Effect of soiling on performances of crystalline silicon PV modules deployed in an arid climate in relation to front glass texture and treatment

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1 Introduction

Solar power generation is particularly interesting in regions of the world where the sun shines stronger and longer. Among these regions, desert areas located between the tropics present a very high yearly insolation. Such locations seem very adequate for solar energy generation and, apart from the high temperatures, for the deployment of photovoltaic (PV) technologies.

Nevertheless, the accumulation of dirt on the surface of PV modules is critical in desert regions. Sand and dust is deposited on the module front glasses, which decreases the amount of irradiance received by the solar cells and therefore the energy output of a system. Due to limited rainfall, this layer of dirt tends to remain for very long periods of time without being washed away. It represents one of the main sources of loss for deployed PV modules, independent of the PV technology used.

The effect of soiling has been studied and reported for standard PV modules employing flat front glasses in various locations throughout the world [1][2][3]. But very little information is available concerning the soiling of textured or self-cleaning front glass. Such textured front glasses are believed to increase performance up to 3.2% compared to standard flat front glasses through light trapping and anti-reflection effects [4]. Moreover, soiling is very difficult to model and quantify. It varies significantly from region to region and depends on the nature of soiling agents and climatic conditions that have great diversity [5]. Climatic conditions alter the characteristics of soiling agents, making soiling more than just a simple deposition of matter on a surface. Therefore, to efficiently study problems linked to soiling in specific climates and regions, it is very beneficial to deploy PV modules directly on site.

This report focuses on the conception, deployment, evaluation and monitoring of a small PV setup (20 modules) in Ras-Al-Khaimah UAE. The aim is to:

- Study the performance decrease of PV modules with various textured and non-textured front glasses when exposed to soiling.

- Assess the impact of an anti-soiling glass coating on the performance of modules with the same type of glass textures.

The report is organized as follows. First, the conception of the PV installation is explained. The different front glasses and glass treatments are described and methods such as IV and electroluminescence used to characterize the modules are explained. A description of the setup as deployed is given and the measurement scheme is explained. Then, the PV setup is evaluated. The precision of the different measured quantities are calculated and issues with the system are analyzed. Suggestions to improve the system are discussed. Following this, two models to evaluate the effect of soiling on the different PV modules are developed and their differences explained. Finally, the effect of soiling on the performance
of the various modules as a function of the front glass texture and anti-soiling treatment is assessed over a period of 43 days.
2 Material and methods

2.1 Module description

Twenty glass / EVA / back-sheet c-Si PV modules of 40x40cm were prepared using a standard lamination process at 140°C (figure 1).

![Figure 1: Typical stack of a c-si PV module](image)

In order to assess the effect of soiling on textured and non-textured front glasses, various types of glass were used:

- Pilkington Optiwhite 3mm (standard non-textured solar-grade glass)
- St-Gobain Albarino P 4mm (deeply patterned solar-grade glass)
- St-Gobain Albarino S 3.2mm (finely patterned solar-grade glass)
- St-Gobain Albarino T 3.2mm (finely etched solar-grade glass)
- St-Gobain VisionLite 4mm (non solar-grade anti-reflective glass with both sides coated)

For each type of glass, 4 modules have been prepared, two of which have been coated with a highly hydrophobic Solar PV anti-soiling treatment from nanoShell. According to nanoShell, the lifetime of the coating is of approximately 4 years. The encapsulants are VistaSolar 486.00 fast cure 0.5mm EVAs. Four AH508200F solar cells from Sunways have been connected in series for each module. The backsheets are Icosolars 2116 from Isovoltaic.

Figure 2 shows a picture of a typical PV module. Figure 3 shows pictures of the different textured glasses. Note that a listing of all PV modules is available in appendix B.
2.2 IV measurements

IV measurements were used to characterize the modules after lamination. A typical IV curve is shown in figure 4. The short-circuit current ($I_{sc}$) corresponds to the generation
and collection of light-generated charge carriers. The open-circuit voltage \( V_{OC} \) corresponds to the maximum voltage available from the cell. It is a characteristic of the PN junction and corresponds to the amount of forward bias due to the light generated current. The fill factor (FF) is defined as the maximum power of a cell divided by its \( I_{sc} \) and \( V_{OC} \). It gives information about the "squareness" of the IV curve. The efficiency of the cell gives how much of the illumination power is converted into electrical power. The slope at \( V=0 \) and \( V=V_{OC} \) give information on the parallel and series resistances.

IV measurements are done according to the following principle. A module is contacted to a device (charge) that forces the module to operate at a certain voltage. The module is then illuminated with a calibrated light source (AM1,5G) at a certain angle of incidence and the output current is measured. This is done for a multitude of voltage points among which \( V=0 \) (short-circuit current) and \( V_{oc} \) (open circuit, \( I=0 \)). It is equivalent to sample the diode equation (1) in the simple diode model (fig. 5):

\[
I = -I_L + I_0 \cdot \exp \left( \frac{qV - IR_s}{kT} - 1 \right) - \frac{V - IR_s}{R_p}
\]

The comparison of the IV curves of the various PV modules was used to verify that they all have approximately the same characteristics and performances, at least by glass types. A classification of the glass performances using IV measurements is made in section 7.2. The behavior of \( I_{sc} \) as a function of the irradiance was also assessed using IV measurements. Results are shown in section 7.1.

### 2.3 Electroluminescence

Electroluminescence is a good quality test for the solar cells. It can reveal bad quality cells, cracks or problems due to cell soldering. It is fast (with a silicon CCD an exposition of a few seconds is sufficient) and non-invasive. On modules it enables to verify that the
encapsulation process has not damaged the cells. Electroluminescence is based on radiative recombinations of charge carriers resulting in light emission. The indirect nature of the band gap transition of silicon implies that in c-Si cells at high injection, most of the recombinations will be non-radiative, whether due to defects or to Auger recombinations. Nevertheless, a portion of charge carriers will recombine radiatively along the first Si transition at 1.12eV. With the phonon assist due to the indirect bandgap, the emission peak has been measured at 1150nm [6] (see figure 6). Therefore, when putting the cell under forward bias, all undamaged zones of the cells will emit around 1150nm whereas zones where the diode structure or the contacting (current injection) are damaged will not, or less. Using a CCD camera with an infrared filter, the state of the module can be assessed. The contrast indicates how well different zones of the cell operate. Bright zones are well functioning whereas dark zones do not generate electricity.

![Emission spectrum of silicon](image)

Figure 6: Emission spectrum of silicon as presented on pveducation.org from [6]

In this work, a 8.3Mpix Samba Ci camera from Sensovation equipped with an infra-red (IR) objective lens Zeiss Distagon 2.8/25mm and an IR long-pass filter at 850nm (80% cutoff capacity) was used. The modules with flat front glasses were easy to image, but the structured glasses blurred the image considerably. Note that using a CCD camera is not very efficient. The quantum efficiency (QE) of CCD cameras reduces dramatically around 1000nm because of the absorption properties of silicon. Therefore long exposures of a few seconds are necessary. InGaAs detectors have a much better QE over the desired range and would therefore enable much shorter exposures and less noise. But they are more expensive. Examples of electroluminescence images are shown in figure 7.
2.4 External quantum efficiency (EQE)

The external quantum efficiency was used to assess the performances of the different glass types. The EQE of a module is defined as the ratio of collected charge carriers over the number of photons of definite wavelength arriving on the module.

\[
EQE = \frac{\text{current/elementary charge}}{\text{illumination power/energy of one photon}}
\]  

(2)

Therefore, the more a glass transmits and traps light, the more the EQE will be high. Measuring an EQE consists in illuminating a cell with a monochromatic beam of known wavelength and power while measuring the cell’s output current. The whole photogenerated current density over the full AM1,5G spectrum is then calculated by integration:

\[
J_{AM1,5G}(V) = q \cdot \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} SR(V, \lambda) \cdot \Phi_{AM1,5G}(\lambda) \cdot d\lambda
\]

(3)

where \( SR(V, \lambda) = \frac{EQE}{h\nu} \) is the cell spectral response and \( \Phi_{AM1,5G} \) the solar spectrum. In our setup, the exact power of the monochromatic beam is unknown. A calibrated monitor cell (which EQE is known) and a beamsplitter are used instead so as to perform EQE measurements on a comparative basis. The EQE of the monitor cell being known it is then simple to extrapolate the EQE of the sample. The setup schematics can be seen in figure 8 and EQE results are shown in section 7.3.
3 Measuring scheme and setup description

3.1 $I_{sc}$ measurements compared to power yield measurements

Soiling (dust, dirt) on module front glasses affects the transmission of light to the PV cells. Absorption of light by soil decreases the amount of light arriving on the cells and therefore decreases the generated current. Reflection of light by soil has the same effect.

