

Technical and economic assessment of cleaning protocol for photovoltaic power plants: Case of Algerian Sahara sites



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ABSTRACT

This study is focused on technical and economic analysis of cleaning protocol of Photovoltaic panels in power plants as function of dust density translated into soiling level. Indeed, the accumulation of dusts on PV panels influences the conversion efficiency of PV modules. The design and operating simulation have been carried out with specific computer calculation code “Helioscope”. The effects of soiling on these clean power plants have been studied for power capacities of 1 and 5 MW and two types of PV panels’ technologies: Cadmium Telluride (CdTe) Thin Films and Monocrystalline Silicon (Mono-Si). By considering databases of environmental dust loads, soiling level of 10 and 15% allows to be close to conditions of two studied locations in Sahara desert of Algeria. The analysis of simulations results for performance index (PR) showed remarkable diminution when PV panels’ fields are soiled. For estimating cleaning cost of PV fields, the design and simulations of PV power plants in Algerian Sahara sites of Adrar (1 MW) and Ouargla (5 MW) demonstrated the existence of soiling threshold allowing cleaning profitability which is situated around 7% in term of minimal level. Besides, it has been shown that the PV panel technologies are affecting sensibly this level and then can be decisive in the choice of the type of PV modules to install. Also, the feed in tariff (FIT) is critical on this soiling threshold.

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1. Introduction

In order to satisfy the important needs of economic and demographic growth in Africa, renewable energies and particularly solar are increasingly applied (Sanoh et al., 2014). Among strategic and sustainable solutions implemented by public authorities there are incentives programs for renewable energy. For example, Algeria, targets 27% of electricity that will be generated from renewables for 2030 with a total capacity of 22 GW including 13.5 GW that will be done in PV technology. In this example of African country, there is a regulatory framework that allows the generated solar electricity to be sold by private companies to the electricity network distributor at a feed-in tariff (FIT) guaranteed for 20 years at 15 Da (0.123 Euros)/kWh in case of PV plants ground mounted and having capacities exceeding 1 MW (Griffiths, 2013). Several PV power plants will be erected and spread across various regions and many of which will be in the Sahara desert. A major benefit of these areas is an important solar irradiance reaching 2600 kWh/m²/Year (Nia et al., 2013). However, it should be noted, two major drawbacks which are the high

temperature and the soiling of PV panels due to sandy environment of the Sahara which will induce losses in annual energy production (Sarver et al., 2013). In order to diminish the negative effects of soiling on profitability for large scale PV power plants (≥ 1 MW), the assessment of the cleaning protocol frequency is examined and optimized to be cost effective. The region of North Africa and Middle East Area (MENA) is one of the most promising territories for the development of solar energy due to its exceptional solar irradiation potential (Qoaider and Liqreina, 2015); however, this region is known to be very dusty. The phenomenon of dust deposition from surrounding environment on the glazing of PV panels is a major constraint in the cost of the maintenance and operating (M & O) for solar plants (Lopez-Garcia et al., 2016). The Setting up of an annual plan for cleaning of solar panels must be optimized in term of earned profits. For that reason, a design study of two photovoltaic plants to install in Algerian desert regions is discussed by analyzing the effects of soiling levels on cleaning cycles. A first PV plant is designed and studied in the Adrar region with a capacity of 1 MW according to photovoltaic modules of monocrystalline Silicon (mono-Si) (Lee et al., 2013). Then, a second power plant was implemented in the region of Ouargla with 5 MW capacity; these localities and their irradiance potential are represented in Fig. 1. In PV plant of Ouargla, the module technology

