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A framework of optimum cleaning schedule and its financial impact in a large-scale PV solar plant: a case study in Senegal

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Abstract. The performance of large-scale PV solar plant installed in sub-Saharan regions is affected by the deposition of dust on the surface of the PV modules. Frequent cleaning of the PV modules increases the profitability of PV solar plants. The objective of this study is to determine the optimal cleaning cycle of a PV solar plant subjected to a wind loaded with sand and dust. This study took place in a PV solar plant installed in Senegal. The measurement data are analysed for a period of two years and used to extract soiling rate. Optimization was done based on the total cost caused by dust on the PV solar plant to minimize the number of days between cleaning events. The results showed that the soiling rate between June and May is 0.34%/day, while a rate of 0.33%/day was recorded in October. The highest soiling rates of 0.42%/day and 0.49%/day were recorded in December and between February and March, respectively. The optimal cleaning cycle for the PV solar plant is 14 days. The total cost of cleaning is reduced by 31% using this optimal cleaning cycle proposed.

Keywords: Photovoltaic / soiling rate / PV solar plant / cleaning frequency / corrected performance ratio

1 Introduction

Energy consumption in all sectors is growing. This increase is due to industrialisation, rising living standards and population growth. The energy consumed increased 2.3 times from 1971 to 2017 [1]. World electricity use is increasing more rapidly than all other energy consumption. From 2012 to 2040, global electricity production could increase by an average of 1.9%/year [2]. Fossil fuels accounted for 65% of global electricity generation in 2017 [3]. The use of fossil fuels causes greenhouse gas (GHG) emissions. GHGs degrade the environment and lead to climate change. Climate change is manifested in rising temperatures, more intense storms and increased drought.

Large-scale use of renewable energy can contribute to reducing the effects of climate change. PV solar is becoming the most rapidly growing renewable energy source. Cumulative total solar PV capacity at the end of 2019 reached at least 627 GW, an annual increase of 115 GW in 2018 [4]. In Africa, over the past decade, the total solar PV capacity has increased by two orders of magnitude, from around 110 MW in 2010 to 12 GW by the end of 2020 [5]. From 2016 to 2018, Senegal has commissioned 140 MWp of PV solar plant. The total capacity solar PV installations may almost be doubled in the coming years to more than 255 MWp in 2020 [6].

Senegal is located in the western part of the Sahel, with a good solar potential and a large dust deposit [7]. The dusty harmattan winds are a recognised phenomenon in the Sahel region of Africa [8]. Indeed, the Sahara desert is the largest source of dust aerosols in the world, with annual emissions estimated at around 600 Mt/year [9,10].

In this context, the dust storms of the Saharan desert are a significant source of dust, frequently affecting Senegal, causing dust to be deposited on the PV modules. This affects the electricity production of PV solar plants. Ndiaye et al. studied the effect of the presence of dust on the PV module under Sahelian environment. In the study, the results showed a more severe power reduction can be from 18 to 78% respectively for the polycrystalline and monocrystalline PV module [11]. In one study, a few microns of dust deposit was found to be enough to decrease the performance of PV module by 50% [12]. For example, a 4.4% reduction in electrical energy of a PV system exposed to dust during 30 days [13]. Urrejola et al. showed that the performance of PV modules decreases between −0.13% and −0.56% per day when soiled in the city of Santiago, Chile [14]. Chen et al. showed that a dust density of 10 g/m^2 can reduce the maximum power of PV modules by about 34% [15]. Guan et al. showed that dust deposition reduces

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the relative transmittance of a PV module by 20% after 8 days [16]. Gholami et al. reported that after 70 days without rain, 6.0986 g/m^2 of dust was deposited on the surface of PV modules. The power loss was then 21.47% of the power output [17].

In order to reduce energy losses and increase the profitability and competitiveness of the large-scale PV solar plants, the cleaning cycle has been extensively studied. In [18], an experimental configuration was designed and installed in Jordan where all three most common types of PV modules were tested against dust accumulation. The summer season was chosen to run the experiments. Authors reported that not following the cleaning schedule could lead to 10% energy loss.

Many studies on optimal cleaning frequency of PV solar plants have been conducted. Zhao et al. reported that the optimal cleaning cycles in northeast China varied by 10.1 and 22.8 days. The energy conversion efficiency was then reduced by 4.5% and 10.2%, respectively [19]. Chiteka et al. estimated the cleaning cycle of the plants in Zimbabwe. It was found that in order to minimise losses due to soiling it was necessary to clean every 15 days [20]. Jiang estimated the cleaning frequency of dirty PV modules in desert regions. The authors found that the cleaning frequency of modules for desert regions was about 20 days [21].

