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Performance Reduction of PV Systems by Dust Deposition

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Abstract

The deposition of dust on photovoltaic modules is of importance as parameter for economic analysis and life cycle assessments to evaluate this kind of technology for generation of electricity. Even though during the last two decades several photovoltaic plants were implemented, only a few studies about this issue were performed. This work tries to estimate the annual loss of generated energy caused by dust deposition on PV modules based on an experimental setup of a grid connected PV plant, monitoring of solar irradiation, onsite determination of dust deposition rate, and processing climatic data to obtain information about the frequency of rainfall occurrence. In Mexico City, air pollution with suspended particulate matter with diameter below 10 µm (PM 10) is almost permanently over 50 µg m^{-3}. This contamination contributed to an average dust deposition rate of 65 g $m^{-2}d^{-1}$ on horizontal surfaces. Dust accumulation during rainless periods of more than 60 days can reduce production of PV systems up to 15%. With the capacity of natural cleaning by rainfalls, annual loss of production is estimated to be 3.6%.

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Keywords: Perfomance ratio; Particulated matter; Soiling

1. Introduction

The implementation of photovoltaic systems (PV) plays an important role in future electricity generation. Some countries like Germany, with an annual growth of 7.6 GW in 2012, have ample experience operating these systems. In contrast, markets in countries like Mexico, with an installed capacity of only 32 MW in 2011 [1], are growing slowly due low economic benefits using this kind of technology for electricity generation [2]. As a consequence Mexico needs to acquire knowledge in planning, installing and operating photovoltaic systems. One factor that affects appropriate operation is the dust deposition over the panel in urban areas like Mexico City, which may cause problems that lead to a poor efficiency of the PV system. A deficiency of self-cleaning due to various extended rainless periods makes situation worse. Recent developments focus on self-cleaning and water repellent surfaces. Also there are glasses with films that reduce reflectance, which can be used in PV panels covered with these

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glasses or in solar concentrators over the reflective mirror [3,4].These glasses are commercialized by companies like Pilkington, however it is very important to evaluate what are the main pollutants in each region in order to assess whether this type of glass is appropriate. Mexico City is a big laboratory because of the presence of many type of pollutants, either as gases or as small particles of different sizes. Thus, some work has been made that is presented in this paper in order to evaluate how a photovoltaic system may work in a big city, like Mexico City, and how its efficiency maybe affected by the pollutants. The investigation focuses to on estimating the performance reduction caused by dust deposition and characterizing the dust deposits with the objective of defining cleaning strategies of photovoltaic systems. The mathematical model is based on experimental data from a PV system with simultaneous irradiance measurement to provide the influence of dust deposition during rainless periods on the performance ratio and statistics of the meteorological station nearest to the photovoltaic system.

Nomenclature

α	Ratio of particle size and wavelenght
β	Tilt angle of PV module
D	Diamenter of particle in μm
DDP	Daily Dust Performance factor
$E_{i,irradiation}$	Intensity of solar irradiation on surface of modules during ith period of 15 minutes of the day
E_{real}	Annual real production of electricity by the inverter
E_{clean}	Annual hypothetic production of electricity by the inverter under clean conditions
FRO	Frequency of rainfall of occurrence
$\dot{m}_{dust}$	Mass of dust deposited on surface per square meter per day
PR_{day}	Calculated performance ratio for a specific day with certain exposition time
$P_{i,nom}$	Normalized power introduced into the grid during ith period of 15 minutes of the day
$P_{i,grid}$	Power introduced into the grid during ith period of 15 minutes of the day
PM10	Particulate matter below 10 μm
$\eta_{modules}$	Efficiency of modules under test conditions
$A_{modules}$	Total surface area of the modules
$T_{i,module}$	Temperature of the module during the ith period of 15 min of the day

2. Materials and Methods

The evaluation of dust contamination was based on the measurement of the reduction of performance rate of a residencial PV. The dust deposition rate by a gravimetric method wasalso cuantified on site. In order to have tools for comparisions, climatic data from nearby stations was recorded.

