

# *Impact of Soiling on Energy Yield of Solar PV Power Plant And Developing Soiling Correction Factor for Solar PV Power Forecasting*

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**Abstract**—In India, the geographical conditions are varied, and the characteristics of dust depend on the local environmental conditions. The solar power generators must incorporate the soiling losses in their estimation for power output. An attempt to develop a methodology to estimate the soiling correction factor was made. The methodology implemented was research of previous studies on soiling, monitoring and analysis of 20 kW rooftop solar power plant and an experiment to estimate the soiling losses. Extensive research was carried out and a comprehensive review was presented on the effect of soiling on performance of PV plants along with case studies of soiling experiments in India and around the world. A soiling experiment was designed to develop the soiling correction factor. A methodology to calculate the soiling correction factor was developed by analyzing the data from the soiling experiment. The effect of rainfall, humidity and wind on soiling have been analyzed and documented. The performance of one 20 kWp PV plant was monitored to study the effect of weather-related parameters on the performance. The soiling correction factor varied from -1.36% to 3.67% during the period between June 2018 and June 2019 in Chennai. It was observed that the average PV conversion efficiency of the 20-kW plant was 11.75% and the average PR was 75%. It was observed that the correlation between module temperature and DC power;

between humidity and DC power; between humidity and DC power varied every month. The  $R^2$  values for each correlation has been tabulated in this paper. The soiling factor developed was incorporated into the short-term day ahead solar forecasting model. The developed methodology can be applied at the sites of large-scale solar power plants for yield assessment, designing as well as operational forecasting purposes.

**Keywords**—soiling; energy yield; solar forecasting; solar power

## I. INTRODUCTION

Researchers in several parts of the world have studied the effect of soiling on solar PV modules. It can be noted that the Middle Eastern countries have done significant amount of research on this topic. The prevalence of perennial problem from dust storms in the deserts can be attributed as the reason for their need to carry out this study. In the year 2010, Monto Mani and Rohit Pillai have comprehensively documented the status of research in studying the impact of dust on solar PV modules along with identifying the challenges to future research on this topic [28]. They had divided their critical appraisal into two phases of study period. During Phase I

(1940 - 1990), they have pointed out a few factors which could have led to ambiguity in the experimental methodology. Most of the studies were conducted to investigate the effect of dust on the transmittance of glazing materials on the PV modules and the results obtained were dependent on the geographical location and tilt of the solar panels. Later during Phase II (1990 – 2010), the properties of dust were studied deeper by simulating dust accumulation under artificial dust. They created a table of recommendations of mitigation measures against impact of dust accumulation with respect to different climatic zones.

Another comprehensive study [37] of technical history in this field of dust effects on performance of solar (PV and thermal) device included a summary of all the key researches between 1942 and 2013. It showed in detail the composition and behaviour of dust. The mitigation techniques listed included effective dust preventive coatings, automated mechanical cleaning systems and sensors to detect the critical point for cleaning of the surfaces.

In a study focused on analysing the power loss due to soiling on solar panels [27], shading due to soiling was classified as hard shading and soft shading. Soft shading was due to smog in the atmosphere or dust particles whereas hard shading occurred due to accumulated dust blocks or bird droppings. It was observed that the current was reduced due to soft shading and voltage was reduced due to hard shading. Hot spots can be caused due to hard shading which will pose a severe problem to the solar panels.

#### **Middle East:**

In a review paper by Sanaz Ghazi on the dust effect on flat surfaces, it was seen that Middle East and North Africa have the worst dust accumulation zones in the world [33]. A study was conducted in Egypt to understand reduction in transmittance of glass cover due to dust deposition [22]. It was observed that when dust deposition density is  $4.48 \text{ g/m}^2$  the reduction in transmittance is 12.38 % whereas when it is  $15.84 \text{ g/m}^2$ , the reduction in transmittance is as high as 52.54 %.

