EFFECT OF DUST ACCUMULATION ON THE PERFORMANCE OF THE GRID CONNECTED 60 kWp PHOTOVOLTAIC SYSTEM AT THE UNIVERSITY AUTONOMOUS METROPOLITAN IN MEXICO CITY

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1. Introduction

Photovoltaic (PV) technology for electric generation has already proven its diverse applications worldwide and during the last years has had a significant growth not only in rural but also in urban areas.

An appropriate design in addition to an accurate installation that theoretically optimizes the solar irradiance of certain location can potentially ensure a sustained yield from a PV system. Nevertheless it can happen that unforeseen events like the deposition and accumulation of dirt and airborne dust on the surface of PV modules could cause troubles and diminish the predicted performance of PV modules. If the dust accumulation continuously increases in the course of time, PV cell efficiency may fall to very low values after only a few days or weeks. The presence and frequency overcast skies, rain, wind speed, as well as humidity and ambient temperature can also have an important role on performance drop.

It has been extensively proved that accumulation of dust deteriorates the performance of solar cells and contributes to appreciable losses in the generated power. Pollution of solar cell surfaces by airborne particles has been recognized since several years ago. The first studies mainly deal with thermal collectors and particularly with the decrease on mirror reflectance as a result of dust accumulation (Dietz, 1963; Garg, 1974; Bethea et al., 1981; Deffenbaugh, 1986). Afterwards the attention was paid in the intensity reduction of solar radiation transmitted through the glass cover by dust accumulation (El-Nashar, 1994; Feuermann and Zemel, 1993). The published works in the last two decades mostly analyze the effect of dust accumulation on the electric performance of PV cells. Several authors tried to simulate the deposition of dust in the laboratory. Thus, El-Shobokshy and Hussein (1993) polluted PV surfaces with different kinds of dust that include materials frequently found in the real atmospheric dust as well as cement and carbon particles from combustion products, and then measured the electric output of the cells under different conditions. It may be concluded from this study that the gradual degradation on the PV performance cannot correlated to the exposure time in a given site. The results also show that the effect not only depends on the dust deposition density but also on the nature of dust, its size distribution as well as the fines particles from a given dust have more deterioration effect than that of the coarser one. Goossens et al., (1999) introduced in the aeolian dust wind tunnel a multi-crystalline silicon cell polluted with natural soil dust. According to the results obtained, it is possible to conclude that in general high wind speeds lead to high dust accumulation; in cases of low wind, dust accumulation is smaller. Also high dust concentrations lead to a higher accumulation on the PV module surface. Elminir et al., (2006) exposed glass samples to the environment strong polluted and concluded that the reduction in glass normal transmittance and energy yield depends on the dust density in conjunction with tilt angle as well as the orientation of the surface respect to the dominant wind direction. Kimber et al., (2006) developed a model for predicting soiling losses that approximates the soiling pattern observed over approximately 250 PV systems from various geographical regions and local environment type. The simulation program involves an interaction of dust and rain. Kaldellis and Kokala (2010) measured in Athens during August-September, a short period without rainfalls, the performance of five pairs of PV modules to evaluate the impact of natural air pollution on the energy production. Likewise estimated the resulting annual income loss €/kW$_p$. Kaldellis and Fragos (2011) carried out a comparative study between identical pairs of PV modules polluted with several amounts of carbon-based ash. From this study it may possible to state that the fly-ash particles existing in the atmosphere of heavy polluted areas, when deposited on PV surfaces cause approximately 30% reduction in the generated power output, for an ash deposition density of 0,4 mg/cm^2. Thevenard and Pelland (2011) developed a methodology to estimate the uncertainty in long term PV system yield predictions. In this work soiling like snow were considered variables which effects are difficult to model or extrapolate from case studies since both depend on the specific site and climate. In conclusion a limited number of published works has quantified the impact of dust deposition on PV surfaces and they have an important restriction: the values on efficiency reduction reported are applicable only to the specific location in which the testing was conducted since they are related to climate and local air pollution where PV system is installed.

A 60 kWp PV system grid connected was installed in October 2009 on the roof of the classrooms building at the University Autonomous Metropolitan Iztapalapa (UAMI, for its Spanish acronym) in Mexico City. The system supply partially electricity needs in the building. The PV system is part of the institutional program Toward Sustainability that has the purpose of create and promote directed practices to take care of the environment and the profitability of the limited natural resources, so that investigation and practice to lay the foundations to turn the university facilities into a prototype of sustainable university.

The PV system had been monitored permanently from the first day of operation. With the aim of quantifying the impact that dust has on the performance of PV modules when deposited on their surface, the performance of the UAMI PV system was examined in February 2011 during unusually drought season. Electrical parameters such as power output, performance ratio, energy generation and efficiency are compared with system data from February 2010.

During February 2011, the electrical performance of one of the 21 sub-arrays that integrates the 60 kWp PV system and was maintained clean, is simultaneously compared with the performance of others sub-arrays with the same electrical characteristics, located in the same area and operated under the same environmental conditions but that were left unclean, in order to make the estimation of energy loss due to dust accumulation and lack of rain.