2.1. Climatic data

The meteorological station operated by the Institute of Atmospheric Research UNAM is located in the Coyoacan district of Mexico City with the coordinates N19° 21' 4.68" ; W99° 9' 21.96". Distance to the studied PV system is 1540 m. From this station the pluvial incidents were recorded and processed fromhistorical data captured as half hourly median of the year 2010, which presents the lowest yearly failure rate with a total of 238 hours [5]. With assistance of a small Excel®routine the data was processed as follows: initial day was the last day of 2009 with a precipitation. Counter of rainless period goes on as no rainfall over 2 mm (during 4 hours) is reported. Otherwise the accumulated period is registered and the counter reset. Finally, the results of half hourly incidents were grouped into daily incidents.This station also provided information about wind speed during the period 11.11.2012 to 22.04. 2013.
The concentration of particulate matter below 10 µm (PM10) was provided from the meteorological station *Hospital General* in the Cuauhtémoc district of Mexico City operated by the Environmental Comission of the Metropolitan Zone (CAM by its acronyms in spanish) [6]. The geografic location of this station is N19° 24' 49.68" ; W99° 9' 10.80" and 5400 m away from the PV system. The concentration of PM10 was provided hourly and from this data the weekly average was calculated.
The total suspended particulated matter is sporadically determined by the CAM at different stations; for 2009 a total of 285 samples were analysed and gavean average value of 105 µg m^{-3} with a standard deviationof 44.5 µg m^{-3}. This value is only given for reference to havean estimateabout particulate matter contamination in Mexico City.

2.2. PV System

Geografic locationof the photovoltaic plant is N19° 21' 54.36" ; W99° 9' 24.84" and is roof mounted at 7.8 m height facing south. The tilt angle of the PV modules is 20.3°. The plant consists of 9 polycristalinum silicium modules (Model: 125 P6HV) assembledin Mexico by the national manufacturer ERDM with the characteristics shown in table 1.

Table 1. Technical Data of the used polycrystalline PV modules

Parameter	Value
Voltage open circuit (Voc)	41.02 V
Voltage optimum (Vop)	33.47 V
Current closed circuit (Isc)	3.96 A
Current optimum (Imp)	3.77 A
Maximum power (Pmax)	125 W
Operation temperature range	-40 °C – 90 °C
Tolerance of power	± 3%
Efficiency	12.6%
Temperature coefficient for power	-0.45 %/k

Data from manufacturer are based for 25°C; q_{irr}=1000 W/m^2; AM=1.5

The PV modules feed into a grid connected inverter from the company SMA (Model: SMA SB1100 European Version with a nominal power output of 1000 W). The inverter feeds into the public grid 2

Phase 125V ~. The input voltage of the inverter for operating at maximum power point (MPP) is in the range of 139V to 320V. The maximum input power is 1210 W and maximum output is 1100 W. Data acquisition, which provided every 15 min a complete parameter set, was realized by communication via a RS485 interface with the Sunny Webbox from the same manufacturer. The PV plant is running since March25th 2012. In view of evaluation the performance ratio of the PV plant a Sunny Sensorbox from the manufacturer SMA was put into operation on January 7th 2013. This Sensorbox measured solar irradiation to the modules (Small PV cell for measurements has same tilt angle than modules), module temperature (PT 100 fixed on the back of third module) and ambient temperature (PT 100 from the company Endress&Hauser placed 15 cm under the modules. Until April 23th, data for determining the performance reduction was recorded. During this period no rain over 2 mm per square meter was recorded. It was planned to clean the modules after 25 days with water, spoon, and rubber wipe. However some rainfall with precipitation below 1 mm per square meter obligated to clean the modules before planned cleaning after 25 days of exposition in 3 events. As a result, reduction of performance ratio due to dust deposition on modules maybe observed over time, with the reference irradiation from the sensor, which was cleaned daily with water. Obviously other effects like wind, shadow incitation, and inverter performance could not be considered. Thus, statistical methods were needed to reveal the effect of dust deposition. The only correction applied was done for the module temperature using the temperature coefficient specified in table 1. The effect caused by a variable solar spectrum may be auto compensated by the fact that the principle of measurement used in sensor is equal to the principle of working of the PV modules.