Another similar study carried out in Saudi Arabia concluded that the glass covers coated with anti-reflective material showed lesser reduction in transmittance as compared to non-coated glass covers [35]. The overall transmittance reduction was 20 % for dust deposition density of  $5 \text{ g/m}^2$  after outdoor exposure of 45 days.

It was reported that Iraq is one of the Middle Eastern countries which has been a victim of many occurrences of sand and dust storms. In Jordan, in an experimental study, the average degradation rate of efficiency for one day was 6.24 %, for one month was 11.8 % and for a year was 18.74 % [29].

Another study undertaken in Qatar used both field measurements and modelling for the analysis of effect of dust on PV performance [12]. It was once again proven that dust concentration alone is a weak predictor of PV soiling and performance but it was indeed the major contributing factor. It was proposed that floating PV applications were more suitable for the hot desert climate because of reduction in dust deposition over the sea and improved energy yield as compared to mainland.

#### **Europe:**

Although the dust deposition phenomenon in Central Europe is not as severe as that in the Middle East, the problem still exists. An experimental study conducted for five months in Belgium proved that there was a constant power loss between 3 % and 4 % [32]. A large-scale experiment was conducted in countryside of Italy [1] on two 1 MWp solar parks to determine the losses due to soiling. It can be noted that the topography of the location of both plants was different and therefore resulted in a huge difference in losses reported, although all other parameters like tilt, make of the solar panels and capacity were the same. The first plant which was built on a sandy site recorded loss of 6.9 % however, the one built on a more compact ground recorded a lower loss of 1.1 %.

The Fraunhofer Institute for Solar Energy Systems assessed the performance of PV modules by monitoring the I-V curves [11]. An important observation in this study was that the partial cleaning of soiled panels had the same effect as that of partially shaded modules which could lead to creation of hot-spots. The University of Malaga in Spain conducted a soiling experiment and found out that the even light rain of below 1 mm was sufficient to reduce the daily irradiation losses to less than 5 % but long periods in summer without rain could lead to daily irradiation losses of 20 %.

#### **Asia:**

The study on soiling of PV modules has been undertaken the most in Asia. A continent which has large arid and semi-arid regions, Asia is the major source of dust in the world. Asia has contributed nearly 55% of the studies done on impact of dust on PV panels [26]. In some cases, dust deposition scenario was simulated under controlled conditions to study the effect of soiling. An experiment was conducted using different obstruction materials such as talcum, dust, sand and moss [34]. The amount of light radiation for all the cases was kept constant and it was observed that the reduction in power was the highest due to moss.

A study was done at Kathmandu [9] over five months and it was observed that the efficiency of dusty solar panel reduced by 29.76 % corresponding to natural dust deposition of  $9.6711 \text{ g/m}^2$ . Apart from natural environmental conditions, a few other anthropogenic factors contribute towards soiling of solar modules. In June 2013, there was a major haze even that occurred over Singapore due to forest and agricultural land clearing fires. It was established that across various PV systems in Singapore, the yield losses were in the range of 15-25% [5].

#### **India:**

The geographical conditions in India are varied. The characteristics of dust is very location specific and it depends on the local environmental conditions. A study conducted by Jim et al., a low-cost artificial dust deposition technique was used to study the effect of soiling losses on PV modules in different locations in India [23]. The soil samples covered diverse climatic conditions and were from six different geographic locations in India. The dust sample from Mumbai showed the highest soiling loss followed by Pondicherry, owing to highest percentage of clay sediments. It was also shown that the effect of soiling was not same for all PV

technologies. Most importantly, it was shown that the spectrum of incoming radiation was altered by the soiling layer on the surface of the PV modules. This study was carried out under controlled conditions where identical density of dust from different geographical locations was deposited on the panels to study their performance. It has been suggested that future investigations on soiling should be conducted in actual conditions to incorporate the impact of dust and cleaning cycles on the energy yield from the PV plant.

Previously, a detailed soiling study was performed using pyrhemometers and pyranometers at the SRRA station in NIWE, to validate the implemented soiling correction procedure. The soiling rate per day for the Pyranometers was 0.25% whereas it was 0.58% for Pyrhemometers. The effect of dust on solar panels has not been analysed so far at this site. This project was executed to analyse effect of dust on the performance of solar PV modules in Chennai.

