GREEN ENERGY PARK

EVALUATION OF SINGLE MODULES DATA

CHEMITEK PV SYSTEM
DATA EVALUATION OF PV STRINGS

FINAL REPORT

From 12th August/2021 to 10th April/2022

Deliverable N°: 03/2022-GEP

Customer: CHEMITEK

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Document History

Version	Date	Comment
V1	23/05/2022	First release

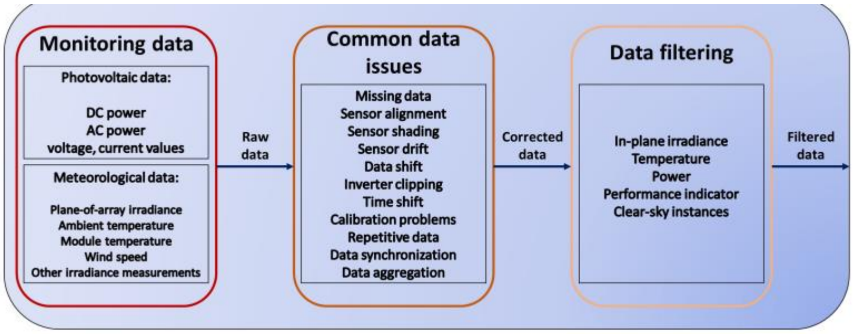
I. General Information

i. Introduction

In order to investigate field behavior of the innovative CHEMITEK coating and cleaning solutions and their sensitivity to soiling and performance in hot conditions as well as the possible degradation mechanisms, an outdoor testing exposure was performed. The system have been evaluated during the dry season (August 2021– November 2021) and the rainy season (December 2021 – April 2022) in Morocco at the Green Energy Park located in Ben Guerir. During this time, the electrical parameters of the PV system are collected by the monitoring system along with the weather parameters collected by the meteorological station within the same site location.

ii. Evaluation Process Flow chart

The figure below defines the necessary steps of monitoring data preparation for any kind of performance evaluation. Firstly, data are imported and are subject to be evaluated in order to detect any possible case of corrupted data. While the second and third steps are closely related as data filtering is used to address some of the common data issues.



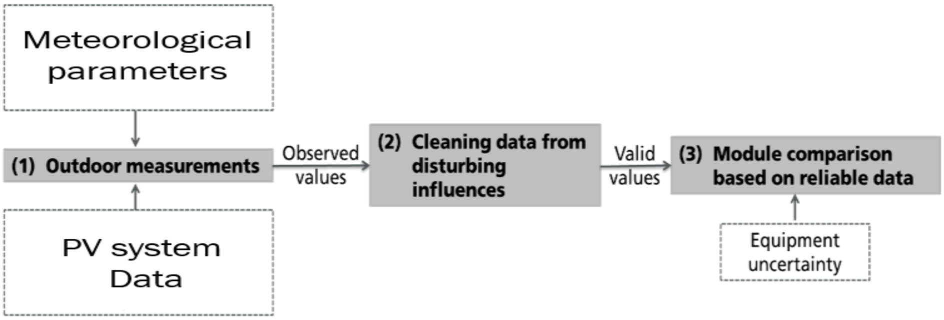


Figure 1 : Monitoring data preparation steps

iii. Modules Information

Module type	TSM-DEO6M.08(II)
	STC (1000W/m², 25 ℃)
Rated Power	335 W [0 – 5] W
Maximum Power Voltage (Vmp)	34.0 V
Maximum Power Current (Imp)	9.85 A
Open Circuit Voltage (Voc)	40.7 V
Short Circuit Current (Isc)	10.48 A
Module Efficiency	19.9 %
No. Of Half-cells	120 (6 x 20)
Front Cover	3.2mm, Anti-Reflection Coated Heat Strengthened Glass, High Transmission.
Cell type / module dimensions	Mono PERC / 2230 x 1134 x 35 mm
Weight	29.79 Kg (62.47 lb)
Frame	35 mm Anodized Aluminium Alloy
J-Box	IP 68 rated
Output Cables	Photovoltaic Technology Cable 4.0mm2 (0.006 inches2), Portrait : N 280mm/P 280mm(11.02/11.02inches) Landscape: N 1200 mm /P 1200 mm (47.24/47.24 inches)

Table 1 : Module Name Plate Information

Product name	**Description**
Solar Wash Protect (SWP)	Cleaning solution
D-Solar Defendor (DSD)	Hydrophobic coating
Industrial Glass Protect (IGP)	Hydrophobic Coating

Table 2 : CHEMITEK's products

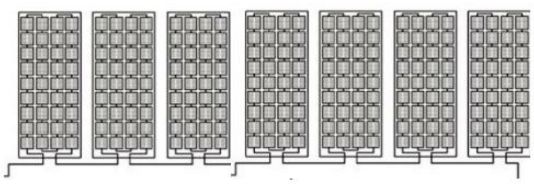
iv. Test Presentation & Data Description

Test location	**Green Energy Park, Benguerir, Morocco** Latitude : 32.22153° Longitude : -7.92798 Altitude : 450.om
Start of testing	12/08/2021
Location of test site	Open rural area, Green Energy Park

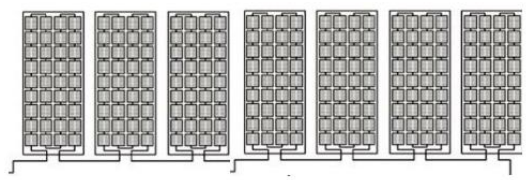
Modules Orientation (optimal Position for the location)	**Fixed at:** Azimuth: 180° (south) Inclination angle: 32°
Meteorological parameters	• Irradiance (global, direct, diffuse & in plane of array), • Ambient temperature, • Wind speed & direction, • Wind gust, • Relative humidity, • Air pressure, • Rainfall & duration, • Solar Spectrum, • Ambient aerosol size distributions,
PV system Data	Pdc, Pac, Uac, Udc, Idc, Iac, energy yields, inverter temperature, string currents, module temperature
Data begin date	15/08/2021
Data end date	10/04/2022
Sampling time	Up to 2-minute interval for PV system data and up to 1 minute for meteorological data
Cleaning Protocol	Full modules cleaning with tap water and a brush, with details of cleaning described in the figure below.

Table 3 : Test presentation

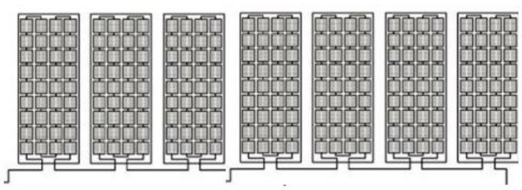
(i) PV string Uncleaned



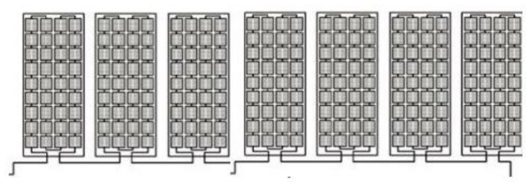
(ii) PV string Cleaned with water



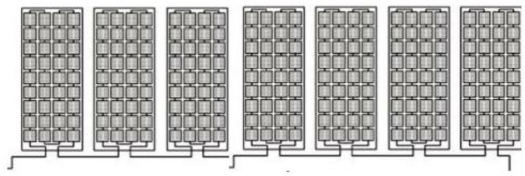
(iii) PV string cleaned with SWP solution



(iv) PV string coated with D-solar Defendor



(v) PV string coated with IGP



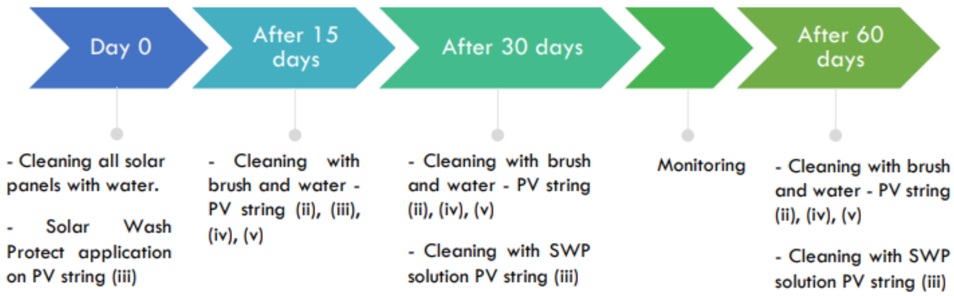


Figure 2 : Cleaning process protocol

v. Filtering Criteria

After the raw data evaluation and quality check, data filtering is used to extract reliable data of interest for better interpretation and visualization. Filtering approaches are used to achieve desired results in later analyses.