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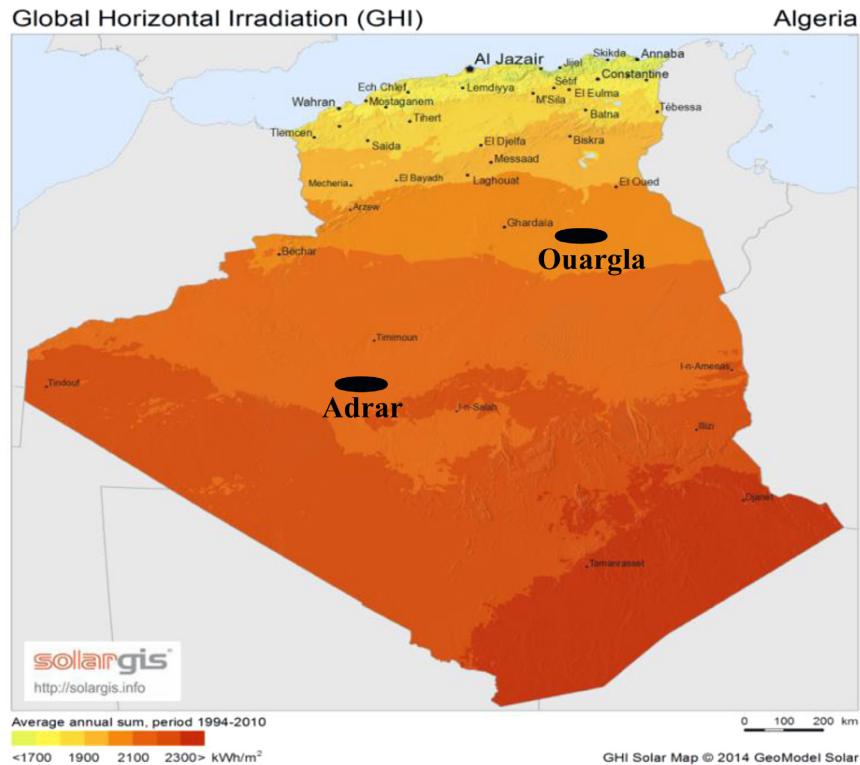


Fig. 1. Algeria global horizontal irradiation (<http://solargis.com/products/maps-and-gis-data/free/download/algeria>).

has been varied from mono-Si to thin films (CdTe) type (Green, 2011). These studies are conducted to increase performance and profits from these solar plants because of harsh environment in term of water scarcity, high levels of soiling and temperatures.

2. Estimated levels of soiling in Sahara regions and factors affecting cleaning cost of PV plants

2.1. Estimated levels of soiling in Algeria Sahara

To conduct this study, it was necessary to make the state of the art for estimation of the soiling level in these locations for better implementation of this parameter in PV plants design and then to optimize the cleaning frequency and its cost. The soiling is a dust deposition phenomenon from the surrounding atmosphere in a process that gives rise to grain particles deposition of 1–500 μm in diameter (Urrejola et al., 2016). The attachment of the dust particles depends on the humidity level, more this rate is high more the grain of dust sticks to the surface of the glazing of PV modules (Kalogirou et al., 2013). In case of dry weather, as in desert areas, the grain of sand or dust can be removed more easily by wind that deposits them just as easily. Previous studies, have estimated the soiling level in several region of the world (Ghazi et al., 2014). Algeria was classified as a level 4 region for dust concentration in the range of 65–96 $\mu\text{g}/\text{m}^3$. Also, it was reported that each g/m^2 of dust load conducts to light transmission decrease of about 4.1%, this corresponds to the parameter called soiling level in the computer simulation of PV plant energy production presented in Section 3 (Ghazi et al., 2014; Astitha et al., 2008; Appels et al., 2013; Boyle et al., 2015). However, in case of sand storm this level could

be multiplied by 6–7 times (Ghazi et al., 2014), but for a limited period because the grain of sand is easily removed from glazing by winds in dry climate regions. In the simulation study presented in Section 3, soiling levels of 10 and 15% at maximum are considered in order to be close to real conditions. During the period 2003–2010, it was recorded an average level of soiling in Algeria of 75 $\mu\text{g}/\text{m}^3$ for dust concentration in atmosphere (Ghazi et al., 2014). The review of this parameter in other MENA countries compared, for example to, UK and USA, showed that the soiling in MENA countries is higher. Also, Algeria is at 5th position after Egypt; the 1st position showing the more dusty location is attributed to Sudan, where this parameter is doubled comparatively to Algeria for an average dust concentration in atmosphere at about 150 $\mu\text{g}/\text{m}^3$.

To confirm this soiling values it have been exploited a simulation tool SKIRON freely available from university of Athens for forecasting of dust loads (Astitha et al., 2008); it gives satellite maps in real time with forecast over several days for studying the evolution of the dust load (mg/m^2); Fig. 2 shows an example of forecasting or real time measurement of Dust loads by SKIRON simulator. From where, it had been noticed that even in the regions of southern Europe (Greece, Italy and Spain) may be affected by these dusty clouds as shown on the map of Fig. 2. This map shows that the northern border of the African Sahara is very exposed to sand storm and soiling, particularly in Algeria. These dust loads conduct to optical losses from 2 to 60% in the transmission of light through the glazing of PV modules and thus in the production of photoelectric energy in these regions (Appels et al., 2013). Where, also the level of rainfall plays a key role in the withdrawal and accumulation of deposited dust (Ghazi et al., 2014). The regions with low rainfall will make them more favorable to the accumula-