For validation of measured irradiance in two occasions a comparison was realized utilizing a portable irradiation sensor type FL A623-GS from Alborn Company, Germany, in combination with a data logger model Almemo 2590 from the same company. Processed data with a cycle time of 5 min differed less than 1% from the data registered by the installed sensor.

Performance ratio, calculated as the ratio of electric energy supplied to the grid by the inverter and the energy that could have been generated under nominal conditions, has to be measured over a longer period e.g. months or even a year. In this study the performance ratio was determined daily with the variable of time of exposition calculating the average of performance ratios obtained in periods over 15 min. In this way, temperature correction could be applied. Because the energy production of every period of 15 minutes during the day is not constant, obtained performance ratios were weighted with total daily production. Consequently, the determined performance ratio was calculated as follows:

$$PR_{day} = \sum_i^n \frac{P_{i,nom}}{\dot{E}_{i,irradiation} \cdot A_{modules} \cdot \eta_{module} \cdot \left(1 - 0.0045 \frac{1}{°C} \left(T_{i,module} - 25°C\right)\right)} \quad (1)$$

PR_{day} is the calculated performance ratio for a specific day with certain exposition time. $P_{i,nom}$ is obtained as follows:

$$P_{i,nom} = \frac{P_{i,grid} \cdot P_{i,grid}}{\sum_i^n P_{i,grid}} \quad (2)$$

When PR_{day} is graphed over the period of rainless days, the influence of dust deposition maybe read out by the slope of the adjusted linear equation. The coefficient of determination calculated from data and linear tendency line were used for the evaluation.

2.3. UV-Vis transmittance of dust deposited

On the same roof where the photovoltaic plant was installed, 42 microscopic slides were placed horizontally on a wide metal grid with 0.5 m^2 for dust collection. Every day two of the microscope slides were separated and stored in a box. After collecting all the microscope slides, the photometric transmittance of dust deposited on them was determined at different wavelengths (1060, 500 and 370 nm) with a Shimadzu UV1601 spectrophotometer. As a blank value principle of measurement, the average transmittance of three slides was taken. Because of the strong absorptions of the sodium-calcium glass slides below 350 nm, the lowest wavelength was fixed at 370 nm. This decision was also taken to avoid lamp adjustment by the photometer, which occurs at 366 nm.

2.4. Measurement of dust deposition rate

The dust deposition rate was determined by a passive sampling system for dry coarse dust. On the same roof as the PV system 3 dust collectors model Sigma-2 described in the guideline from the German Engineering Association [7] were placed. The metal tube has an inner diameter of 105 mm and is 260 mm high with a cap on top. The offsetted openings on the top guarantee free sedimentation inside the cylinder. On the bottom, a 3 mm thick glass with an area of 60 cm^2 was used as collector. Once a week the glass plates were weighted with a balance model XT 120A from Precisa Gravimetrics, company Switzerland, with a precision of 0.1 mg. After weighing, the samples were cleaned with an alcohol-water solution 70/30 (v/v) and a cleaning tissue for optics. After drying, the glass plate was weighed again and the difference of the two weights was considered the dust deposition.

2.5. Analysis of particle size distribution of deposited dust

Particle size distributions of dust deposited on glasses from the dry dust collector were analyzed by the laser diffraction method. The dust collected during one week was taken from the glass with 20 mL of water using a spray bottle. The whole sample was analyzed in the micro liquid module with laser diffractometer from Beckmann Coulter, Brea, California, model LS 13 320. The interval detection for particles is between 0.375 to 2000 µm.

