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Long-term soiling of silicon PV modules in a moderate subtropical climate

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Abstract

The results of 28 silicon-based PV modules which were installed from 1981 to 1985 in a free rack configuration in the outdoor test facility of the European Solar Test Installation (ESTI) and dismantled at the end of 2014 without cleaning were analysed. The system was composed of modules with two series-connected laminates mounted in a single frame produced by the same manufacturer but using different cell layouts and cover glasses (plain glass or textured glass). The effects of long-term soiling on the PV module performance for more than 30 years of outdoor exposure in a moderate subtropical climate and the influence of different cleaning methods from manual cleaning to the use of high pressure water washing were investigated. The influence of the cover glasses and the mismatch due to the particular manufacturing design were also analysed. It was observed that a manual cleaning was effective at improving the output of all the module types. However, additional high pressure water spraying on plain glass modules showed no further improvement, but showed small improvements on the textured glass modules. Overall improvements in P_{max} after cleaning ranged from 3.5% to 19.4%, with an average value of 9.8% and an average improvement in I_{sc} of 6.7% were obtained.

Keywords: Soiling; PV performance; Silicon modules

1. Introduction

Accumulation of dirt on the surface of photovoltaic (PV) modules, referred to as "soiling", is one of the main loss factors affecting the system energy generation and this also presents a challenge to long-term performance prediction and lifetime estimates (John et al., 2014; Piliougine Rocha et al., 2008). The soiling is considered an important agent of optical losses that imply that the photovoltaic cells receive less irradiance (in the case of soiling uniformly distributed), or partial shading on the cells if it is not homogeneously distributed. Module soiling can result from various mechanisms such as pollution, particulate matter originating from agricultural activity, construction, the accumulation of dust, pollen, bird droppings or the growth of lichen (particularly at the lower edge of framed modules). Bird droppings or lichen, for example, present a serious problem as, contrary to dust, they cannot be easily washed away by rainfall (Thevenard and Pelland, 2013). The soiling is a complex phenomenon influenced by diverse site-specific environmental and weather conditions, tilt angle of the PV modules, the type of soiling agent and also the texture of the front glass (Piliougine Rocha et al., 2008; Mani and Pillai, 2010).

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The soiling effects on PV module performance have been investigated by several groups for different location, technologies, tilts and module design, with a number of papers found in the literature (Ryan et al., 1989; Caron and Littmann, 2013; Appels et al., 2013; Hammond et al., 1997; Kimber et al., 2007; Sarver et al., 2013; Schill et al., 2011, 2015; Kalogirou et al., 2013; Qasem et al., 2014). However, most of the works report on short-time soiling, from some days up to 6 years, considering that the modules are naturally cleaned by rain events or can be manually cleaned (Ryan et al., 1989; Mejia and Kleissl, 2013). An extensive review of natural soiling studies is reported by Sayyah et al. (2014). Heavy rainfall is considered to be the most efficient natural cleaning agent for removing contaminant particles from PV surfaces, demonstrating the significant restorable effects of sufficient rainfall, which make regular manual surface cleaning unnecessary. However, the build-up of dirt and dust over the years, or decades, is not so easily washed away by the rain and eventually leads to some permanent soiling. The conventional solution to the problem of soiling is to clean the PV modules with water or other standard glass cleaning products. However, this can be expensive and/or impractical at locations where water access is not feasible. The investigation on long-term soiling in PV systems should also assess the impact in economic terms (Massi Pavan et al., 2013). It has been reported, for instance, that in regions of mid-north Europe it could be uneconomic to clean the PV systems meanwhile an economical benefit can be observed in southern regions of Europe (Stridh, 2012). This study points out that with a cleaning cost of 2500 €/MW each cleaning has to recover between 1.0% (2.3%) of one year's production in Southern regions to 3.0% (5.2%) in northern European regions to give breakeven with the cleaning cost assuming industrial electricity price and (spot electricity price), respectively. Manual and automatic PV cleaning services are offered by emerging companies and PV performance losses due to soiling need to be studied to assess whether these services are cost-effective or not.

This study reports on the results of 28 silicon-based PV modules which were installed from January1981 to March 1985 in the outdoor test facility of the European Solar Test Installation (ESTI) of the European Commission's, Joint Research Centre. All of the modules were dismantled at the end of 2014 without cleaning, that is, after almost 30–33 years of outdoor exposure, depending on the installation date. The system was composed of modules with two series-connected laminates mounted in a single frame produced by a single manufacturer using either plain glass or surface textured glass. The effects of long-term soiling on the PV module performance for more than 30 years of outdoor exposure in a moderate subtropical climate and the influence of different cleaning methods were investigated. To our knowledge, this study represents the longest exposure time for soiling of Si PV modules. Despite the fact that this is a specific case and that the soiling behaviour will depend on the site, the study may be indicative of the general behaviour of dust accumulation in moderate subtropical climates with frequent rain events incorporating standard modules of the 80's and a typical tilt angle. The influence of the cover glasses and the mismatch due to the manufacturing design were also analysed.

2. Experimental method

2.1. Module characteristics

The array was composed of a set of 28 crystalline silicon wafer based photovoltaic modules which were subjected to long-term continuous outdoor exposure for more than 30 years without cleaning. The system was composed of modules produced by a single manufacturer, but they were manufactured at different times and as such incorporate different materials (e.g. modules using plain glass (6) or surface textured glass (22)). Each module is composed of two laminates incorporating round 10 cm diameter monocrystalline silicon solar cells connected in series. The two laminates can be contacted separately, thus giving the choice of connecting the two parts of the module in series or in parallel. At the beginning of the 1980s, the PV module manufacturing was in an early stage and most of the processes were performed manually. The module designs which consists of two laminates in a single frame is likely due to the fact that it was easier to manage a smaller area to place the cells manually into the liquid silicone based encapsulant.