During the early days of solar power penetration in the renewable energy scenario, the efficiency of the solar modules was very less. With improvement in the efficiency of the solar modules, there is more focus on optimizing the energy yield obtained from the PV panels. In India, with the focus on need for forecasting, the solar power generators must incorporate the soiling losses in their estimation for power output. The fact that soiling is location specific and highly dependent on the tilt angle is well established by several researches. Many researchers have also recommended cleaning schedules and methods depending on the environmental conditions of a particular site [6]. The effect of aerosols, humidity or wind speed and wind direction on the soiling of panels must be investigated deeply. In order to accurately estimate the soiling losses, it is necessary to carry out a long-term experiment at the site location.

The study of effect of soiling on solar PV modules is still in its nascent stage in India. The soiling experiments carried out till date have been very small in number increasing the scope for more research that needs to be carried out in this regard. An initial study by Garg et al. in Roorkee, was on the effect of dust transmittance of glazing materials for solar collectors [21]. The experiment showed that on rainless days, there was a reduction of 8% in transmittance of glass with a tilt angle of 45° after 30 days. One of the early experimentations was done in Bhopal [16] using a single 36 W solar panel and the parameters were measured at an interval of one hour. The accuracy of the measuring equipment is not specified, and it was reported that dust reduces the power production by 92.11% and efficiency by 89 %. The methodology used to conduct this experiment is not very acceptable as the degradation in the performance of PV modules reported is very high.

A detailed experimental study was conducted at Vellore Institute of Technology [18] using a set of three monocrystalline and polycrystalline modules each. It was observed that the dust deposition was highest for panels with 0° tilt angle whereas the efficiencies were higher for the panels mounted with 30° tilt angle. At IISC Bengaluru, the effect of dust was studied through indoor simulation and outdoor experimentation [2]. The amount of dust deposited in indoor simulation was higher and therefore

the reduction in maximum power output was 45-55 % whereas in the outdoor set-up, subjected to natural soiling, the reduction was only 5-6 %. In the indoor set-up, the dusty panels showed an increase in the module temperatures in the range of 1-2°C higher than the cleaned panels. However, in the outdoor set-up, no significant temperature differences were observed.

A case study in Maharashtra on roof top PV systems showed that soiling decreased power production by 2-3% [3]. It was also noticed that if soiling was not addressed, it could lead to permanent hotspots which causes decreased life of PV modules. New Delhi is considered to be one of the most polluted cities in India which led to an analysis of the PV yield losses due to soiling in Delhi. The daily soiling loss accumulation rates of 0.3 % to 0.6 % were reported during the study period of 3-4 months. A key finding in this analysis was that the performance ratio of the solar plants improved in the range of 27-39%. With the thrust on solar forecasting in India, it becomes essential to conduct soiling study on the site for large PV plants.

#### *Effect of environmental parameters on soiling:*

Several environmental parameters have been shown to have varied influence on the rate of soiling of PV modules. In 2017, Wasim Javed and team applied artificial neural network to for modelling the relationship between soiling loss and environmental variables. This study was undertaken in Qatar and indicated that PV soiling loss is a complex function of environmental variables [38]. However, it was also seen that the correlation between soiling loss and any individual environmental variable was weak and therefore there were several other factors which influenced the PV performance loss due to soiling.

#### *Wind Speed:*

The deposition of dust depends on the wind speed and its direction. The lift and transportation of dust particles is dictated by wind. The role of wind in deposition and removal of dust from the surface of the PV modules is a function of wind speed and direction. Goosens et al. conducted wind tunnel experiments and field investigations to study the eolian dust deposition on solar collectors [15]. It was observed that at wind speeds 0.57 m/s the dust deposition was lesser when compared to dust deposition for wind speed higher than 0.95 m/s. It was also noted that the deposition of dust with respect to elevation, decreases with increased wind speeds.