3. Results and Discussion

One of the main factors for the performance reduction by dust deposition is the duration of the period without rainfall. During the last decade from historical data it can be seen that the last rainfall in the year with high probability occurs in the last week of October or the first week of November. Then sometimes rainfall can be induced due to artificial fireworks during New Year’s Day. However first rain of the year could also happen some days later. This is the reason that in Fig. 1, where the occurrence of rainless periods is plotted, the longest period without rain is between 60 and 70 days (absolute occurrence once a time). The dry season still predominating to May, with only a few rainfalls, is the reason for the occurrence of other rainless periods of 20 to 40 days. The probability that these four rainfalls have equal duration is quite low and as consequence their absolute occurrence is 1. During the rainy season between May and October no extended rainless periods over two weeks are reported for the year 2010. Obviously, as shorter the rainless period is, its absolute frequency of occurrence increases. Thus, a total of 24 times a year there are subsequent days with a registered rainfall.

The computed data obtained by the Excel routine can be verified applying the following trial and error method. The sum over each dot of a rainless period multiplied by its frequency of occurrence gives the 365 days of the year. The effect of performance reduction by dust deposition on module surface in first order depends on quantity of dust deposited. The dust deposition rate on the observed PV modules determined by the passive sampling cylinders on the same roof where PV system is installed is shown in Fig. 2. The average deposition rate from week 48 in 2012 to week 18 of 2013 was 65 g $m^{-2}d^{-1}$. The error bars showing the standard deviation of the three plates analyzed weekly are relatively large with an average variation of 23%. The main factor that contributed to this variation is that weekly dust deposit of about 2 mg on the plates was measured with an accuracy of 0.1 mg given by the balance. Doubtless higher exposition time can lead to more precise data. However, exposition time of one week was chosen to compare dust deposition with concentration of particulate matter in air. The dust deposition may correlate with PM 10 in air. At least the concentration of PM 10 in air goes up and down following the same trend as dust deposition for weeks 11 to 18. The concentration of PM 10 determined 5.4 km from the site varied between 40 and 80 µg m^{-3}. Because PM10 concentration mostly resides above 50 µg m^{-3}, Mexico City has to be considered as a city with alarming air quality. European regulations try to restrict PM10 concentration not to exceed50 µg m^{-3} more than 35 times a year [8]. The dotted line above 100 µg m^{-3} represents the average of total suspended particulate matter in the metropolitan zone of the capital. It seems that PM10 comprises more than 50% of total suspended particles. The total suspended particulate matter is measured only sporadically by some stations. Also, it has to be considered that total suspended particulate matter concentration may vary locally more than PM 10 due to a higher sinking velocity of this type of particles. As a consequence, this parameter has to be seen as an orientation.

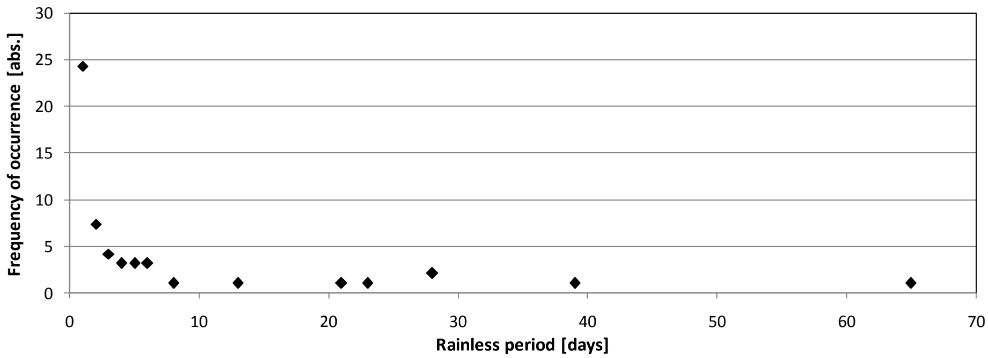

Fig. 1. Frequency of occurrence of rainless days (criteria for rain is precipitation > 2 mm m^{-2} within 4 hours) in the metropolitan area for the year 2010. Climatic data were taken from the meteorological station operated by PEMBU in Coyoacan with a distance of 1.5 km from the observed PV system.

