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EVALUATION OF THE EFFICIENCY LOSS OF PHOTOVOLTAIC MODULES DUE TO URBAN DIRT – A CASE STUDY

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Abstract. *A photovoltaic (PV) power plant must operate at its maximum efficiency, which can be impacted by dirty accumulation. This study aims at evaluating energy efficiency losses due to dirt deposition through comparison between cleaned and uncleaned PV modules, in a 12-years operating PV system. A supervisory has recorded at every minute the incident global solar radiation, ambient and PV module's temperatures, the individual and total currents, and the PV array's voltage. All modules have never been actively cleaned before. Only three modules were daily cleaned with water plus detergent, jumping the weekends. This procedure was executed with a wet and dry season steps. The efficiency of each module was calculated dividing its daily energy output by the daily incident solar energy. For accounting energy efficiency losses only due to dirt deposition, the aging effect was removed from the analysis, taking the most degraded module as a reference and subtracting its efficiency from the other modules, to put all modules at the same level of aging. In wet periods, active cleaning is not cost-effective since raining promotes spontaneous cleaning. Daily average efficiency improvement rate due to cleaning was found at 0.07 % and 0.29 % in the wet and dry seasons, respectively.*

Keywords: *photovoltaic, solar energy, efficiency loss, dirt deposition, PV aging*

1. INTRODUCTION

A photovoltaic (PV) power plant must operate at its maximum efficiency due to its high investment cost. Dirt deposition decreases its power output, but scheduled cleaning results in additional costs. Dirt accumulation on the surface of PV modules reduces their glass cover transmittance with more impact on PV technologies with spectral responses concentrated in the low wavelengths.

PV module aging is another factor commonly not taken in account in economic feasibility appraisals. Literature indicates a mean value of 1 % per year in power output loss due to aging, but there is a great dispersion in power loss even if among PV modules coming from the same manufacturing batch. Aging and dirty promote a lumped effect in power loss, both are impacted by the local environment of the PV installation. Aging has a more predictable behavior than dirt accumulation; the last is strongly site dependent, requiring experimental evaluation to quantify its effect on efficiency loss.

Tonini et al. (2013) evaluated the influence of air pollution on short-circuit current and open-circuit voltage of eight PV modules in Vitória, ES, through daily cleaning half of them. The authors found that air pollution significantly reduces both PV characteristics.

Cristaldi et. al, (2014) presented a simplified method for evaluating the impact of both aging and dust deposition as sources of the loss of efficiency of photovoltaic plants. To validate the proposed method, the authors used a 5 Wp polycrystalline silicon photovoltaic panel belonging to the same manufacturing batch of the panels installed in the PV plant, which was periodically cleaned. The panel was connected to an electronic load which had allowed setting the operating point on the V–I plot. Measurements were performed between May and June 2013 in Italy at one-minute intervals. The measurements of the PV module frame temperature and solar radiation were made through a resistance thermometer PT100 and a pyranometer, respectively. The difference between the energy actually produced and that produced at the beginning of its operating life was used to evaluate the aging effect. The authors concluded that the method presented satisfactory results.

Hickel (2017) evaluated the loss of performance in solar photovoltaic systems caused by the accumulation of dirt on its surface using I x V curves measured in the field at Florianópolis, SC, and found losses with very discrepant values between different PV technologies, with values of the order of 16 % through the accumulation of dirt.

In Goiânia, GO, Alves (2018) found that the power generation efficiency of PV modules analyzed was reduced by 3.2 % for accumulated soiling in periods of 45 days, and by 18 % for accumulated soiling in a longer period of 3.5 years. The characterization of the soiling showed that in addition to mineral particles, there is also organic matter derived from biofilms, which makes it difficult to clean the modules by natural methods (rains and winds). The author estimated that the periodicity of the hygiene should not exceed 60 days, with that; the effects of the soiling are reduced significantly.

Barbosa et al. (2018) studied the effect of dirt deposition on energy output from an on-grid PV system in Pato de Minas, MG. Only one of three PV module strings was cleaned once per week in a 30-day evaluation period. The authors found a 10 % decrease in energy output due to dirt.