Three different types of modules could be identified which differed in the number of cells (68 or 72), the front cover glass (flat glass or textured glass) and the cells layout. In all cases the substrate of the modules was white silicone and the encapsulant was silicone. One difference to be mentioned is the presence of a rubber gasket around the edge of each laminate for modules "Type A" and "Type B" which is not present in modules "Type C". These "Type C" modules have instead a rubber spacer between each laminate. The modules main design details are shown in Table 1. Although the modules were of three different types, they were divided into four groups for the purpose of this study, as the initial testing and installation of the 15 modules of "Type C" was performed in two separate batches, one consisting of 7 modules, with identification codes COxx, and the other consisting of 8 modules, identification code BOxx. The "Type A" and "Type B" also incorporate bypass diodes in each laminate, which have been detected by means of thermography images in reverse bias, while "Type C" do not have bypass diodes.

The array was left in an open-circuit configuration for most of the outdoor exposure period as this installation was to be used in an application requiring high DC voltage. Fig. 1 shows the view of the whole array before removal of the modules from the rack and the typical soiling distribution on a "Type C" module with the accumulation of dirt between laminates is shown in Fig. 2.

Table 1
Module characteristics.

Module group	Type	No. modules exposed	Superstrate	Encapsulant	Substrate	Bypass diode	No. cells	Years outdoor	Cell type	Cell layout
BBxx	A	6	Flat	Silicone	White silicone	Yes	68	30	Ø 10 cm mono-Si	
SOxx	B	7	Textured	Silicone	White silicone	Yes	68	32	Ø 10 cm mono-Si	
COxx	C	7	Textured	Silicone	White silicone	No	72	33	Ø 10 cm mono-Si	
BOxx	C	8	Textured	Silicone	White silicone	No	72	33	Ø 10 cm mono-Si	

2.2. Environmental conditions

Modules were installed in a South oriented fixed structure tilted to 45° sited at the ESTI facilities, in Ispra. The climatic conditions of Ispra (located in northern Italy) at 220 m above sea level, where the weathering was executed, are considered to be a moderate subtropical climate (−10 °C to +35 °C, with less than 90% RH). The Ispra site is characterised by a high level of precipitations with an average annual rainfall (taking into account the last 33 years) above 1550 mm. The precipitations occur mainly from September to November and from April to June. Over the entire year, the most common forms of precipitation are moderate rain (38%), thunderstorms or heavy rain (34%) and light rain (15%). The Ispra site presents a yearly wind speed variation from 0 m/s to 4 m/s with an average value of 2.2 m/s (weak wind, calm to gentle breeze with occasionally strong northerly winds with foehn effect). The wind is more often from the North–NorthWest and in a lesser extent from South–SouthWest. The relative humidity typically ranges from 45% to 95% with average values as high as 70%, representing a humid climate.

The weather conditions before dismantling the PV modules were characterised by an absence of rainfall events and wind (except two days of strong wind) in the 11 days before removal the modules from the field. Just before that, a series of three rainfall events with more than 20 mm by day took place.

2.3. Cleaning procedure

The modules were dismantled in October 2014 and different characterisations were performed, prior to cleaning the surface of the modules, in order to assess the extent of long-term soiling. The PV array was never cleaned during the outdoor exposure period and the PV modules were subjected to manual cleaning, one by one, after remove from the field using a soft sponge with a standard commercially available glass cleaning detergent sprayed on the cover glass and a final clean with a cloth. Times of approximately 10 min were employed for each module during the manual cleaning. Following intermediate characterisation, an additional cleaning using a commercially available high pressure water sprayer was performed for 3 min at a distance of 30 cm with the PV module mounted vertically. The tap water used (north-west Italy) can be considered soft water (in average, <20 °F). It has been shown that the transmittance losses due to dry residues using soft tap water (15 °F) are very similar to those using demineralized water (Appels et al., 2013) and are less than 2%. The modules were dried in air and characterised electrically. Fig. 3 shows images of a typical module showing long-term soiling in "Type A" module (Fig. 3a), a clean "Type A" module which has been stored in the basement (Fig. 3b) and the typical rear side of a soiled module with the two laminates, part A and part B, with the wires and junction box visible (Fig. 3c).

Fig. 1. View of the whole array.