To monitor the effect of soiling on PV power generation, the power output $P$ of modules should be monitored. But this requires the use of expensive equipment. As an alternative, $I_{sc}$ is measured in this work. In theory, $I_{sc}$ linearly decreases with the irradiance arriving on the cell. This is well verified experimentally (see section 7.1). $I_{sc}$ therefore reflects how soiling affects light transmission to the cells. Since $I_{sc}$ is not affected by irradiance in the same way as $P$, performance comparisons between soiled and cleaned modules using $I_{sc}$ as an indicator may deviate from comparisons made using power output measurements. To determine if $I_{sc}$ losses are representative of power output losses, one must analyze the role of $I_{sc}$ in the power generation equations. The maximum power output being expressed as $P = FF \cdot I_{sc} \cdot V_{OC}$, $I_{sc}$ is linear with $P$ at constant temperature if the product of the fill-factor FF with the open-circuit voltage $V_{OC}$ stays constant. The $V_{OC}$ diminishes logarithmically with the generated current and therefore with the irradiance:

$$V_{OC} = \frac{n k T}{q} \ln \left( \frac{I_L}{I_0} + 1 \right)$$  (4)
$I_L$ is the current generated by light, $I_0$ is the dark saturation current. Since $I_0$ is orders of magnitude smaller than $I_L$ under reasonable illumination, $V_{OC}$ doesn’t vary much. On the other side, the fill factor FF increases a bit with diminishing irradiance. This increase is supposed to be quadratic since less current means less Joule dissipation due to the series resistance of the cell.

For a typical module, IV measurements give the following results for a 50% loss of irradiance (such losses are expected for soiling after a few months). Between 1000 and 500 $\text{W/m}^2$, $I_{sc}$ decreases by 49.2%. In the same interval, $V_{OC}$ decreases by 2.4%, FF increases by 3.2% and the maximum power output decreases by 48.8%. In this case, a 50% loss of irradiance results in a 48.8% loss of power output and a 49.2% loss in $I_{sc}$. The decrease of P and $I_{sc}$ relatively to a decrease of 50% of irradiance is nearly identical (less than 1% linearity error). For smaller irradiance decreases, the relative loss of P and $I_{sc}$ should also be very close since the variations of $V_{OC}$ and FF are limited.

All upper considerations were done under the assumption that soiling only affects light transmission to the cell. But soiling on PV module fronts also affects the modules temperature, either increasing it in the event where the soiling absorbs light and turns it into heat, or decreasing it if soiling reflects light back into the atmosphere. $I_{sc}$ and P are both affected by temperature. The Sunways cells have a $-19\text{mW/K}$ temperature factor for P and a $1.1\text{mA/K}$ temperature factor for $I_{sc}$ [8]. Therefore $I_{sc}$ increases with increasing temperature whereas P decreases with increasing temperature. For a typical module, a 10°C difference results in an augmentation of 0.1% of $I_{sc}$ and in a diminution of 4.6% of P. The mismatch between $I_{sc}$ and P measurements is then of 4.7%. Therefore, $I_{sc}$ measurements deviate from P measurements if soiling affects module temperature in large amounts. As will be seen in section 7.5, this is not the case.

Finally, $I_{sc}$ measurements are a good alternative to power yield measurements for low budget studies as long as soiling doesn’t induce a big temperature difference between clean and soiled modules. The behavior of $I_{sc}$ with varying illumination is nearly identical to the one of P. For a 50% decrease in performances, the accuracy of $I_{sc}$ measurements compared to power yield measurements is under 1%. For a 50% decrease in performances and a 10°C temperature difference due to soiling, this number goes up to 5.7%.
3.2 Measurement devices

The quantities that are measured are the following:

- The $I_{sc}$ of each module.
- The back-sheet temperature of each module.
- The cell temperature of 3 modules that have thermocouples laminated directly behind the cell.
- The temperature of the measuring devices.
- The irradiance in the PV module plane.
- Meteorological data (outside temperature, wind speed, wind direction, rain accumulation, rain rate, UV dose and humidity).

The first four items are measured by the module measurement apparatus named acquisition box. The irradiance and meteorological data are measured using a weather station from Davis (Vantage Pro2 Plus 6162FR).

The acquisition box (fig. 9) is home built with the help and sponsorship of ALRO Communication SA. It is orchestrated by an ethernet TCP/IP programmable fieldbus controller from Wago (750-843, later referred to as ”controller”). This controller is programmed to perform the measurement sequences and store the data temporarily. It is connected to three 8-channel digital output modules and one 4-channel digital output module from Wago (750-530 / 750-504). In addition to these, the controller is connected to a 2-channel analog input module for thermocouples (Wago 750-469) configured for type-T thermocouples. Finally, the controller is also connected to a 2-channel analog input module for 0-10 V from Wago (750-467). This last module collects the signal coming from an open-loop hall effect DC current transducer from LEM (DK-C10 U, later referred to as LEM) that measures currents between 0-20A and converts them to signals between 0-10V. The controller is configured to convert the signals coming from the different modules into the physical values of interest. For simplicity’s sake, the controller and its different modules will be referred to as the controller. Electrical schematics of the acquisition box can be found in appendix D.1.

3.2.1 Short-circuit current measurement

Each module is connected to a separate relay (Finder 66.82-x300). The relays are controlled by the controller using the 4 digital output modules from Wago. All relays are closed (open circuit) except the one corresponding to the module being measured. When a relay
Figure 9: Acquisition box setup before installation.

Figure 10: Open loop hall effect transducer scheme. $I_p$ is the measured primary current, $I_c$ the hall sensor control current and $V_o$ the output voltage. from ChenYang tech
is opened (current passing through), the PV module is short-circuited. The current is then measured by the LEM and the output recuperated by the controller using the 0-10V input module from Wago.

The open loop hall effect transducer (LEM) works according to the following principles (schematics in figure 10). The primary current (which has to be measured) passes through a magnetic core. The magnetic flux is then "concentrated" in an air gap where a Hall effect sensor is located. The output voltage of the Hall sensor is then proportional to the primary current as a consequence of Biot-Savarts law and Hall-effect theory (5).

\[
B = \frac{\mu_0 I_p}{4\pi} \int \frac{dl \times r}{r^2}
\]

\[
V_H = \frac{-I_c B_{ned}}{n cd}
\]

where \(I_p\) is the primary current and \(I_c\) the control current passing through the Hall sensor. This output voltage \(V_H\) is then signal conditioned between 0-10V.

### 3.2.2 Temperature measurement

A type T thermocouple runs from the backside of each PV module to a separate relay. All relays are closed (open circuit) except the one corresponding to the module temperature being measured. When a relay is opened, the voltage formed by the thermocouple is read by the type T thermocouple reader and recuperated by the controller. In addition to the backside temperatures, 3 thermocouples integrated in three PV modules are connected to 3 other relays. A thermocouple measuring the temperature of the acquisition box is connected to a fourth relay.

Thermocouples use the Seebeck effect. It states that any conductor experiencing a thermal gradient generates a voltage between the hot end and the cold end. To measure this voltage, a second conductor must be used, thus generating another voltage opposing the first one (fig. 11). By using two different kind of conductor materials, the two voltages will not cancel themselves. By choosing carefully the conductor materials, the resulting voltage can behave linearly as a function of the temperature difference between the hot and cold ends in a certain temperature range. Type T thermocouples made of copper and constantan have a sensitivity of 43\(\mu V\)/K and can be used between -200°C and 350°C.