This study aims at experimentally evaluating the PV module's efficiency losses due to dirt deposition in a 12-years operating PV system.

After determination of the dirt accumulation effect on efficiency loss, the remaining differences in power output will proportionate to find the aging annual mean rate of each PV module, through comparison between predicted and measured power output.

2. LOCAL CLIMATE

According to climate-data.org, (2018), the climate of the city of Rio de Janeiro is classified as Am by the Köppen-Geiger system. The average annual temperature is 23.2 °C with a range of 5.5 °C throughout the year. Annual precipitation reaches about 1,278 mm with a difference of 94 mm of precipitation between the driest (January) and wettest (July) months, as shown in "Fig. 1".

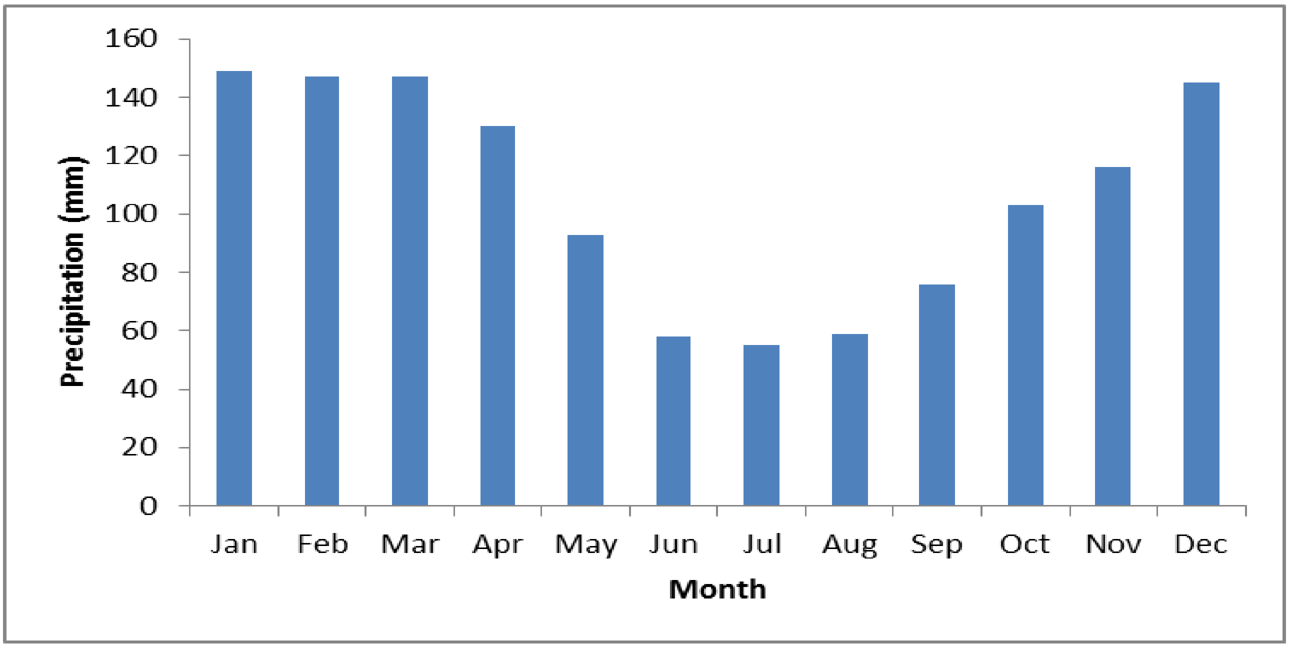

Figure 1 – Annual precipitation at the city of Rio de Janeiro, adapted from Climate.org (2018).

3. EXPERIMENTAL SETUP

The PV system under study was installed in 2007 at the Rio de Janeiro State University's Campus located in the São Cristóvão neighborhood in the city of Rio de Janeiro and has continuously functioned until now in the off-grid mode. It is composed by fifteen polycrystalline silicon MSX120 modules, manufactured by BP Solar, but only seven are encompassed by this investigation.

The PV modules are fixed on a metallic frame north oriented with an inclination angle of 32°, over the roof of the Annex building, near to 25 meters above the lateral street, called Cadete Ulisses Veiga. This place was strategically chosen to prevent shading from the main building with 18 floors, throughout the year.