Various methods have been used to forecast the optimal cleaning frequency of PV solar plants.

Hammad et al. proposed a multivariate linear regression (MLR), and an artificial neural network (ANN) to determine cleaning frequency for a case study in Jordan. It is found that average period length between cleanings is 13 and 15 days for the whole study period using MLR and ANN models and 12 and 13 days for the individual periods using MLR model. These optimal cleaning frequencies agree with the recommendation published in other experimental and theoretical works using different techniques and models for the MENA region [22].

Al-Kouz et al. proposed artificial neural network (ANN) and extreme learning machine (ELM) models to investigate the optimum cleaning frequency of a photovoltaic system built at the Hashemite University, Jordan. It was found that the optimal cleaning interval by the optimized ELM model is 14 days, while an optimum cleaning interval of 15 days was obtained using the optimum ANN model [23].

The research papers presented above show the optimal cleaning frequency is strongly influenced by the climatic conditions of the site and the models used. The optimal frequency of cleaning varies according to the energy production profile, the electricity tariff and the cleaning costs, as well as seasonal variations in soiling losses.

To our knowledge, no study has focused on optimising the cleaning cycle frequency of a PV solar plant in the climate of Senegal. The present study investigates the soiling rate and optimal cleaning frequency of a large-scale PV solar plant in sub-Saharan regions. A PV solar plant installed capacity of 29.491 MWp is used to test the framework developed in our research.

The remaining part of our paper is structured as follows. In Section 2, we describe the PV solar plant and data measurement; the mathematical formulation for the soiling rate and optimum cleaning is presented. Section 3 presents the results and discussion of optimum cleaning schedule and the financial impact. The conclusion is presented in Section 4.

2 Materials and methods

2.1 Presentation of PV solar plant and data analysis

The PV solar plant is installed in western Senegal, between 16.35° West longitude and 15.09° North latitude. Senegal's climate is characterised by its two seasons. The dry season is from November to May. The rainy season is from June to October. The site has a topography with elevations varying between 39 and 44 m, thus an overall difference in level of 5 m. With its large surface area, the distribution of the dust can be varied over the surface of the PV modules. This can be explained by several factors, including topography, distribution of PV modules and exposure to roads or open areas. The tractor cleaning system is used to clean all the PV modules, as shown in Figure 1.

The solar irradiance, ambient temperature, output power and PV module temperature are measured spanning January 2019 to December 2020. The data is automatically recorded by a data acquisition system. Erroneous measures are found in the recorded data, generally due to a technical issue.

Therefore, it is necessary to use a suitable data preprocessing method that is not only able to exclude outliers, but also robust against erroneous measurements during normal operation. The data has been filtered according to IEC61724-1: 2017 [24]. Duplicates, outliers and abnormal values have been detected and removed. Only solar irradiance data used above 500 W/m^2 was considered. It corresponds to the time near solar noon to reduce solar irradiance uncertainty and with less variation in the angle of incidence. Also, with the limiting power of the PV solar plant, the converters can only produce power over a certain range. For the performance calculation, the output power and solar irradiance are used excluding these periods of clipped operation.

2.2 Corrected performance ratio

The main parameter used to analyse the performance of a PV solar plant is the performance ratio (PR). It is defined in [25]

$$PR = \frac{\sum_i P_{AC}}{\sum_i \left[P_{STC} \left(\frac{G_{POA,i}}{G_{i,ref}} \right) \right]}. \tag{1}$$

This metric quantifies the global effect of losses. However, variations in the losses due to weather or seasonal conditions are not properly reflected in this indicator. The PR varies with changes in meteorological conditions. For one period, a significant variation in PR values can be obtained, which makes the analysis of the results difficult [14]. This variation in PR can be mitigated by defining a modified metric. This paper uses the advanced NREL methodology to determine the weather-corrected PR of the PV solar plant [26]. This method

Fig. 1. Cleaning system of PV modules.

corrects factors that affect ambient temperature, wind and solar irradiance. The weather-corrected PR of the PV power plant is calculated using equation (2):

$$PR_{corr} = \frac{PR}{1-\gamma\left(T_{cell\_typ\_avg} - T_{cell,i}\right)}. \qquad (2)$$