Wind also removes deposited dust and it can be seen that the rate of dust removal is more effective for high tilt angle of the PV module [6]. The dust deposition and removal by wind also depends on size and mass of the dust particles [28]. A dust storm can reduce the power output of a solar module drastically. It can be as high as 15% reduction in PV module efficiency for a period of one month in the dust storms [29].

#### *Rainfall:*

It is very common to see that the solar PV modules are left to be cleaned by the rains where there is no proper cleaning schedule maintained which could be due to scarcity of water or lack of adequate man power to clean the panels. Rain is considered as a restorative method for PV modules whose efficiency has been reduced due to

soiling. It should also be noted that light rainfall can increase the problem of soiling because the rain droplets can collect the airborne particulate matter and deposit them on the surface of PV modules.

A minor rainfall can lead dust accumulation on the lower cell rows which causes partial shading leading to formation of hotspots [11]. A study in California showed that a rainfall event had recovered most of the lost PV efficiency which went back to 7.1 % from 5.6 % [17]. While studying the seasonal effect of dust on performance of PV modules, it was observed that the seasons with less rainfall showed higher dust deposition compared to those seasons with higher rainfall [24].

#### Humidity:

One of the other important factors which are responsible for dust accumulation is humidity. High humidity can lead to formation of dew on the PV module surface which can lead to coagulation of dust. This leads to formation of sticky dust layers on the surface. It can be observed that the dust accumulation begins to increase with a gradual decrease of relative humidity. Through research it has been established that there is a formation of water capillary bridge between dust particles and glass surface which is caused by humidity.

It was proven that there is a weak negative correlation between humidity and dust accumulation [9]. High wind velocity leads to decreased relative humidity which results in high PV efficiency.

## II. METHOD

### A. Methodology to analyse performance of 20 kW solar power plant

For analysis, the data of the environmental parameters was extracted from the server at NIWE for the ten months from January to October of the year 2018. The electrical parameters of the solar power plant were downloaded from the Growatt inverter web portal. All the values logged are instantaneous values. The PV module conversion efficiency and the Performance ratio values are calculated to analyse the performance of the plant.

The instantaneous PV module conversion efficiency is calculated as [25]:

$$\eta_{PV} = \frac{P_{DC}}{G_t * A_s} \quad (1)$$

Where,  $A_s$  - Total surface area of the Solar PV modules

$P_{DC}$  - DC power output of the solar PV module

$G_t$  - Total inplane irradiation

Ahmad Mohd Khalid et al. have recommended that the PR be calculated according to the IEC 61274 standard titled "Photovoltaic system performance monitoring Guidelines for measurement, data exchange and analysis". According to their study, this methodology is highly beneficial for countries to assess the performance of the grid connected PV systems.

The PR of the solar power plant is calculated as [4]:

The reference yield  $Y_R$  is the ratio of the total useful output energy to the nominal power of the PV system.  $E_{AC}$  is total useful output energy and  $P_O$  is nominal power of the PV system.

$$Y_F = \frac{E_{AC}}{P_O} \quad (2)$$

The reference yield  $Y_R$  is the ratio of the total inplane irradiation to the PV's reference irradiance.

$$Y_R = \frac{G_t}{G_I} * \tau_t \quad (3)$$

Where  $G_I = 1 \text{ kW/m}^2$  and  $\tau_t$  is the corresponding time interval.

Performance Ratio (PR) is the ratio of the final yield to the reference yield.

$$PR = \frac{Y_F}{Y_R} \quad (4)$$

The above formulae were coded on MATLAB and the results are tabulated in a Microsoft Excel file. Since the time interval between the instantaneous values of the electrical parameters was not constant, the environmental parameters were manually averaged by visual inspection of the time stamp of the data. The effect of environmental factors on the performance of the PV plant was analysed using linear regression on Microsoft Excel.

### B. Methodology to analyse the result of soiling experiment

The current drawn from a solar panel is proportional to the incident solar radiation. Two identical solar panels (80 W each) are used in this set-up. Therefore, the experiment is designed to measure the power drawn from the panels to arrive at a soiling loss estimation.