The performance evaluation and energy produced by grid connected PV systems in Mexico is still limited. Lack of financing and other incentives have hindered a faster growth of the PV market in this country. In addition to the UAMI PV system in Mexico City there are two among others systems, with the same installed capacity (30kW$_p$): one is the first grid connected PV system installed in Mexico (December 2005) the other installed at the Technology Museum of the national utility (2010).

2. Air pollution in Mexico City

The atmospheric dust at elevated concentrations is a very complex local problem but common in highly air polluted urban environment, affected by diverse site-specific topographic, environmental and weather conditions. Air pollution in the Metropolitan area of Mexico City is a multifaceted environmental problem. Mexico City is one of the biggest cities in the world, and the largest urban area in Mexico. A high population density, an increased vehicle fleet, its topography and climate contribute to trapping the pollution across the broad valley that surrounds the capital and have caused significant degradation of the urban air quality. According to Cicero-Fernandez et al., (2001) one of the factors that make it difficult to comply with the national and the World Health Organization air quality standards in Mexico City is its geographic situation. Mexico City is located at an average altitude of about 2240 m above sea level and 19.5°N latitude in a valley surrounded on three sides by mountains with average elevations over 3000 m. The lower atmospheric oxygen levels at this altitude, approximately 23% lower at sea level (Molina, 2002) cause incomplete fuel combustion in engines and higher emissions of carbon monoxide, hydrocarbons and volatile organic compounds. At this latitude, it receives high energy solar radiation throughout the year which induces high concentrations of ozone and related oxidants as well as particulate matter. The climatic conditions induces absence of winds and stationary masses of cold air during the winter as well as thermal inversions aggravated by the surrounding mountains that tend to isolate the city from the winds of regional weather patterns avoiding air dispersion. The government has implemented air quality programs (PROAIRE I and II, 2000-2010) during the last decade. Lead, carbon monoxide and sulfur dioxide are now under control but the concentrations of ozone and its precursors as well as aerosol particles still exceed significantly air quality standards and are causing health effects, ecological damages and economic losses. In 2009, ozone levels exceeded standards on almost 50% of days (SMA-GDF, 2010).

3. Description of system

PV modules are installed on a flat roof of 4 floors building on a metal support structure (figure 1). They are facing south, with a tilt angle of 19° to maximize the yearly energy production. The separation of the rows is 0.8m in order to avoid shadows. The total system power is 60.06 kW_p at standard test conditions. The PV generator consists of 286 modules 210 kWp of nominal power Tenesol TE 2000 of multi-crystalline cells. They are distributed in 19 subsystems of 14 modules (two strings connected in parallel, each string of seven modules) and 2 subsystems of 10 modules by string. Each subsystem is connected to a single phase EI 2500 Tenesol inverter. These are connected by a RS485 interface to a data acquisition system (DAS) Energrid Data EG32 to measure electrical parameters and also to monitor meteorological parameters such as irradiance on both horizontal and module plane and ambient temperature, the performance data was averaged at 10 minute intervals. The system is connected to the 500 KVA, 3 phase electrical network of the building located at the ground of the same building. The 21 inverters break switches, interruption switches and the DAS are located in control room in the roof.

Figure 1. 60.06 kW_p Photovoltaic System at the University Autonomous Metropolitan in Mexico City

4. Parameters for performance analysis of grid connected PV system

The performance ratio PR is one of the most used parameters to evaluate PV system performance. It allows make comparison of PV systems operating at different locations. PR is the ratio of PV energy produced to the energy theoretically available. It is a dimensionless quantity that accounts for the total losses at operating conditions of the cells. In practice, it is specified in percent and describes the effectiveness of the PV system compared with PV system that operates under nominal operation conditions without losses. Nevertheless it cannot used to identify system failures or system efficiency drop.

To estimate the impact of dust deposition on PV module surface it is useful to know the generator efficiency from the output DC energy.

The Performance ratio PR is calculated from

$$PR = \frac{E_{AC}}{\frac{E_{Gi}}{G^*} P*} \quad \text{or} \quad PR = \frac{Y_f}{Y_r}$$

(eq. 1)

$$Y_r = \frac{E_{Gi}}{G^*}$$

(eq. 2)

$$Y_f = \frac{E_{AC}}{P^*}$$

(eq. 3)

Generator efficiency is calculated from:

$$\eta_G = \frac{E_{DC}}{E_{Gi} A_G}$$

(eq. 4)

Where A_G: PV generator area (m^2); E_{AC}: output energy AC (kWh); E_{DC}: output energy DC (kWh); E_{Gi}: tilted irradiation (kWh m^{-2}); G^*: standard irradiance (1kW m^{-2}); P^*: PV generator power under standard conditions STC (AM 1.5, 1kW m^{-2}, 25°C) (kW_p); Y_r: reference yield (kWh kW_p^{-1} d^{-1}); Y_f: final yield (kWh kW_p^{-1} d^{-1}).

5. Soiling events in the first year of operation

5.1. First year of operation: October 2009-September 2010

The optimal grid connected PV system performance depends on PV modules efficiency, inverter characteristics, local climate and the coupling system to the grid (Sidrach-de-Cardona and López, 1999). Other factors that influence are the orientation and inclination of PV array, operating temperature of the modules and shadows incidence on the PV array. According to De Soto et al., (2006) the electrical power output from a PV module depends on the incident solar radiation, the cell temperature, the solar incidence angle and the load resistance.