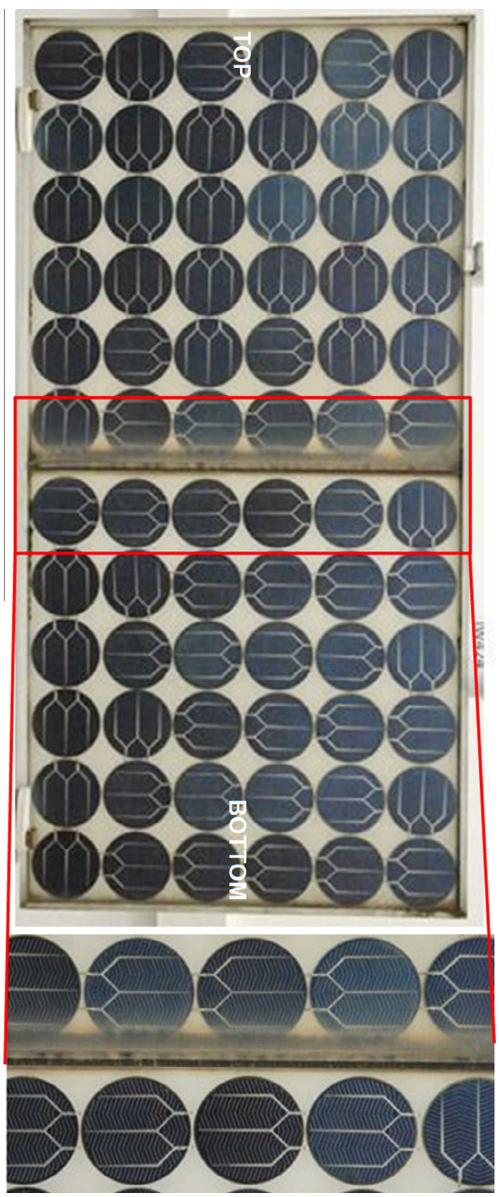

Fig. 2. View of one module with detail of heavy soiling accumulation near the frame.

2.4. Module characterisation

I–V characteristics of the modules were measured indoor using a PASAN IIIB solar simulator at ≈1000 W/m^2 and 25.0 ± 0.1 °C, with all measurements corrected to 1000 W/m^2. The spectral responsivity of one module of each type was measured using the differential spectral response technique with a large area pulsed solar simulator equipped with a number of filters to obtain illumination of modules with monochromatic light (Van Steenwinkel, 1986). No mismatch factor correction was applied to the resulting *I–V* curves due to that its effect in the comparison of electrical performances before and after cleaning (which was the purpose of this work) was found to be less than 0.15%. Different defects such as cracked cells, dark areas in cells corresponding to inactive areas, finger interruptions and scratches on the cell surface were observed by Electroluminescence (EL). EL images were obtained in the dark with the module biased at I_{sc} and at $0.1I_{sc}$ with an exposure of 300 and 600 s, respectively, using a Sensovation digital camera SVSB14-M. However, no relevant information was obtained from the images taken at $0.1I_{sc}$ due to the noise produced by the long exposure times. Infrared thermography images were obtained with a Fluke Ti55 camera with the module biased at I_{sc} mounted in a fixed vertical track and showed hot spots.

3. Results and discussion

3.1. Electrical performance

In order to characterise the full size module performance, the two laminates were connected in series. However, the *I–V* curves of each individual laminate were also determined and the results will be discussed later. *I–V* curves of a typical "Type A" module with a plain cover glass before cleaning (strongly soiled), after manual cleaning, and with an additional high pressure water procedure are shown in Fig. 4. The shape of the *I–V* curve of the soiled module suggests that partial shading of the cells had occurred, which has been observed with inhomogeneous soiling (Schill et al., 2015). After a manual cleaning, both the I_{sc} and FF increased and the nominal *I–V* curve shape was recovered. It is also evident that additional high pressure water spraying gives no additional improvement to plain glass modules. A similar behaviour is observed for modules with a textured front glass (Fig. 5). However, this type of modules shows a further small improvement using a high pressure water spray, following manual cleaning, as has been reported previously (Martín et al., 2011). In general, manual cleaning is effective on all the modules with the majority of improvements in the electrical characteristics observed from manual cleaning alone.

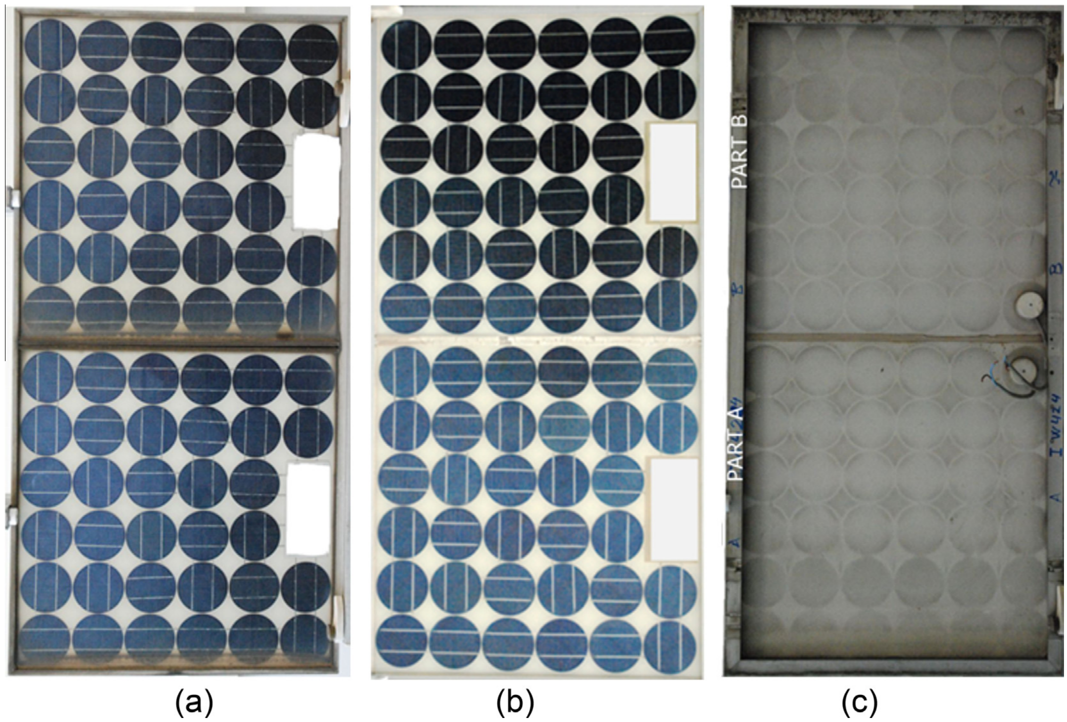

Fig. 3. (a) Field exposed "Type A" module with soiling, (b) "Type A" module not field exposed (stored in the basement) and (c) rear side of a soiled module with the two laminates (part A and part B).