Each module consists of 72 cells resulting in a nominal power of 120 Wp. According to the manufacturer's datasheet, the module comprises 3 mm-thick tempered glass at the front, ethylene vinyl acetate base, polymer back coating and aluminum frame. Its nominal absorption area and efficiency is 1.1 m^2 and 10.9 %, respectively. PV module electrical characteristics are shown in "Tab. 1".

Table 1. BP MSX 120 electrical characteristics, from manufacturer datasheet

PV Module characteristic	Value
Maximum power (P_{max})	120 W
Voltage at P_{max} (V_{mp})	33.7 V
Current at P_{max} (I_{mp})	3.56 A
Minimum P_{max}	114 W
Short-circuit current (I_{sc})	3.87 A
Open-circuit voltage (V_{oc})	42.1 V
Temperature coefficient of I_{sc}	(0.065±0.015) %/ °C
Temperature coefficient of V_{oc}	-(80±10) mV/ °C
Temperature coefficient of power	-(0.5±0.05) %/ °C
Normal operating cell temperature	47±2 °C

The seven PV modules are connected in parallel and feed a purely resistive load of 1.5 ohm, which allows the PV array to operate next to its maximum power point. There is no maximum power point tracker.

A supervisory has recorded at every minute the incident global solar radiation, illuminated and shaded PV module's surfaces and ambient temperatures, the currents of each PV module, the total current, the voltage of the PV array and the air relative humidity. "Tab. 2", reproduced from Soares et al. (2017), presents all sensor characteristics. The supervisory was developed in LabVIEW using Compact Field Point as external computer interface, both from National Instruments Inc. Labview has been proven to be very adequate for monitoring PV systems (Koutroulis and Kalaitzakis, 2001; Ahmed, 2013). Compact Field Point is a programmable logic controller in a modular architecture, supported by specific signal conditioner cards mounted in accordance to the user's needs. Five TC-120 cards receive signals from thermocouples and two AI-110 cards read the other sensors. This monitoring system starts functioning on September, 2017, but the current configuration was put in place on February, 2018.

Table 2. Sensors used (reproduced from Soares et al., 2017)

Type	Manufacturer	Model	Range	Precision / sensibility
Thermocouple - T type	Thermomax	TP 3279	0 ºC to 370 ºC	±1.0 ºC
Current transmitter	SECON	05T420ADC-24VDC	0 to 5A_{DC}	±1 %
Current transmitter	SECON	35C420ADC-24VDC	0 to 35A_{DC}	±1 %
Voltage transmitter	SECON	50V420ADC-24VDC	0 to 50V_{DC}	±1 %
Solar irradiation	Kipp and Zonen	CMP3	0 to 2000W/m^2	5 to 20 μV/W/m²

4. METHODOLOGY

All PV modules have never been actively cleaned before this study. Only the modules number 2, 5 and 6 were daily cleaned with water plus detergent around 8 a.m., jumping the weekends. This procedure was executed with a wet and a dry season steps, respectively from March, 15th to April, 5th and from June 18th to July, 2nd, as detailed in "Tab.3"(a ,b).

Table 3(a). Cleaning schedule of the PV modules in the wet season

Month	March 2019																	April 2019				
Day	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5
Cleaning (Yes or No)	Y	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y

Table 3(b). Cleaning of the PV modules in the dry season

Month	June 2019													July 2019	
Day	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2
Cleaning (Yes or No)	Y	Y	N	N	N	N	Y	N	Y	Y	Y	N	N	Y	Y

The days were classified in clear, intermittent solar radiation or cloudy sky, according to own methodology developed in other research going on. Rainy days ware included in the last class "Fig. 2", illustrates a typical daily solar radiation plot of each class. Efficiency of each PV module was calculated dividing its daily energy output by the daily incident solar energy.