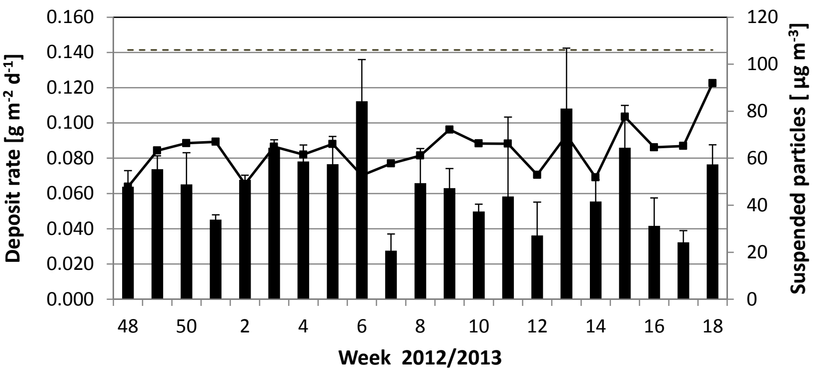

Fig. 2. Dry dust deposition on horizontal glasses form 12.11.2012 to 12.05.2013 at site (bars with standard deviation), weekly average concentration of particles smaller 10 µm measured at the metrological station 5.4 km to site (line) and the annually average concentration of particles in the metropolitan zone (discontinuous line)

Because the relationship between dust deposition rate and PM 10 concentration in air is not commonly reported, there exist only scarce information about their correlation between these two parameters. Since PM10 concentration is reduced slightly during the night, there must be also deposition of PM10 on surfaces. To reveal this, the particle size distribution of dust on the plates was determined.

Analysis shows that 28% of deposits are comprised of particles smaller than10 µm. Mean diameter of dust deposits is 17.02 µm. Low industrial activity on the residential site may be a reason for the absence of particulate matter over 45 µm, which is characterized by a low travel distance. A sinking velocity of more than 6.1cm/s for these particles is an effective airstream separating form street level to roof mounted PV system. These facts explain the cut at 45 µm rather than the self-cleaning effect by resuspension of particles on non-adhesive surfaces, which is observed for bigger particles at higher wind speed [9]. Also, climate of Mexico City is classified as windless. This was confirmed by meteorological data with an average wind speed of 0.6 m/s during experimental period with a maximum gust of 17.9 m/s. The frequency of gusts over 12 m/s may be responsible for any resuspension, which were registered only 72 times. Goossens showed in his experiments applying wind speeds from 0.63 m/s to 2.65 m/s that dust deposition becomes more and more disturbed when wind speed increases [10].

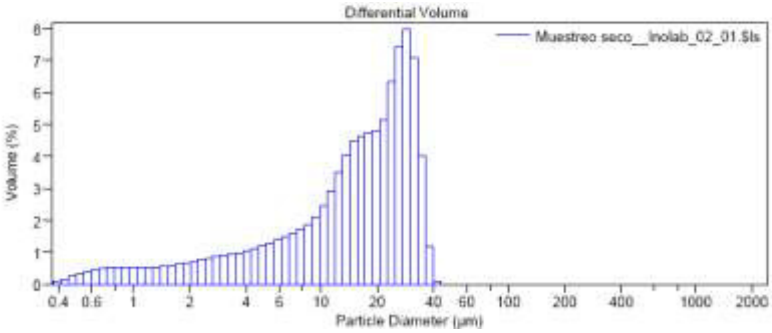

Fig. 3. Size distribution of dry dust collected on horizontal glasses during week 11 in the year 2013

El-Shobokshy [11]reports that fine particles of dust cause a worse effect on performance of photovoltaik modules than the bigger ones. Also, carbon deposits from combustion processes reduce the performance more than other particles like cement or pollen. To obtain data howdust on a surface inhibits free transmission of photons, optical transmittance in a UV-Vis Spectrometer of the dust collected on microscopic slides with different exposition time was employed. Fig. 4 shows how transmittance is reduced with exposition time for the wavelengths 370, 500 and 1060 nm. First, the level of transmittance deterioration increases as the number of exposure day increases. This is due to the continuous accumulation of dust particles on the PV surface. Second, deterioration persists due to smaller tilt angles, like in this case where the tilt angle of the PV modules is 20.3°, and long exposure periods as more coarse and fine particles are caught by the semi-horizontal surfaces. Another interesting effect is the different slopes of tendency lines for the showed wave lengths. The highest slope is observed measuring transmittance at370 nm followed by 1060 nm and finally lowest transmittance reduction by 500 nm wavelength with an incline of -0.745 %/day.