We modelled the PV solar plant in SAM software for the calculation of the average annual cell temperature from one year using the project weather file.

$$T_{cell_{typ_{avg}}} = \frac{\sum\left[G_{POA\_typ\_j} * T_{cell\_typ\_j}\right]}{\sum G_{POA\_typ\_j}}. \qquad (3)$$

In our study case, PV module temperatures were measured using a single surface-mount temperature sensor placed centrally on the back of each module. The cell operating temperature is calculated using equation (4):

$$T_{cell_i} = T_{m_i} + \left(\frac{G_{POA\_i}}{G_{i\_ref}}\right) * \Delta Tcnd. \qquad (4)$$

2.3 Soiling extraction

The production data is used for extracting the soiling rate of the PV solar plant in this paper by the application of the methodology of Deceglie et al. [27]. The soiling ratio is used to determine the soiling rate on the PV modules. The value of soiling ratio (SR) decreases as the contamination level of the PV module increases [28,29]. The more dirt losses, the lower the SR value, while a SR of 1 indicates no losses.

$$SR = \left(\frac{RP_{corr}}{RP_{corr,ref}}\right) \qquad (5)$$

$RP_{corr,ref}$ is defined as the 95th percentile of the time series RP_{corr} [28].

This method automatically detects the soiling intervals and finds the soiling rate during these periods.

The soiling rate is determined by measuring the slope of the time series of the SR for intervals of more than 14 days in the dry periods. Theil-Sen linear regression is used to estimate the slope. The Theil-Sen estimator is calculated for a collection of points by taking the slopes between all pairs of points in a data set and then taking the median value of these calculated slopes [30].

$$\beta_n = Med\left\{b_{i,j} = \frac{SR_i - SR_j}{d_i - d_j} : d_i \neq d_j, 1 \leq i \leq j \leq n\right\}. \qquad (6)$$

This regression provides a more robust and efficient assessment than the least squares calculation. Theil-Sen linear regression is also less influenced by anomalies [27].

2.4 Determination optimal frequency cleaning

Cleaning is applied only in the dry season to reduce dust from PV modules to the PV solar plant. The other cleaning system is natural corresponding to the rain in the rainy season. Optimizing the cleaning cycle provides a balance between the cost of lost energy and the cost of cleaning PV solar plant.

The cleaning cycle is the number of days in the cleaning season over the number of days between cycles.

$$Cycl = \frac{N}{n}. \qquad (7)$$

In this study, cleaning was only taken into account for the dry season and therefore $N = 273$ days.

The energy losses caused by dust during the cleaning interval are given by:

$$E_{losse} = E_{AC,avg,N} \times SL \times Cycl. \qquad (8)$$

Dust losses can be modeled assuming a linear degradation rate or exponential function. In this study, a method developed by Ilse et al. adopted to take into account the daily variations in soiling loss over a cleaning cycle [31].

$$SL = \sum_{j=1}^{n} j \times SR_{rate}. \qquad (9)$$

The rate of dust accumulation is assumed to be constant during each cleaning interval.

$$E_{losse} = SR_{rate} \times E_{AC,avg,N}\left(\frac{n+1}{2}\right) \times N. \tag{10}$$

The loss of revenue due to dust accumulation is shown as follows:

$$C_{pl} = E_{losse} \times P_{electricity}. \tag{11}$$

The cost of cleaning and maintaining the PV solar plant cleaning cycles.

$$C_{cl} = \frac{N}{n} \times P_{cyc}. \tag{12}$$

During the operating period of mechanical cleaning, the total cost caused by dust on the PV solar plant is shown as follows:

$$C_{Total} = C_{pl} + C_{cl}. \tag{13}$$

The optimal number of days between cleaning cycles is obtained by minimizing the total cost objective function $C'_{Total} = 0$.

$$E_{AC,avg,N} \times SR_{rate} \times P_{electricity} = \frac{2}{n^2} \times P_{cyc} \tag{14}$$

$$n_{opt} = \sqrt{\frac{2 \times P_{cyc}}{E_{AC,avg,N} \times SR_{rate} \times P_{electricity}}}. \tag{15}$$

3 Results and discussion

Figure 2 shows the variation of the monthly average daily output power and solar irradiance. Figures 2a and 2b show the years 2019 and 2020 respectively. Solar irradiance analysis shows the seasonal variations over the two seasons. September and July have the lowest average value of solar irradiance, respectively, 234.1 W/m^2 and 223.67 W/m^2. Indeed, this low solar irradiance at this period is explained at the beginning of the rainy season marked by an often cloudy and rainy days.