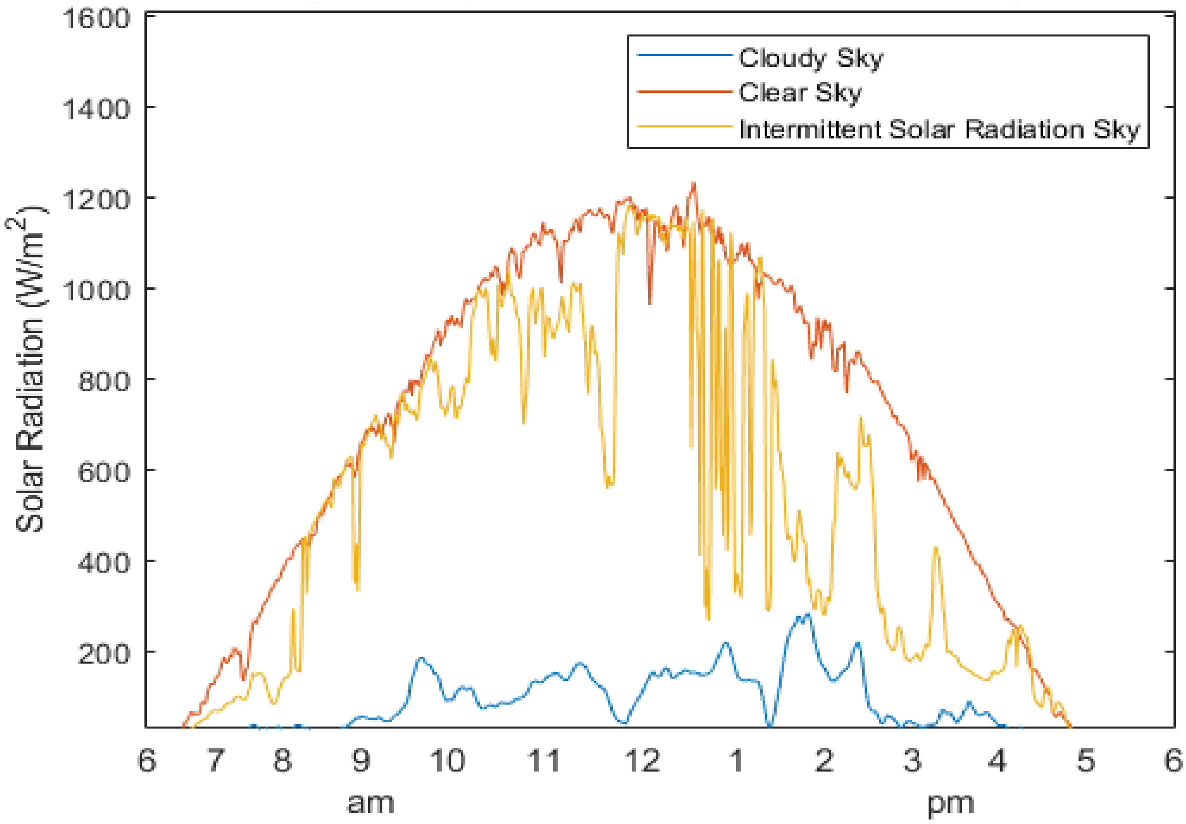

Figure 2. Classification of the days in relation to solar radiation

The 7 PV modules have different power losses due to aging, as depicted in "Fig. 3", where daily energy output differences in relation to module 6 are plotted for January, 22nd and 23rd corresponding to a clear sky and an intermittent solar radiation day, respectively. For eliminating the aging effect from the analysis, it is proposed here to take the most degraded module as the reference, subtracting its efficiency from those of each other modules, in order to bring all to the same aging level. So, differences found can be attributed to dirt deposition.

Even if all PV modules have just been installed and started operating, this leveling procedure is also need because it is expected some power output differences among them. In the present case, the PV module manufacturer informs in the product datasheet a decrease up to 6 W (5 %) in power output in the Standard Reporting Condition, at starting operating.

Although module 5 has exhibited the worst performance in the present evaluation, there is lack of information from it in some days due to bad functioning of its current sensor, obligating to take module 6 as the reference. So, each average difference in efficiency in relation to the module 6, evaluated between February, 15th and March, 12nd, was adopted as the respective aging leveling factor, shown in "Tab. 3". Note that modules 1 and 4 have higher and close efficiencies, highlighting that both were not cleaned. Since modules 1 and 2 have thermocouples on their illuminated faces, a better couple for a single comparison between clean and dirty module performances is 6 and 7, what is not the case here.