As thermocouples only give a voltage corresponding to a certain temperature difference, the temperature at one end (called cold junction) must be known. In the acquisition box, as it is the case usually, the temperature at the cold junction is taken into account by the thermocouple reader (cold junction compensation). Therefore it is important that the temperature between the thermocouple connections (in this case the relays) and the thermocouple reader remains constant. Two ventilators are installed in the acquisition box to ensure that there is no temperature gradient inside.
Figure 11: Thermocouple measuring scheme, [Wikipedia](https://en.wikipedia.org/wiki/Thermocouple)

Figure 12: Measurement timeline

- **Acquisition Box measurements**
- **General Timeline**
  - h:00
  - h:15
  - h:30
  - h:45
  - (h+1):00

- **Legend**
  - **Blue** Acquisition Box measurements (duration : 166s)
  - **Red** Weather station measurements, the Linux box recuperates data of acquisition box
  - **Green** Measurement of PV module current and back-sheets temperature (duration : 5s)
  - **Purple** Pause between measurements (duration : 2s)
  - **Orange** Measurement of the temperature inside the acquisition box (duration : 5s)
  - **Yellow** Measurement of laminated thermocouples (duration : 5s)
3.2.3 Measurement timeline and data retrieval

The acquisition box initializes a measurement sequence (fig. 12) every 15 minutes. 20 currents, 20 backside temperatures and 4 additional temperatures are then measured. For cost reasons, all modules are not measured simultaneously, but only sequentially, although backside temperature and $I_{sc}$ are measured simultaneously for each module. The controller starts with the first module. $I_{sc}$ and backside temperature are measured at the same time. For this, the controller opens both current and backside temperature relays corresponding to the module for 5 seconds. During these five seconds, 20 values are collected for both $I_{sc}$ and the backside temperature. A mean of the values 5 to 14 is done and saved by the controller. The other values are neglected in order to give enough time for the electrical circuit to stabilize. The controller then pauses for two seconds and goes on to measure the next module. All 20 modules are scanned sequentially in the same way. Once all modules have been measured, the controller scans sequentially the 4 remaining relays to measure the 3 integrated thermocouples and the acquisition box temperature. The whole sequence lasts under 3 minutes.

When the measurement sequence is completed, the data is stored in the controller until the next measurement sequence. Data retrieval from the controller is done by a small computer called linux box. It acquires the data from the controller maximum 2 minutes after the end of the measurement sequence and labels it with a time and date. As the controller doesn’t have its own clock, all measurements are labeled with the time at which the linux box retrieved them. This induces a shift of maximum 5 minutes between the real measurement time and the labeled measurement time. Small incoherences in the measurements can therefore be induces, for example in the eventuality where a small cloud shades the installation during a part of the measurements. The linux box then creates a file per day with all measurements inside. A file containing a concatenation of all measurement since the beginning is also actualized. The files can then be accessed remotely by SFTP or by SSH from any location.

The weather station acquires data at the same time as the linux box retrieves data from the acquisition box (fig. 12). The time label of all different data is therefore the same for each measurement sequence. The weather data is then accessible remotely using the WeatherlinkIP software from Davis. For more information about data retrieval, see appendix C.
3.3 Description of the PV installation as deployed

The entire PV setup is located on the PV site of the CSEM-UAE in Ras-Al-Khaimah (UAE). The site is located in an industrial zone (severe pollution) and well exposed to desert conditions found in the area. Ambient temperatures reach up to 50°C in the summer and precipitations are rare. Sand, dust, saline air (proximity to the sea), wind, dew and pollution (heavy industry) are the main soiling factors for any outdoor equipment in the area. Soiling is very pronounced and can be noticed after a few days only on everything, e.g. cars, buildings, windows, and of course PV modules. The 20 PV modules (40cm x 40cm) are mounted side by side on a 2m x 1.6m stand facing south (fig. 13 & 14, the module listing and disposition is shown in appendix B). The stand has a 22° incline (standard for these latitudes) and is positioned at 1m above ground level. The stand is not exposed to any external shadowing. The pyranometer is attached to the PV stand in the PV module plane and connected to the weather station. The weather station is placed behind the stand at approximatively the same height. The acquisition box is placed in a weatherproof box (fig. 15) under the PV stand. The weather station console is placed in a cabin behind the stand. The linux box is also located inside the cabin. A schematic view of the installation is shown in figure 13, a picture of the installation in figure 14. The PV modules, the stand and the weather station have been stabilized and fixed in the event of high speed winds. The acquisition box is in a weatherproof box and all the cables are tied in order to avoid stresses. All electrical equipment is connected to an uninterrupted power supply which is charged by a PV module and a generator.

![Figure 13: Schematics of the installation](image)

Figure 13: Schematics of the installation
Figure 14: General view of the installation
4 Setup evaluation

This section aims to evaluate the potential of the installation. The precision of the measurements is assessed and the major error sources discussed.

4.1 I_{sc} measurements

A typical acquired I_{sc} curve is shown in figure 16 next to an irradiance curve. Both curves are well aligned and coherent. As expected, the I_{sc} curve correlates well with the irradiance curve. The I_{sc} values at a given irradiance correspond to IV measurements. All 20 I_{sc} curves give similar results. The limitations of the setup for current measurements are the following:

- The electrical installation to measure I_{sc} (LEM) has an accuracy of 1%.
- The measurement timeline (section 3.2.3) induces a time shift of maximum 3 minutes between the different I_{sc} measurements (measurements are sequential but the time label is equal for all). Some modules may be affected by short events like shadowing from small clouds while others may not. The same happens with the pyranometer.
Figure 16: \( I_{sc} \) of a typical PV module and corresponding irradiance measured by the pyranometer. Point A shows a short event that didn’t affect the pyranometer. Point B shows an event that affected both measurements (see section 3.2.3).

Label A in figure 16 show an event affecting a module but not the pyranometer, while label B shows an event affecting both.

- A slight shadowing of the PV modules from the stand on which they are deployed was noticed early in the morning and late in the afternoon (fig. 17). The stand has a slight edge of approx. 3cm high on the sides. When the sun is low, this edge shadows the modules that are right next to it. The modules that are shadowed in the morning are not the same than the modules shadowed in the afternoon. By comparing the performances of (clean) modules suffering from shadowing with (clean) modules (of the same type) without shadowing, the error has been quantified. Shadowing affects the total daily integrated \( I_{sc} \) up to 2.5%.

Considering all these points, daily integrated current values (integration of \( I_{sc} \) over the whole day) can be achieved with an overall accuracy of 3.5% for sunny days.

4.2 Temperature measurements

A typical example of temperature curve for a module back-sheet is shown in figure 18. As expected, the temperature rises as soon as the sun starts to shine in the morning and goes down when the irradiance falls. All 24 temperature curves give similar coherent results. Accuracy of thermocouple measurements are typically of the order of one degree. Unfortu-
Figure 17: $I_{sc}$ curves for a pair of identical modules (same glass, no soiling). Shadowing in the late afternoon translates itself by a decrease in $I_{sc}$ compared to a module of same type not suffering from shadowing. Note around 700min. that both modules do not have exactly the same performances.

Figure 18: Typical back-sheet temperature of a PV module.

Fortunately, an additional shift in temperature was observed when using the Wago thermocouple reader compared to other calibrated thermocouple readers. The shift was therefore characterized using an independent calibrated portable thermocouple reader (see figure 19). The shift is characterized with a 26% accuracy. The accuracy of temperature measurements is then of $\pm [1 + 0.26 \times (0.27 \cdot T_{measured} - 2.8)]^\circ C$ where 1 is the temperature error from the thermocouples, 0.26 is the error in the shift characterization, and the rest is the shift fit (see figure 19). For a measured and corrected temperature of 50$^\circ$C, the residual error is then of $\pm 3.8^\circ$C.
4.3 Comparing back-sheet and cell temperatures

The back-sheet temperature is measured on all 20 PV modules. Nevertheless, 3 additional thermocouple were laminated directly behind the cells of 3 different modules with different front glasses. This was done to verify that the back-sheet temperature is identical to the cell temperature. If not, a model must be used to calculate the cell temperature from the back-sheet temperature (see appendix A).

Measurements show no significant difference between cell temperatures and back-sheet temperatures (all differences are confined in the error and are not systematic). The temperature difference between the cell and the back-sheet was also investigated in the case of wind. For speeds up to $6\text{ m s}^{-1}$, wind has no effect on the temperature delta. This difference has not yet been assessed for higher wind speeds (no data). But the very low caloric inertia of the modules (noticeable at sunrise and sunset) makes us believe that back-sheet temperature will not deviate much from cell temperature in that case either.

4.4 Pyranometer sensitivity, alignment and timeline issues

Slight shifts of the module $I_{sc}$ measurements compared to the pyranometer curve have been observed (fig. 20):

1. On figure 20, both module’s $I_{sc}$ curves are not perfectly aligned. Since all modules are deployed in the same plane, this indicates that the problem comes from the timeline (section 3.2.3). Module B is measured 98 seconds before module U. This very small difference is sufficient to shift the $I_{sc}$ curve of module U to the left. In the

Figure 19: Shift in temperature between the Wago TC measurements and those done with an independent calibrated thermocouple reader. The shift changes with temperature.
morning, module U sees higher values of irradiance than module B, and the reverse is valid in the afternoon.