The output power follows the same trend as the solar irradiance. The highest energy productions were recorded during the dry season. This period marked by good sunshine and low fluctuations in solar irradiance. The highest monthly average production of the PV solar plant was recorded in March and April for 2019 and 2020, as shown in Figures 2a and 2b. This energy production from the PV solar plant is less important during the rainy season. Indeed, the solar irradiance of this period is marked by fluctuations accompanied by significant falls and the interventions for maintenance are more important during this period.

Although solar irradiance is available most of the year, there are certain other climatic conditions, environmental and technical that could make the PV solar plant less than expected.

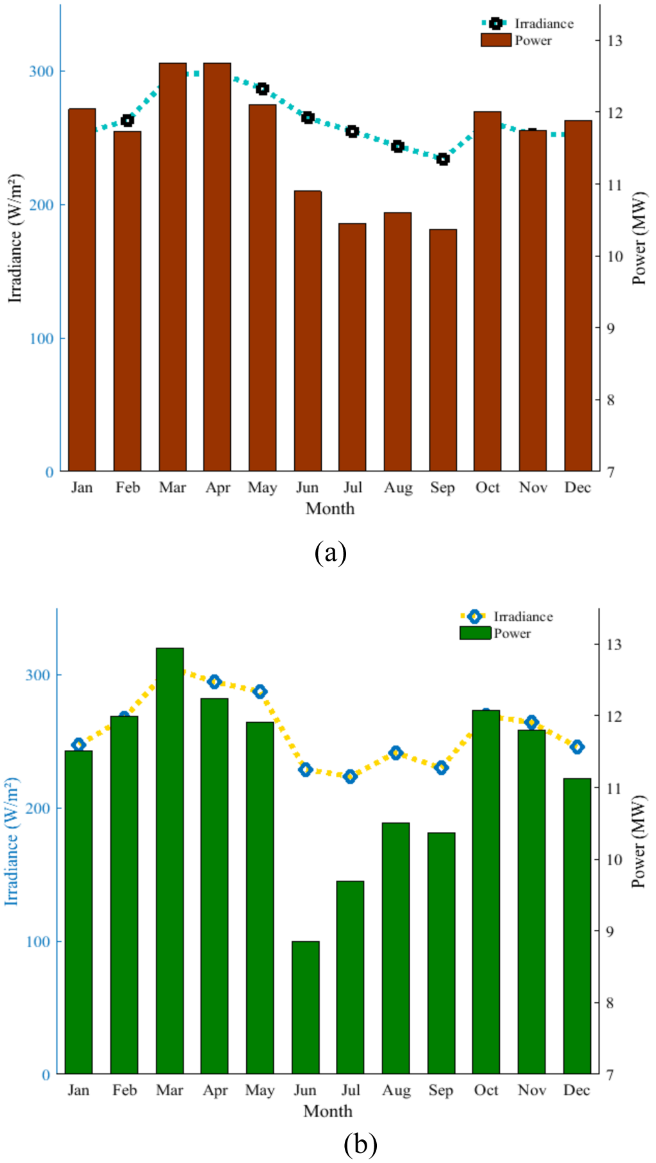

Fig. 2. Monthly average daily solar irradiance and output power.

In our case study we will only be interested in the soiling factor of PV modules by removing all the effects of other factors on the performance of the PV solar plant.

Figure 3 compares the PR and weather corrected PR per hour. The PR is always higher than the corrected one. The PR takes into account only the solar irradiance. Variations in other losses associated with weather or seasonal conditions will not be properly accounted for in this indicator.

The weather correct PR essentially solves the problem of seasonal and weather variations.