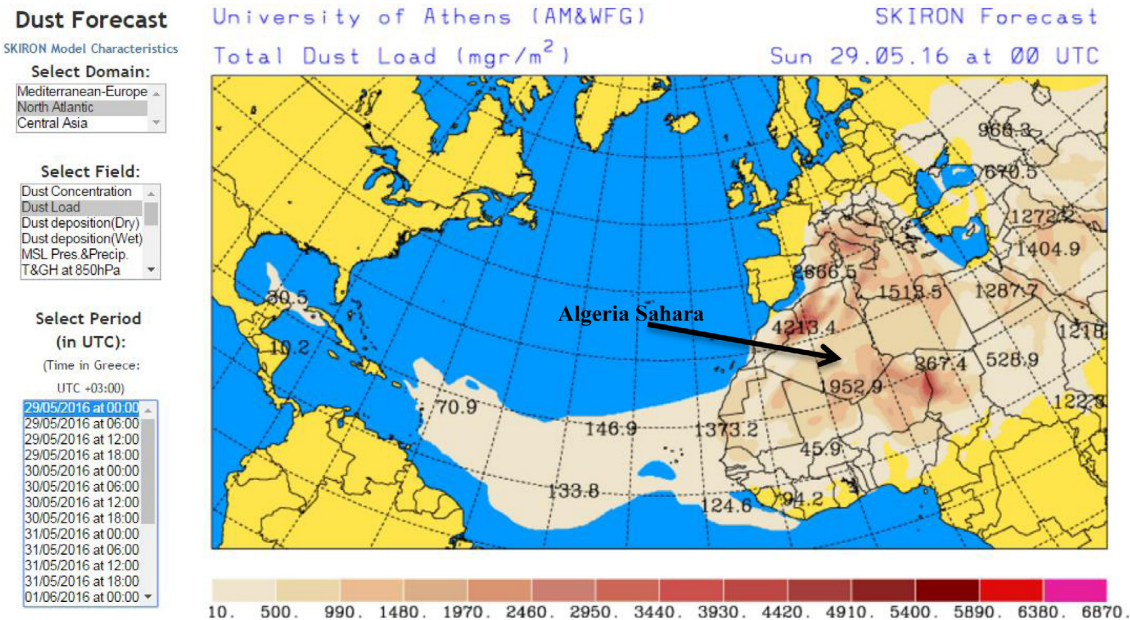


Fig. 2. Measurement on 29th May 2016 of Dust loads by SKIRON online data maps from University of Athens (Astitha et al., 2008).

tion of soils on surfaces. For example, during the day on Sunday, 29th May 2016, several northern regions of Algeria and North Africa have witnessed sand deposition from the rainfall charged by Sahara dusts.

According to the forecasting obtained from SKIRON tool in Fig. 2, it was really observed, that after a downpour of rain there is presence of red-colored dust deposits on PV panels as shown on pictures of Fig. 3. This situation is usually associated with an air mass stream from south which moves towards North Africa and South of Europe.

2.2. Factors affecting the cleaning cost of PV plants

The power losses due to dust accumulation may generally represents between 6% and 7% of the total energy produced by the PV module and can reached 70% in desert for about one hour if there is sand storm (Maghami et al., 2016). The cost of cleaning the solar panels is a major parameter in the expense of maintenance and operating of PV plants for these dusty regions. The total cost reserved for the cleaning of PV power plants depends of the

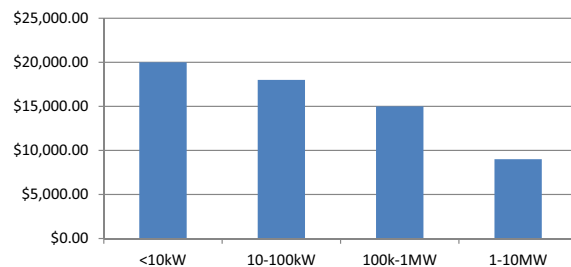


Fig. 4. The cost of cleaning per MW in function of the PV power plant capacity range (http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html).

labors cost, of the water cost, of the applied method, of the installed PV panels' type, of the total power capacity installed for the photovoltaic field and of the cleaning cycle. The cleaning cycle is the period between each full cleaning of PV panels' fields in its total power capacity for the plant; the cleaning cycle is variable (Sayyah et al., 2014). Regarding the technology of installed PV



Fig. 3. Pictures of accumulation of Dust layer on PV modules in North Algeria (Tipaza region) on 29th May 2016 confirming SKIRON online results data maps.