Previous to installation of PV system at the UAMI it was carried out a feasibility study for the PV system. The solar resources assessment of Mexico City is based upon historical measured meteorological data from National Meteorological Service. The data base contains the 10 minutes average values of irradiance in the horizontal plane. Also it was used the RAD II software developed by the Institute of Engineering of the National University Autonomous of Mexico to obtain the mean daily values of irradiation for any point of the Mexican Republic for horizontal or inclined surfaces from the values of the latitude and the longitude of any specific site. For the PV system at the UAMI the values used were for latitude 19°21'N and for longitude 99°8′ W.

The PV system started operations in October 2009. The total energy generated during the first year was 89353.1 kWh (1487.7 kWh/kW_p). The monthly value of normalized energy yield by the system is shown in figure 2. The values are normalized to kW_p with the data sheet for the module. The energy produced during July was lower than estimated. There were two damage modules that were replaced in January 2010.

Values of PR remained relatively constant throughout the year however the system shows a gradual decrease in performance that coincides with the drought season during which dust is accumulated on the PV modules. The system performance usually returns to its normal level after a heavy rain falls. On the other hand if the rainfall is light the performance falls remarkably.

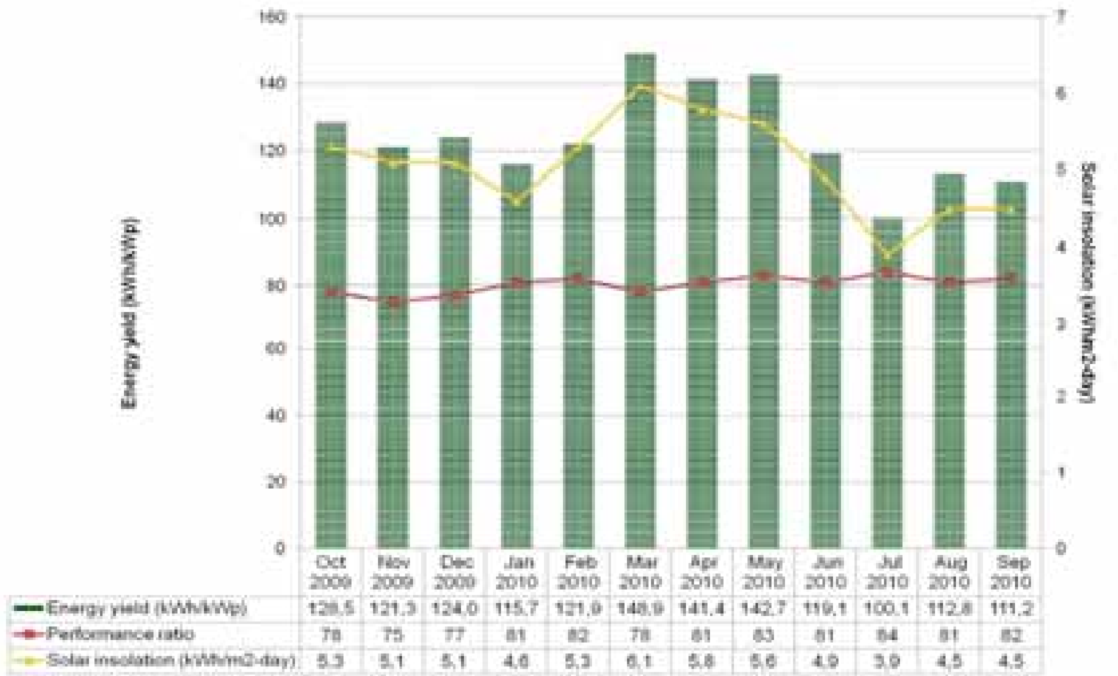

Figure 2. Monthly normalized values of energy yield in the first year

Mexico City climate is temperate sub humid. Table 1 shows the monthly and the annual total rainfall for Mexico City reported by the National Meteorological Service. The PV modules were keep more or less clean thanks the rain fell with the exception of November 2009.

During the first year of operation it was necessary to wash the PV modules one time. It was done in December 2009.

Mexico City	January mm	February mm	March mm	April mm	May mm	June mm	July mm	August mm	September mm	October mm	November mm	December mm	Yearly mm
2011	0,1	0,7	8,1	39,8	28,0	129,8							
2010	25,8	55,3	1,6	14,9	27,3	94,3	203,3	174,5	93,7	3,7	1,4	0,1	697,9
2009	13,2	6,8	8,6	5,9	41,7	86,3	103,6	143,0	227,8	72,1	0,7	3,4	713,0
2008	0,1	2,9	3,1	39,4	42,6	152,8	164,0	184,7	113,6	37,7	0,0	0,0	747,5
2007	6,0	22,0	20,4	21,4	60,9	104,5	173,8	168,5	172,8	38,0	7,2	1,6	797,0
2006	2.2	1.2	11,8	27,6	75,7	105,6	168,6	215,7	153,6	77,4	38,7	4,3	882,6
1941-2005	8,0	4,4	9,3	23,5	49,9	124,8	154,8	145,8	126,0	54,2	11,3	6,6	718,6