The standard IEC 61724:2016 part three, provides guidelines of initial minimum filters for monitored High-resolution variables. The most relevant ones are represented in the table below:

20W/m2	<	Plan of array Irradiance	< 1500 W/m2
-30 °C	<	Ambient Temperature	< 50 °C
0 m/s	<	Wind Speed	< 32 m/s

Table 4 : Recommended filter of part three from IEC 61724:2016

IEC 61724:2017 part one recommends an in-plane irradiance threshold of 20 W/m2, keeping measurement only during daylight hours. The filters represented here are meant to be for performance loss evaluation. However, filtering will always depend on the purpose of the study.

vi. Maintenance and Failures Records

Dates:	**16,20,21,22 August 2021**
Type: Modules Temperatures Data loss	
Comment: **Temperature data were not collected during these periods due to a disconnection of the temperature sensors.**	

Dates:	**12,26 August 2021** **10 September 2021** **10 October 2021**
Type: IV curves measurement in module level	
Comment: An IV curve measurement was taken after each cleaning cycle (Day_0, Day_15, Day_30, Day 60) in order to evaluate the performance of PV module after each cleaning cycle.	

Dates:	**02 September**
Type: Uncleaned string disconnection	
Comment: A Burnt MC4 cable occurs between 7:12 AM to 11:12 PM which lead to energy loss during the 02nd of September. Data acquisition failure during September 04 lead to an outlier value in the IGP string. See Appendix 1	

Dates:	**1, 2, 4, 6 September** **5, 12, 13, 14 November** **22 October** **19 ,30 December** **27 February 2022**
Type: data acquisition failure	
Comment: Data acquisition failure during September 04 lead to an outlier value in the IGP string. See Appendix 1 Fig 17. interruptions in the DC system data, see Appendix 1 Fig 18	

Dates:	**20/21/24/26 September** **9 October 2021** **6 April 2022**
Type: Grid Loss (Blackout)	
Comment: The interruption in data is due to a grid connection loss and a maintenance operation on the grid injection facility.	

Dates:	**13, 14 August** **12,13,14,19,23 September & 6 October**
Type: High intermittence periods	
Comment: Periods with high intermittences should be filtered from the analysis	

Dates:	**4 September - 15 December**
Type: Inverter Communication Failure	
Comment: DD, SWP and IGP Inverters showed an abnormal behavior leading to an outlier value in the corresponding strings	

II. Summary of the Cleaning strategy

The cleaning protocol is performed using a pressure sprayer machine and a brush in order to remove the accumulated dirt on top of the PV modules. Solar panels will be cleaned either early in the morning or evening time. Time and amount of water will be monitored during each cleaning cycle (Day 15, Day 30, day_60) in order to evaluate the easiness, fastness, and efficiency of the dirt cleaning in each situation.

The table below shows the amount of water and time spent during the first two cleaning cycles:

System Type	Day_15		Day_30		Day_60	
	26/08/2021		10/9/2021		10/10/2021	
	Time (Minutes) per string	Water quantity per string	Time (Minutes) per string	Water quantity per string	Time (Minutes) per string	Water quantity per string
Uncleaned	Not Cleaned	Not Cleaned	Not Cleaned	Not Cleaned	Not Cleaned	Not Cleaned
Water cleaned	11	4.5	12	4	15	6
D-Solar Defender	13	4.5	11	4	16	6.5
IGP	14	4.5	11	4	15	6.5
SWP	12	4.5	10	2.25	16	6

Table 5:Water and Time monitoring during cleaning cycles for each string

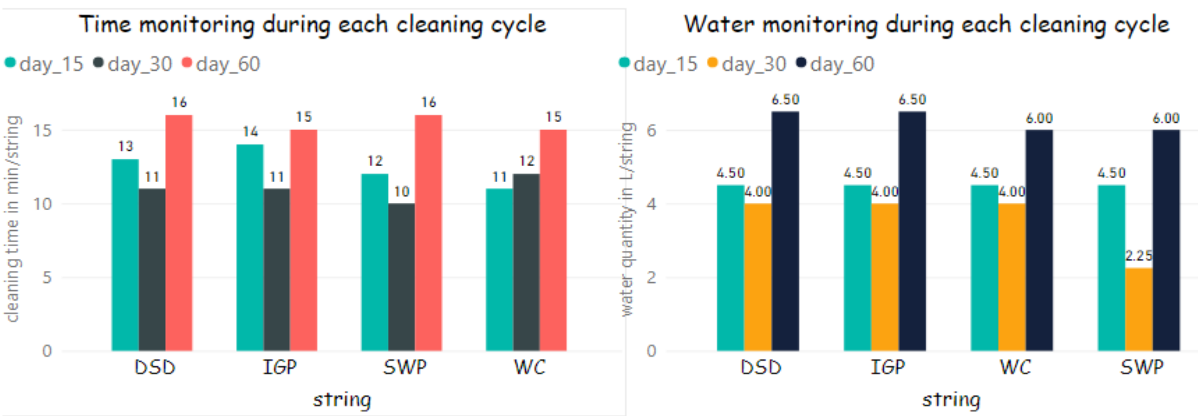


Figure 3 : Water and Time monitoring during each cleaning cycle

It can be observed that after 15 days of outdoor exposure the application of the SWP solution during day 30 reduces the amount of water used by 50% with respect to the cleaning with only water during day 15. Either, the cleaning time has been decreased from 12 minutes (cleaning with water) to 10 minutes (cleaning with SWP solution), nevertheless for the second period after 30 days of exposure it has shown only -0.5L of water saved compared to the other solutions.
Another analysis can be observed regarding the "Water Cleaned" is that the cleaning with only water, make the panels surfaces hard to clean which confirm the increase the duration of cleaning.

The other strings coated with IGP and DSD shows the same behavior by reducing the amount of water from 4.5 [L/ string] during day 15 to 4 [L/string] during day 30, and also for day_60 (6.5L/string), the cleaning time is reduced in the second cleaning which reflect the effectiveness and easiness of dirt cleaning using CHEMITEK's products.

III. Summary of the weather data

i. Temperature and humidity

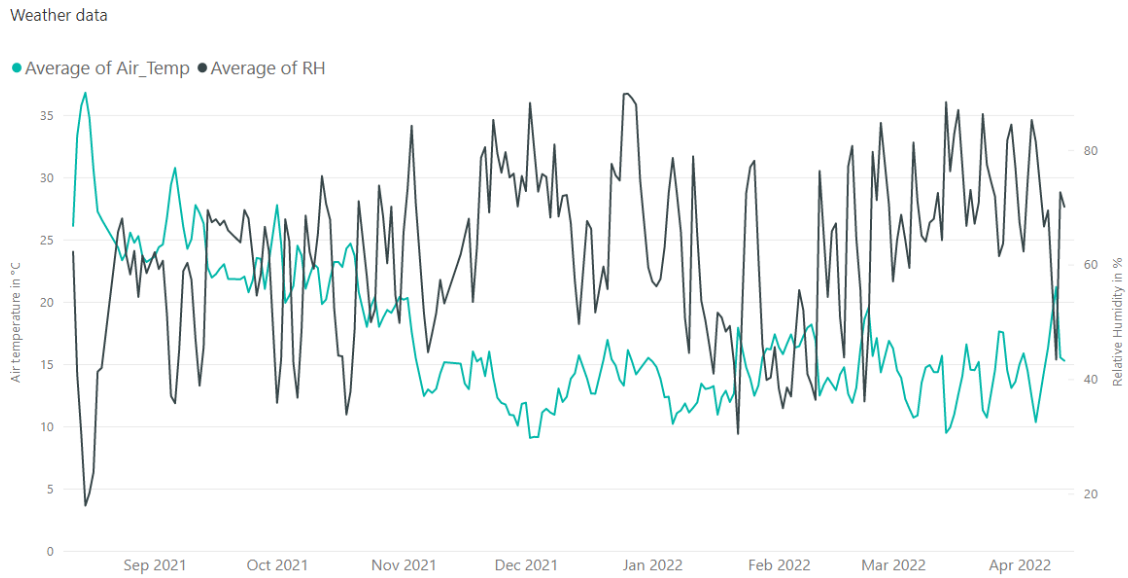


Figure 4 : Daily average ambient temperature and relative humidity over time

Figure 4 represents the evolution of air temperature, wind speed and relative humidity over time. The evaluated weather data starts from 12 august 2021 to 10 April 2022, which correspond to 8 months of exposure time during which PV systems will be evaluated.