Table 1
Reported cost of cleaning solar panels related to various techniques and power capacity.

PV plant capacity	Cost	References
1 MW-Italy	2,500 Euros for 1 day cleaning/1 MW	Pavan et al. (2011)
2 MW-Saudi Arabia	53,000\$	Fathi et al. (2017)
100 kW-Solarpalaza	1430 Euros	http://www.solarplaza.com/channels/asset-management/11400/pv-module-cleaning-does-it-pay-back
[1–10 MW]	9,000\$/MW/YEAR	Jones et al., 2016; http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html
20 MW-California	60,000\$	http://www.greentechmedia.com/articles/read/do-you-wash-your-solar-modules-often-enough

panels, the dusty module behavior varies with the type of technology (Jones et al., 2016). Each method of cleaning will have a specific cost. It was reported that the cleaning methods with machines allow reducing 50% of fees comparatively with the manual labor method, in the case of large scale installations of several tens of MW (Jones et al., 2016). Also, PV module installation location influences the nature and quantity of deposited dust particles. In reality, the nature of deposited dust is depending from surrounding environment as for Saharan area dust particle is of mineral (sand: quartz, silica, etc.). Furthermore in agricultural location the dust particles are organics (pollens, bird droppings, tree leaf, etc.) and sometimes muds. On the other hand, in areas close to seaside there is an accumulation of salts on glazing of PV panels by evaporation phenomenon which conducts to have a white aspect of front glass of solar panels. While, in the urban locations the dust particles consist mainly of black carbon generated from vehicles traffic.

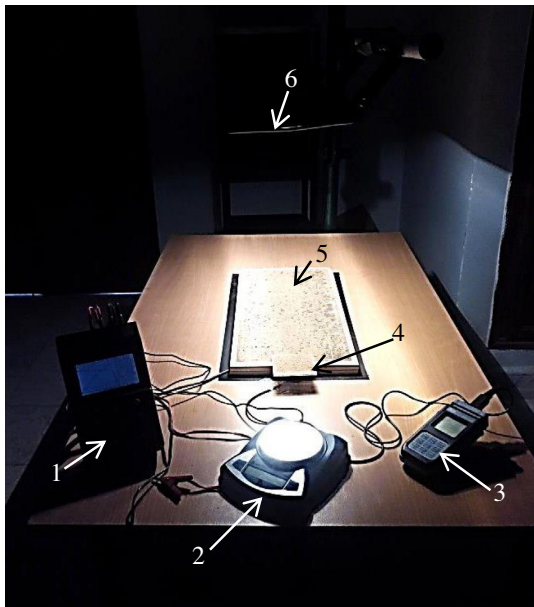


Fig. 5. The experimental setup for measurements of dust load effects on PV module performances. (1) ProvaSolar Module Analyzer, (2) Balance, (3) Radiometer, (4) Glass sample, (5) Dusty PV Module, (6) Halogen Lamp.

Thus, developers of large scale PV plants need to estimate all of these parameters, which are helpful for their design optimization of energy production and setting up of cleaning schedule; for that reasons, it is highly recommended that the companies of EPC (Engineering Procurement and Construction) in charge of PV power plant projects install measurement devices with dust sensors several months before PV plant construction]. For the capacity parameter of the photovoltaic field, The National Renewable Energy Laboratory (NREL) gives an estimated cleaning cost versus the capacity of the PV plant (http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html). It is shown on Fig. 4, that the cleaning cost per MW is reduced by 55% when power capacity varies from 10 kW to 10 MW. Table 1 illustrates these mentioned earlier results additionally to PV plant capacity, cleaning method and number of cleaning cycles affects the cleaning cost.

This reduction in the relative costs per MW of cleaning as the capacity of the plants increases is due to the automation of the cleaning process for the large capacity plants. In addition, new water-saving techniques such as hydrophobic self-cleaning coating and air blowing methods are used (Fathi et al., 2017).

2.3. Experimentations of dust accumulation impacts on power production of PV modules

To verify the soiling effects on PV modules energy production found in the literatures and before starting simulation and calculation of cleaning profitability, it has been found to be important to practice some experimentation. Indeed, several tests have been conducted by varying dust load (g/m^2) and examining its impact on PV power decreases called “derating”. The experimental set-up for dust deposition and power efficiencies measurements is shown in Fig. 5. It is composed of PV module, radiometer for measuring illumination values, measurement aperture PROVA full PV modules characterizations under outdoor sun illumination or indoor illumination assured by a Halogen lamp. Also, there is an electronic balance of high precision to quantify the deposited Dust during testing of PV module on a Glass sample.