Although, both the panels were similar in make and specifications, their performance was not identical. Therefore, the current drawn from each panel varied at all instants. To estimate the difference in performance, the panels were tested for five days from 2<sup>nd</sup> July to 6<sup>th</sup> July 2018. The GHI and GTI data were plotted for all the five days. It was concluded by visual observation that 5 July 2018 was a clear sky day. The slope of the line joining the current points on the scatter plot on 5th July 2018 was chosen as the reference slope. It is referred to as  $\text{Slope}_{\text{cleaned}} = 0.9831$  for the calculation of soiling loss.

Before the start of the experiment, both the PV panels were thoroughly cleaned. One solar panel is cleaned every day. The soiled panel is cleaned at various intervals to analyse soiling. Ideally the soiled panel should be cleaned after two weeks. During monsoon, the amount of dust deposition on the panels was less. Therefore, the soiled panel was cleaned after one month. The weather conditions for each day are observed and noted. A cleaning schedule was duly maintained with observations of each day noted. To estimate the soiling loss, the output of the clean PV panel and the soiled PV panel will be compared.



Figure 1. 80 W Solar Panels





Figure 2. Experimental set-up location



Figure 3. DC Energy meters connected to load



Figure 4. DC Energy meter readings

The current drawn from the solar panel is directly proportional to the incident solar radiation. The current of the solar panels was the parameter used to estimate the soiling loss. The current drawn from the cleaned panel ( $I_{\text{cleaned}}$ ) was plotted on X-axis and current drawn from soiled panel ( $I_{\text{soiled}}$ ) was plotted on Y-axis. The slope of line joining the current points in the scatter plot is  $\text{Slope}_{\text{soiled}}$ .

The formula used for estimating the soiling factor is as follows:

$$\text{Soiling Loss (\%)} = \left(1 - \frac{\text{Slope}_{\text{soiled}}}{\text{Slope}_{\text{cleaned}}}\right) \times 100 \quad (5)$$

### III. RESULTS AND DISCUSSION

#### A. Performance analysis of 20 kW solar power plant

The input data for the analysis was filtered manually by visual inspection of the timestamp of the SRRA data and Growatt inverter data. The data was processed on MATLAB and Microsoft Excel to obtain the results. It was observed that the correlation between module temperature and DC power;

between humidity and DC power; between humidity and DC power varied every month. The coefficient of determination ( $R^2$ ) values for each correlation have been tabulated below.

Table 1. Correlation between DC Power and Environmental Parameters

Environmental Parameters	January $R^2$ (%)	February $R^2$ (%)	March $R^2$ (%)
Global Tilted Irradiation	90.54	92.37	90.29
Ambient Temperature	29.11	28.43	27.85
Relative Humidity	22.45	23.17	27.72
Wind Speed	3.28	6.95	1.03

Table 2. Correlation between DC Power and Environmental Parameters

Environmental Parameters	April $R^2$ (%)	May $R^2$ (%)	June $R^2$ (%)
Global Tilted Irradiation	90.54	96.18	95.20
Ambient Temperature	29.11	68.77	43.09
Module Temperature	-	-	84.47
Relative Humidity	22.46	68.74	29.79
Wind Speed	3.29	1.05	4.50

The PV conversion efficiency and the performance ratio (PR) of the 20-kW power plant from January to June 2019 are tabulated below.

Table 3. PV Conversion Efficiency and PR

Month	PV Conversion Efficiency (%)	PR (%)
January	12.19	78
February	11.95	76
March	12.07	77
April	12.19	78
May	12.08	77
June	10.03	64

A very important observation was made in the month of June with regard to module temperature. Temperature sensor was attached on the back of one of the 255 W panels in the 20-kW power plant. It was observed that there was a correlation of 84.47% between the DC power and module temperature whereas it was only 43.09% for ambient temperature and DC power. This emphasized on the need for module temperature sensors for the measurement of the actual temperature of the solar panel. The maximum module temperature reached 66.33 °C whereas the maximum ambient temperature was only 37.84 °C.