We remark that this period of exposure is divided into four main periods:

- **P1** [From August 15 to November 1]: represent the dry period where high ambient temperatures and low relative humidity occurs. For the ambient temperature it ranges from a maximum of 36°C and a minimum of 20°C while relative humidity ranges from 17.91 % and 75.45%.
- **P2** [From November 1 to April 10]: represent the winter period where low ambient temperatures and high relative humidity occurs. For the ambient temperature its ranging between 9.15°C and of 21.19°C while relative humidity ranges from 30.43 % and 89.83%.

ii. Wind Speed

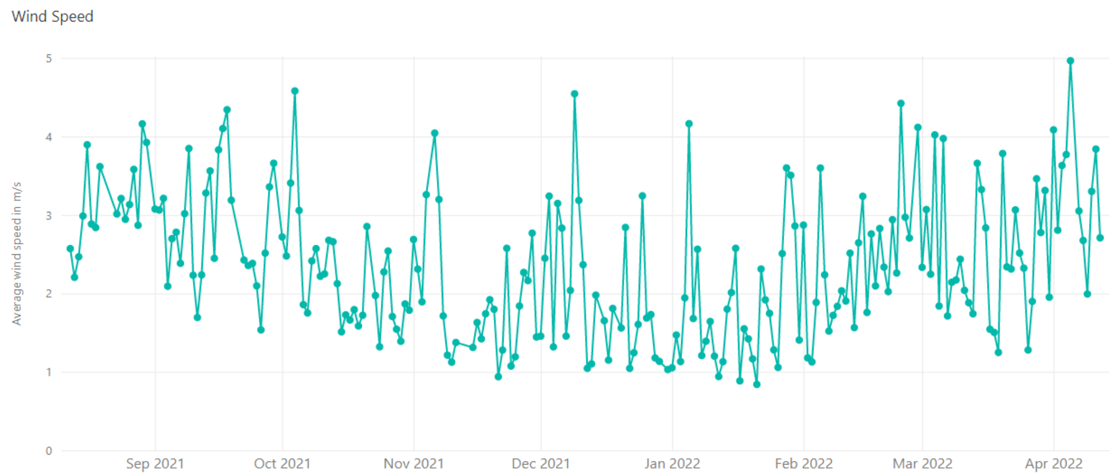


Figure 5: Wind speed over time

Regarding Wind speed variability, during the test period, it has a daily average between 1m/s and 5m/s with relatively low values between December and February.

iii. Rain Events:

The period of the test in considered as one of the driest seasons in Benguerir Morocco, with a significantly low rain rates, with a maximum of 15 mm/day reached in March 14 2022. **(See Appendix 1 table 7)**

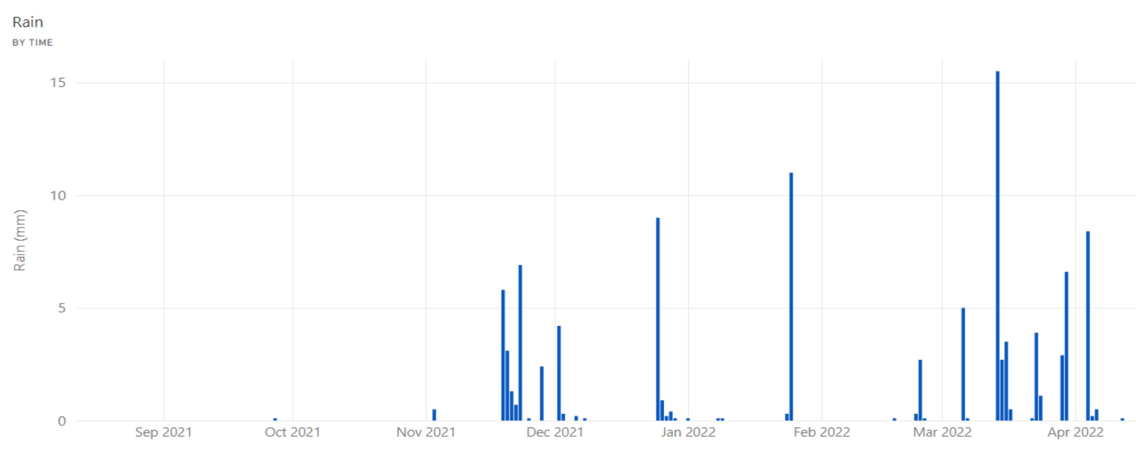


Figure 6: Rain events during the test period

iv. Global Tilted & Horizontal Irradiance

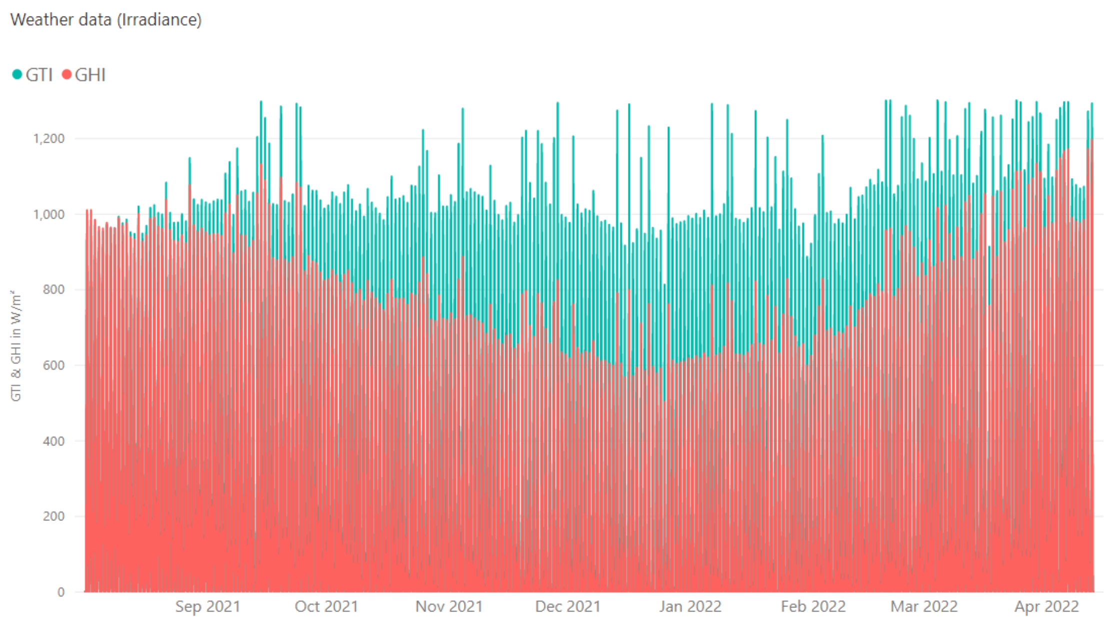


Figure 7 : The evolution of Global horizontal irradiance (GHI) AND Global Tilted irradiance (GTI) over time

Figure 7 represent the evolution of the global horizontal irradiance (GHI) and the global tilted irradiance (GTI) over time. It can be concluded that the GTI remain always greater than or equal to the GHI, which is normal due to the inclination of PV panels to the optimum tilt (31°) for the purpose of producing the maximum yield during the year. We can also remark that the GHI decreases compared to the GTI in the period between October and February, this is mainly due to the fact in the winter season the declination of sun is lower, so the GHI is lower and GTI keep collecting maximum irradiance due to the chosen inclination of 31 degree.

IV. Results

i. Reference Yield

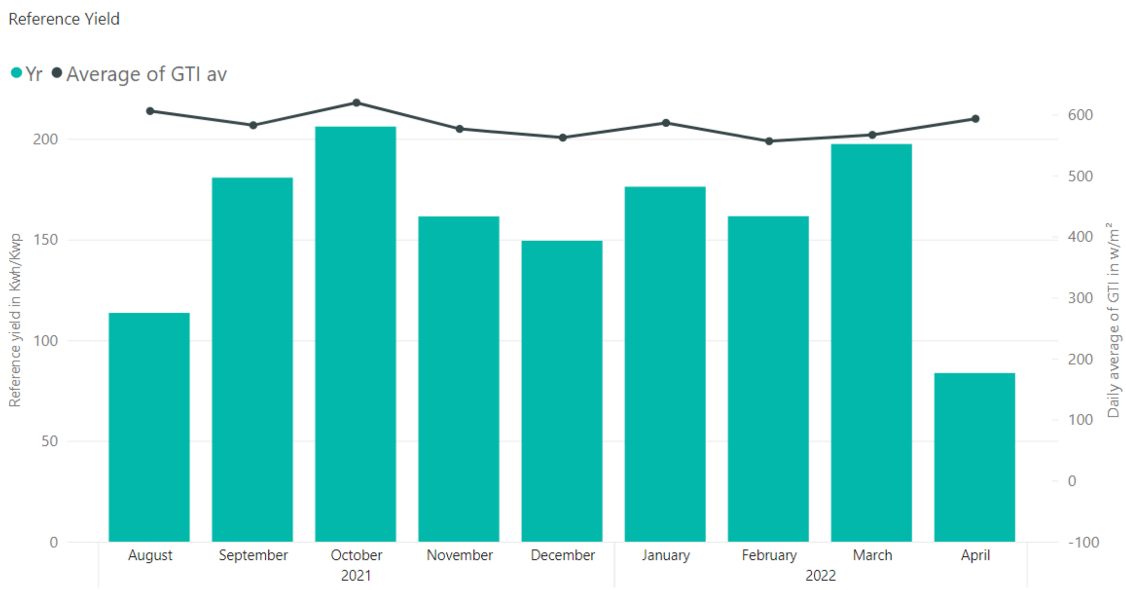


Figure 8 : Reference Yield with correspondent average GTI evolution over time

The reference yield represents the solar irradiance resource for the PV system. It represents also the number of sun peak hour under 1 KW/m2 of irradiance. The reference yield is equal to the total in-plane irradiance (GTI) divided by the PV reference irradiance (Under STC). It is a function of location, array orientation, and weather conditions.

$$Y_R = \frac{G_I}{G_{STC}} \text{ (kWh/kW)}$$

Where G_I is GTI (Global tilted irradiation) (kWh/m2) and G_{STC} is the reference irradiance at STC (1kW/m^2).

