EFFECT OF THE SELF-CLEANING COATING SURFACE IN THE TEMPERATURE AND SOILING LOSSES OF PHOTOVOLTAIC MODULES

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ABSTRACT: Soiling on photovoltaic modules has a straight effect on the transmittance and hence significant energy losses. The economic cost due to these losses can be important in the case of large-scale plants, especially for those located in dry areas. Asahi Kasei Corporation has designed and developed a new coating for photovoltaic modules with self-cleaning and anti-reflectiveness properties. The deposition of such coating on the surface of the modules has a positive effect on their global performance. The objective of this paper is to evaluate this coating by comparing the energy produced by several modules of the same model, some of them with anti-soiling coating and other without it. Obtained results quantify the relationship between soiling and energy losses. During long periods without rain, these losses grow up gradually until first rainfalls. Modules with the coating have experimented mean daily energy losses around 2.7%, whereas in the case of the modules without the coating this value reaches 3.6%.

Keywords: Anti-soiling Coating, Energy Rating, Optical Losses

1 INTRODUCTION

In arid climates, photovoltaic systems have a high risk of being affected by dramatic losses due to the accumulation of dust on the surface of the modules. This phenomenon, called soiling, has awakened interest in photovoltaic experts for many years. Soiling implies a significant decrement of the transmittance and hence of the produced energy. Piliougine et al. [1] report losses due to soiling greater than 15% when it has not rained for a long period of time. Regular washing with water is the only solution for reducing such losses. However, in arid regions this way of cleaning may unfeasible or very expensive.

Asahi Kasei Corporation has designed and developed a coating film with self-cleaning and anti-reflectiveness properties. This coating layer is made of nanoparticles of metal oxide over a special polymer binder. This new hybrid binder has been developed to allow a thick deposition over the module in order to avoid an early degradation of the film, increasing its useful life. Narushima et al. [2] state that the application of this film over the surface of a photovoltaic module improves its performance between 0.5% and 1.0%. The composition, the morphology and the thickness of coating film can be easily controlled in order to achieve a uniform layer [3].

A set of tests have been applied in order to sure the resistant of the film to external factors such as heat and dust. In the work by Hirose et al. [4], it is reported that this coating has high transmittance and low water contact angle even after several resistance test, passing also an impact test and adhesion tape test without presenting any micro-cracks through the microscopy.

In this work, the effectiveness of this coating film has been evaluated by means of comparing the energy produced by six polycrystalline silicon (pc-Si) photovoltaic modules with identical specifications (see Table I). Whereas the coating film has been applied over three of them, the other three modules have not been altered. All of them have been exposed to real sun for one year. Their electrical characteristic *I-V* curves and the main meteorological parameters have been registered.

2 PREVIOUS WORKS

A high number of papers have attempted to understand the phenomenon of soiling in the context of solar energy. Early studies about the losses in transmittance due to dust accumulation date back to more than forty years. However, most of them study the problem for solar thermal applications, as the work by Garg [5]. Since 1990 it is possible to find more articles where this problem is approached from the point of view of the photovoltaic systems. For example, Said [6] carries out a set of experiments in order to quantify the evolution in performance of photovoltaic and thermal devices for a period of several months in Saudi Arabia.

El-Shobokshy et al. [7] study the relationship between the accumulation of dust and the performance of photovoltaic cells using a solar simulator. The results reveal the complexity of the problem and they conclude that several factors must be taken into account, such as the size and shape of dust particles, their composition and the deposition density.

Al-Hasan [8] carries out a mathematical study over photovoltaic modules about the influence of soiling on the transmittance of only the beam radiation. He proposes a model that takes into account the density of dust particles, the size of that particles, the angle of incidence of the light beam and its wavelength. Moreover, this theoretical model has been validated against experimental measurements.

Table I: Specifications of the photovoltaic modules

Type of cell	pc-Si
Short-circuit current I_{SC}	8.27 A
Open-circuit voltage V_{OC}	32.5 V
Maximum power P_M	195 W
Maximum power current I_M	7.50 A
Maximum power voltage V_M	26.0 V
Conversion efficiency η	13.4%
Current temperature coefficient α	+0.08% / °C
Voltage temperature coefficient β	–0.32% / °C
Power temperature coefficient γ	–0.38% / °C
Nominal Operating Cell Temperature NOCT	47 °C

Biryukov [9] investigates the deposition of dry particles on the reflective surfaces of concentrating collectors. As the regular cleaning with water is expensive, several alternatives have been studied, mainly based on repulsive physical interactions between the surface and the dust particles.

The authors of [10] use a microscope system controlled by computer in order to study the physics of dust particles adhered to the surface of solar collectors and photovoltaic modules. In this way, they can calculate the particle size distribution and the ratio of surface area covered by soiling.