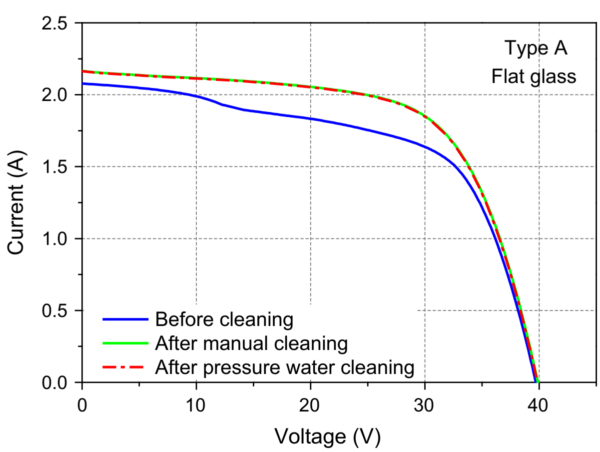

Fig. 4. *I–V* curves of a "Type A" module before cleaning (blue), after manual cleaning (green) and after high pressure water spraying (dotted red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Results by module type

The change of electrical parameters which took place after the different cleaning processes is analysed with the modules divided into three groups or types (with the "Type C" divided, in turn, in two groups) according to their cover glass and cell layout. A batch of 14 selected modules was cleaned manually and then cleaned with an additional pressure washer. The impact of the additional cleaning using a high pressure spray is shown in Fig. 6, which shows the average change (%) of the main module characteristics (I_{sc}, V_{oc}, P_{max} and FF) between manual cleaning and additional pressure spraying. A very small difference between manual cleaning and the additional cleaning with a high pressure spray is observable. The slight increase in the P_{max} (~0.9%) of "Type B" modules after the additional cleaning with high pressure water is mostly due to an increase of the I_{sc} (~0.7%) (Fig. 6). For the rest of the modules, the values can be considered within the measurement uncertainty band. As such, the whole set of 28 modules were measured following both cleaning processes.

The average change (%) in module parameters after both cleaning procedures, compared to the original soiled state, is shown in Fig. 7, where the maximum and minimum change values for each type of module are represented by the black lines. The average increase in the P_{max} ranged between 8.1% and 11.5%. The average increase in P_{max} after both cleaning procedures, compared to the soiled modules, is greatest for "Type A" followed by the "Type B" modules. This change is mainly influenced by an increase in the FF values (6.4% and 5.1%, respectively), with a smaller increase in I_{sc} (4.4% and 5.1%, respectively). However, the P_{max} increment in the "Type C" (both COxx and BOxx) is mostly due to the increase on the average I_{sc} values, which ranged from 4.4% to 8.5%. It should be mentioned that this correlation between P_{max} and I_{sc} increase in type C modules could be related to the different cell design in comparison to the "Type A" and "Type B" modules.

It should be noted that the variation in the extent of soiling for the textured glass modules is much higher than in

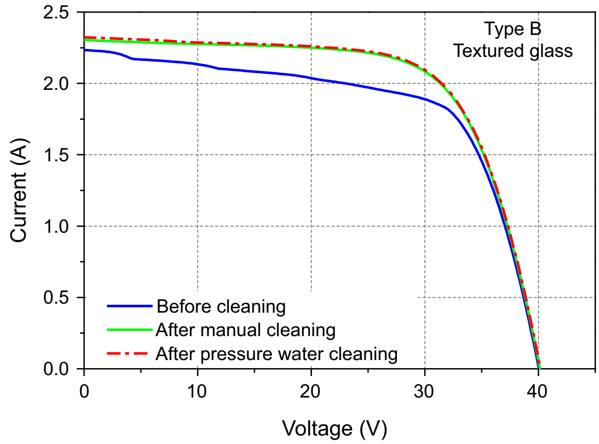

Fig. 5. *I–V* curves of a textured glass "Type B" module before cleaning (blue), after manual cleaning (green) and after high pressure water spraying (dotted red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

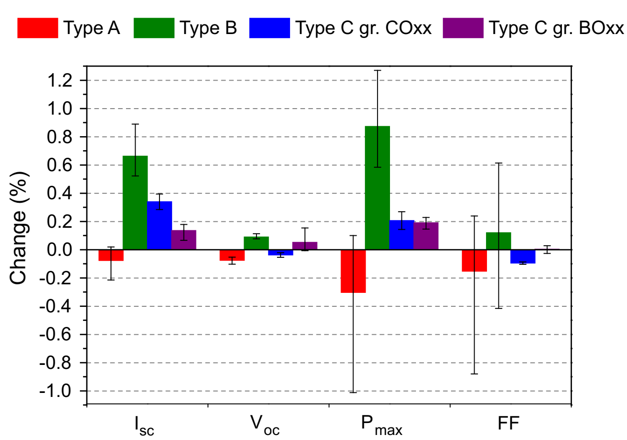

Fig. 6. Average change (%) of electrical parameters after cleaning with high pressure water spray compared to manual cleaning. Maximum and minimum values are represented with the error bars.