The Reference yield is a common value between all the PV strings and it gives an idea on how much is the theoretical energy that would be produced by the system, the Y_R reaches a maximum of **206.10 KWh/KW/Month** during October 2021 with a daily average of **6.65 KWh/KW/Day.**

ii. Energy yields

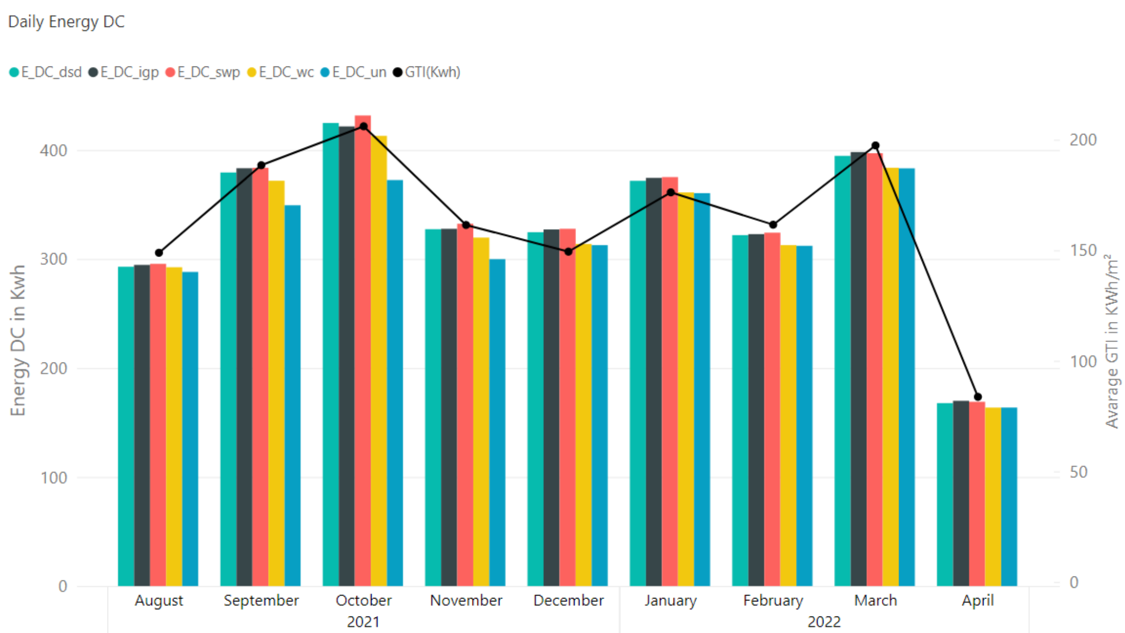


Figure 9: Monthly Energy yield KWh

Figure 9 represents the evolution of the monthly energy yield (kWh) (DC side) and the monthly global in plane irradiance GTI (W/m²) over time during the test period where the 5 PV systems (strings) are evaluated and taking into consideration the effect of cleaning that occurs in the 12 August (Day_0), 26 August (Day_15), 10 September (Day_30), 10 October (Day_60) and November 10.

the system's Energy output in the first cleaning cycle (August) are relatively identical, while the difference occurs after the successive cleaning where the SWP was the highest performing string during the dry season, the energy output reaches its maximum in October due to the high Reference yield. While in the last period of the study and with the amount of rain rates measured, the IGP outperforms the SWP and DSD respectively during days of precipitations. In general, the washing solution string (SWP) and the coated strings (IGP, DSD) outperforms the reference strings (WC, UN) in all the periods.

iii. Array Yield

The array yield is the DC energy production of the PV array over a given period of time normalized by PV rated Power. It represents also the number of hours during which the PV system is operating under its rated power.

$$Y_A = \frac{E_{DC}}{P_{PV\ rated}}\ (\text{kWh/kW})$$

Where:

E_{DC} : is the DC energy in kWh

$P_{PV\ rated}$: is the installed Capacity (kW)

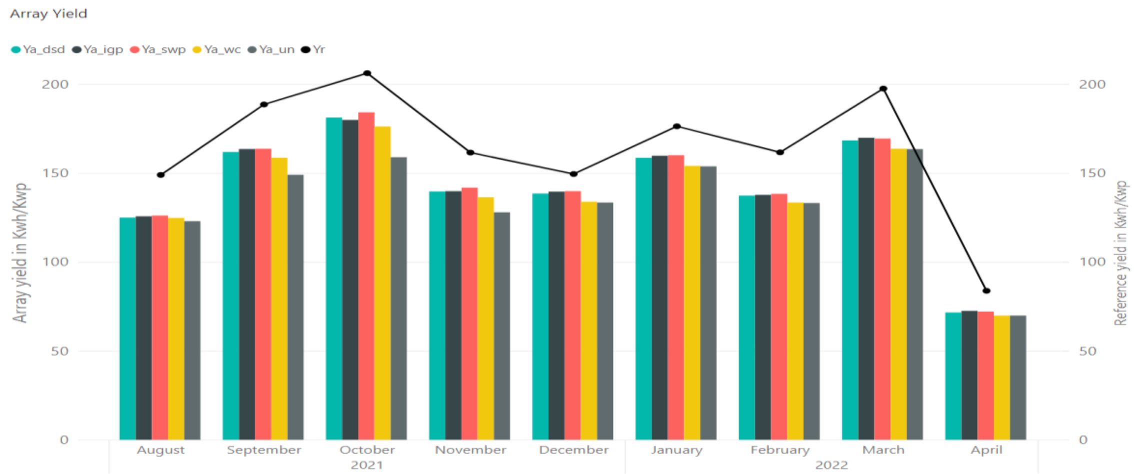


Figure 10 : PV strings Array Yield over time

Figure 10 represents the evolution of the daily Array yield (kWh/KWp) (DC side) and the Reference Yield (KWh/KWp) over time. It can be observed that:

- During the first 15 days (August) of exposure, the 5 strings were operating most of the time at their rated power.
- After the second cleaning (Day_15), the Uncleaned array yield dropped below all PV strings mainly due to the dust accumulation. Otherwise, SWP performed better after the first cleaning with respect to IGP and DSD.
- During the period between 10 Sep and 10 Nov which corresponds to the Day_30, the 3 solutions show a higher yield with the SWP being the most performant since it's a dry season solution. While the DSD and IGP are relatively similar and outperform the WC system.
- After the last cleaning of November 10, it can be observed that the SWP has the highest output between November and February with very low rain rates, while in the period between March 10 and April 10 the IGP outperforms the SWP solution which can be due to the higher rain rates.

iv. Capture losses

PV system performance is mainly affected by multiples losses causing a decrease in term of PV producibility and the well behaving of its components. In this case study, we will be focusing on the losses that occurs in the PV side (DC side), also called array capture losses. It Represents failures in DC part and combine all losses that prevents fully utilization of incident irradiance. Array capture losses is the difference between reference yield and the array yield.

PV array capture losses are divided into two sub-losses:

- Thermal losses: caused by temperatures higher than 25 degrees.
- Miscellaneous capture losses: caused by wiring, string diodes, low irradiance, partial shadowing, mismatch and soiling.

$$L_T = Y_R - Y_{CR} \text{ (kWh/KW)}$$

$$L_{CM} = Y_{CR} - Y_A \text{ (kWh/KW)}$$

$$L_C = Y_R - Y_A \text{ (kWh/KW)}$$

With:

Y_R is the reference yield

Y_A is the Array yield.

Y_{CR} is the corrected reference yield.