Table 1. Monthly and annual rainfall

5.2 Extended accumulation dust, November 19th 2009

Every day a visual inspection of PV system was systematically realized from the first day of operation. On November 19th 2009 the PV modules surface looked unusually without brightness. The glass did not have the typically dust but a blackish coat strongly stuck. The value of PR was reduced from 78 to 71 (9%, fall) compared to the previous day notwithstanding the solar irradiation and the maximum ambient temperature registered during PV system operation were almost similar in both days (5.529 kWh m^{-2}, 31°C, day 18th) and (5.528 kWh m^{-2}, 31°C, day 19th). On December 2th the rain fell but it was insufficient for a complete cleaning of the PV modules. On December 8th half of PV array was washed, and on December 9th all the array was cleaned and the PR returned to its historic level (figure 3).

Figures 4, 5 and 6 illustrate the effect of dirty accumulation on the PV system power output and energy yield evaluated on December 8th. The test was performed between two similar subsystems. One sub-array was cleaned and the other was unclean due to dust accumulation since November. Both subsystems are similar consisting of: 14 PV modules, arranged in two parallel strings with 7 modules in each, connected to a 2500

W inverter. The incident global irradiance in the array plane, the voltage and the current for every sub-array were averaged for every 10 minutes and stored at the DAS.

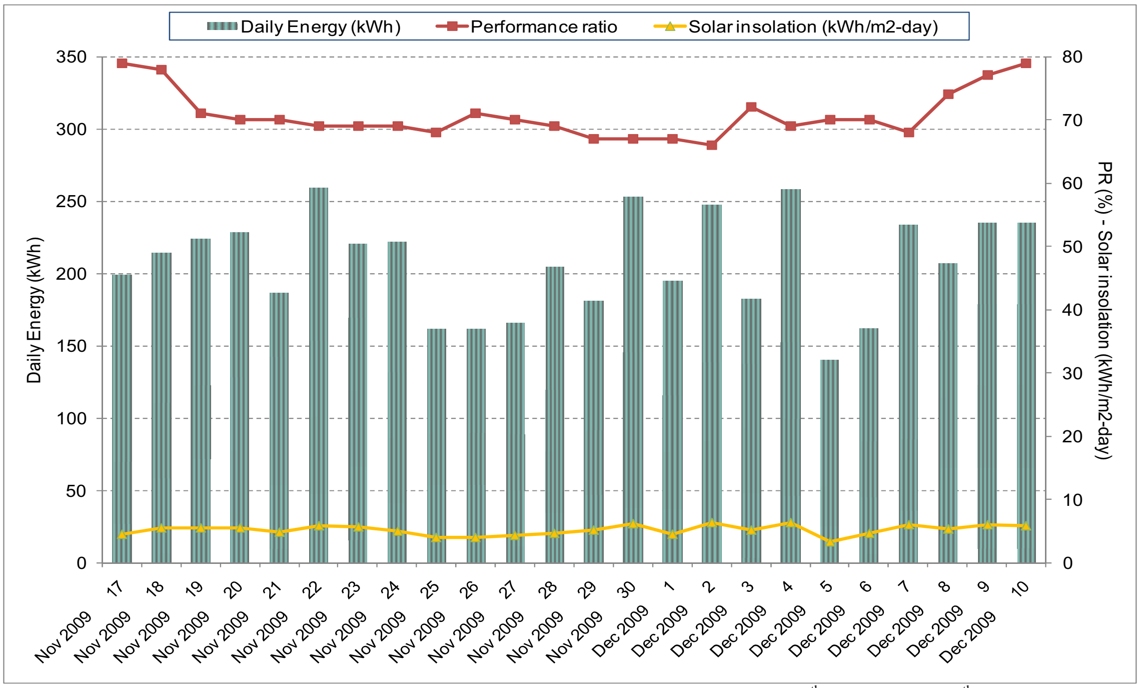

Figure 3. Daily energy yield, PR and solar insolation from November 17th to December 10th

Figure 4 shows the electrical power of the clean sub-array and the dirty one. It was determined by measuring the DC current and voltage generated by each subsystem. The generated current is function of the solar radiation incident on the cell and cell temperature. Assuming that temperature of both sub-arrays was the same, the difference in power generated can be attributed to the attenuation of radiation intensity due to light absorption by dust.