The graphs for performance analysis of the 20-kW power plant for nine days in the month of June 2018 are shown below. The correlation between the DC power and the environmental parameters can be clearly observed in these graphs.

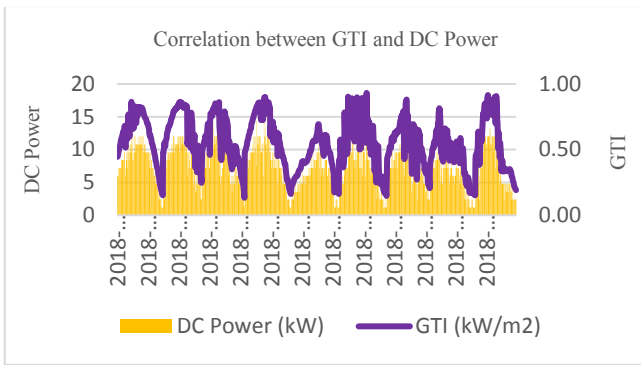


Figure 5. Correlation between GTI and DC Power

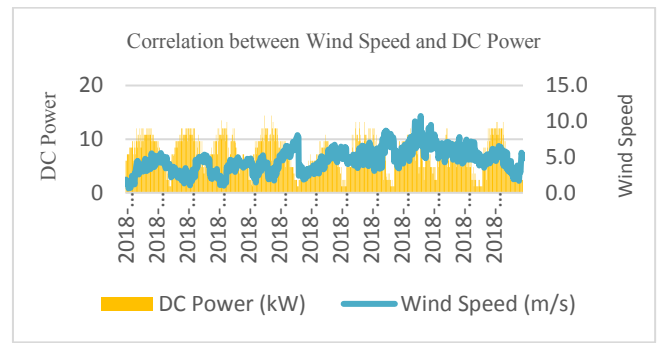


Figure 9. Correlation between Wind Speed and DC Power

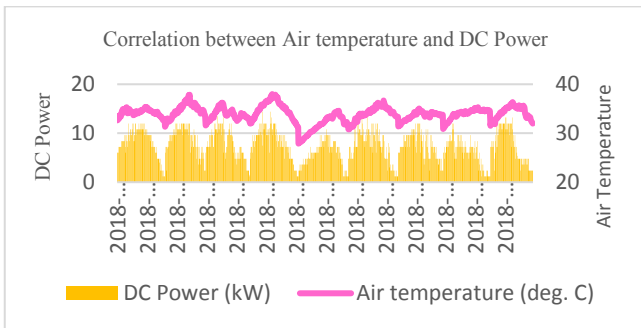


Figure 6. Correlation between Air temperature and DC Power

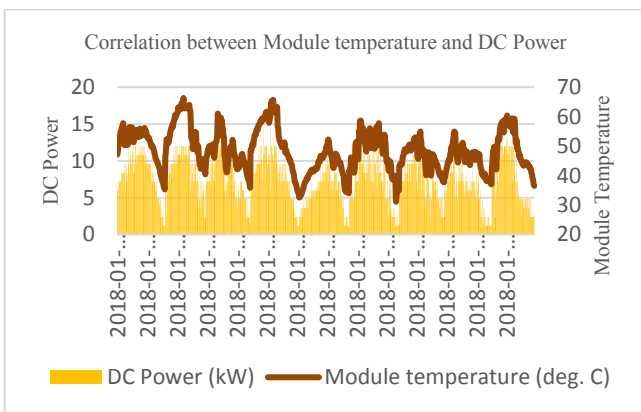


Figure 7. Correlation between Module temperature and DC Power

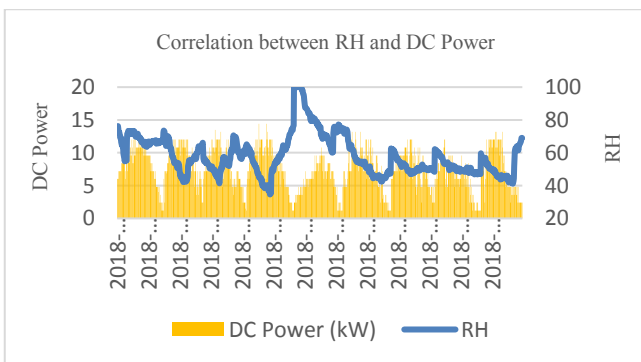


Figure 8. Correlation between RH and DC Power

### B. Soiling loss analysis

From 1<sup>st</sup> June 2018 to 25<sup>th</sup> June 2019, there were 153 days of data which qualified for the analysis. On these days, one panel was cleaned whereas the other panel was left for natural soiling on an average for a period of one month. It has to be there were 67 rain days out of the 153 days. When the amount of rainfall was less the soiling loss increased whereas for heavy rain, the soiling loss value was negative indicating that the panel performance improved significantly. During the said period of observation, the soiling loss varied from -1.36% to 3.67%. Soiling loss was estimated for each day of observation and it varied depending on the amount of rainfall and other environmental factors.