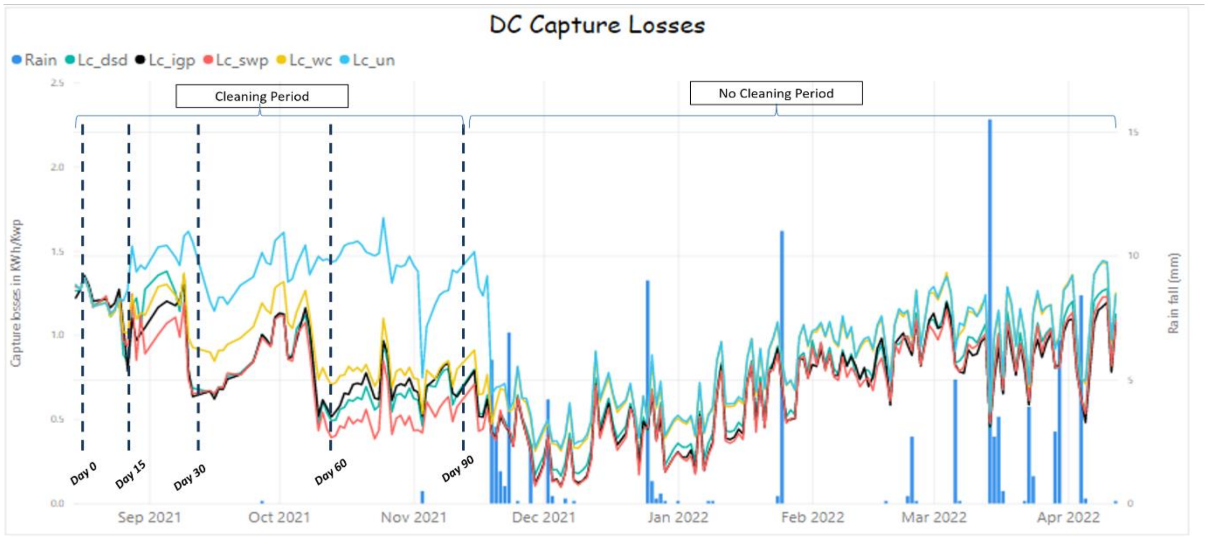


Figure 11: DC Capture losses

Figure 11 represents the evolution of the array losses that occur in the system (DC side) over the test period. It can be observed that the systems behave the same way until the second cleaning day (Day_15), where PV system capture losses increase for the "UNCLEANED" string due to dust accumulation. The DSD and IGP system losses have dropped below all others PV strings right after the second cleaning (Day_15) which is a good sign of the effectiveness and the easiness of the dust removal using only water cleaning.

After the cleaning of day_30 and within the 30-day cleaning cycles (10 Sep – 10 Nov) the SWP has the lowest capture losses followed by IGP and DSD respectively, while the UN remains with the highest losses due to dust accumulation. While with the rain events occurring in 19th-23rd November the UN regains its performance and becomes relatively identical to WC, either the SWP remains the highest performing with the Lowest losses due to the low rain rates. With the increasing rain rates the IGP outperforms the SWP in the last period of test (March-April).

v. Module Temperature

The figure 12 below illustrates the daily average module temperatures it can be observed that the values measured from the systems are relatively similar during the test period with the low temperatures occurring in the winter season with respect to the ambient temperature. the daily average ranges from a maximum of 36.06 °C in September 6 and a minimum of 9.63°C in December 2.

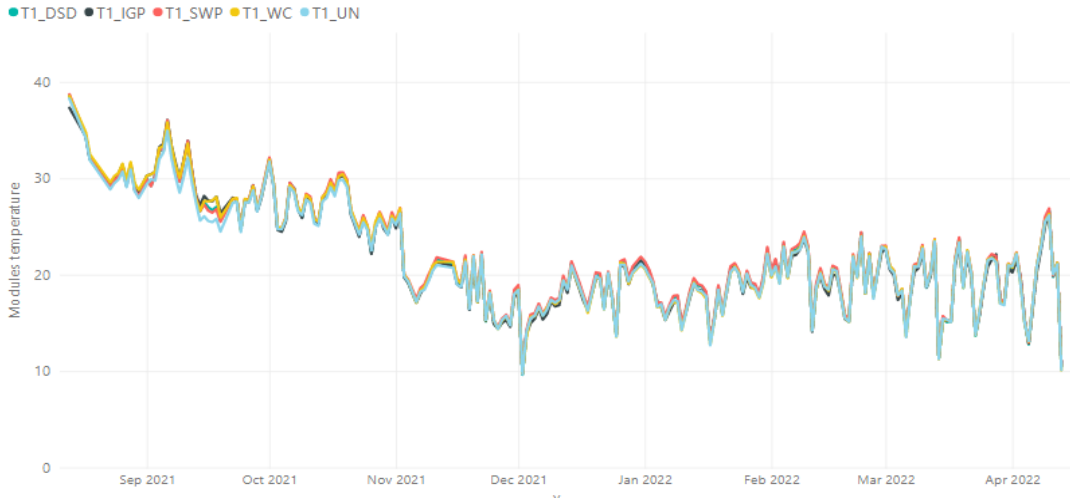


Figure 12 : Daily average module temperatures (°C)

V. Performance Indicators

The main goal is to analyze the behavior of the PV strings performance indicator in accordance with the irradiance to identify their behavior in high and low light conditions as well as in hot conditions.

Performance Indicator	Description	Equation
Performance Ratio (PR) *"IEC 61724-1: Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis –"*	performance ratio refers to the relationship between actual yield and target yield. It indicates the losses within the PV modules due to heat, soiling, degradation or operational issues	$PR = \frac{\frac{\text{Output Power}}{\text{Power at STC}}}{\frac{\text{Irradiance}}{\text{Irradince at STC}}}$
PV string efficiency	Represent the efficiency of the PV string by dividing the Produced DC energy by the theorical reference energy.	$\eta_{PV} = \left(\frac{Produced\ DC\ Energy}{In\ plane\ irradiance\ x\ \ String\ area}\right)$x 100

Performance ratio deviation from uncleaned	Define the deviation of each PV string from the Uncleaned string as a reference.	$dev_{sys} = (\frac{PRsys}{PRun} - 1) * 100$
Cumulative energy gain	Represent the gain of energy for each system taking as a reference the Water cleaned system.	$Gain_{energy} = (\frac{Running\ Total(Psys)}{Running\ Total(P_{Wc})} - 1) * 100$

Table 8: Presentation of the investigated performance indicators.

i. Performance ratio DC

The DC performance ratio represent the difference between the array yield and the reference yield. It is a key performance indicator for evaluating the behavior of the PV system considering only its DC side which allow us to differentiate between PV strings without the influence of any other component (Inverter, BOS,).