Table 3. Average differences in efficiency in relation to module 6 (%)

Module Number	1	2	3	4	5	6	7
Average differences in efficiency in relation to module 6 (%)	0,53	0,14	0,22	0,58	-0,23	0	0,12

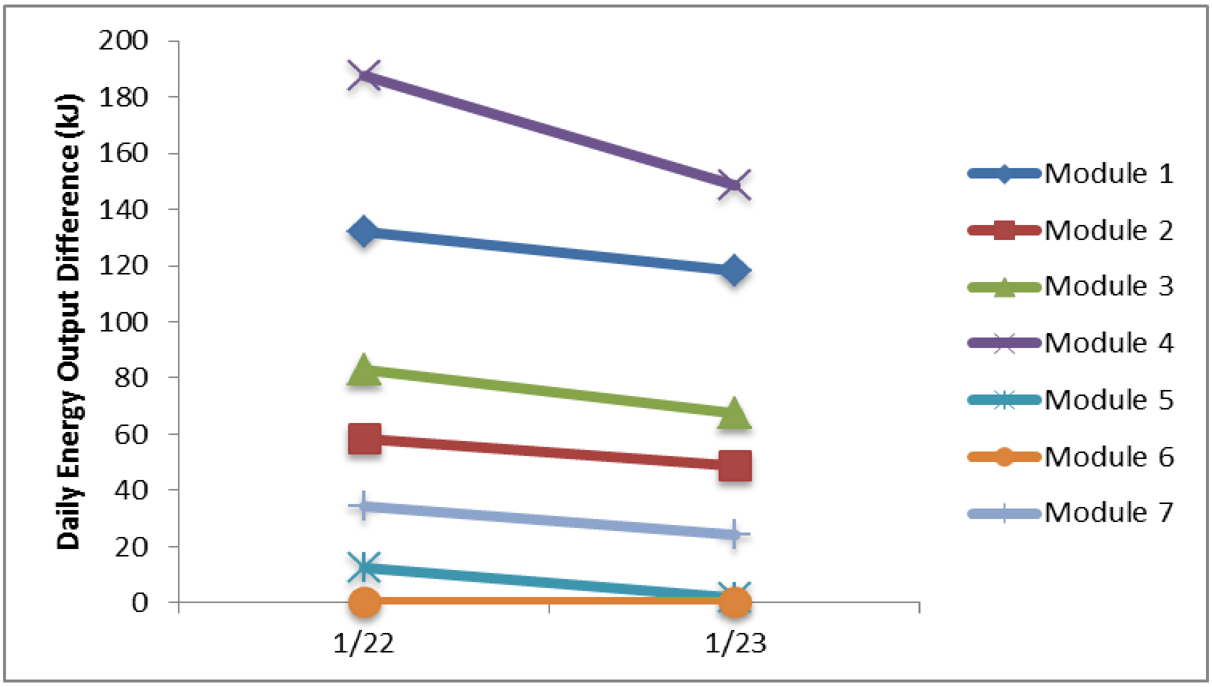

Figure 3. Daily energy output differences on January, 22nd and 23rd.

Daily differences between the efficiency averages of the cleaned modules 2 and 6, and the uncleaned modules 1, 3, 4 and 7 were calculated and correlated with the type of day and with the rainfall, from own local raining observation complemented by precipitation data coming from the São Cristóvão weather station far only 700 m in straight line. Uncomplete information coming from module 5 was only qualitatively included in the present analysis.

The days without cleaning were utilized to analyze efficiency loss rates due to daily dirt accumulation on cleaned modules and efficiency improvements through spontaneously cleaning by the raining.