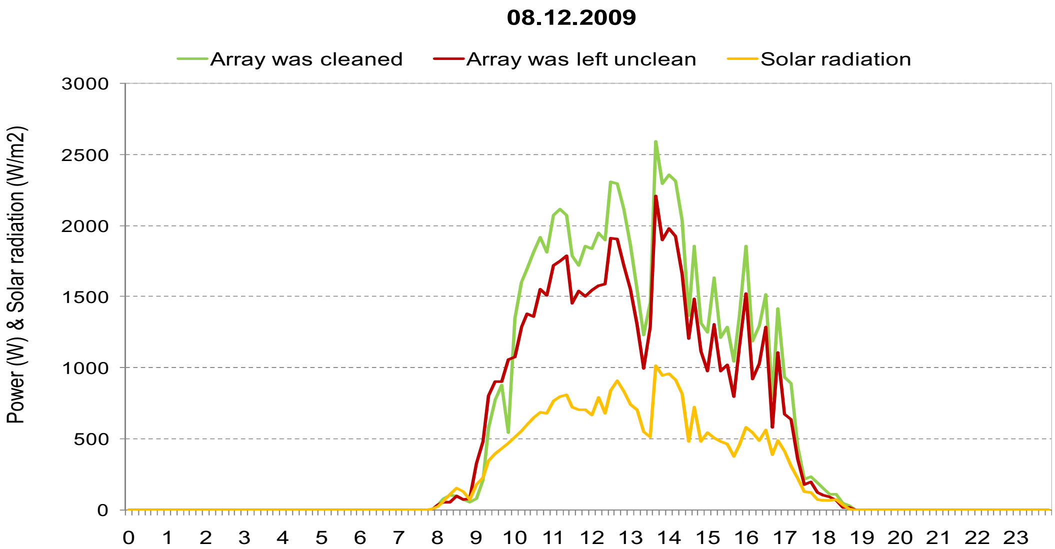

Figure 4. Clean and unclean arrays power output

Figure 5 illustrates the effect of dust accumulation on the electrical power produced by the unclean subsystem compared with the clean one. At solar radiation levels between 435 and 1015 W m^{-2} it can be noted that power reduction remains fairly constant. This behavior was observed from 10 to 18 hours.

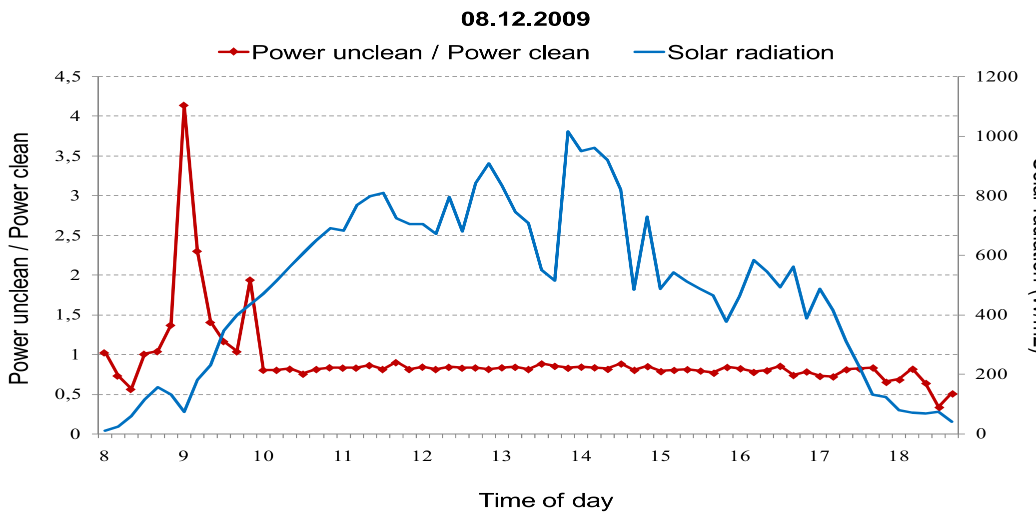

Figure 5. Effect of dust accumulation on power produced by sub-array unclean compared with the clean one

Figure 6 shows the total DC energy generated by the 2 subsystems on December 8th. The clean sub-array produced 13.19 kWh (4.49 kWh/kW$_p$) i.e. 18.3% more than 11.15 kWh (3.79 kWh/kWp) produced by the unclean sub-array.

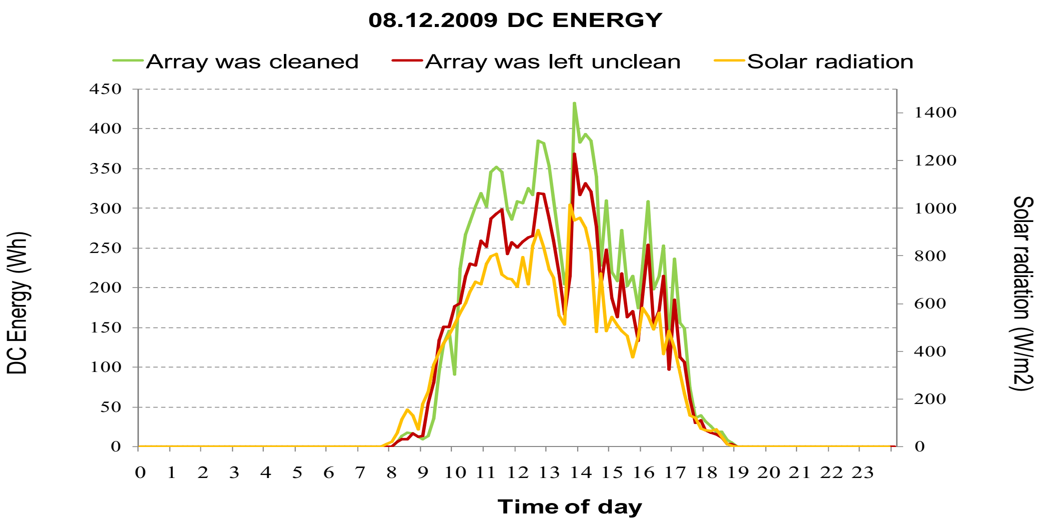

Figure 6. DC Energy generated by 2 subsystems

6. Soiling impact on PV system performance during February 2011

The rain was scarce during the last two months of 2010 as well as in January and February 2011(see table 1) so self-cleaning due to rainfall was not effective during this period. The dust was accumulated day after day on the modules surface ant its effect was detected on the PR systematic decay.