Goossens and Van Kerschaever [11] describe several experiments carried out in a wind tunnel in order to study the influence of air dust concentration and wind velocity on the performance of photovoltaic cells. *I-V* curves are measured using different concentration of dust. The variation of the main electrical parameters is analysed.

In the work of Pang et al. [12], the impact of pollutants on module efficiency is analysed. A couple of copper indium diselenide (CIS) modules are exposed under natural sun light in a densely polluted location. *I-V* curves are measured at regular time intervals covering a wide range of values of solar irradiance and module temperature. They provided a cleaning guideline to optimise the balance between cleaning cost and energy yield.

AlBusairi and Möller [13] present a study about the performance of cadmium telluride (CdTe) modules under outdoor conditions in Kuwait, focussing on the specific environmental parameters present in this area, such as high temperature and dust. They recommend a variable cleaning schedule based on meteorological conditions at each moment.

A complete state of the art about the impact of soiling on photovoltaic devices can be found in the paper by Mani and Pillai [14]. They also present a framework to understand the multiple factors that are involved in the accumulation of dust such as air temperature, humidity, rainfall, wind movements and dust properties, among others. They conclude that the phenomenon of dust settlement is extremely complex and its complete comprehension is a future challenge.

García et al. [15] study the soiling and other optical losses in solar-tracking photovoltaic plants. The authors report values of daily energy soiling losses from 2% to 6% on the tracking system.

Recently, Qasem et al. [16] investigate the effect of dust on photovoltaic modules with respect to concentration and spectral transmittance. Measurements have been performed over several samples of glass at different tilt angles, determining the spectral transmittance at the top, the middle and the bottom of each sample. In addition, these results are combined with the spectral responses of several photovoltaic technologies, concluding that amorphous silicon is more affected than crystalline silicon or copper indium gallium diselenide (CIGS).

Finally, Zorrilla-Casanova et al. [17] states that the mean daily irradiation losses is around 4%. However, after long periods without rain, this value can be higher than 20%. In addition, they propose a simple theoretical model that describes the qualitative behaviour of the irradiance losses during the day. This model not only takes into account the angle of incidence, but also the percentage of dirty surface and the diffuse/direct irradiance ratio.

3 MEASUREMENT SYSTEM

The *I-V* curves have been taken using a four quadrant power supply (this means that it can deliver as well as dissipate power). Then, it is possible to acquire *I-V* points beyond the first quadrant and around the axes. A computer controls the power supply through the GPIB protocol in order to perform a voltage sweep, whereas module voltage and current are measured using two digital multimeters. These multimeters are synchronized by a square signal that triggers them simultaneously. The duration of the voltage sweep has been set to 1 second. Finally, irradiance is measured through a pyranometer Kipp & Zonen CMP21 and the cell temperature of each module is measured using a Pt100 sensor. These values are registered at the beginning and at the end of each measurement by the acquisition data system. Other parameters, such as rainfall, wind direction and speed, air temperature, relative humidity and atmospheric pressure have been also measured. This measurement system is provided with a relay box that allows us to measure several modules in a short period of time, in such a way that it can be assumed that all measurements have been acquired at once, i.e., under the same weather conditions.

A complete description and the estimation of the uncertainties have been published in a previous paper by Piliougine et al. [18].

4 MEASUREMENT CONDITONS

The measurements have been carried out on the roof of the Photovoltaic Laboratory at the University of Málaga, Spain (latitude 36.7° N, longitude 4.5° W and elevation 50 m). The installation is located between an industrial state and a residential area with several roads with heavy traffic. The set of measurements used in this work started on 1 November 2010 and finished on 31 October 2011 (1 year). The modules have been oriented towards the south and with a tilt angle equal to 21°.

Air temperature has been between 20 °C and 30 °C for around three quarters of the period, so it can be said that the temperatures have been quite warm. The accumulated global irradiation during all the period has been equal to 1983 kWh/m^2 (that means a daily mean of 5.4 kWh/m^2). Finally, the total rainfall throughout all the period has been of 1266 L/m^2 (Fig. 1 plots rainfall month by month). That is about twice what it rained the previous year. Due to the proximity of the Mediterranean Sea, the registered values of humidity are quite high. This is a key factor in our study since it significantly increases the adhesion of dust particles to the surface.

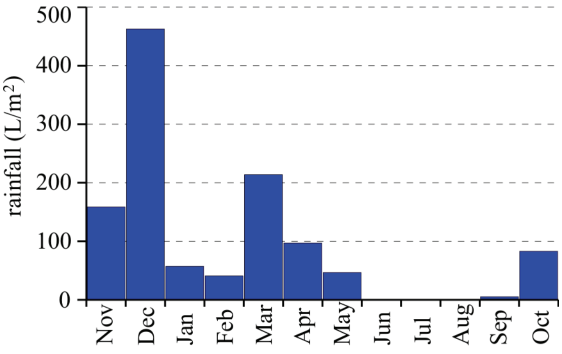

Figure 1: Values of rainfall month by month.