2. $I_{sc}$ curves are not perfectly aligned with the irradiance curve. Considering point 1, module B $I_{sc}$ curve should be more de-centered from the pyranometer curve than module U $I_{sc}$ curve (the irradiance is measured after all $I_{sc}$ are measured). The opposite happens here. This is because the pyranometer is not adjusted exactly in the module plane but has a slight unintentional angle compared to it. It is very slightly tilted to the west. This implies that the irradiance curve is shifted to the right compared to the $I_{sc}$ curves.

3. Considering points 1 and 2, the irradiance curve is shifted to the right compared to $I_{sc}$ curves, but all $I_{sc}$ curves are measured before the irradiance curve, shifting them also to the right compared to the irradiance curve. Both effects therefore counteract each other partially. For $I_{sc}$ curves measured at the beginning of the timeline, they almost counteract themselves perfectly (module B $I_{sc}$ is more or less centered in figure 20 compared to irradiance), whereas for $I_{sc}$ curves measured later in the measurement sequence, point 2 prevails and a shift is observable between the $I_{sc}$ and the irradiance curves (module U $I_{sc}$ is shifted compared to irradiance in figure 20).

4. Finally, the insets in figure 20 show that the pyranometer resolution is low at low irradiance values. On the right, the pyranometer curve goes under the red $I_{sc}$ curve.
Therefore it should rise before the red $I_{sc}$ curve in the left inset. This is not the case, both curves being superimposed. This brakes the linearity that should be observed between irradiance and $I_{sc}$ curves at all times. The pyranometer therefore underestimates the irradiance early in the morning and late in the afternoon when the sun and the irradiance are low.

Correcting these shifts is very difficult. Shifting the time labels cannot be done easily since it would require interpolation of the data. This should be done with great precision what is unrealistic. Additionally, the shift may evolve if the system has to be rebooted. Finally, evaluating the exact time shift is difficult. Nevertheless, suggestions to minimize these problems are given in section 5.1.
5 Suggestions to improve the installation

This section brings suggestions to improve the issues discussed in section 4. It also brings a couple of suggestions to improve the installations capabilities and lifetime.

5.1 Modification of the timeline and alignment of the pyranometer

Since all measurements are not done at exactly the same time, small shifts have been observed between $I_{sc}$ curves themselves and irradiance curves also (section 4.4). In addition, short events like small clouds can affect the measurements of a few values but not of the whole measurement sequence (see sections 3.2.3, 4.1 and 4.4). These effects could be limited by shortening the measurement sequence and improving the alignment of the pyranometer with the module plane.

Actually, measuring the values of one module takes 7 seconds (section 3.2.3) : after switching the relays, a 250ms pause is observed, after which 20 values of $I_{sc}$ and temperarure are measured every 250ms. After 5.25 seconds, measurements are finished and a mean of the values 5 to 14 is done. The other values are not considered to prevent errors due to the electrical stabilization of the circuit. A 1.75s pause is then observed before going on to the next module. This sequence is not optimal. Hereafter, an optimized (2.25s) sequence is proposed : one begins with a 750ms pause after switching the relays in order to equilibrate the circuit. Temperature and $I_{sc}$ values are then measured every 250ms and a mean is done on 5 values. A 500ms pause is observed before switching to the next module in order for the computer to make the mean. Implementing this potentially reduces from 166s to 54s the time needed to run the full measurement sequence.

The pyranometer alignment may be improved on site. After alignment, the irradiance should be measured in the middle of the measurement sequence. This would minimize the shifts between $I_{sc}$ curves and irradiance curves. Of course, if the irradiance could be measured using the acquisition box and not the weather station, this would enable to measure an irradiance curve for each $I_{sc}$ curve and eliminate this issue.

An additional modification to improve the precision of the installation would be to run a measurement sequence every 5 minutes instead of every 15 minutes actually. This would provide more precision in the morning and afternoon where the $I_{sc}$ and irradiance curve slopes are steep. Events like small clouds that only affect a few modules during the measurement sequence would then have less effect on the integrated daily values. An odd point in a 15 minutes interval trapezoidal integration has much more weight than an odd point in a 5 minutes interval.
5.2 Addressing the shadowing issue

As explained in section 4.1, a slight shadowing due to the stand itself occurs on some of the modules early in the morning and late in the afternoon. This shadowing is due to the height of the stand edges and only affects the modules placed directly next to the edges (half of the modules). This problem can be dealt with by slightly elevating the PV modules (2-3cm). Such an improvement would take a couple of days to achieve. It would theoretically reduce the measurement imprecision calculated in section 4.1 from 3.5% to 1% for sunny days.

5.3 Measuring the $V_{OC}$

Measuring the module $V_{OC}$ gives valuable information concerning the modules condition. Deprecations due to temperature stresses and humidity induce damages to the cells. If the cells bulk is modified, the pn junction is modified. This induces a variation of $V_{OC}$. Problems like contact oxidation unfortunately affect the fill factor more than the $V_{OC}$ and therefore cannot be seen in this way. In addition to giving values on the state of the modules, measuring $V_{OC}$ will enable to check if the variations in $V_{OC}$ are not too big, and therefore give an idea of the precision of $I_{sc}$ measurements instead of power output measurements.

Measuring the $V_{OC}$ of the modules can be done by slightly modifying the acquisition box and its software. The physical modifications to undertake are relatively simple. $I_{sc}$ is measured with the LEM in short-circuit conditions. Therefore a copper wire comes from the positive connection of the modules, goes through the LEM and joins the negative side. An additional relay could be installed in series with the cable. The positive side would connect to the relay, come out from the relay and go through the LEM before joining the negative side. Therefore by switching the relay using the relay control card (one slot is still available), one could switch the circuit from short circuit to open circuit conditions. Using a voltmeter connected to each side of the relay, when in open circuit, one could measure the modules $V_{OC}$. It happens that the acquisition card used to recuperate the signal from the LEM reads voltages between 0-10V and has a free entry port. Our modules have a $V_{OC}$ of approximately 2.5V (4 cells in series) which can be read natively by this acquisition card. Therefore, physical modifications of the circuit are very simple and would not cost much. The electrical schematics of the acquisition box with the modifications necessary to measure the modules $V_{OC}$ (in red) can be found in appendix D.2. Nevertheless, measuring the $V_{OC}$ of the modules at each measurement sequence would lengthen the sequence in contradiction with timeline improvement proposed in section 5.1.
Therefore, $V_{OC}$ could be measured only once a week or even once a month. For this, a small Codesys program could be made exclusively to measure $V_{OC}$. It could be launched manually on site whenever needed.

5.4 Improvement of the acquisition box lifetime

The 4 digital output modules (see section 3.2) that control the relays are short-circuit protected. The relays are therefore protected from electrical induction by a diode when they are switched on and off. But the contacts where the modules and the thermocouples are connected are not protected. With time this can cause carbonization of the relay contacts and deteriorate their quality. This can be prevented by adding a diode on each relay between the two contacts where the modules and thermocouples are connected.
6 Soiling modeling

The PV setup is composed of 10 pairs of equivalent modules. Half of these modules and the pyranometer are cleaned twice a week (sufficient to avoid soiling). In this way, for each pair of modules, one is kept clean while the other, the soiled one, is left untouched (soiling accumulates on it at a natural rate). In the following, two models to evaluate the effect of soiling on module $I_{sc}$ with our installation are presented.

6.1 Basic approach : first model

The simplest model to evaluate the effect of soiling consists in comparing the performances of two identical PV modules, one cleaned, the other soiled. The needed assumptions are the following:

- No degradation of the PV modules appears over the monitoring period (or at least the degradation is the same for all modules).
- Both cleaned and soiled modules are identical. They behave identically regarding $I_{sc}$ variations due to temperature and the front glasses have identical optical properties. This is quite well verified, but not exactly as can be seen on figure 17 where both modules don’t have exactly the same performances at noon.

The relative percentage of $I_{sc}$ loss due to soiling between a cleaned and a soiled module is then:

$$k_{soil} = \frac{I_{sc \text{ clean}} - I_{sc \text{ soiled}}}{I_{sc \text{ clean}}}$$

This method is purely comparative and takes into account every effect of soiling on the $I_{sc}$ (losses in irradiance and temperature variations). As seen in section 3.1, it is a good approximation of the effect of soiling on the modules power yield. In this way, the performances versus soiling of the different glass types and treatments can be assessed.

The main advantage of this model relies in its simplicity. Only the $I_{sc}$ measurements are used, and therefore the results are not sensitive to temperature measurement problems or irradiance measurement issues.