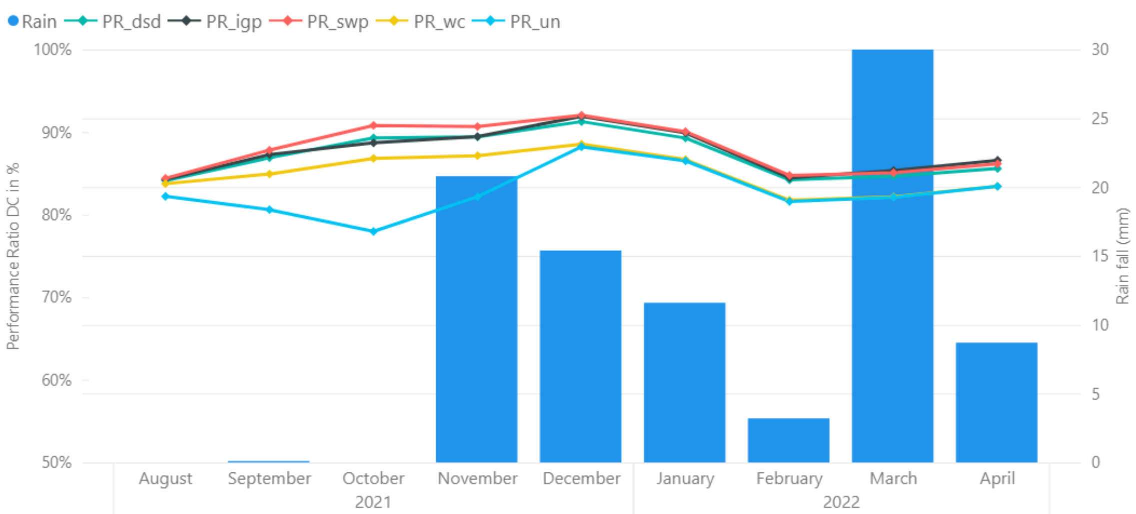


Figure 13: Monthly Performance Ratio DC side in %

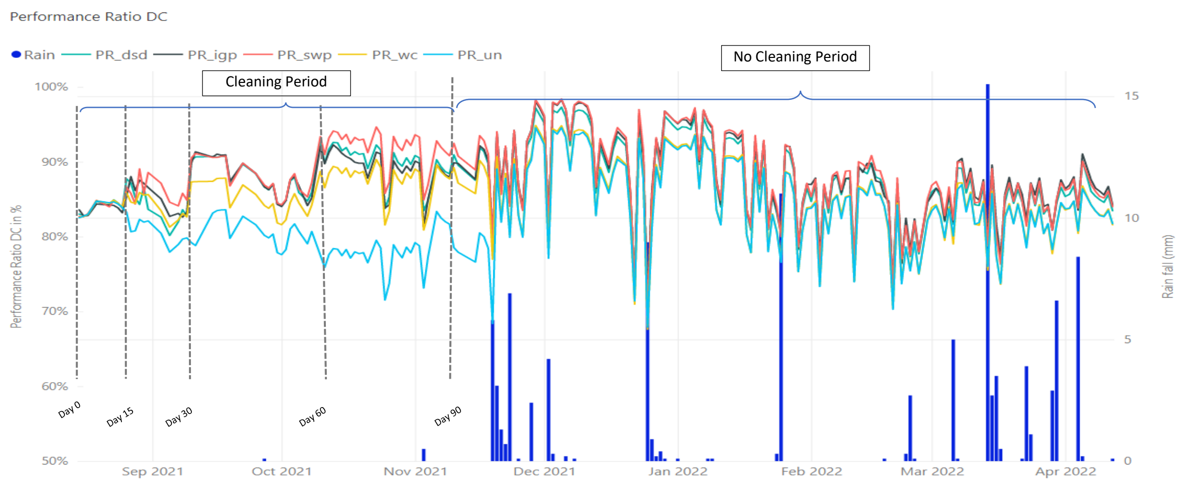


Figure 14 : Daily Performance ratio DC side in %

The figure 14 illustrates the daily performance ratio DC side during the period of the test we can conclude that:

- In the first cycle **[Aug 15 – Aug 26]**, the systems are relatively similar in terms of performances taking into consideration that they are new modules installed and in the same conditions.
- After the second cleaning (Day_15) **[26 Aug – Sep10]**, the performance ratio of the "Uncleaned" string remains below all others PV string's PR while all other string's PR increased during this day due to dust removal. It is clearly observed that PV strings using hydrophobics solutions (SWP, IGP and DSD) perform better during the cleaning days where their PR is the highest compared to the Water cleaned string.

- After the Day_30 **[Sep10 – Oct 10]**, the SWP remains the highest performing string followed by IGP and DSD respectively.
- In the second 30-day cycle **[Oct 10 – Nov 10]**, the SWP surpasses the other systems, while DSD outperforms the IGP in the first days after the cleaning.
- After the last cleaning applied in November 10 **[Nov 10 – Feb 10]**, the SWP remains the highest performing system due to the effectiveness of the solution in the low rain rates occurring during this period, while the IGP regains its performance after the first rain events occurring in 19^{th}-23^{rd} November. the UN becomes very close to the WC after the rain events and has the same behavior.
- During the last period **[Feb 10 – April 10]**, at first, the SWP remained the highest performing string with very low rain rates, although with the increasing rain rates after March 6^{th} the IGP surpassed the SWP, whereas the DSD remained below SWP.

ii. Performance ratio indicators

a) PR deviation from UNCLEANED string:

In order to study the behavior of the different coatings and cleaning solutions in dusty environment, a confrontation of performance ratios with the uncleaned PV system was conducted to identify how effective these solutions are in dusty environments.

$$dev_{sys} = (\frac{PRsys}{PRun} - 1) * 100$$

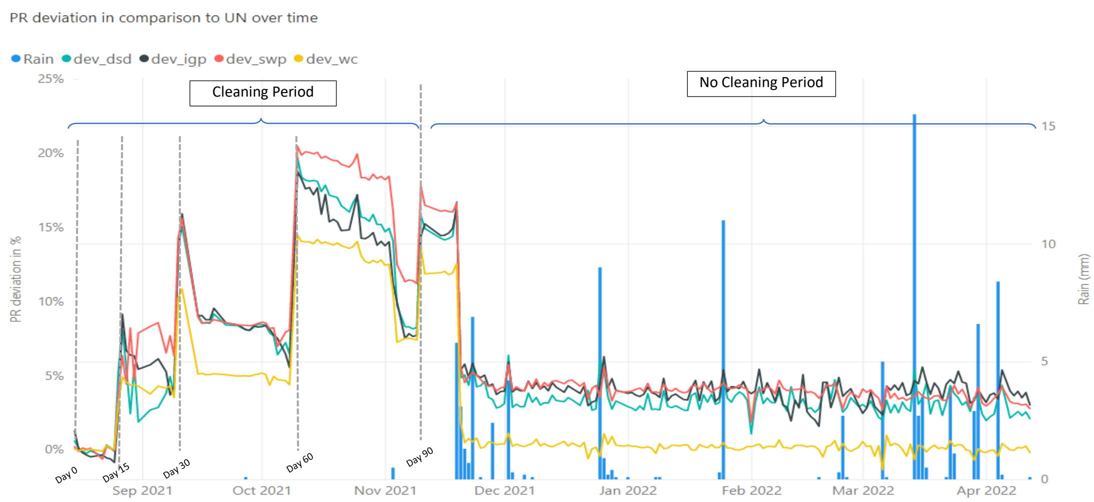


Figure 15:strings PR deviation in comparison to uncleaned

Figure 15 represents the deviations of PR for each PV string using as a reference the Uncleaned String. We can conclude that PV strings start to deviate from the uncleaned right after the first cleaning day (26 August) with the highest rate maintained by the SWP system. While after the second cleaning (10 September), we can see that DSD, IGP and SWP deviate with the same rate from the uncleaned system, and that the Water cleaned system keeps its deviation lower and constant at approx. 5% from the Uncleaned system. The deviation reaches its maximum value of 20.46% after the cleaning of day_60 (October 10), This behavior can reflect the advantage of the coating solutions used during this period of test. After the rain events occurred in 19-23 November the uncleaned system regained its performance and the gain dropped to an average value of 3% for the 3 solutions with the same behavior stated before in the Performance ratio graph, while during the cleaning and rainy days, the DSD and IGP outperform the SWP.

The table below illustrates the gain of the systems compared to the reference system (UN) during the rainy days:

		Energy gain with respect to reference (non-coated system)		
Day	Rain (mm)	DSD	IGP	SWP
18/02/2022	0.1	2.77%	1.58%	3.48%
23/02/2022	0.3	3.63%	4.94%	3.69%
24/02/2022	2.7	2.11%	3.17%	2.33%
25/02/2022	0.1	2.80%	3.83%	3.48%
06/03/2022	5	3.38%	3.75%	4.08%
07/03/2022	0.1	2.33%	3.28%	3.26%
14/03/2022	15.5	6.09%	5.35%	4.29%
15/03/2022	2.7	2.75%	4.13%	3.58%
16/03/2022	3.5	3.25%	5.32%	3.38%
17/03/2022	0.5	4.65%	4.73%	3.63%
22/03/2022	0.1	3.16%	4.38%	3.30%
23/03/2022	3.9	3.71%	4.09%	3.08%
24/03/2022	1.1	3.54%	4.23%	4.10%
29/03/2022	2.9	4.26%	4.03%	4.07%
30/03/2022	6.6	3.49%	3.99%	4.13%
04/04/2022	8.4	3.93%	3.86%	4.21%
05/04/2022	0.2	3.90%	4.93%	3.81%
12/04/2022	0.1	2.29%	3.22%	2.97%

Table 6: Energy gain with respect to reference system

From Table 6, we can see that the hydrophobics systems (DSD and IGP) are the most impacted by rain, where they are gaining more energy after the day of precipitation. DSD retrieve its performances during high precipitation rates achieving +6.09% with a precipitation of 15.5 mm during March, 14, and the IGP retrieve its performances during medium precipitation rates achieving +5.35% with a precipitation of 3.5 mm during March, 16. While SWP was able to achieve up to +4.29% during March, 14 with a precipitation of 15.5 mm.