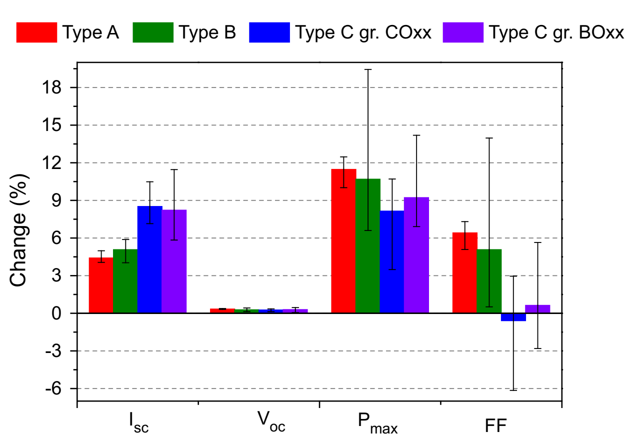

Fig. 7. Average change (%) of electrical parameters between soiled modules and after all cleaning procedures. Maximum and minimum values are represented with the error bars.

the flat glass modules. The maximum change in P_{max} following the complete cleaning procedure is found in a "Type B" module (SO04) with an increase of 19.4% mainly due to an increase in the FF (14.0%). It should be noted, as it will be seen in the mismatch section that the change is predominantly in one of the laminates (part A) with an increase in FF of 15.3%, while part B exhibits just a 1.5% increase. This could be indicative of the non-uniform distribution of the soiling on the module which accumulates on each laminate, but mostly in one of the parts, shadowing a region of the cells of a complete string and hence reducing the FF. The minimum change in the P_{max} occurred in a "Type C" module (CO07) with an increase of 3.5% after all the cleaning processes. As it has been commented, the change is produced by an increase in the I_{sc} (10%), however, in this case the FF decreased (−6.2%). For the module CO07 the change is mainly due to the change of I_{sc} of the part B, that is, the soiling of the part B was limiting the current of the complete module (laminates connected in series).

3.3. Overall results

The average change in modules parameters of the whole array are listed in Table 2. Despite the full set of modules exhibiting small module design differences; the study of the complete array can provide information of non-uniform systems. On average P_{max} increases by 9.8% and I_{sc} by 6.7%, after all the cleaning procedures for the whole set of modules. The average annual soiling rate is calculated as an average of the P_{max} (also for I_{sc}) values of each module type divided by the number of years exposed outdoor each type. An average yearly soiling rate of 0.31% in P_{max} and 0.20% in I_{sc} was obtained. However, only a small average change between the different cleaning procedures is observed (within the measurement uncertainty band). Figs. 8 and 9 show the average change (%) distribution of the P_{max} and the I_{sc}, respectively, of the whole array in the same position than in the field (viewed from the front). It can be observed that the right-side modules present a slightly higher change in the P_{max} (Fig. 8) and a lower change in the I_{sc} (Fig. 9). A slight trend can also be observed in that those modules mounted at the top of the system are more soiled as evident from the greater increase in the change on the P_{max} (a greater soiling, greater P_{max} increase after cleaning). This may be due to the fact of an increase in the amount of water on the lower modules which receive water directly from the rain and also water flowing from the modules mounted above.

Most of the literature reports on the loss in the I_{sc} with the soiling for crystalline Si-based modules. Hammon et al. reported on a 5.4% decrease in fixed array for modules with 5 years of outdoor exposure without cleaning (Hammond et al., 1997). In other study, Martin et al. presents a relative

Table 2
Average change (%) and standard deviation of the electrical parameters of the whole set of modules.

	I_{sc}	V_{oc}	P_{max}	FF	I_{sc}	V_{oc}	P_{max}	FF
Before cleaning-after all cleaning processes					Cleaning manually-pressure water			
Average Δ (%)	6.68	0.30	9.80	2.67	0.19	−0.01	0.13	−0.05
SD (%)	2.17	0.09	3.03	4.05	0.31	0.08	0.53	0.33

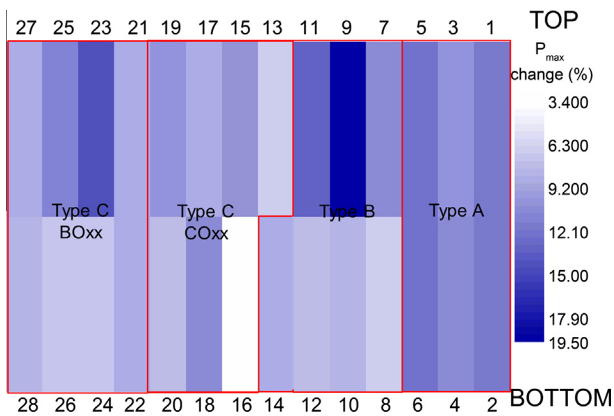

Fig. 8. P_{max} average change (%) distribution of the whole array in the same position than in the field (viewed from the front).