6.2 Advanced approach : second model

Soiling affects the module performances in two main ways. First and most importantly, soiling reduces the amount of light getting to the cell. It may absorb or reflect part of the light and its diffusive properties may alter the angle of incidence of the light onto the
module. We call these the optical effects of soiling. Then, soiling may alter the modules
temperature. If the cell receives less light, it will heat less. But if the soiling absorbs a
lots of light and transforms it into heat, it could bring the cell temperature up. We call
this the temperature effect of soiling. In further studies, it may be interesting to decouple
both effects in order to study in details the optical properties of soiling. For this reason,
a second model is proposed.
In this model, $I_{sc}$ measurements, back-sheet temperatures and irradiance measurements
are considered. Using IV measurements (section 2.2), the $I_{sc}$ is known as a function of
irradiance in standard test conditions (experimental results in section 7.1). By measuring
field irradiance in the PV module plane (the effective irradiance perceived by the modules),
the $I_{sc}$ the modules should produce is extrapolated. But in field, many parameters deviate
from standard conditions.

- Cell temperature deviates from standard conditions for all modules.
- Light angle of incidence deviates from standard conditions for all modules.
- Soiling is present on soiled modules.

Variations of $I_{sc}$ due to cell temperature variation are corrected using the manufacturer’s
cell temperature coefficients. Light angle of incidence losses (AOI losses) are calculated
for each type of front glass using the clean modules. The effect of soiling is then assessed
for soiled modules. The complete scheme is better understood by looking at the model
master equation:

$$I_{sc}^m = I_{sc}^t - k_T \cdot I_{sc}^m - k_{AOI} \cdot I_{sc}^t - k_{soil} \cdot I_{mp}^m$$

(7)

$I_{sc}^m$ is the measured module $I_{sc}$.

$I_{sc}^t = \frac{\partial I_{sc}}{\partial G} \cdot G$ is the theoretical $I_{sc}$ that would have been measured on the lab simulator
at the corresponding irradiance G in standard test conditions. G is measured by the
pyranometer.

$k_T \cdot I_{sc}^m$ is the $I_{sc}$ loss / gain due to temperature variations from the temperature at
which IV curves have been measured.

$$k_T = - \frac{k_s \cdot (T - 23^\circ C)}{I_{sc}^{IV,1000}}$$

(8)

$k_T$ (8) is the temperature loss rate where T is the module temperature, $k_s = 1.1 \cdot 10^{-3} A$
the $I_{sc}$ temperature coefficient given by Sunways and $I_{sc}^{IV,1000}$ is the $I_{sc}$ from IV measure-
ments at 1000 $W/m^2$ in standard test conditions. ($T-23^\circ C$) is the temperature difference from
the conditions in which IV curves were measured (T=cell temperature). The numerator gives the temperature factor correction for 1000 $\frac{W}{m^2}$ irradiance (what corresponds to a certain $I_{sc}$ value), the denominator normalizes it as a function of $I_{sc}$. Therefore $k_T$ is a rate of loss or gain and the absolute value is given by its multiplication with the actual measured $I_{sc}$.

$k_{AOI} \cdot I_{sc}^T$ are the angle of incidence (AOI) losses. These are additional reflection losses that occur when light impinges on the front glass at non-normal angles. To get the total losses due to reflection, one must add the reflection coefficient of the module at normal incidence to the AOI losses.

\[
k_{AOI} = -\frac{I_{sc}^m - I_{sc}^T + k_T \cdot I_{sc}^m}{I_{sc}^T}
\]  

This $k_{AOI}$ factor is measured on the clean modules where the soiling factor $k_{soil}$ is by definition equal to zero. The AOI losses are considered to be the same on the soiled module than on the clean module (same front glass). Therefore any modification of the AOI losses due to soiling will be accounted for in the soiling term of the equation.

$k_{soil} \cdot I_{sc}^{mp}$ are optical losses due to soiling. They are equal to zero on soiled modules. These losses occur either by light absorption / reflection / diffusion by the soiling medium resulting in less light arriving on the cell.

\[
k_{soil} = -\frac{I_{sc}^m - I_{sc}^T + k_T \cdot I_{sc}^m + k_{soil}^{mp} \cdot I_{sc}^T}{I_{sc}^{mp}}
\]  

$I_{sc}^{mp}$ and $k_{soil}^{mp}$ are the short circuit current and AOI loss rate from the corresponding clean module. Note that because variations of $I_{sc}$ due to temperature are taken away (8), $k_{soil}$ only represents the optical losses due to soiling. Note also that AOI losses induced by soiling are not decoupled from $k_{soil} : k_{AOI}$ only take into account the AOI losses of a clean front glass. Decoupling AOI losses induced by soiling from $k_{soil}$ could be done by modeling the soiling’s optical properties and comparig with soiling data acquired using with this model.

The assumptions made in this model are the same than for the first model (see section 6.1). Note that contrarily to the first model, this model is sensitive to pyranometer alignment and timeline issues (sections 4.4 & 3.2.3). Note also that temperature corrections as seen above are orders of magnitude smaller than AOI and soiling losses. Therefore, problems with temperature measurements (section 4.2) have virtually no importance on the results.
6.3 Indicators

Two main indicators are used to measure the effect of soiling.

- The integrated $I_{sc}$ currents over the full day are compared. In equation 6, the $I_{sc}$ values are replaced by the corresponding integrated $I_{sc}$ values. This indicator is referred to as the integrated indicator.

- The maximum daily $I_{sc}$ outputs of the PV modules are compared. In equation 6, the $I_{sc}$ values are replaced by the corresponding daily $I_{sc}$ maxima. This indicator is referred to as the maximum indicator.

The integrated indicator has the advantage of taking into account the effect of soiling during the whole day at all the different light angles of incidence. To compare glass performances versus soiling, it is the most interesting one. Nevertheless it is very sensitive to punctual events like short shadowing. When looking at a module pair, one can be measured shadowed while the other one not. Since measurement points are taken every 15 minutes, the integrated $I_{sc}$ loss in such an event is big and disturbs considerably the measurement of soiling effects. Therefore, the integrated indicator must only be used on nice days and days with singular values should be dismissed.

The maximum indicator is less subject to these problems. But it only takes into account one point so singular measurements may be dismissed. This indicator considers the soiling losses at the highest angle of incidence (closest to normal) achieved each day and therefore offers a less complete view of the effect of soiling on $I_{sc}$ than the integrated indicator. Nevertheless it offers a good evaluation of soiling losses when the power generation is at the highest.
7 Results and analysis

In this section, results of module characterization are shown. Moreover, the effect of soiling over a period of 43 days (21/11/2011 - 02/01/2012) is assessed using both models (section 6). All results are analyzed, compared and discussed.

7.1 Short-circuit current as a function of irradiance

In order to assess how the $I_{sc}$ changes as function of the irradiance $G$, IV curves at 200, 500 and 1000 $W/m^2$ with AM1,5G spectrum were performed for each module. The behavior of $I_{sc}$ as a function of $G$ was expected to be linear, what is very well verified. Figure 21 shows the linear trend for a typical PV module. These results are used to calculate theoretical standard conditions $I_{sc}$ values in the second model (section 6.2).

Figure 21: $I_{sc}$ as function of irradiance $G$ for a typical PV module.

7.2 Glass performance comparison from IV measurements

By comparing the dependance of $I_{sc}$ to the irradiance $\frac{\partial I_{sc}}{\partial G}$ of the different modules obtained in section 7.1, a first classification of the different glass performances at normal incidence with AM1,5G spectrum is made. In figure 22, modules are regrouped by type and clearly show different $\frac{\partial I_{sc}}{\partial G}$ values. The AlbarinoP highly textured glass is the most performant with more than 3% performance increase compared to Optiwhite standard flat glass. It is closely followed by AlbarinoS and AlbarinoT that are slightly better than Optiwhite standard PV-grade glasses (around 1.5%). VisionLite glasses come last with a decrease of approximately 4% compared to the Optiwhite glass. Results are shown in table 23.
The increased performances of textured front glasses (AlbarinoP,S,T) compared to standard OptiWhite flat front glasses are expected [4]. This shows that light-trapping and anti-reflection effects due to texturing are effective. The VisionLite front glass performs poorly compared to all other front glasses. This is because it is not a solar-grade glass (less transmission) and because its anti-reflective coating (on both sides) is optimized for air-glass-air interfaces and not air-glass-eva-cell interfaces. It is originally meant for window shops.