The soiling loss experiment results for the month of June 2018 are tabulated as shown below.

Date	Rain (mm)	Soiling Loss (%)
01-Jun-18	0.6	1.36
03-Jun-18	1	0.88
04-Jun-18	0.3	0.82
05-Jun-18	0	0.58
06-Jun-18	2.4	0.83
07-Jun-18	0.9	0.78
08-Jun-18	1.5	0.41
11-Jun-18	0.8	0.75
19-Jun-18	0	0.60
20-Jun-18	0	0.55
21-Jun-18	0	0.57
27-Jun-18	0	1.36
28-Jun-18	0.3	1.67
29-Jun-18	0.4	1.92

From the above table it is observed that when the amount of rainfall was 0.3 mm on 28<sup>th</sup> June 2018, the soiling loss increased from 1.67% to 1.92%. When the amount of rainfall was 2.4 mm on 6<sup>th</sup> June 2018, the soiling loss decreased from 0.83% to 0.78%. During the course of the experiment, it was observed that the soiling losses were estimated to be lowest, less than 1% on all days, in February 2019. The soiling losses touched the highest value of 3.6% in May and June 2019.

The soiling factor that is obtained after the analysis in this experiment will be incorporated into the solar forecasting

chain. There are several blocks in the forecasting chain which includes some important conversion models. The soiling factor will be an input to the block that converts DC power to AC power.