iii. Cumulative energy gain

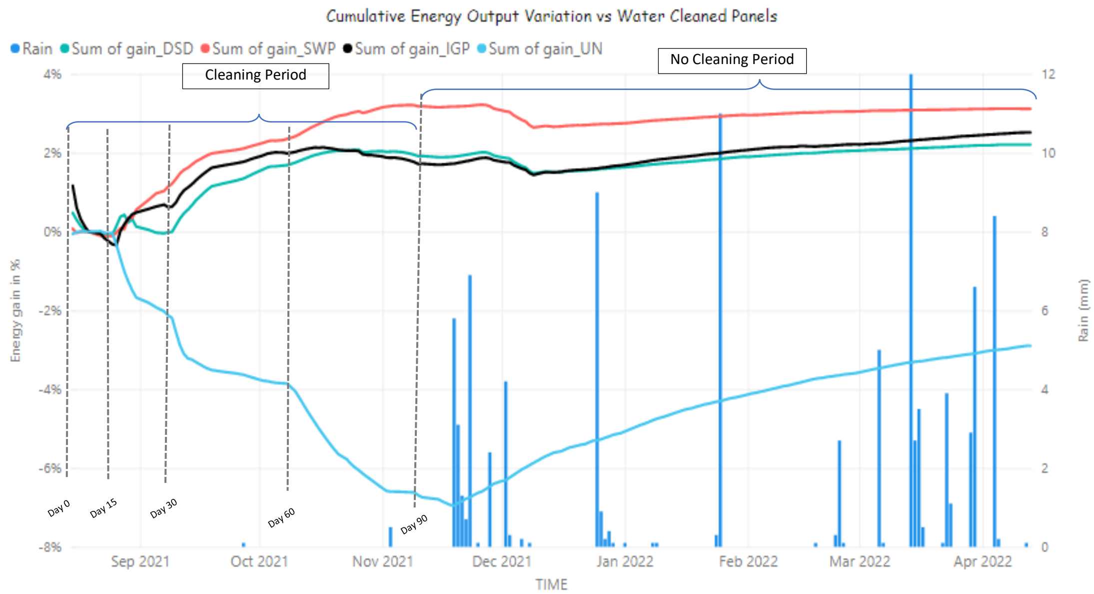


Figure 16 : cumulative energy gain from water cleaned system

Figure 16 represents the energy gain accumulated by each system compared to the water cleaned system. As shown in the graph above, all systems have approx. the same energy generation). Otherwise, the SWP system is increasingly deviating to reach more than 3.22% of cumulated energy gain compared with the Water cleaned in the dry season, followed by the DSD and IGP reaching 2.01% and 1.89% respectively of the cumulated energy gain. While the Uncleaned system starts to lose its energy with a negative energy gain from the Water cleaned system, reaching a value of -6.94% at the end of the dry period.

Otherwise, during the rainy period of the test the gain of the systems has dropped due to the natural cleaning of the WC string and the uncleaned system regains its performance, during the period between Nov 10 - Apr 10, while the IGP surpasses the DSD and reach a gain of 2.52% and 2.21% respectively while SWP has the highest gain of 3.12% which is due to the low rain rates measured during the period of test.

VI. General Conclusions

A field test has been done for 5 types of PV strings; each string is formed by 7 PV modules with a rated power of 335 W. Full modules cleaning with tap water and a brush has been performed for a first tested period of 60 days (From 12 August to 10 October), with details of cleaning described in page 7, figure 2.

In terms of water and time monitoring, it was concluded during this period that the Solar Wash Protect (SWP) solution decreases the water consumption by 50% in Day_30 with respect to the consumption of Day_15 which was performed with only water. Either, a reduction in term of water and time was also observed for the Industrial Glass Protect (IGP) string and the D-solar Defender (DSD) string from 4.5 L/string to 4 L/string and from 12 minutes to 10 minutes respectively during Day_15 and Day_30. While for the Water cleaned string, the cleaning with only water, make the panels surfaces hard to clean.

Concerning the performance evaluation of the PV strings, it was necessary to see the electrical behavior of the tested systems under outdoor conditions. During this report and for each string, we have been analyzing their production mainly the DC energy production, Referential yield, Array yield, Array capture losses. And to conclude on their performance some key performances indicators has been set, mainly the Performance ratio, the PV string efficiency, PR deviation from the uncleaned and the cumulative energy gain in order to study the performance of the different anti-soiling solutions, and to identify which is the most effective one in dusty environment.

The analysis of the KPI demonstrated that during the first two weeks the behavior of all PV strings was approx. the same. While after performing the second cleaning (which correspond to Day_15 of the cleaning protocol), the "Uncleaned" performance and production is below all other PV strings due to dust accumulation. While the systems with the hydrophobics coating (SWP, IGP and DSD) represent a higher performance (Higher PR and higher energy generation) compared to the Water cleaned system. Whereas, during the period of cleaning, either IGP , DSD and SWP represent a good behavior in terms of dust removal where their losses becomes the lowest compared to the water cleaned system. During the cleaning period [Aug 12th – April 10th] corresponding to the dry season the SWP remains the highest performance system reaching a gain of 20.46% with respect to the uncleaned system after the cleaning of Day_30 followed by DSD and IGP reaching a gain pf 19.71% and 18.75% respectively. With the increasing rain rates starting from November 19th the IGP surpasses the DSD while WC becomes identical to the Uncleaned. During the period of November - February SWP remains the highest performing string due to the effectiveness of the cleaning solution lasting up to 6 months and the relatively low rain rates, although in March and April with the high rain rates the IGP surpasses the SWP system reaching an average gain of 3.7% compared to WC (SWP reaches 3.27% and 2.58% for DSD).

To conclude on the anti-soiling solutions and their performances, SWP is more performant in terms of dust removal when applying the SWP solution during the dry season (August February) with low rain rates, while in the rainy period (March – April) the IGP is more performant than SWP followed by DSD with a small difference.

Appendix 1

- **<u>SWP abnormal behavior:</u>**

We can see that SWP does not follow the curve of the GTI on September 6th. A disconnection in the PV system occurs in the afternoon, which causes a decrease in the daily DC energy (Figure 7) and Array Yield (Figure 9), an increase in the capture losses (Figure 10) and a decrease in the PV system PR (Figure 11) and modules efficiency (Figure 12).

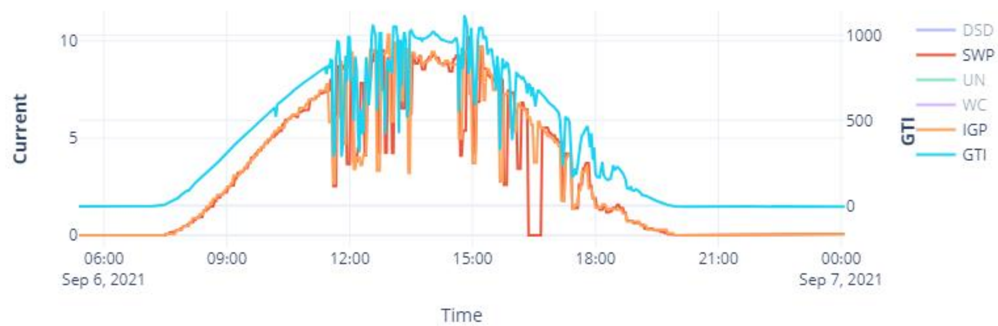


Figure 17 : Abnormal behavior of SWP and DSD during Sept 06)

- **<u>MC4 DC cable burned:</u>**

The figure below shows the disconnection that occurs during the September 2. We can clearly see the Uncleaned string's current start at 11:12 AM which lead to a big DC energy loss during the morning (Figure 7) which will automatically affect the Array yield (figure 9) and the high increase in capture losses (Figure 10) and results in lowering the PR of the system (Figure 11).

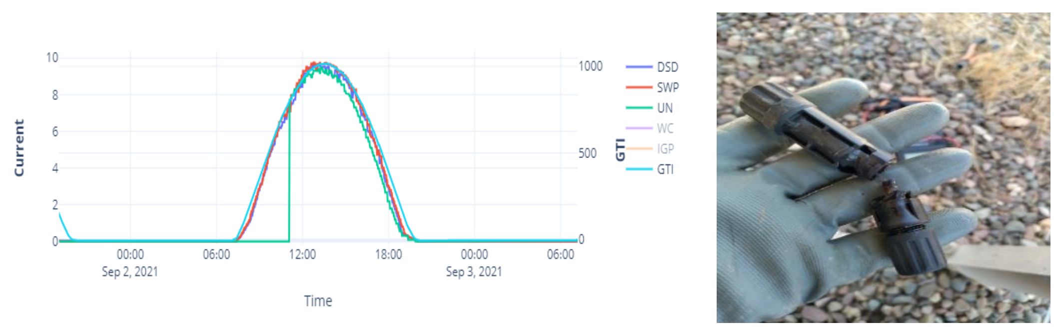


Figure 18 : Uncleaned string disconnected due to MC4 DC cable burnt

- **<u>Data acquisition failure:</u>**

We can see that the IGP deliver a high current after 3 PM. This is an outlier and can be argued by the non-proportionality of the DC current and the global tilted irradiation received.

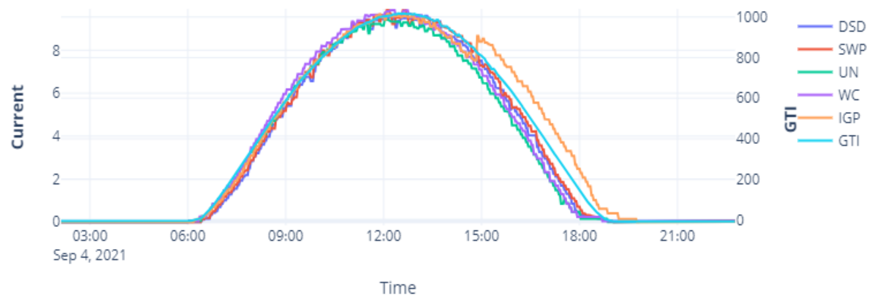


Figure 19 : Data acquisition failure

- **Communication Failure :**

A failure in the communication system occurs in September 1 and caused many interruptions in the DC system data, as observed in the figure below all PV strings knows some moments of current shut-down during the same day while the Global tilted irradiance remains constant.