Note that all modules performances are regrouped by type of glass. This indicates that the preparation (soldering, lamination, ...) of the modules is reproducible. Note also that angular IV curves could provide interesting additional information for comparing in-lab glass performances with field performances, especially for textured glasses. Highly textured glasses are indeed thought to show an even higher increase in performances at higher angles of incidence compared to flat front glasses [4].
7.3 Glass performance comparison from EQE measurements

The EQE measurements where performed on stacks of front-glass / index matching liquid (IML) / cell instead of the modules (these where already deployed at that time). The cell was a Sunways as used in the modules, the IML was an Immersol 518N immersion oil for microscopy with a refractive index of 1.518 (close to glass and EVA). IML was used in order to prevent reflection due to an eventual air layer between the glass and the cell. Since the stacks are not identical to the modules, the obtained results (fig. 24) do not represent absolute values for the modules but can be treated in a relative way to assess glass performances.

As for IV measurements (see section 7.2), the AlbarinoP is the most performant glass with approximatively 2% increase in performance compared to Optiwhite standard glass. It is followed by the AlbarinoT and AlbarinoS glasses (approximatively +1.5%). The VisionLite glass comes last with nearly 4% performance decrease compared to the Optiwhite glass. The results are shown in table 25. Note that no difference in EQE was noticed using a glass with or without anti-soiling treatment. The anti-soiling treatment therefore does not affect the glass optical properties.

![Figure 24: EQE of the 5 different stacks.](image)

<table>
<thead>
<tr>
<th>Glass</th>
<th>Performance Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>OptiWhite (ref.)</td>
<td>35.48 [mA/cm²]</td>
</tr>
<tr>
<td>AlbarinoT</td>
<td>+1.66%</td>
</tr>
<tr>
<td>AlbarinoS</td>
<td>+1.55 %</td>
</tr>
<tr>
<td>AlbarinoP</td>
<td>+1.94 %</td>
</tr>
<tr>
<td>VisionLite</td>
<td>-3.75 %</td>
</tr>
</tbody>
</table>

![Figure 25: Relative performances of the different front glasses from EQE measurements. The OptiWhite standard flat front glass is taken as reference.](image)
7.4 Comparing IV, EQE and Field glass performance classifications

In sections 7.2 and 7.3, classifications of glass performances were made according to IV and EQE measurements. Comparing the results given by both methods with real field results enables to see what are each methods limitations and which method is most appropriate for in-lab glass characterization. Table 26 shows glass performance classifications according to IV, EQE and field measurements.

<table>
<thead>
<tr>
<th></th>
<th>Lab measurements</th>
<th>Field measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IV</td>
<td>EQE</td>
</tr>
<tr>
<td>OptiWhite (ref.)</td>
<td>8.62 [$mA\cdot m^2$]</td>
<td>35.48 [$mA/cm^2$]</td>
</tr>
<tr>
<td>AlbarinoT</td>
<td>+1.47 %</td>
<td>+1.66 %</td>
</tr>
<tr>
<td>AlbarinoS</td>
<td>+1.65 %</td>
<td>+1.55 %</td>
</tr>
<tr>
<td>AlbarinoP</td>
<td>+3.26 %</td>
<td>+1.94 %</td>
</tr>
<tr>
<td>VisionLite</td>
<td>-4.21 %</td>
<td>-3.75 %</td>
</tr>
</tbody>
</table>

Figure 26: Relative performances of the different glasses using IV, EQE and real field measurements. Max($I_{sc}$) is the daily maximum value of $I_{sc}$ measured in field. The integrated daily $I_{sc}$ is the integral of the $I_{sc}$ over the full day. All values are the median of the performances of the four modules (for each glass type). Standard flat OptiWhite glass performances are used as a reference for each type of measurements. The deviations from OptiWhite performances are visible for the other glass types. Note that all field measurements where done on the 21/11/11. The weather was sunny and the irradiance curve has a nice smooth shape. All modules where cleaned the previous evening so measurements are not affected by soiling.

IV and EQE measurements give very similar results. Nevertheless a big difference can be seen for the AlbarinoP glass modules. This could be explained by the fact that the hybrid LED/halogen sun simulator used to measure IV curves uses a diffused light source instead of a collimated light source. To counteract this, a calibrated monitoring module with a flat front glass is used. When the monitoring module’s $I_{sc}$ value corresponds to the exposition of the monitoring module to an AM1,5G light source, the sun simulator’s diffused light source mimics an AM1,5G collimated light source. However, when measuring a textured front glass module, an over-estimation of the $I_{sc}$ value could be induced. The diffused light source mimics an AM1,5G collimated light source for flat front glasses, but for textured front glasses, because of the anti-reflection effect, more light is transmitted through the glass. Therefore the diffused light source is no more equivalent to an AM1,5G collimated light source, and a textured glass monitoring cell should be used for more precision.

Field measurements in table 26 have a 1% precision. Since the differences in performance
of the different modules are very small, this precision isn’t enough to resolve them. It is
nevertheless nice to notice that the in-lab measurements exhibit the same trends as real
field measurements. Therefore both IV and EQE measurements are fit for in-lab glass
characterization.

All different measurement methods show the same trends: textured front glasses bring
higher module performances than standard flat solar-grade Optiwhite glass. Nevertheless
the difference is small and the performance gain does not justify the difference in cost
between flat and textured front glasses.

7.5 Soiling according to the first model

The relative percentage of $I_{sc}$ loss is assessed using the model developed in section 6.1.
Data from days with nice irradiance is used to avoid timeline problems (section 4.1). Both
the integrated and the maximum indicators (section 6.3) are calculated. The integrated
indicator has a ±5% absolute uncertainty, the maximum indicator a ±1.5% absolute un-
certainty. Measurements span out over 43 days, from the 21/11/2011 to the 02/01/2012.
All PV modules where cleaned the evening before the measurements started. No rain
was observed during the whole measurement period (no natural cleaning of the modules).
Note that soiling is not found to affect module temperature. Therefore, $I_{sc}$ measurements
correlate well with P measurements for the evaluation of soiling as seen in section 3.1.

7.5.1 Modules without anti-soiling coating

Results for both indicators are exposed in figures 27 and 28. As expected, the maximum
indicator gives lower soiling values than the integrated indicator. This may be due to
several factors:

- The optical thickness of soiling is smaller at higher angles of incidence (nearer to
  normal incidence) when assuming that soiling is deposited in a homogeneous layer.
  This results in less absorption of light by the soiling medium.

- At lower angles of incidence, reflection of light from the soiled front glass may be
  higher than reflection due to the clean glass alone.

Nevertheless, all PV modules show the same trend versus soiling for both indicators. The
following observations can be made:

- Soiling is a quick process. In less than a month, a 10% performance decrease can be
  observed, going up to nearly 20% after 43 days on all types of front glasses. Soiling
  is expected to appear even quicker in the summer as suggested by observations from
  prior studies of the CSEM-UAE. It is also expected to bring performance decreases
  up to 30-50%.
Figure 27: Performance decrease due to soiling on modules without anti-soiling using the integrated indicator, over a period of 43 days starting the 21/11/2011.

Figure 28: Performance decrease due to soiling on modules without anti-soiling using the maximum indicator, over a period of 43 days starting the 21/11/2011.
• After 43 days, no difference in performance can be made between the textured and non-textured front glasses regarding the precision of the setup.

• For all types of front glasses, soiling seems to be due to punctual events. Long plateaus followed by steep performance decreases can be seen. The meteorological data from the weather station (humidity, dew point, temperature, windspeed, wind direction, rain) was checked but no particular meteorological events could be correlated with these steps. It may be that meteorological events (wind, storms, ...) happening far away from the installation convey soiling to the modules. Monitoring the installation for a longer time may provide answers to this phenomenon.

Monitoring the setup for a longer time will give more information about the soiling process. Our hypothesis is that the performance decrease due to soiling will reach a steady state after some time. A representative fit of the soiling data will then be possible. Moreover, differences between the modules may also become apparent and resolvable, and more information may be available to better understand the plateaus apparent in figures 27 and 28.

7.5.2 Modules with anti-soiling coating

Results for both indicators are exposed in figures 29 and 30 for modules with anti-soiling coating (AS). The following observations can be made:

• After 40 days, the anti-soiling coating reduces typically the effect of soiling around 3% absolute for all modules, increasing the performance of the modules by the same amount. This corresponds to a 15-20% relative diminution of the effect of soiling. The effect of the anti-soiling coating can be seen to start right away and stabilizes around day 25.

• An exception can be made for the AlbarinoP type front glass modules. Results with/without AS coating are very close, indicating that the AS coating treatment is ineffectual in this case. This may be because applying the AS coating on deep textured glasses is difficult, or that soiling gets stuck in the texture and cannot evacuate as easily than on flat front glasses.