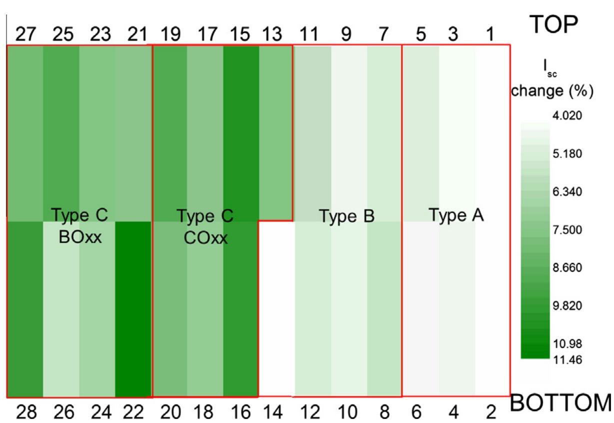

Fig. 9. I_{sc} average change (%) distribution of the whole array in the same position than in the field (viewed from the front).

decrease between clean and six month soiled textured modules of 4.3% for a tilted angle of 40° and 6.2% for 10 (Martín et al., 2011). Schill et al. reported on a drastic decrease between 13% and 27% of the initial value of the power output after 5 month without a rainfall and a serious dust event produced by a building construction (Schill et al., 2015). In other work, Ryan et al. showed an annual average loss in I_{sc} of 1.4% for unwashed modules compared to those washed (Ryan et al., 1989). Kimber et al. noticed annual losses of 3.5–5.1% in Los Angeles confirmed previous model for the average annual loss from 1.5% to 6.2% (Kimber et al., 2007).

The average change values for I_{sc} and P_{max} reported in this work are considerably lower than the values reported in the literature. This relative low value can be explained by the fact that rainfall events in this site are significantly high as explained in the experimental section with average annual precipitation above 1550 mm being usually as a moderate rain or thunderstorms that prevent large soiling accumulation on the modules. Also, the outdoor exposure time in this work is significantly longer than all other studies. Finally, many soiling studies have obviously concentrated on modules and systems in geographical areas with a high dust or sand content, which lead to high soiling rates.

3.4. Effects of mismatch

I–V measurements were performed for each module on both laminates separately (part A and part B) and on the complete module, with the two laminates connected in series as was the case when these modules were installed in the field. The three *I–V* measurements were performed on the as removed soiled modules from the field and then repeated after the manual cleaning and finally after the high pressure spray cleaning. To avoid misunderstandings, the part A and B were set as the left side and right side, respectively, looking at the module from the rear and with the electrical connections on the bottom.

The difference of currents (I_{sc} and I_{mpp}) between the two parts of the module was analysed and the effect of their difference in the reduction of the total power of each single module was studied. For each module, the I_{sc} mismatch expressed in percentage was calculated following the equation:

$$I_{sc}\ \text{mismatch} = \frac{I_{scA} - I_{scB}}{\text{Avg}(I_{scA}, I_{scB})} \times 100 \quad (1)$$

where I_{scA} is the sort circuit current of the part A, I_{scB} is the sort circuit current of the part B and Avg(I_{scA}, I_{scB}) is the average value of the I_{scA} and I_{scB}. The same calculation was performed for quantifying the mismatch of current at maximum power point as described in the equation:

$$I_{mpp}\ \text{mismatch} = \frac{I_{mppA} - I_{mppB}}{\text{Avg}(I_{mppA}, I_{mppB})} \times 100 \quad (2)$$

The mismatch calculated in this way will allow quantifying the current loss due to the fact that one of the two parts has a lower current, thus limiting the output when the two laminates are connected in series. The analysis is concentrated on current as this is the electrical parameter that can cause the most severe problems when a series connection configuration is implemented as in the case of this set of modules. The P_{max} loss of each module was defined as follow:

$$P_{max} \text{ loss} = \frac{(P_{maxA} + P_{maxB}) - P_{max}}{P_{max}} \times 100 \quad (3)$$

where P_{maxA} and P_{maxB} are the maximum power of each laminate and P_{max} is the maximum power of the complete module. In this case the loss in maximum power is calculated as a percentage of P_{max}; the higher the value of this parameter, the greater the loss of maximum power when the two laminates are connected.

Fig. 10 shows the averages and standard deviations (as error bars), for the complete module set, of I_{sc} and I_{mp} mismatch and the average of P_{max} loss, all calculated both before and after cleaning. It can be clearly noticed that the cleaning procedure leads to a reduction of currents mismatch and P_{max} losses. This was expected as soiling can affect the two laminates to a different extent, especially considering that soiling tends to accumulate at the lower edge near the frame or at the rubber spacer between the laminates (Fig. 2). Once the modules are cleaned, the difference of current due to soiling is strongly reduced, and the difference in current that we measure is due to the intrinsic difference of electrical performance of the laminates. It is shown clearly a reduction for the averages for both parameters. While the cleaning procedure resulted in more uniform values for P_{max} losses, as we can see from the reduction of the standard deviation, this was not the case for I_{mpp} mismatch, where the standard deviation did not change, due to the presence of outliers and the limited number of samples.