5 ANALYSIS OF ENERGY LOSSES

Our aim is to perform an analysis of the energy losses throughout the day. For this study all measurements registered in the period have been taken into account without performing any filter or previous selection. For each *I-V* curve (without translating to STC) the maximum power value is estimated getting a sequence of power values P_{M} along the each day. From this sequence of values, an estimation of the energy that the module would generate could be computed by integration of that sequence throughout the day:

$$E_{daily} = \int_{sunrise}^{sunset} P_{\mathrm{M}} \cdot dt$$

In order to compute this integral a trapezoidal approximation has been implemented:

$$E_{daily} = \sum_{i=sunrise}^{sunset} \frac{1}{2}\left(\langle P_{\mathrm{M}}\rangle_{i+1} + \langle P_{\mathrm{M}}\rangle_{i}\right)\cdot\left(t_{i+1} - t_{i}\right)$$

In the same way, from the sequence of measured values of irradiance, it is possible to compute the daily irradiation:

$$H_{daily} = \int_{sunrise}^{sunset} G \cdot dt$$

And using trapezoidal integration again we have:

$$H_{daily} = \sum_{i=sunrise}^{sunset} \frac{1}{2}\left(\langle G\rangle_{i+1} + \langle G\rangle_{i}\right)\cdot\left(t_{i+1} - t_{i}\right)$$

Using the formulae given by Marion et al. [19], the daily yield and the daily performance ratio can be computed. The daily yield is the daily energy divided by the nominal P_{M} at STC that appears in the specifications of the module (it is expressed in Wh/Wp):

$$Y_{daily}\ (\mathrm{Wh/Wp}) = \frac{E_{daily}}{P_{\mathrm{M}}^{\mathrm{STC}}}$$

Another daily magnitude is the daily reference yield. This value does not depend on a specific module and it can be calculated as the ratio between the daily irradiation and the irradiance at STC that is equal to 1000 W/m^2:

$$Y_{daily}^{\mathrm{R}}\ (\mathrm{Wh/Wp}) = \frac{H_{daily}}{G^{\mathrm{STC}}} = \frac{H_{daily}}{1000\ \mathrm{W/m^2}}$$

Finally, the daily performance ratio (PR) is calculated as the daily yield of a specific photovoltaic module and the reference yield of that day:

$$\mathrm{PR}\ (\%) = \frac{Y_{daily}}{Y_{daily}^{\mathrm{R}}} \cdot 100$$

Whereas the value of yield depends on both irradiation and losses, the value of performance ratio depends only on the different types of losses.

6 COMPARATIVE RESULTS

The results of the analysis of energy losses are presented in this section. First, for each module and each month, we have represented the mean value of the daily yields of all days of that month (see Fig. 2). During the first months, the daily yield values of all the modules are very close because the amount of accumulated dust is very little. However, during the last months, the differences between one module and its reference module have been grown progressively due to the lack of rainfall. This effect is masked by the fact that in the winter season the received irradiation is lower, and therefore the yield is also lower. In this figure, it is difficult to appreciate differences between coated and uncoated modules. Whereas the dirty coated modules have a mean daily yield (along the period) equal to 5.3 Wh/Wp, the dirty uncoated ones have a value equal to 5.2 Wh/Wp. This little difference is due to the unequal evolution of both types of modules during the dry season. Finally, the mean daily yield of both reference modules is equal to 5.4 Wh/Wp.

There are several parameters (different type of losses) which have more or less influence on the value of the performance ratio PR. On the one hand we have the level of soiling and the module temperature. On the other hand we can cite the angle of incidence and the spectral losses. However, these later parameters are equal for all the modules because all of them are exposed to the sun under the same conditions.

Of great interest is the plot of the daily performance throughout all the year (see Fig. 3). We cannot appreciate important differences during the first months of the period, because the rainfall cleans the modules with enough frequency avoiding the accumulation of dust on their surfaces. Moreover, the module temperatures during these months are close to 25 °C. Then, the losses due to soiling and temperature have been kept low for this period. However, the worse results in terms of performance ratio are achieved during the dry season due to soiling and high temperatures. Values of PR greater than 100% in the winter are due to a combination of module temperature lower than 25 °C with a perfectly clear-sky day without any mist. In addition, the surface of the photovoltaic modules will probably very clean since in this period rainfalls are frequent.

