passage of time, the output power of dirty module gradually decreased compared to the clean module due to the dust deposition on its surface. Similar trends of weekly average power reduction can be seen at 12 a. m. and 3 p. m. as shown in figs. 6 and 7, respectively. It can be seen from figs. 5-7 that during the weeks 1, 4, 5, and 11, the average output power of all modules were lower than the other weeks, which was due to the fact that most of these reading days were cloudy. At 9 a. m., the c-Si and p-Si PV module with dust deposition, showed 18.7% and 14.1% less output power, respectively, compared to the clean module of same type

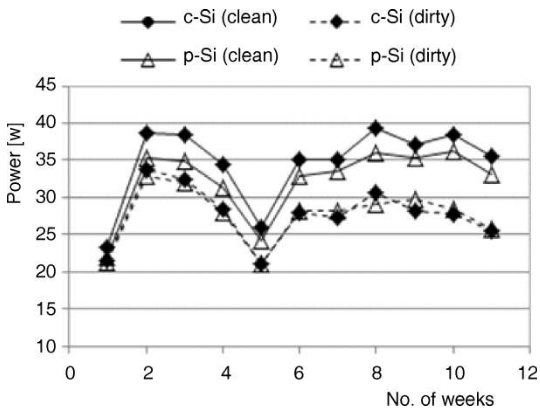

Figure 6. Variation of weekly average output power of c-Si and p-Si modules at 12 a. m.

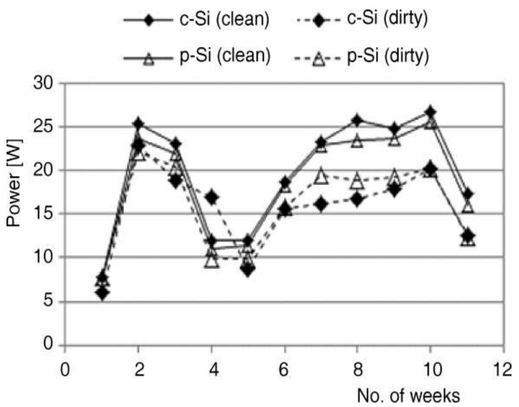

Figure 7. Variation of weekly average output power of c-Si and p-Si modules at 3 p. m.

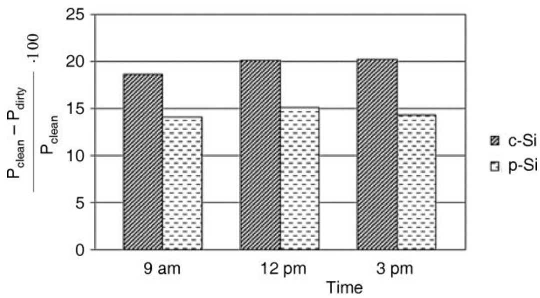

Figure 8. Average percentage reduction of output power of dirty modules (c-Si and p-Si) compared to the clean module of same type

after 11 weeks as shown in fig. 8. At 12 a. m., the output power of modules was much higher due to high solar irradiance. c-Si and p-Si PV modules at 12 a. m. showed 20.2% and 15.2% less output power, respectively compared to their clean modules (as shown in fig. 8). At 3 p. m., the reduction of output power for c-Si and p-Si module was 20.8% and 14.2%, respectively, fig. 8. It was found that c-Si PV module showed higher output power than p-Si module and showed higher per centage reduction of output power due to dust deposition on its surface.

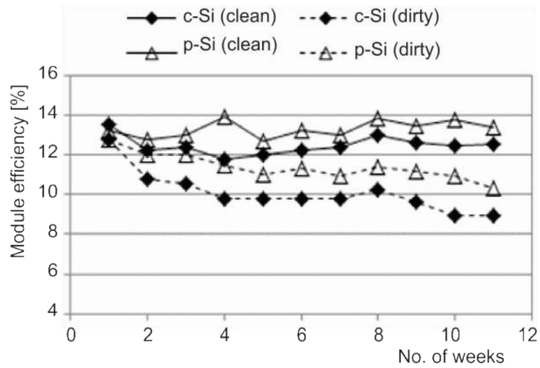

Figure 9. Variation of weekly average module efficiency of c-Si and p-Si modules at 9 a. m.

Effect of dust on the module efficiency of PV modules

The module efficiency depends upon the output power of PV module and solar irradiance and it degrades with the dust accumulation on PV module surface. The module efficiency showed an inverse relation with the solar irradiance and module temperature [19].

At the beginning, the module pair of same type has almost equal module efficiency. The variation of weekly average module efficiency of dirty modules com pared to their clean modules is shown in figs. 9-11. The module efficiency gradually decreased with the increase of dust density deposited on the module surface at 9 a. m., 12 a. m., and 3 p. m. As shown in fig. 12, the average module efficiency of c-Si and p-Si modules at 9 a. m. showed a decrement of 19% and 13.8%, respectively, with the dust deposition of 0.9867 mg/cm^2 after 11 weeks of study.