When light passes through a surface covered with dust, it may be refracted, absorbed inside the particle, reflected, or diffracted by particles. Geometry analysis reveals that the smaller particles on the surface result in a higher area covered. However, when size of particulate matter is close to wavelength, scattering is governed by a function of particle size diameter and wavelength of beam. When the ratio $\alpha = (\pi \cdot D)/\lambda$ is smaller than 12, the function can be described by Mie scattering and for a ratio $\alpha < 0.3$ it can be described by Rayleigh scattering [12]. In this case, the loss of intensity of a beam increases, as diameter of particle reduces. At visible light wavelengths these effects are observed for particles smaller than 2 µm [13] and are the reason that transmittance reduction depends on wavelength, because of their presence in deposits on microscopic slides.

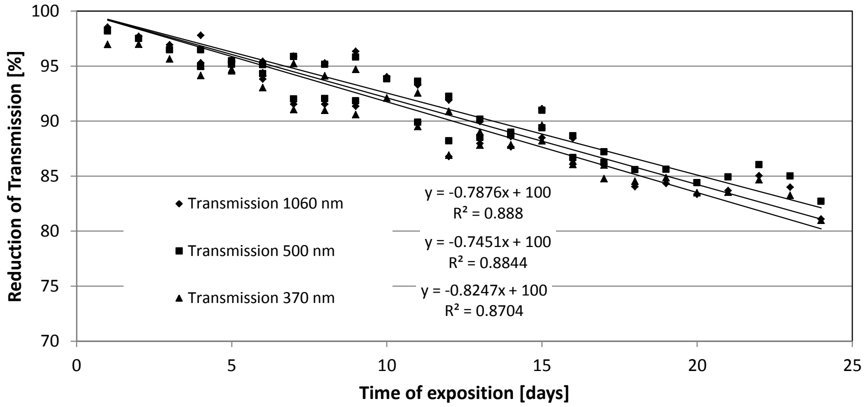

Fig. 4. Effect of the accumulation of dust depositions on horizontal exposed glasses to the reduction of light transmission for measurements at 1060, 500 and 370 nm

Surprisingly, a first impression is that the slope of the trend line in Fig. 5 has a flatter angle than the one in Fig. 4 even though for both lines the interaction of dust with photons is reason for the slope of trend line. This phenomenon can be explained easily by the fact that most of the diffracted light in the photometer does not reach the optic sensor, while most diffracted light by dust on surface of PV modules still reaches Silicon surface on the other side of the glass cover. Less valuable contribution is by the different tilt angle of the PV modules and of horizontal exposed microscopic slides. The tilt angle of modules results in a reduction of 6% of the surface projected to the horizontal.

Fig. 5 reveals for clean modules a performance ratio of 0.838, but it has to be taken into account that it refers to the performance ratio corrected by temperature. The real performance ratio (without temperature correction) for clean modules is 0.774. Other reports indicate that the performance ratio for PV Systems can vary from 75% to 85% [14]. Some aspects, like ambient temperature over 25 °C, and considering that the study was done on a small plant, justify that performance ratio is established near to 75%. The slope of the trend line reflects the influence of dust on the PV modules to the performance ratio and is named daily dust performance factor (DDP). So each day of deposition results in an additional reduction of performance of 0.24%. Thus, days after a longer period of exposition without rainfall are affected more. Its performance reduction for a period of 60 days can reach 15%.