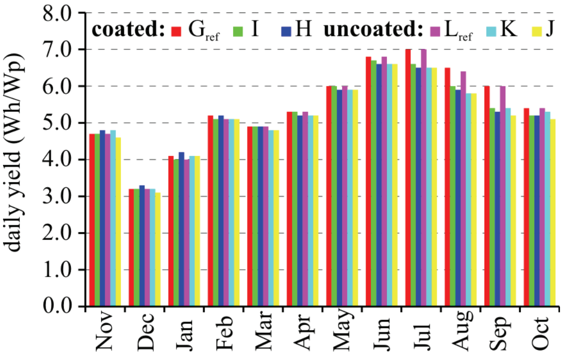

Figure 2: Evolution of the mean daily yield.

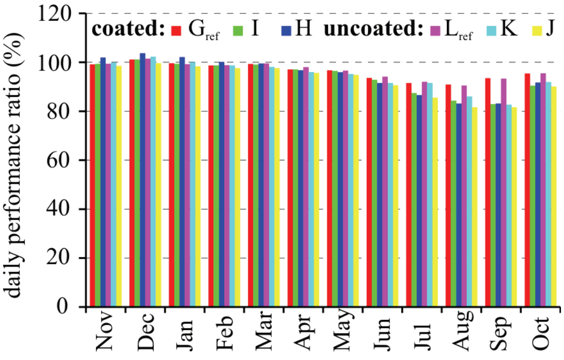

Figure 3: Evoltion of the mean daily performance ratio.

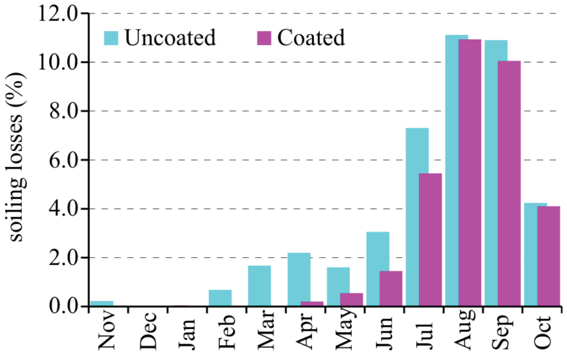

Figure 4: Monthly soiling losses.

Now, we are assuming that a clean module could have the same thermal behaviour than a dirty module. In addition, we could say that a clean module has a PR value equal to 100% at STC (neglecting other type of losses). Then, we can estimate the soiling losses of a dirty module as the difference between its PR value and the PR value of its reference module. If we calculate the mean value along the year of these soiling losses, we obtain a mean value equal to 2.7% for coated modules versus a value of 3.6% for uncoated ones.

We have plotted these soiling losses for coated and uncoated modules (see Fig. 4). As can be seen, the uncoated modules show soiling losses greater than the coated ones in all months. However, and contrary to what it might be expected, these differences decrease when the soiling level is already too high (August and September). The reason could be due to the fact that the amount of dust accumulated on the bottom of the module is significantly greater than the dust accumulated on its top, in such a way that the shape of the *I-V* curve present a step that affects dramatically to its fill factor (FF) and hence to its maximum power value P_{M} .

7 CONCLUSIONS

From a set of six polycrystalline silicon modules (three with coated film and other three without it), an evaluation and comparison have been carry out. *I-V* curves of those photovoltaic modules have been acquired under outdoor conditions in Málaga (Spain) for a year.

In terms of daily yield, whereas the dirty modules with anti-soiling coating are characterised for having a mean daily yield throughout the year of 5.3 Wh/Wp, the modules without this coating have a value equal to 5.2 Wh/Wp. This very little difference is due to the unequal evolution of both types of modules during the summer. Finally, the mean daily yield of both reference modules is equal to 5.4 Wh/Wp.

In terms of daily performance ratio, the observed behaviour is very close to the evolution of the daily yield along the year. The average value of the energy losses due to soiling has been equal to 2.7% for the coated modules and equal to 3.6% for the uncoated ones.

Once the period of measurement has been finished, a deep cleaning of all the modules has been performed and it has been verified that all of them have recovered their initial values in terms of electrical behaviour. This means that the modules and the coating film layer have not been affected by degradation after a year of exposure under outdoor conditions.

This work can be summarised saying that the incorporation of such an anti-soiling coating film to photovoltaic modules is an effective way in order to improve their energy performance because the soiling losses are significantly reduced. This factor is especially critical in large-scale photovoltaic system.

ACKNOWLEDGEMENTS

This work has been carried out under a collaboration project (No. 806/57.3183) between the company Asahi Kasei Corporation and the University of Málaga.

We also acknowledge to the “Junta de Andalucía” (grant No. P07-RNM-02504) for financial support.

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