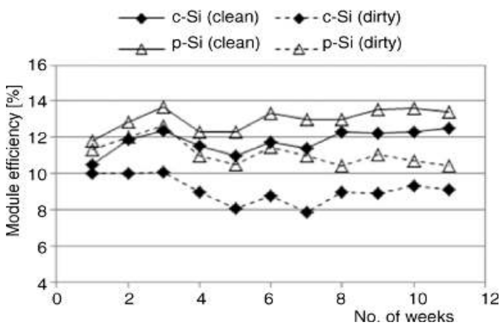

Figure 10. Variation of weekly average module efficiency of c-Si and p-Si modules at 12 a. m.

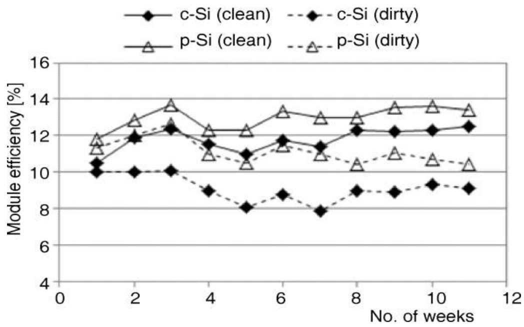

Figure 11. Variation of weekly average module efficiency of c-Si and p-Si modules at 3 p. m.

At 12 a. m. there was higher average solar irradiance and output power of the module, the module efficiency showed large decrement due to dust deposition. The average module efficiency of 14%, respectively, fig. 12. Similarly at 3 p. m., the dirty modules of c-Si and p-Si showed 15.8% and 13.5% less module efficiency, respectively, compared to clean modules of same type, fig. 12.

As shown in fig. 13, the percentage reduction of module efficiency has shown near linear relation with the density of dust deposited on the modules surface. After the time period of 11 weeks, the percentage reduction of module efficiency of c-Si and p-Si modules was 3.55% and 3.01% with dust deposition of 0.9867 mg/cm^2, fig. 13.

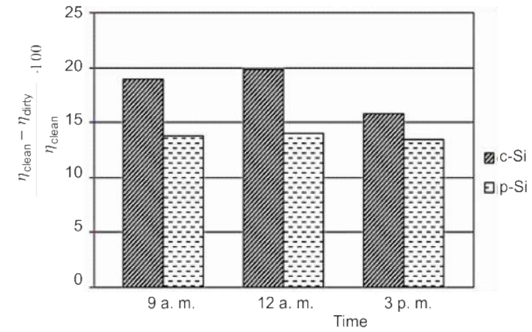

Figure 12. Average percentage reduction of module efficiency of dirty modules (c-Si and p-Si) compared to the clean modules of same type

During the study, the weather conditions were normal as most days were sunny with no storm. In fact, there would have been quite a large loss of module efficiency if solar panels were exposed to more dusty areas of Pakistan like sandy deserts of Thar and Cholistan facing enormous sandy storms. Although rain causes the cleaning of module and increase output power, it cannot be relied on it for cleaning as the rain occurs occasionally and minimally in Taxila. The PV modules thus require regular cleaning to minimize the efficiency loss.

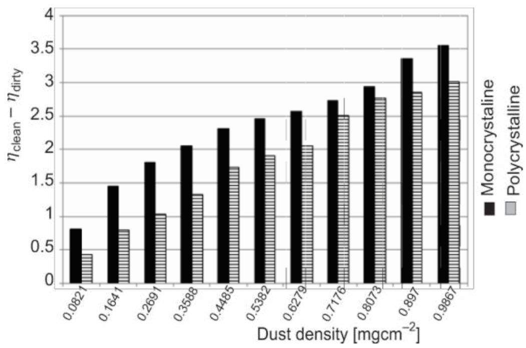

Figure 13. Weekly average efficiency reduction of monocrystalline and polycrystalline modules at varying dust densities

Conclusion

The dust effect on the performance of PV modules of two different technologies was investigated. The PV modules were exposed to the real outdoor conditions of Taxila for 11 consecutive weeks. The density of dust deposited on the PV module surface was

0.9867 mg/cm^2 at the end of experimentation. The results indicated that performance of PV modules decreased progressively with the amount of dust deposited on its surface. The average output power of monocrystalline and polycrystalline PV modules showed decrement of 20% and 16%, respectively, for dust deposition of 0.9867 mg/cm^2. The module efficiency also showed a significant degradation under the effect of dust deposition. The percentage efficiency reduction of monocrystalline module was higher than polycrystalline module. In case of monocrystalline module, the percentage efficiency reduction was 3.55% and for polycrystalline module 3.01% after 11 week of environmental exposure. The PV modules thus require regular cleaning to minimize the efficiency losses.

Nomenclature

A – actual area of the module, [m^2]
C-Si – monocrystalline photovoltaic module
G – global solar irradiance [Wm^{-2}]
I_{max} – maximum current, [A]
P_{clean} – output power of clean module, [W]
P_{dirty} – output power of dirty module, [W]
P_{max} – maximum output power, [W]
p-Si – polycrystalline photovoltaic module
V_{max} – maximum voltage, [V]

Greek symbols

η_{clean} – efficiency of clean module, [–]
η_{dirty} – efficiency of dirty module, [–]
η_{module} – module efficiency, [–]

Acronyms

PV – photovoltaic module
STC – standard test condition

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