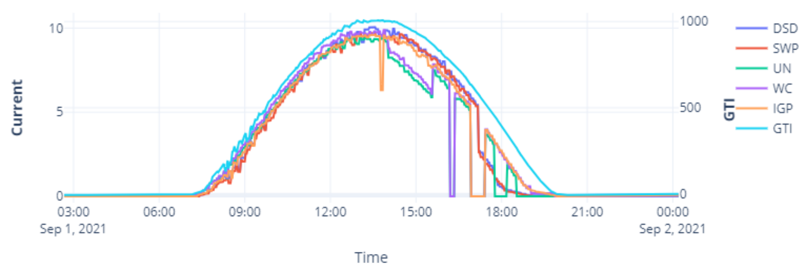


Figure 20 : Bug in the communication system

- **I-V tracer measurement periods**

I-V measurements took place after each cleaning periods in order to evaluate the performance of different PV modules and their behavior, mainly during the following periods:

- 12 August (Day_0).
- 26 August (Day_15).
- 10 September (Day_30).
- 10 October (day_60)

For this purpose, the system was interrupted during the mentioned periods, especially during the noon time as represented in the following graphs:

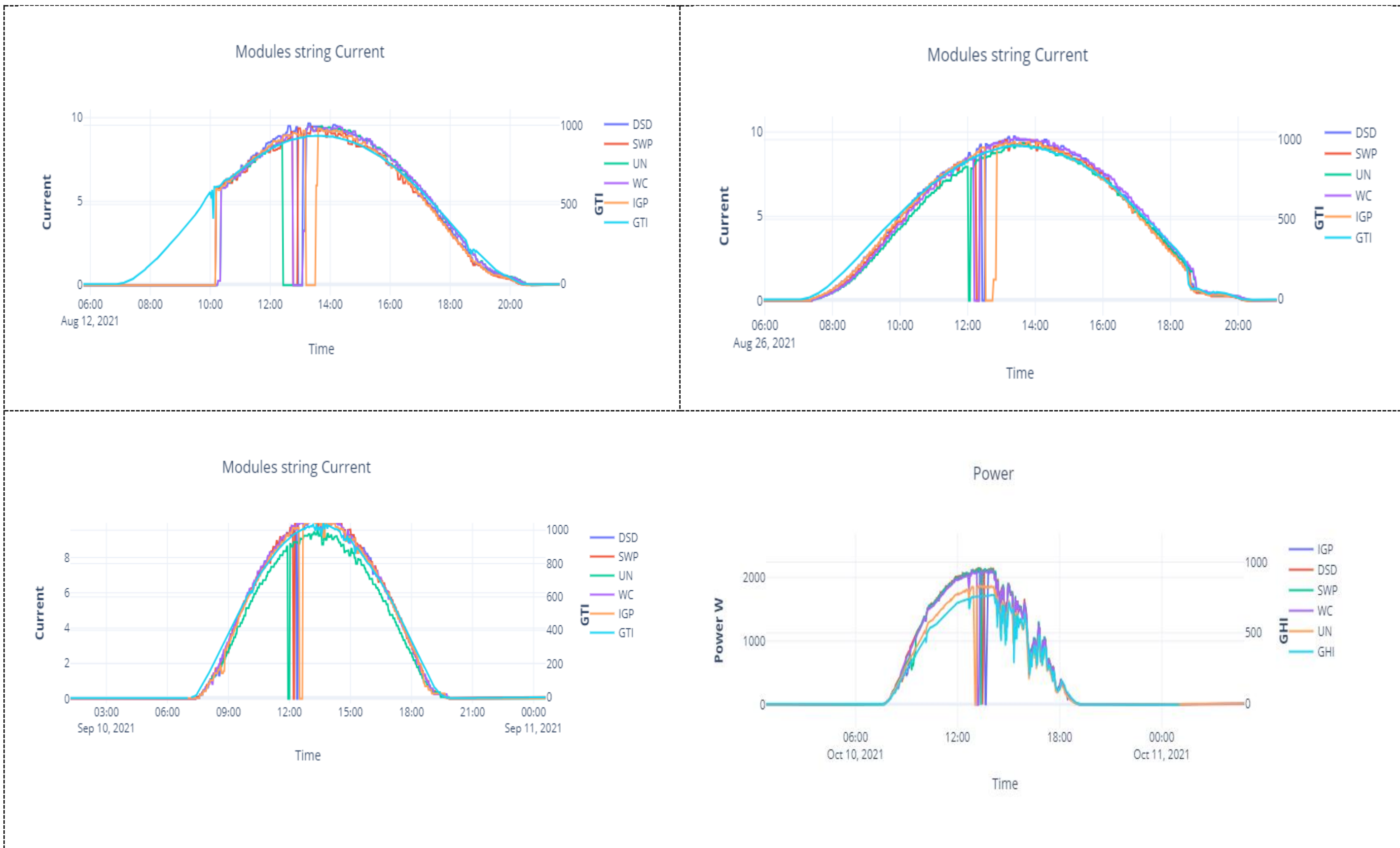


Figure 21: System interruption due to I-V tracer measurement

- **Grid loss :**

The interruption in data that occurred in 20 ,21,24,26 September and 9 October is due to a grid connection loss and a maintenance operation on the grid injection facility.

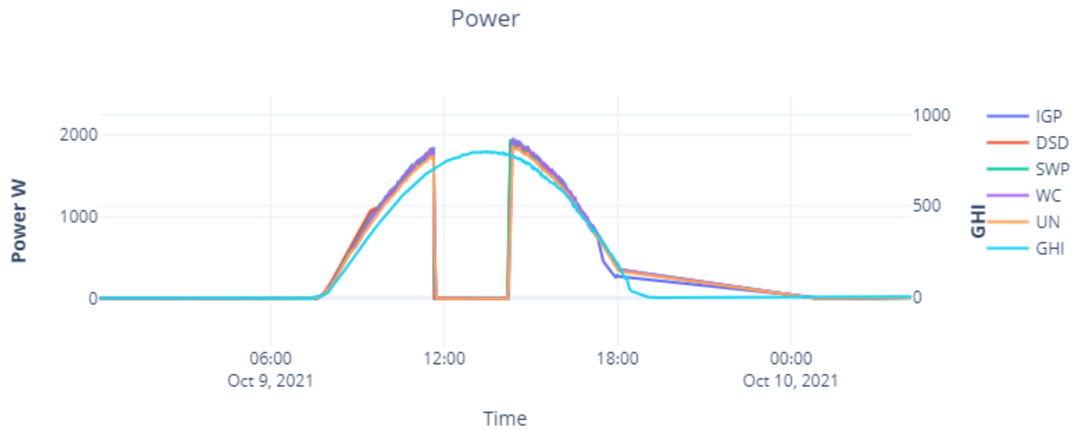


Figure 22 : grid loss

- **Rain Events**

Date	*Rain(mm)*	*Date*	*Rain(mm)*
September 27, 2021	***0.1***	***January 9, 2022***	***0.1***
November 3, 2021	***0.5***	***January 24, 2022***	***0.3***
November 19, 2021	***5.8***	***January 25, 2022***	***11***
November 20, 2021	***3.1***	***February 18, 2022***	***0.1***
November 21, 2021	***1.3***	***February 23, 2022***	***0.3***
November 22, 2021	***0.7***	***February 24, 2022***	***2.7***
November 23, 2021	***6.9***	***February 25, 2022***	***0.1***
November 25, 2021	***0.1***	***March 6, 2022***	***5***
November 28, 2021	***2.4***	***March 7, 2022***	***0.1***
December 2, 2021	***4.2***	***March 14, 2022***	***15.5***
December 3, 2021	***0.3***	***March 15, 2022***	***2.7***
December 6, 2021	***0.2***	***March 16, 2022***	***3.5***
December 8, 2021	***0.1***	***March 17, 2022***	***0.5***
December 25, 2021	***9***	***March 22, 2022***	***0.1***
December 26, 2021	***0.9***	***March 23, 2022***	***3.9***
December 27, 2021	***0.2***	***March 24, 2022***	***1.1***
December 28, 2021	***0.4***	***March 29, 2022***	***2.9***
December 29, 2021	***0.1***	***March 30, 2022***	***6.6***
January 1, 2022	***0.1***	***April 4, 2022***	***8.4***
January 8, 2022	***0.1***	***April 5, 2022***	***0.2***
		April 12, 2022	***0.1***

Table 7:Rain events