Loss of P_{max} versus I_{sc} mismatch for all modules is reported in Fig. 11, before cleaning and after the final cleaning step with a high pressure water spray. We can notice that before cleaning the range of values for I_{sc} mismatch is higher than for the measurements after cleaning. However, it is not possible to identify a clear relation between the electrical parameters shown in Fig. 11, and there are indeed cases of modules showing a very limited mismatch but a high P_{max} loss, which can be attributed to differences in other parameters, such as FF, between

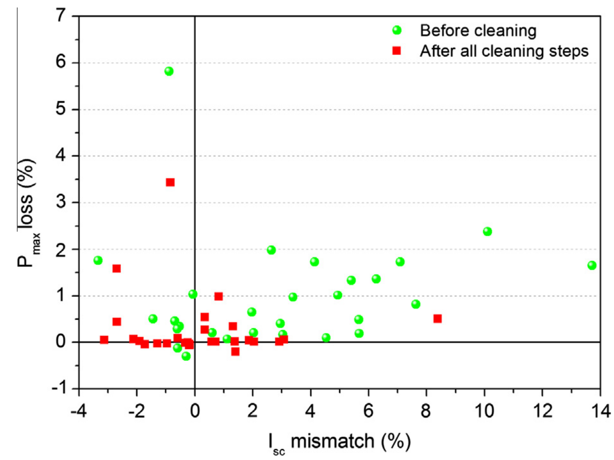

Fig. 11. P_{max} loss vs I_{sc} mismatch for all modules before and after cleaning.

the two laminates. The poor correlation between I_{sc} mismatch and P_{max} losses can be explained by the fact that in some cases one of the two laminates can have a higher I_{sc} but a lower P_{max} than the other one, for example in the case of an I–V curve where kinks are present in the region between I_{sc} and P_{max} (Fig. 12). This effect is often present when part of the module is not working or shaded, as in the case of extensive soiling.

A similar analysis was performed on how the mismatch of the current at maximum power point between the two laminates affects the power output of the complete module (Fig. 13). In this case, results show a correlation between I_{mpp} mismatch and P_{max} losses; results are in the 1st and 2nd quadrant depending on which laminate has the highest I_{mpp}. Before cleaning, I_{mpp} mismatch is in the range of $\pm15\%$, with P_{max} losses up to 2%, with the exception of an outlier module, code SO04, showing higher mismatch and consequently higher P_{max} loss (-21% and 5.8% respectively). After the cleaning step with high pressure water, the I_{mpp} mismatch and P_{max} losses of SO04 module were

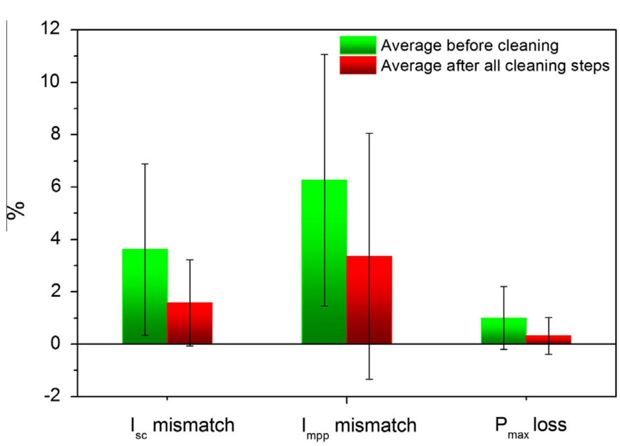

Fig. 10. I_{sc} and I_{mpp} mismatch and P_{max} losses before and after cleaning (average of the complete module set). Standard deviations are represented with the error bars.

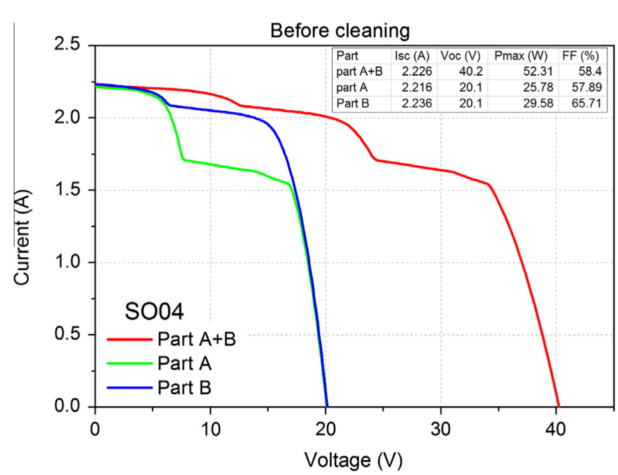

Fig. 12. I–V curves of each laminate measured independently (part A and part B) and with the two laminates series connected of the soiled SO04 module.

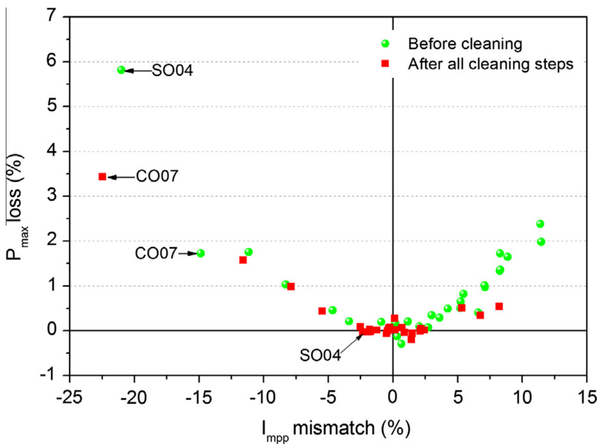

Fig. 13. P_{max} loss vs I_{mpp} mismatch for all modules before and after cleaning.

strongly reduced to −1.9% and 0% respectively, thus proving that the differences of I_{mpp} were mainly due to soiling and that the mismatch caused by soiling was responsible for a loss of P_{max} of nearly 6% when the two submodules were connected in series.