To estimate annual loss of energy generation, daily dust performance factor has to be combined with the frequency of rainfall occurrence presented in figure 1 and can be described with the equation as follows:

$$\frac{E_{real}}{E_{Clean}} = 1 - DDP \cdot \frac{\sum_{i=1}^{n} FRO_i \cdot \frac{i}{2}(i-1)}{365} \quad (3)$$

Because this estimation does not consider seasonal variation of solar irradiation, the model is only applicable on sites with low monthly variation. In the current study, monthly production ranged relatively close between a minimum of 104 kWh/kWp during November and a maximum of 136 kWh/kWp in March. If it is supposed that DDP is proportional to dust deposition rate, it may be calculated with the following equation taking into account DDP and an average dust deposition of 65 g $m^{-2}d^{-1}$ observed during this experiment:

$$DDP = 0.0039\frac{\%\cdot m^2}{g}\cdot\cos\beta\cdot\dot{m}_{dust} \qquad (4)$$

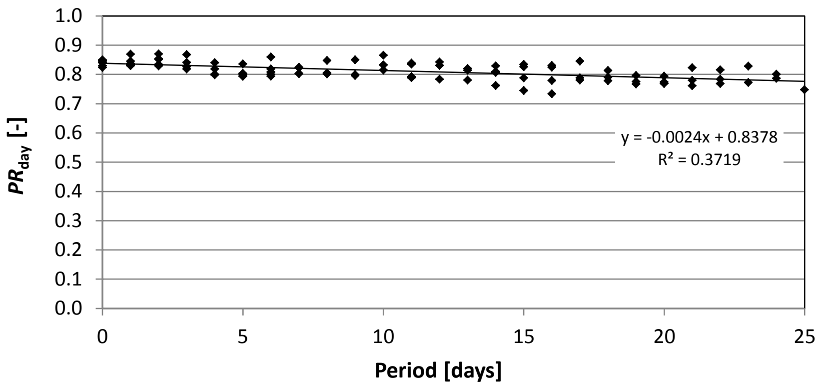

Fig. 5. Observed reduction of performance ratio during periods without rain

Under circumstances exposed in this study, the annual loss of electric energy into the grid is estimated in only 3.6%. This data is in accordance with experimental findings by other reports [15,16] and commonly used factors for estimation of life cycle assessments for PV systems [17]. As a consequence, the benefits of additional cleaning of modules could be questioned.

It may also be questioned that model proposed in first order may have some variation due to coefficient of determination R^2 (37.2 %), which is quite low in spite of the large number of data points. However, statistical analysis of processed data results in a linear dependency of performance ratio on dust deposition in an interval of confidence greater than 95% (Durbin Watson Statistic) and a DDP of 0.2445% ± 0.033%.Thus, to obtain higher precision of the effect of dust on modules surface its performance has to be measured in laboratory with test equipment for PV modules.

A more precise estimation may be achieved taking into account the seasonal variation of daily solar irradiation, but requires monitoring of experimental set up on specific sites for longer periods. This leads to the situation that the proposed model based on the function of frequency of rainfall occurrence and daily dust deposition rate cannot be extrapolated to other situations.

4. Conclusions

Climatic conditions in Mexico City with rainless periods over 60 days do affect performance of PV systems by dust deposition on modules. The dust deposition rate on horizontal surfaces varied between 24 and 102 g $m^{-2}d^{-1}$. After 60 days of dust deposition on modules without rain as natural cleaning systems, the performance ratio is reduced by almost 15%. However, more important is the annual reduction of production caused by the dust deposition, which is lower. The estimation in this study based on the frequency of rainless periods and the factor of performance reduction of 0.24% per day of exposition without cleaning results in an annual loss of production of 3.6%, which is in accordance to other studies.

The daily dust deposition rate and frequency of occurrence of rainless periods are useful to describe loss of production of PV systems, but other factors like monthly variation of solar irradiance leads to estimations with certain error. Since it is difficult to include the parameters in the models, an accurate determination of the influence by dust precipitation is only possible by experimental monitoring of selected plants. Thus, this study contributes in helping to expand existing knowledge about this phenomenon.

Design and operation of PV systems should consider free access to modules in view of cleaning purposes, and cleaning should be performed one to two times a year parallel to other maintenance on PV plant.

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