5. RESULTS

5.1. CLEANING BY THE RAIN

"Figure 4" shows daily average efficiency differences between clean and uncleaned modules from April, 9th to 14th. These days just after the end of the first cleaning period were utilized to analyze the effect of the cleaning by the rain on module efficiencies. Rainfall cleans equally all modules, so in rainy days it is expected a decrease in the differences in efficiency between clean and uncleaned modules. A high intensity storm reached all Rio de Janeiro Metropolitan Region in the first 2 days. São Cristóvão weather station recorded 96.6 mm, 70.0 mm and 14.0 mm of daily precipitation respectively on April, 9th, 10th and 11th.

This 3-day heavy rain accompanied by high intensity winds was able to promote a full cleaning of all modules, clearing the efficiency difference that stayed for 2 days at almost null level, because rain also cleans the air and wet the land, highly reducing dust in suspension. The difference started to increase only in the third day without raining, probably because the never cleaned modules have retained some residual dirt not removable with pure water that allows a quicker dirt adherence.

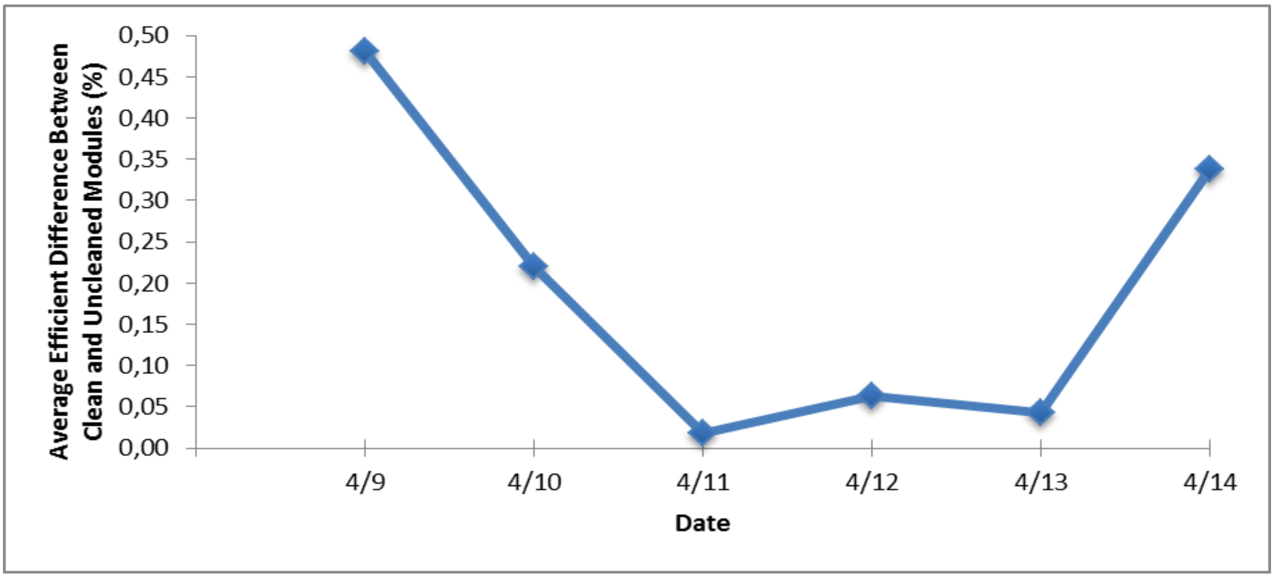

Figure 4. Daily average efficiency difference between clean and uncleaned modules from April, 9th to April, 14th

5.2. THE WET SEASON STEP

"Figure 5" shows daily average efficiency differences between clean and uncleaned modules from March, 15th to April, 5th. The first seven days reproduces a typical trend of the experimental results, the 2 first rainy days without active cleaning reduces the efficiency difference between clean and uncleaned modules, followed by a five cleaning days with an increase of this difference, approximately repeated in the next week. In the last week the cleaning has maintained clean and dirty modules at the same level of difference in efficiency.

In the rainy period, average daily improvement efficiency rate due to cleaning was 0.07 %. Since frequent rainfall promotes cleaning, the performance improvement due to scheduled cleaning is low.