Figure 7 shows the daily normalized values of energy produced by the PV system against solar radiation in February 2010 and 2011. The daily normalized value of energy produced by the system in February was 4.35 kWh/kW$_p$/day on 2010 and 3.84 kWh/kW$_p$ /day on 2011.

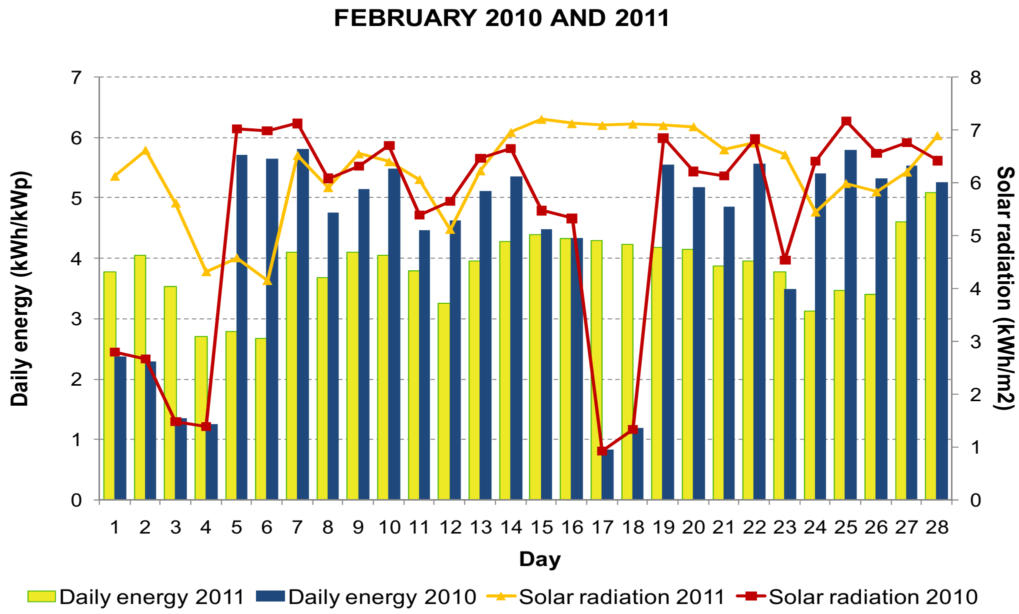

Figure 7. Comparison of the daily energy production for February 2010 and 2011

Table 2 shows some meteorological and electrical parameters recorded in February 2010 and 2011. The results registered show a great difference in the normalized values of energy yield. It is observed that regardless of irradiation is 17% higher in 2011 the energy yield decreases about 13.3% compared to the same month of the previous year. The average values of minimum temperature are similar; the average value of maximum temperature increases 5°C over the temperature test conditions for 2011 but it is not an extreme high module temperature. So the great difference observed can be attributed to the amount of rainfall on 2010, which helped to maintain clean the PV modules surface.

February	Irradiation (kWh m^{-2})	Rainfall mm	Tmin (°C)	Tmax (°C)	Energy yield (kWh)	Energy yield (kWh/kWp/day)	Performance Ratio
2010	5.3	55.3	8	25	7321.1	4.35	82
2011	6.2	0.7	9	30	6464.6	3.84	61

Table 2. Meteorological and electrical parameters

With the purpose of quantifying the impact that soiling has on the PV modules performance when deposited on their surface during no rainfall, an analysis of the sub-arrays performance was made for operating data of February 2011. One of the 21 sub-arrays was maintained clean and the rest of the PV plant was kept unclean.

Figure 8 shows the PV plant distribution. Each sub-array is identified with a specific color. The 14 modules of subsystem 10 were maintained clean from February 4th until the 26th, day in which were registered 0.7 mm of rainfall. Figure 9 illustrates a view of cleaned and unclean modules corresponding to analyzed period.

The performance of sub-array 10 was specifically compared with the sub-arrays 2, 6, 7 and 17, because all of them have had a variation < 1% about the monthly energy production during 2010 (figure 10).

Figure 11 shows the daily energy generated by the clean and unclean sub-arrays. The total electricity delivered by each subsystem analyzed during February was 339.34 kWh (clean sub-array), 306.82 kWh, 304.90kWh, 305.99 kWh and 298.82 kWh by sub-arrays 2, 6, 7 and 17 respectively. The energy produced was almost similar for all them during the first 3 days. From the 4th day, the subsystem 10 was maintained clean; the energy generated by this sub-array was 24% more than the unclean sub-arrays. The gap on energy production was steadily until the difference in energy production reached 44%, this happens just before the rainfall. Although the amount of rain was not sufficient to completely clean the modules surface the subsystem 10 only produced 10% more than the others after the natural cleaning process of the PV modules due to rainfall. The average monthly energy for the unclean sub-arrays was 31.3% lower in comparison with the cleaned sub-array.