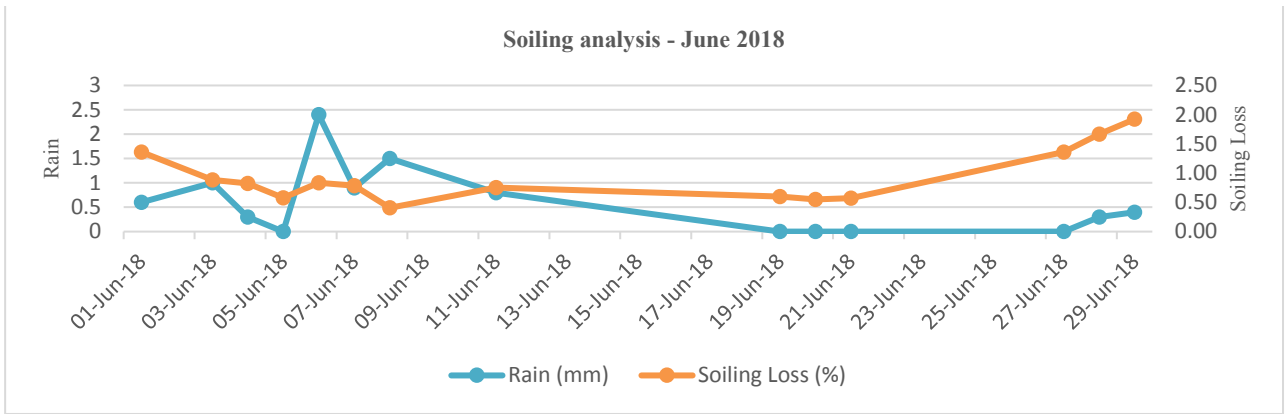


Figure 10. Soiling analysis - June 2018

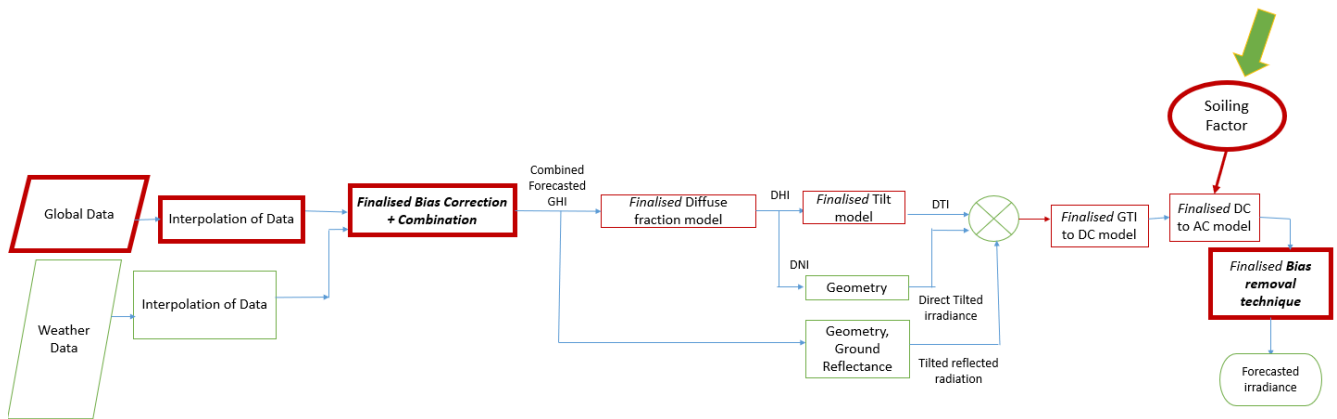


Figure 11. Solar Forecasting Model Chain

IV. CONCLUSION

In this project, detailed study has been done on the topic “Effect of soiling on Performance of PV plants” and it has been documented. The performance of 20 kW rooftop solar power plant has been analysed. The correlation between module temperature and DC power; between humidity and DC power; between humidity and DC power varied every month. The highest correlation was observed between GTI and DC power whereas the least correlation was observed between wind speed and DC power. The correlation between module temperature and DC power was almost twice the correlation observed between ambient temperature and DC power. Therefore, it is important to measure the module temperature to gauge the performance of a solar panel.

The experiment for the estimation of soiling losses has been successfully set-up at NIWE. The experiment will be carried out further to estimate the soiling losses for future analysis. The methodology developed to study the soiling losses at NIWE will be extended to other real-life PV plants in India. It is important to carry out the experiment more diligently to collect the data of soiling for the maximum number of days in a year.

This project is a part of the broader ongoing activities carried out at the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) under the Green Energy Corridors Project. The solar forecasting model at NIWE

requires a soiling correction factor to be incorporated in order to estimate the output power accurately. Soiling factor is very location specific. As a result, with forecasting being made compulsory to solar power generators above 5 MW and the announcement of deviation charges, it is imperative to conduct soiling experiment at every major solar PV plant. The longer the duration of the experiment, the estimation of soiling losses will be more reliable. It is important that the soiling experiment be carried out for at least one year at the site location. No generalised soiling factor can be derived for the various sites in different regions. The soiling factor has to be incorporated into the day-ahead forecasting model because the amount of soiling varied on a daily basis. As a result, the soiling factor for each day in a year must be calculated. Weekly or monthly average values of the soiling factor will only lead to errors in forecasting because it will not be able to reflect the soiling losses accurately. The experimental set-up designed for this project has been successful in estimating the soiling loss factor. This project could pave way for further research and analysis on effect of soiling on performance of solar PV modules and yield assessment of solar power plants in India.

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