Figure 4 shows the measurement of the dust accumulation rate on the modules of the solar PV plant over the year 2019 and 2020. The periods marked by a gradual decrease in the soiling ratio were chosen. The PV solar plant adopts a fixed cleaning cycle of one month. Therefore, the magnitude of the change in the daily soiling ratio due to

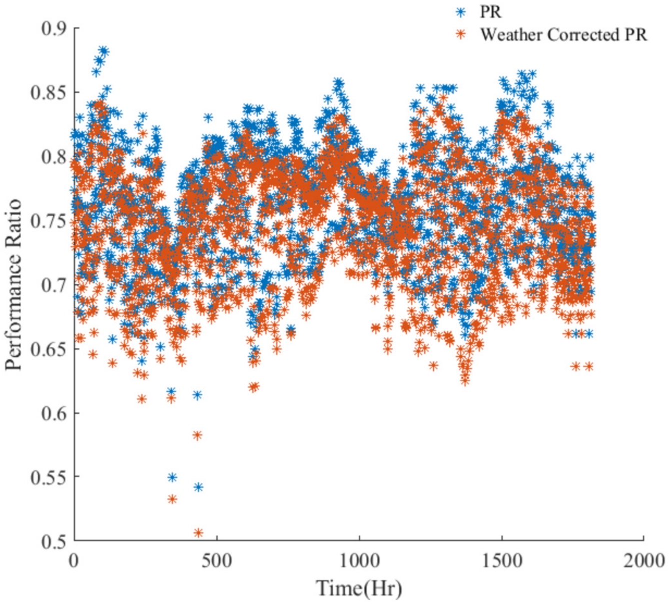

Fig. 3. Comparison of PR and weather-corrected PR for PV solar plant as a function of time.

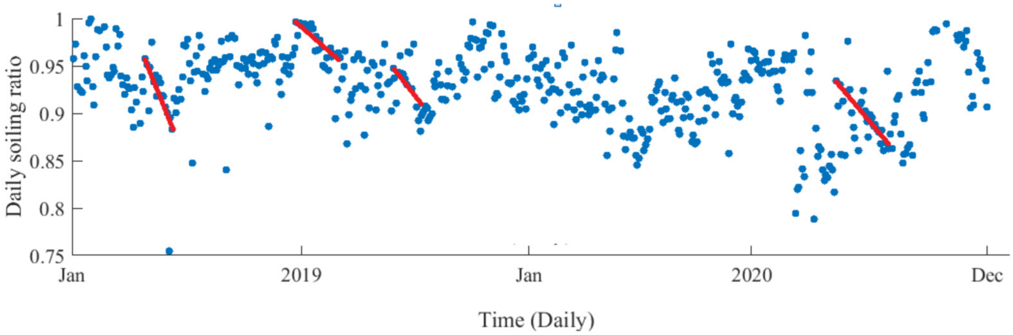

Fig. 4. Daily soiling ratio.

cleaning is not very significantly in Figure 4. This amplitude of the change in the soiling ratio is visible at certain times of the year and shown by red arrows on Figure 4. The slope of this regression line is taken as the soiling rate for this period.

The equation (6) is used to determine the slope of these intervals.

- $\beta1$ (13 February–05 March), a high soiling rate was noted 0.49%/day.
- $\beta2$ (20 May–04 June), a soiling rate 0.34%/day was determined.
- $\beta3$ (16–31 December), a high soiling rate with 0.42%/day.
- $\beta4$ (17–30 October); a soling rate 0.33%/day.

The two parameters that most affect the deposition of dust on the surface of PV modules are relative humidity and wind speed. Figure 5 shows the weather file data of the monthly humidity and wind speed of the PV solar plant site. As Figure 5 shows, it is apparent that an increased daily average wind speed has resulted in an increased average soiling loss during the period's $\beta1$ and $\beta2$. This can be explained by the wind, which facilitates the accumulation of dust on the surface of the PV modules and increases the soiling rate.

The reduction of the soiling rate during the period's $\beta2$ and $\beta4$ can be attributed to the decrease of the wind speed. In addition, the increased humidity can affect the quantity of dust that accumulates on the surface of the PV modules. An increased humidity will therefore lead to a decrease in the soling rate.

Figure 6 shows the total cost caused by dust as a function of cleaning intervals for different soiling rate scenarios. It can be seen that, the total caused as a function of soiling rate and the interval cleaning. Optimization will done based on the total cost caused by dust on the PV solar plant to minimize the number of days between cleaning events. The total cost minimized is the cost of energy loss and the cost of cleaning.

Therefore, the location of the PV solar plant, it can be considered that the dust accumulation rate on the PV modules is 0.42%/day in the dry season.