Results of modules measured after the high pressure water spraying step show a reduced range of values for the mismatch of I_{mpp}, and consequently reduced P_{max} losses that for the large majority of modules is less than 1%. Also in this case there is an outlier, module CO07, having I_{mpp} mismatch of −22.5% and P_{max} loss of 3.4%. This module showed an increase of mismatch and losses after the cleaning procedure, and this was due to the fact that one of the laminates (CO07-A) was malfunctioning, having low fill factor and some non-active cells, as shown in the electroluminescence (Fig. 14) and thermography images (Fig. 15). The cleaning procedure in the case of this module increased the performance of laminate B only, thus increasing I_{mpp} mismatch and P_{max} losses for the complete module.

In order to quantify the change which occurred after the cleaning procedure, the variation of I_{mpp} mismatch and the P_{max} were calculated and are plotted for each module in Fig. 16. A reduction of the mismatch was exhibited for most of the modules, with a corresponding increase in

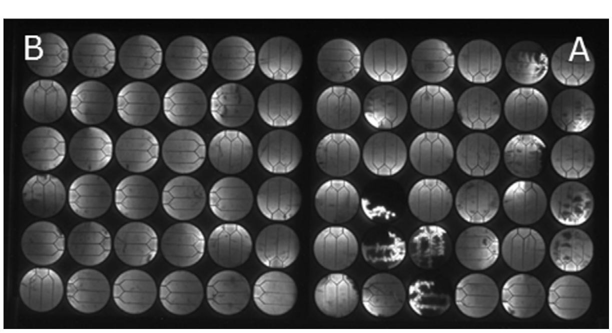

Fig. 14. Electroluminescence image of the CO07 module under bias close to I_{sc}.

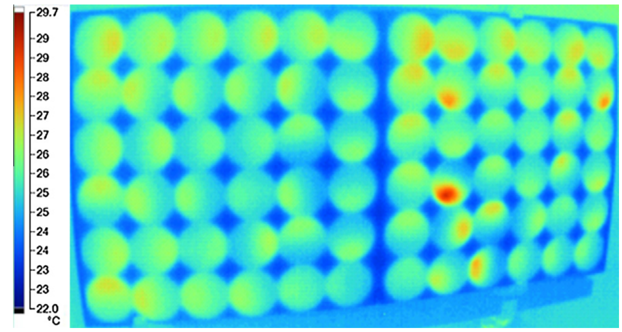

Fig. 15. IR thermography image of the CO07 module under bias close to I_{sc}.

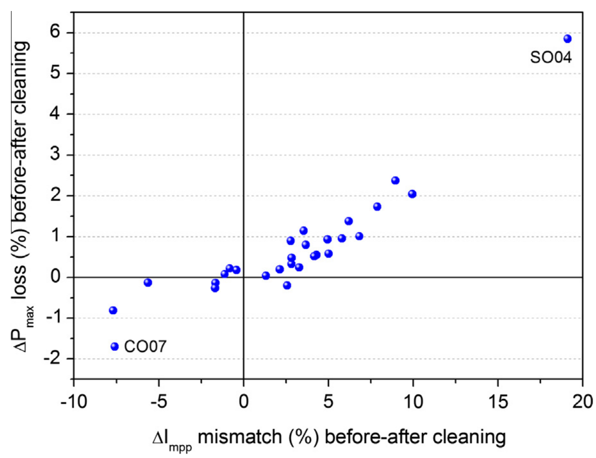

Fig. 16. Variation of I_{mpp} mismatch and the P_{max} losses before cleaning and after all cleaning procedures.

P_{max}. In some cases there was a slight decrease in the performances, and this can be attributed to the uncertainties in the measurements, as the reduction found is close to zero. Only in few cases a larger increase in P_{max} losses were found, in the range of 1–2%, and this is due to damaged modules as previously explained in the case of module CO07.

4. Conclusions

The effects of long-term soiling on the performance of a set of 28 Silicon-based PV modules which have been exposed outdoor for more than 30 years without cleaning in a moderate subtropical climate were investigated. The influence of different cleaning methods from manual cleaning to the use of high pressure water spraying on the modules with different cover glasses and cell layouts were also analysed. More uniform soiling behaviour was observed for the flat glass modules whereas those with textured glass exhibited a greater variation in soiling. It was observed that manual cleaning was effective at improving the output of all the module types. However, additional high pressure water spraying on plain glass modules showed no further improvement, but small improvements on the textured glass modules were observed. Overall improvements in P_{max} after cleaning ranged from 3.5% to 19.4%, with an average value of 9.8%, which imply an average annual soiling rate of 0.31% in P_{max} and 0.20% in I_{sc}. This relative low value can be explained by the fact that rainfall events in this site are significantly high as explained in the experimental section with average annual precipitation above 1550 mm being usually as a moderate rain or thunderstorms that prevent large soiling accumulation on the modules. For this reason, the average losses due to soiling calculated in this long-term period (>30 years) are lower than those calculated for studies over shorter period of time and in geographical areas chosen for a high dust or sand content.

The system was composed of modules with two series-connected laminates mounted in a single frame and the mismatch between the two halves has been also studied. Average loss of P_{max} when the two laminates are connected in series was found to be 1% on soiled modules, and a correlation between P_{max} losses and I_{mpp} mismatch was found. Cleaning procedures were found to reduce the mismatch of I_{mpp} as well as P_{max} losses, when the two laminates are connected in series, which were reduced to 0.3% (average of all module set). Reduction of I_{mpp} mismatch after the cleaning procedures is found to be correlated with the reduction of P_{max} loss.

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