A combined graph with both indicators for modules with and without AS coating is presented in figure 31 for the standard flat OptiWhite glass. The impact of the anti-soiling treatment on the effect of soiling can be seen very clearly, stabilizing between 3% to 4% after 25 days. The difference between both indicators is also visible. Note that no rain was detected during the monitoring period. As the anti-soiling coating is hydrophobic, it may, in the event of rain, help to clean the front glasses. Differences between modules with and without AS coating may then be considerably increased.
Figure 29: Percentage of performance decrease due to soiling on modules with anti-soiling (AS) using the integrated indicator over a period of 43 days starting the 21/11/2011.

Figure 30: Percentage of performance decrease due to soiling on modules with anti-soiling (AS) using the maximum indicator over a period of 43 days starting the 21/11/2011.
7.6 AOI losses and soiling according to the second model

Using the second model explained in section 6.2, the typical daily AOI losses as well as the soiling losses were assessed. The results are exposed in the following sections.

7.6.1 AOI losses

The AOI losses are the additional reflection losses that occur when light arrives on the front glass at non-normal angles. They are derived for the clean modules using equation 9 in section 6.2.

A nice AOI loss curve in percents is displayed for the 02/01/2012 in figure 32 (module B). It exhibits an expected U-shape: the AOI losses are indeed greater at low angles of incidence (far from normal incidence) than for high angles of incidence. A typical reflection curve for an air-glass interface illustrates this in figure 33. Nevertheless, AOI losses are expected to be equal to zero for normal/high angles of incidence. The fact that the plateau (corresponding to high angles of incidence) presents around 5% losses may be due to a combination of the following factors:

- A large ratio of the irradiance comes from diffused light.

Figure 31: Performance decrease due to soiling on optiwhite modules with and without anti-soiling (AS) using both indicators. The impact of the anti-soiling treatment can be seen to stabilize in this case around 4% after 25 days using the maximum indicator. Note that the application of the anti-soiling treatment on non-textured optiwhite glasses is optimal compared to textured glasses.
• The pyranometer is not calibrated in the same way than the sun simulator therefore over-estimating irradiance values.

• In winter time, the sun never goes high enough to get high incidence angles. In january, the maximum sun height is of 40° [9]. For light to arrive at normal incidence on the PV modules, the sun should be at 68°.

The integrated AOI losses over a full day can be assessed using equation 11.

$$\frac{\int_{day} (k_{AOI} \cdot I_{T})}{\int_{day} (I_{sc})}$$  \hspace{1cm} (11)

We were not able to calculate them because of the errors induced by the pyranometer and the timeline (sections 3.2.3 and 4.4). As the shift between $I_{sc}$ curves and the pyranometer curve changes along the measurement sequence, the shape of the AOI losses changes also. Two AOI curves, one at the beginning of the measurement sequence (less error) and one at the end (bigger error), are exposed in figure 34. The module B AOI curve (beginning of the sequence) exhibits the expected U-shape. The pyranometer and timeline issues more or less cancel out. At the opposite end of the measurement sequence, module YY
AOI losses module B
AOI losses module YY
Irradiance

Figure 34: AOI and irradiance curves for the 02/01/2012. In red, module B AOI (beginning of the measurement sequence). It has the expected U-shape. In green, module YY AOI (end of the sequence).

AOI is severely altered. It is underestimated in the morning and overestimated in the late afternoon. This deformation is gradual along the measurement sequence. For these reasons, the AOI integrated losses could not be calculated with precision. Suggestions to correct this issue are presented in section 5.

7.6.2 Soiling on modules without anti-soiling coating

Despite the problems with the AOI curves (section 7.6.1), the effect of soiling could be assessed using the second model. This is because AOI losses are small compared to soiling losses (therefore the error is smaller), and that errors partially cancel out during integration.

Moreover, the effect of soiling on module performances is expected to be the same in both first and second models. The second model’s soiling results differ from the first model’s results only by the correction of the soiling’s effect on cell temperature. Since it is two orders of magnitude lower than the effect of soiling on module performances, the results should be almost the same. The effect of soiling for modules without anti-soiling treatment using the integrated indicator is exposed in figure 35.

The trends are the same than those found using the first model (see section 7.5.1 and figure 27). The soiling appears in a stepwise fashion and after 43 days, all modules exhibit approximatively the same performance decrease values (between 17% and 21%). Note that after 43 days, the absolute soiling values obtained with this model are a few percents higher than those obtained with the first model (section 7.5). Neglecting the temperature correction, all the differences between the first and the second model results come exclu-
Figure 35: Performance decrease due to soiling on modules without anti-soiling using the second model from the 21/11/2011 to the 02/01/2012.

sively from issues with the AOI measurements. Improvements to minimize these issues are presented in section 5.

Another interesting fact visible in figure 32 (section 7.6.1) is that soiling induces its own AOI losses. The green curve represents the performance decrease due to soiling in percents. It shows a slight U-shape. This means that the performance decrease due to soiling changes with the angle of incidence of the impinging light. For small angles of incidence, the losses are higher than for high angles of incidence. This shows that soiling induces AOI losses on the front glass that are different from the AOI losses of the clean front glass.

7.6.3 Soiling on modules with anti-soiling coating

The effect of soiling for modules without anti-soiling treatment is exposed in figure 36. The trends are the same than those found using the first model (see section 7.5.1 and

Figure 36: Performance decrease due to soiling on modules with anti-soiling using the second model from the 21/11/2011 to the 02/01/2012.
The soiling appears in a stepwise way and all modules exhibit approximately the same performance decrease values. Again, for the AlbarinoP front glass modules, results with/without AS coating are very close, indicating that the AS coating treatment is ineffectual. As postulated in section 7.5.2, this may be because applying the AS coating on deep textured glasses is difficult, or that soiling gets stuck in the texture and cannot evacuate as easily than on flat front glasses.

The effect of the anti-soiling treatment after 43 days leads to an increase of module performances of approximately 5%. This value is to be compared to the value of 3% found during the same comparison using the first model (section 7.5.2). Nevertheless, values given by the first model are more accurate than those given by the second because of AOI losses issues.
8 Conclusions

A small PV plant was deployed in collaboration with the CSEM-UAE in Ras-Al-Khaimah UAE to study the effect of soiling on c-Si modules as a function of their front glass texture and treatment. The setup has been tested and its precision characterized. Typically, integrated $I_{sc}$ values over a full day are measurable with a 3.5% precision. Soiling can be assessed with a $\pm 1.5\%$ absolute precision for single value measurements while integrated daily measurements are made with $\pm 5\%$ absolute precision. The key parameters affecting the precision of soiling results are the calibration and alignment of the pyranometer, the duration of the measurement sequence, and the shadowing due to the stand itself. These points will be optimized in the future in order to increase the resolving power of the setup, lowering the error on $I_{sc}$ daily integrated measurements to 1%.

Moreover, two analytical models have been developed to assess the effect of soiling on the performance of modules. The first, purely comparative, takes into account every effect of soiling on the module’s $I_{sc}$, including temperature. The other concentrates on the optical influence of soiling only and enables assessment of the different angle of incidence losses due to the various front glasses. Using both models, soiling was found to cause a decrease in performance on the order of 10% in less than a month and slightly under 20% after 43 days for all modules. No differences were noticed between the various front glass modules, but improving the setup’s precision may allow observation of small differences in the future. The anti-soiling coating was found to decrease the effect of soiling by 15-20%. This corresponds to a module performance increase of approximately 3%. Finally, all glass types seem to respond equally well to the anti-soiling coating except the AlbarinoP glass (deep texture) on which it seems ineffective.