The price of the electricity used was 74.1 XOF/kWh while the price of cycle cleaning was estimated at 4,000,000 XOF for each cleaning cycle. The considered daily energy

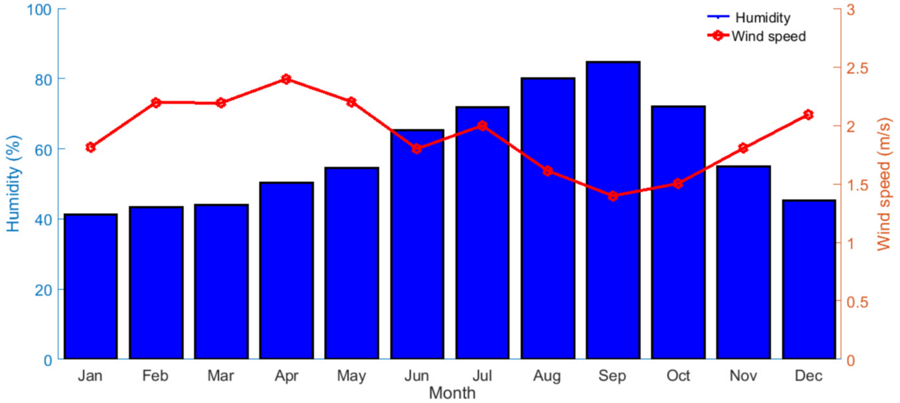

Fig. 5. Monthly average daily humidity and wind speed.

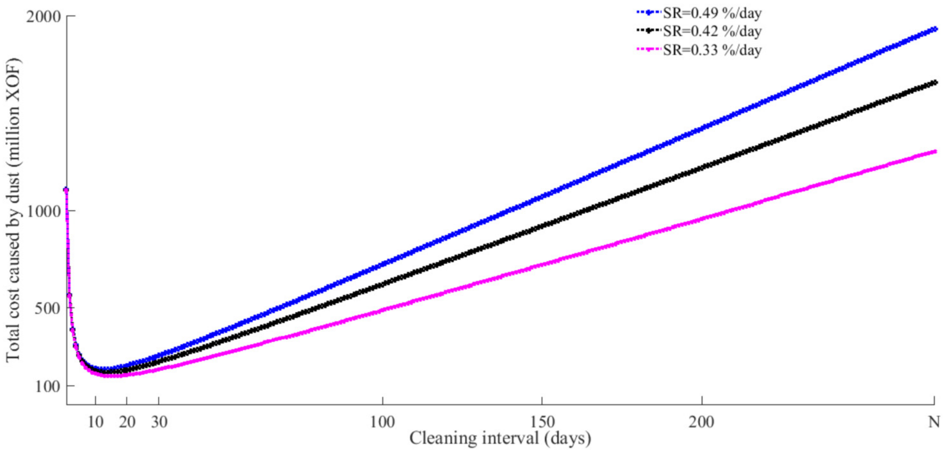

Fig. 6. Total cost caused by dust as a function of cleaning intervals.

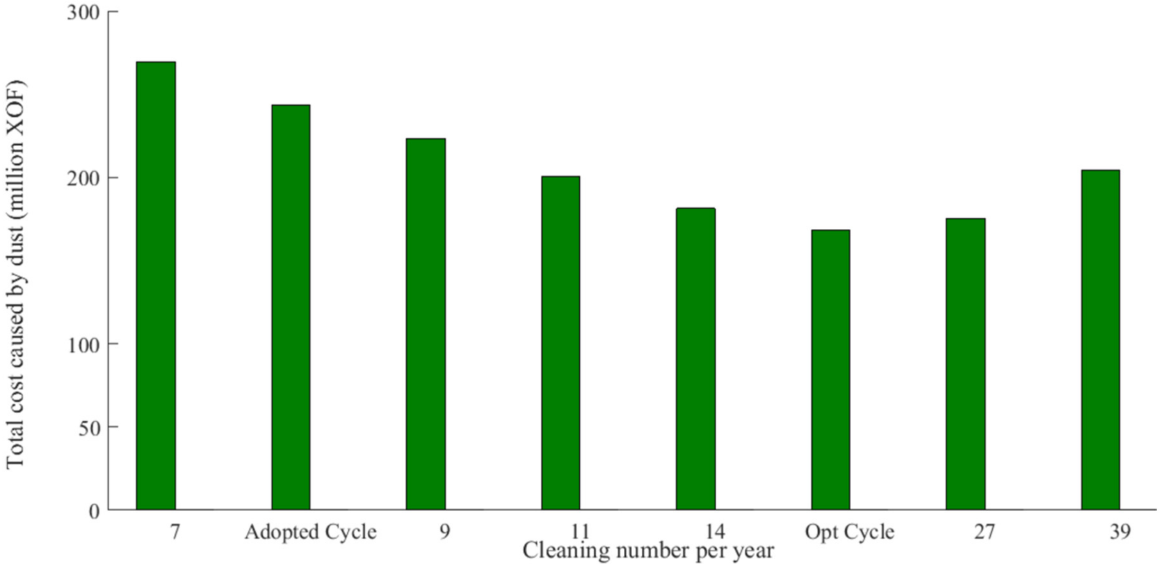

Fig. 7. Total cost caused by dust as a function of the cleaning cycle.

production of this PV solar plant in the dry season is 1,42,000 kWh/day.