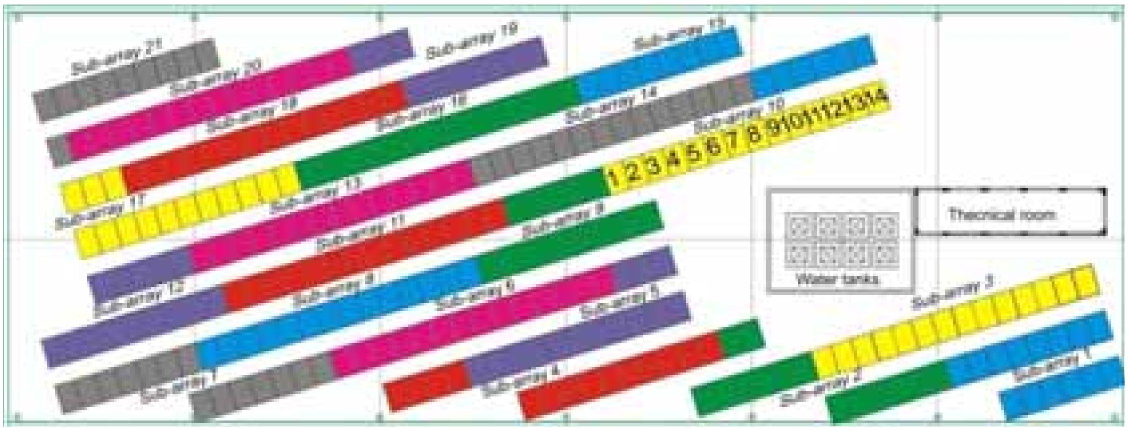

Figure 8. PV plant distribution

Figure 9. Sub-arrays February 10, 2011

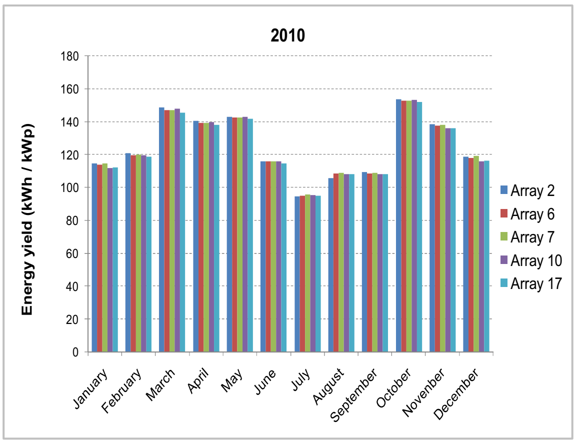

Figure 10. Monthly energy produced by 5 sub-arrays

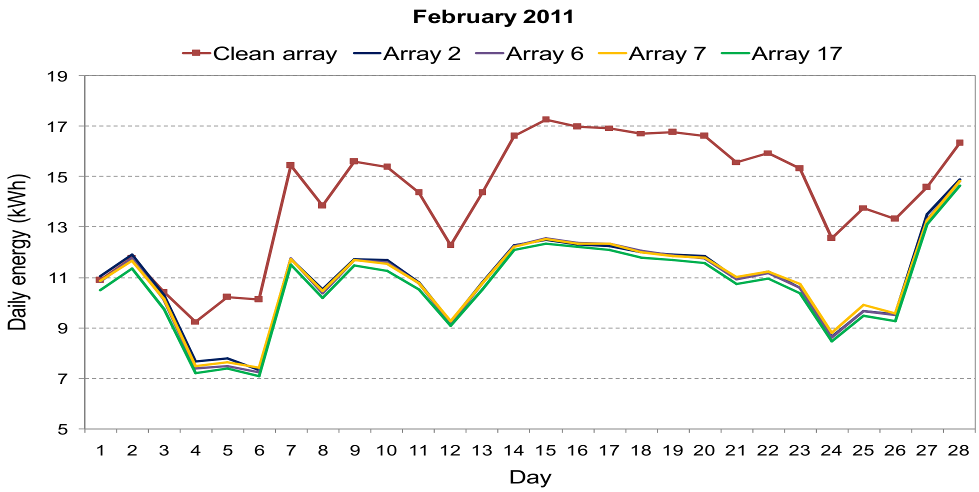

Figure 11. Energy generated by clean and unclean sub-arrays

Figure 12 shows daily performance ratio for the same subsystems during the same period. The average value was 77.4 for the clean and 59.3 for unclean subsystems. At beginning of February the PR was 61 and decreased for the dirty sub-arrays until 54 and then increased to 73 just after the rain.