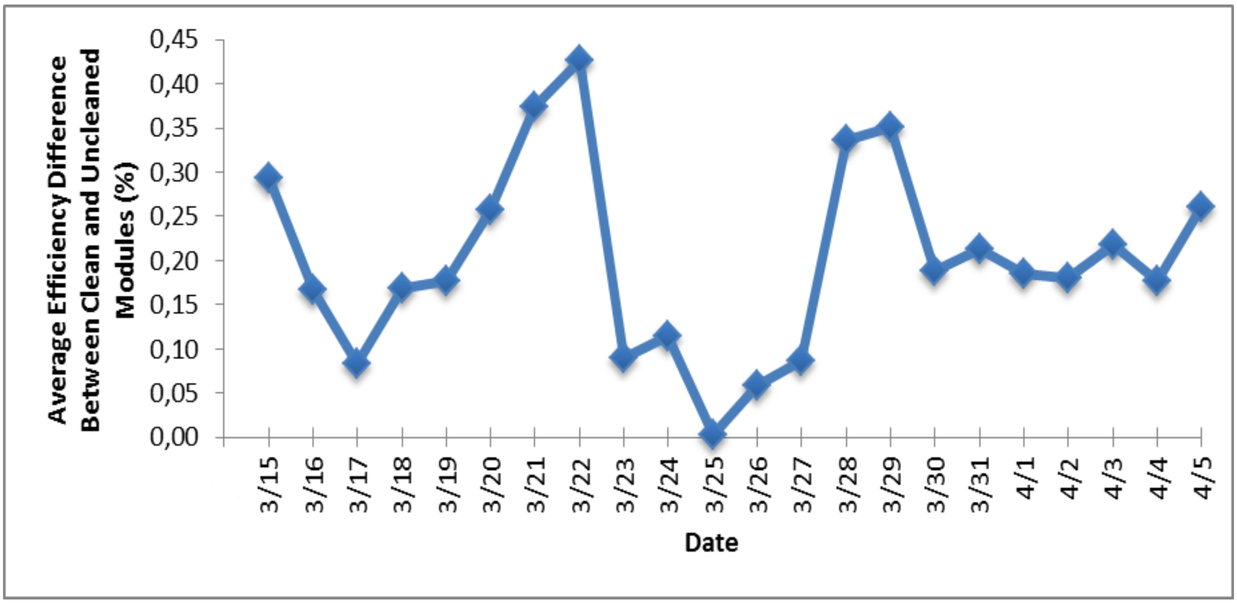

Figure 5. Daily average difference between clean and uncleaned modules from March, 15th to April, 5th.

5.3. THE DRY SEASON STEP

It was observed the expected trend of increasing efficiency differences between clean and uncleaned modules in consecutive dry days, this difference is reduced after raining because all are consequently cleaned, what is easily noticed because this reduction is enlarged by the distinguishable aging-related better performance of the uncleaned modules 1 and 4.

This can be seen in “Fig. 6”, where the differences between clean and uncleaned modules increased in the first 2 days with cleaning and without raining, they decreased by the rain and return to continuously increase in the last 10 days dry period with the cleaning schedule put in practice. The average daily increment in module efficiency by cleaning reaches 0,29 %, and in the increasing sequence of 9 days shown in “Fig. 6” including 3 uncleaned, the accumulated efficiency gain reached 2,63 %, which corresponds to 24,09 % of the nominal efficiency of the module. Increasing efficiency difference between clean and uncleaned modules in days without cleaning can be attributed to easier dirt impregnation on the modules never actively cleaned.