From equation (15), the optimal cleaning cycles for the solar power plant is 14 days corresponding 20 cleanings per year. Therefore, 12 additional cleanings per year should add compared to 8 cleanings per year adopted at the PV solar plant to optimize the total cost caused by dust.

Figure 7 shows the total cost caused by dust as a function of the cleaning cycle at the location considered in this study. This aims to estimate the reduction in the total cost caused by dust on PV solar plants through optimal cleaning frequency. It was found from the results that an increase of one cleaning per year from 8 to 9 causes the decrease of total cost caused by dust 20 million XOF per year. The same observation is noted on these results: a decrease of one cleaning per year from 8 to 7 leads to an increase of total cost caused by dust to 26 million XOF per year. The total cost resulting from dust from PV modules is reduced by 31% using this optimal cleaning cycles.

4 Conclusion

The optimization of the cleaning frequency of PV modules was established on the basis of the total cost caused by dust. Data from two years of operation of the PV solar plant were collected and filtered, from January 2019 to December 2020. The results obtained reveal the highest energy productions were recorded during the dry season. This period has the highest average monthly solar irradiation value and is marked by the absence of precipitation which favours the accumulation of dust on the PV modules.

The dust accumulation rate was assessed by measuring the slope of the daily soiling ratio. Therefore, a soiling rate on PV modules of 0.42%/day was considered at the location considered in this study. It was noted that the optimal cleaning cycle was found to be necessary 14 days. Therefore, 12 additional cleanings per year should add compared to 8 cleanings per year adopted at the PV solar plant to optimize the total cost caused by dust. The total cost resulting from dust from PV modules is reduced by 31% by adding 12 additional cleanings per year. However, it is interesting to do an analysis on the evaluation of cleaning technology based on cleaning frequencies to better minimize the total cost resulting from dust.

Nomenclature

PV	Photovoltaic
P_{AC}	Measured AC electrical generation (kW)
$E_{AC,avg,N}$	Daily average produced energy in dry season (kWh)
C_{pl}	Loss of revenue due to dust from PV modules (XOF)
C_{Total}	The total cost caused by dust on the PV plant (XOF)
P_{STC}	Summation of installed modules' power (kWc)
G_{POA}	The measured plane of array (POA) irradiance ($\mathrm{kW/m^2}$)
$G_{i,ref}$	Module's reference in-plane irradiance, $G_{i,ref} = 1\,\mathrm{kW/m^2}$
PR	Performance ratio
RP_{corr}	Corrected performance ratio
$P_{electricity}$	Price of the electricity (XOF/kWh)
γ	Temperature coefficient for power (%/°C) at STC
T_{ref}	Reference temperature reference, $T_{ref} = 25\,°\mathrm{C}$
T_{m_i}	PV module temperatures (°C)
C_{cl}	Cost of cleaning and maintaining the solar PV plant cleaning cycles (XOF)
N	Number day of dry season
n	Number of days between cleaning cycles
SL	Soiling lose (%)
E_{LOSSE}	Energy losses caused by dust on the solar PV plant (kWh)
$\mathrm{SR_{rate}}$	Soiling rate (%/day)
P_{Cyc}	Price of cycle cleaning (XOF)
$T_{cell_{typavg}}$	Average annual cell temperature using the project weather file (°C)
$T_{cell\_typ\_j}$	Calculated cell operating temperature for each hour (°C)
T_{cell_i}	Predicted operating cell temperature (°C)
ΔT_{cnd}	Conduction temperature drop, $\Delta T_{cnd} = 03$
β_n	Theil-Sen estimator

Author contribution statement

M.C. Diouf and M. Faye designed the study. M.C. Diouf developed the theory and performed the computations. M. Faye was involved in planning and supervised the work. All authors discussed the results and contributed to the final manuscript.

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Conflicts of interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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