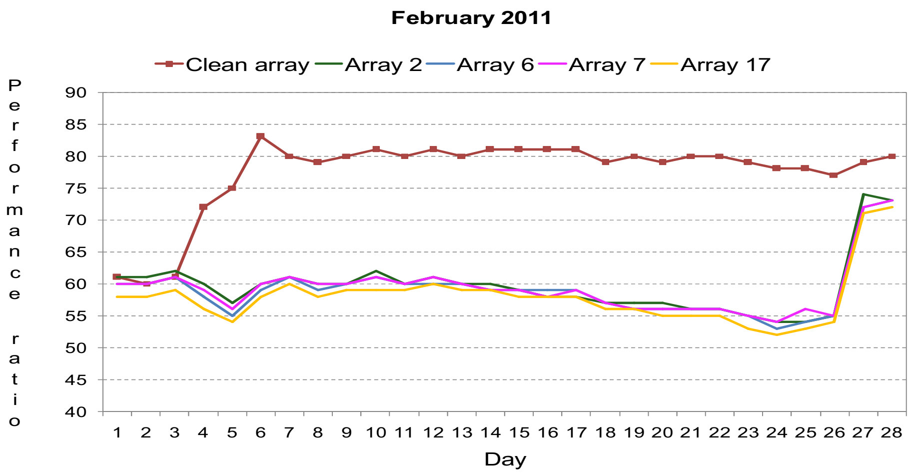

Figure 12. Performance ratio of clean and unclean sub-arrays

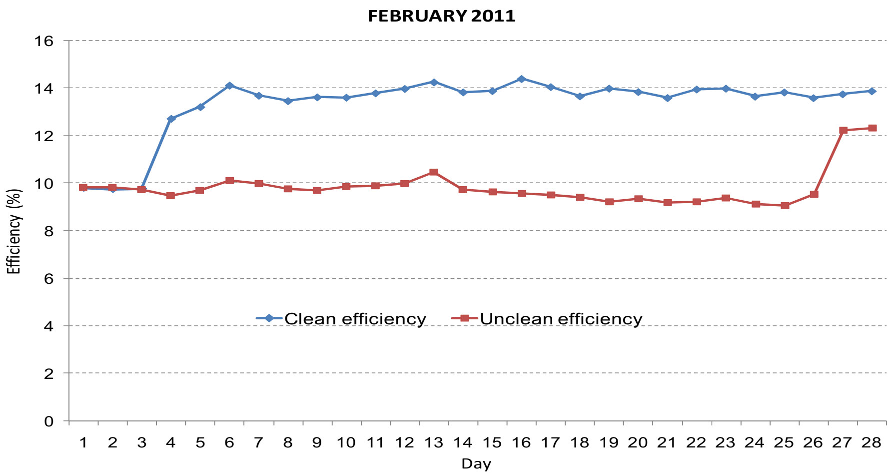

Figure 13. PV generator efficiency for clean and unclean subsystems

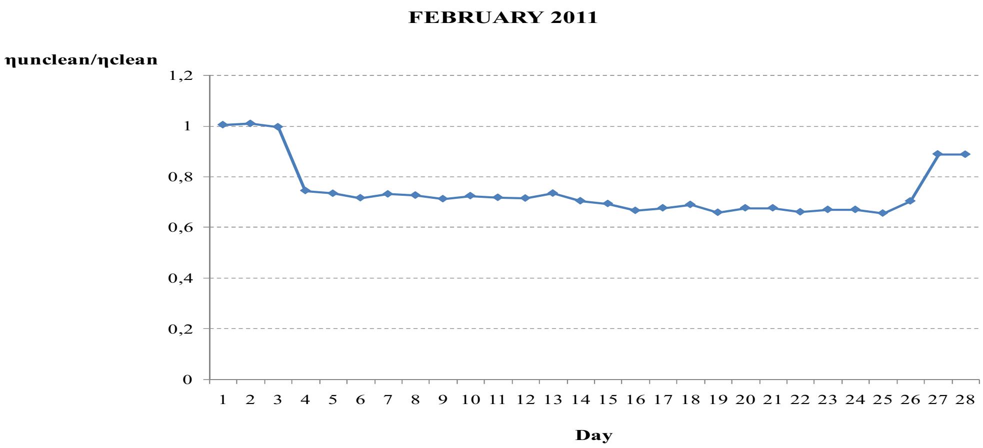

Figure 14. Efficiency ratio un clean/clean sub-array

The PV generator efficiency drop was evident in polluted systems compared with the clean one (figures 13 and 14). The difference in average monthly efficiency reached 31.3%

7. Conclusions

A severe impact on the performance of PV system due to dust accumulation has been observed at the UAMI PV system during the analyzed period. In this case the system would have generated about 2023 kWh more in February if it had not been polluted or if it would have been washed in time. The energy losses could have a big impact on the economics of the systems. Since this type of energy losses dependent of pollutants emitted by neighboring factories in combination with rainfall absence it is difficult to develop a methodology to estimate in long term PV system energy production.

According to analyzed data, the PV modules efficiency gradually decreases through time and can be reduced up to 44%. While this information is useful it is limited of the relatively small number of data and time evaluated. More work on this subject is still needed in order to drawing statistically significant conclusions.

It is also indispensable to explore the effect of wind velocity and direction in addition to identify the specific pollutants present in the atmosphere.

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