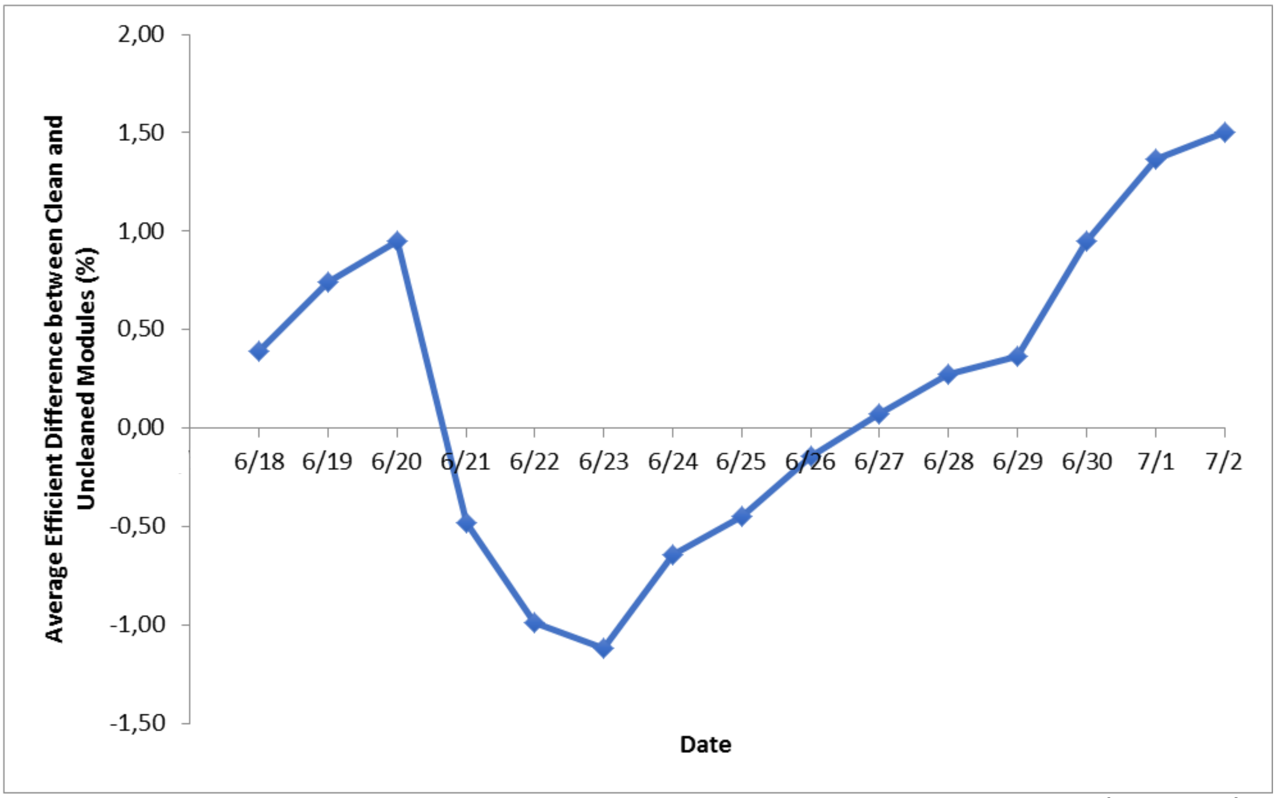

Figure 6. Daily average efficiency difference between clean and uncleaned modules from June, 18th to July, 2nd.

6. CONCLUSIONS

The proposed methodology to take the worst performance module as a reference, in order to eliminate aging effects from the analysis as described in the section 4, has been proved to be suitable for the experimental evaluation of efficiency losses due to dirt accumulation.

Experimental data have shown that the rain promotes cleaning, so in the wet periods the cleaning is probably unnecessary and not cost effective. After a heavy rain there is an expressive reduction in dirty in suspension, consequently the cleaning can assuredly be jumped by one day.

Daily average efficiency improvement rate due to cleaning were found at 0.07 % and 0.29 % in the wet and dry seasons, respectively. The last was accumulated up to 2.63 % in the observation period, which corresponds to 24,09 % of the nominal efficiency of the module. Larger sampling period is need to evaluate its maximum, but is clear that in a long sequence of dry days the cleaning reaches the economic feasibility. It was notice that after cleaning there is some inertia to dirt accumulation, so a schedule of cleaning in alternate days seems to be more appropriated.

Daily average efficiency difference between clean and uncleaned modules was found not dependent of the type of day.

Results from this research must not be generalized, because the PV system studied is 25 m above the lateral street level that have very low traffic and at least 40 m above the main street level. The last has moderate traffic without bus lines. Additionally, wind direction and magnitude will not be the same, as well as the position of the dirt sources.

Future research may be focused on the development of automatic cleaning devices for PV arrays and also in determining the cleaning periodicity that reaches the optimum in the economic appraisal.

7. ACKNOWLEDGEMENTS

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