Monitoring the installation for a longer period will give a more complete view of the effect of soiling on module performances. The rate at which soiling develops will be further assessed and soiling may be seen to reach a steady-state. In addition, the effect of the anti-soiling coating in the event of rain will be studied. All these observations will provide further interesting pieces of information for PV system cost balance calculations in the UAE.
Figure 37: Soiling status after 20 days. Soiling can be seen on the top modules according to figure 39 in appendix B.
References


A Cell temperature modeling

To measure the cell temperature, 3 additional thermocouples were laminated directly behind the cell in 3 different modules with different front glasses (OptiWhite, AlbarinoT & AlbarinoP). In the event where back-sheet temperatures would not correspond to cell temperatures (section 4.3), the cell temperature could be interpolated using the back-sheet temperature measurements done on each modules:

The back of each module (EVA + backsheet) is considered as a homogeneous material of constant thermal conduction coefficient. The conduction coefficient doesn’t change with temperature and thermal contact resistances are included in it. Radiative thermal losses are neglected. The power loss equations for conduction and convection are then given by:

\[
P^\text{conv} = h \cdot S \cdot \Delta T^\text{conv} \\
\]

\[
P^\text{cond} = k \cdot S \cdot \frac{\Delta T^\text{cond}}{e}
\]

where \( h \) is the convection coefficient of the surface, \( k \) the conduction coefficient of the modules back, \( \Delta T^\text{conv} = (T_{\text{back}} - T_{\text{air}}) \) the difference in temperature between the modules back and the air, \( \Delta T^\text{cond} = (T_{\text{cell}} - T_{\text{back}}) \) the temperature difference between the cells and the modules back, \( S \) the modules back surface and \( e \) the thickness of the modules back (EVA + backsheet). The values of \( k, h \) and \( e \) are unknown, but are not necessary as can be seen in the following:

In steady-state operation, the following condition is fulfilled:

\[
P^\text{conv} = P^\text{cond}
\]

\[
=> h \cdot \Delta T^\text{conv} = k \cdot \frac{\Delta T^\text{cond}}{e}
\]

\[
=> \frac{k}{h \cdot e} = \frac{T_{\text{back}} - T_{\text{air}}}{T_{\text{cell}} - T_{\text{back}}}
\]

\( T_{\text{air}} \) is given by the weather station. The coefficient \( \frac{k}{h \cdot e} \) can therefore be determined on the module that have integrated thermocouples that measure the cell temperature (assuming modules are identical). Finally, on the modules where only the backsheet temperature is measured, the cell temperature is given by:

\[
T_{\text{cell}} = \frac{e \cdot h}{k} (T_{\text{back}} - T_{\text{air}}) + T_{\text{back}}
\]
The coefficient $k_{h e}$ can be calculated with only one measurement point $(T_{\text{cell}}, T_{\text{air}}, T_{\text{back}})$, although a mean is preferable. But the value of the convection coefficient varies with wind conditions. $k_{h e}$ must therefore be evaluated for each wind conditions. Note that since integrated thermocouples are not available on all types of glasses, the $k_{h e}$ coefficient is considered to be the same for all types of modules.

This model gives a first approximation of the cell temperature. The error can be approximatively assessed by using the calculated $k_{h e}$ coefficient on another module with an integrated thermocouple at another time (with same wind conditions).
B  Module listing and deployment order

Table 38 lists all deployed modules with their specifications. The PV modules are disposed on the stand as in figure 39 (seen from front). PV modules that have to be cleaned periodically are shown in red and are the most accessible ones. The other PV modules should not be touched.

<table>
<thead>
<tr>
<th>PV module name</th>
<th>Type</th>
<th>AS-coating</th>
<th>TC relay</th>
<th>I relay</th>
<th>Remains clean</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>VisionLite</td>
<td>yes</td>
<td>1</td>
<td>a</td>
<td>yes</td>
</tr>
<tr>
<td>r</td>
<td>VisionLite</td>
<td>yes</td>
<td>2</td>
<td>b</td>
<td>no</td>
</tr>
<tr>
<td>s</td>
<td>VisionLite</td>
<td>no</td>
<td>3</td>
<td>c</td>
<td>no</td>
</tr>
<tr>
<td>zz</td>
<td>VisionLite</td>
<td>no</td>
<td>4</td>
<td>d</td>
<td>yes</td>
</tr>
<tr>
<td>f</td>
<td>Albarino P</td>
<td>yes</td>
<td>5</td>
<td>e</td>
<td>no</td>
</tr>
<tr>
<td>h</td>
<td>Albarino P</td>
<td>yes</td>
<td>6</td>
<td>f</td>
<td>yes</td>
</tr>
<tr>
<td>i</td>
<td>Albarino P</td>
<td>no</td>
<td>7</td>
<td>g</td>
<td>yes</td>
</tr>
<tr>
<td>xx</td>
<td>Albarino P</td>
<td>no</td>
<td>19(back) &amp; 22(in)</td>
<td>s</td>
<td>no</td>
</tr>
<tr>
<td>j</td>
<td>Albarino S</td>
<td>yes</td>
<td>8</td>
<td>h</td>
<td>no</td>
</tr>
<tr>
<td>k</td>
<td>Albarino S</td>
<td>yes</td>
<td>9</td>
<td>i</td>
<td>yes</td>
</tr>
<tr>
<td>l</td>
<td>Albarino S</td>
<td>no</td>
<td>10</td>
<td>j</td>
<td>yes</td>
</tr>
<tr>
<td>m</td>
<td>Albarino S</td>
<td>no</td>
<td>11</td>
<td>k</td>
<td>no</td>
</tr>
<tr>
<td>o</td>
<td>Albarino T</td>
<td>yes</td>
<td>12</td>
<td>l</td>
<td>yes</td>
</tr>
<tr>
<td>p</td>
<td>Albarino T</td>
<td>yes</td>
<td>13</td>
<td>m</td>
<td>no</td>
</tr>
<tr>
<td>z</td>
<td>Albarino T</td>
<td>no</td>
<td>14</td>
<td>n</td>
<td>yes</td>
</tr>
<tr>
<td>ww</td>
<td>Albarino T</td>
<td>no</td>
<td>18(back) &amp; 21(in)</td>
<td>r</td>
<td>no</td>
</tr>
<tr>
<td>u</td>
<td>OptiWhite</td>
<td>yes</td>
<td>15</td>
<td>o</td>
<td>yes</td>
</tr>
<tr>
<td>x</td>
<td>OptiWhite</td>
<td>yes</td>
<td>16</td>
<td>p</td>
<td>no</td>
</tr>
<tr>
<td>y</td>
<td>OptiWhite</td>
<td>no</td>
<td>17</td>
<td>q</td>
<td>no</td>
</tr>
<tr>
<td>yy</td>
<td>OptiWhite</td>
<td>no</td>
<td>20(back) &amp; 23(in)</td>
<td>t</td>
<td>yes</td>
</tr>
</tbody>
</table>

Figure 38: Deployed PV module listing. All thermocouple relays and \( I_{sc} \) relays are labelled with a number or a letter. These are printed on small stickers sticked on the relay switches. The "TC relay" column indicates on which relay a thermocouple coming from a module back-sheet is connected. For lines with two numbers, the second corresponds to the relay on which the integrated thermocouple is connected. Note that the temperature of the acquisition box is measured using relay 24 (not indicated on the list). Column "I relay" indicates on which relay switch the contacts of a certain module are connected. The "remains clean" column indicates which modules are cleaned twice a week by an engineer at CSEM-UAE.
Figure 39: PV module disposition as seen from front. Modules marked in red are those that are cleaned periodically.

C Accessing data locally and remotely

C.1 Weather data

The weather data is accessed using the WeatherLinkIP software from Davis. All information to configure WeatherLinkIP is available in the software manual. All other information concerning the WeatherLink account (usernames and passwords) is written hereafter:

- Davis data logger device ID (DID) : 001D0A003DC3
- Key : 264524
- Username : pvlab
- Password : packaging
- E-mail : valentin.chapuis@epfl.ch
- Weather station URL : http://www.weatherlink.com/user/pvlab

C.2 Data from acquisition box

Remotely, the Linux box can be accessed by SFTP and SSH. For SSH connections, the address is "csempvce.dvrdns.org", the username is "root" and the password is "adm4epfl". SFTP connections happen on port "22" with the same address, login and password. All data can be found in the data/data folder. A data file per day can be found there named
by the day date. A concatenated data file named mois.txt containing all data since the beginning of measurements is also available.
Locally, the Linux box presents itself as in figure 40. All data is stored on the USB key in the data/data folder. The LinuxBox communicates with the acquisition box with the 192.168.1.101 IP, is connected to the internet via the routeur on the 192.168.9.20 IP and can be accessed manually from the maintenance port with the 192.168.77.77 IP. For this last point, the computer needs an IP of type 192.168.77.* with * between 1 and 255 and other than 77. When connected in such a fashion on the Linux box, the data from the acquisition box can be visualized in real time on the following http adress: http://192.168.77.77/servlet/ch.alronet.webaristide.AristideServlet.

![Figure 40: Photograph of the Linux box labelled with the different connection ports](image-url)
D  Acquisition box electrical diagram

D.1  Actual schematics

The electrical schematics of the acquisition box are displayed hereunder in figure 41. This is a truncated version where only the first two PV modules and concerned thermocouples are displayed. All other PV modules and thermocouples are connected in the same way.
D.2 Potential schematics to measure $V_{OC}$

The electrical schematics of the acquisition box upgraded to measure the modules $V_{OC}$ is exposed hereunder in figure 42. The modifications compared to the actual version (section D) are displayed in red.

Figure 42: Potential improvements (red) to the electrical schematics of the acquisition box to measure modules $V_{OC}$. 