Table 2 represents Power and efficiency measured at various dust loads by the mean of set-up bench introduced in Fig. 5 of PV module. These results are plotted on the curves of Fig. 6 where is shown the derating of power versus dust loads. It has been found that each g/m^2 conducts to about 6.8% derating in power; it is a bit close to the transmission decrease, that have been already announced from Boyle et al. (2015) for the transmission which is 4.1% for each $1 \text{ g}/\text{m}^2$ of dust load. This different value is probably

Table 2
Power and efficiency measurement at various dust loads of PV module.

PV electrical parameters	As clean PV Dust: $0 \text{ g}/\text{m}^2$	Dusty PV Dust: $3 \text{ g}/\text{m}^2$	Dusty PV Dust: $4 \text{ g}/\text{m}^2$	Dusty PV Dust: $6 \text{ g}/\text{m}^2$	Dusty PV Dust: $8 \text{ g}/\text{m}^2$
P_{max} (W)	15.43	12.50	10.61	9.447	7.201
η (%)	13.30	10.77	9.151	8.144	6.207
$\Delta (P_{\text{max}}\%)$	0	−18.98	−31.23	−38.77	−53.33
$\Delta (\eta\%)$	0	−19.02	−31.19	−38.76	−53.33

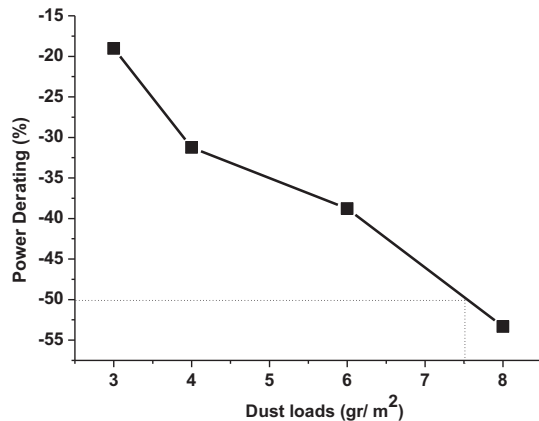


Fig. 6. The derating of power versus dust loads.

due to nature of considered dust for the test and its granulometry (Maghami et al., 2016).

3. Design and simulation of 1 MW and 5 MW PV power plants implanted in Sahara desert sites

3.1. Description of simulation software Helioscope and study parameters

In order to pursue the technical and economic study to predict the profitability of the cleaning process of the solar panels to set up, design of PV plants in two regions of southern Algeria in 1 and 5 MW power were proposed. Furthermore, the technologies of PV panels have been varied from the two main types which are the crystalline Silicon (Mono-Si) and Thin films (CdTe). The design and simulation of the operation of these two PV plants feed into the electricity network is done using the software Helioscope. This last is an online software tool for solar design engineering and performance modeling, developed by Paul Gibbs and Paul Grana, at Folsom Labs in USA. It is considered as an advanced PV system design tool that integrates system layout and performance modeling to simplify the process of engineering and selling solar projects (Riley et al., 2016). It has many benefits like: quick evaluation of a potential site helps with the decision in design analysis and simplification of work flow. The parameters of interest that have been evaluated for the present study are: the Performance index PR (%) and the produced annual energy E (MW h). Then, the revenue income is calculated following the guaranteed prices for 20 Years of Feed in Tariff (FIT). Likewise, the Return On Investment (ROI) parameter is estimated taking into account the initial cost of the plant, the revenue income from the FIT and the annual maintenance from only the cleaning costs. This is in order to allow us to estimate cleaning cost effect alone on profitability of PV power plant while varying the soiling parameter. The PR index of photovoltaic plants performance is defined as the ratio between the real energy injected yearly (Y_f) and the theoretical energy injected yearly (Y_t). The theoretical injected energy takes in account the installed peak power and the number of hours of sunshine at Standard Test Conditions (STC) for the chosen site. The real injected energy is that which is at the output of the inverters and fed into the grid, it takes into account the electrical line losses, thermal losses of the PV field and other losses such as the level of soiling monthly and annually. With the applied calculation code “Helioscope”, it is possible to vary the soiling parameter and

simulate PR index annually or monthly. These previous parameters are given in the following calculation equations (Riley et al., 2016):

$$PR = \frac{\text{Inverter Output Energy produced kW h}}{\text{Theoretical Output Energy kW h}} = \frac{Y_f}{Y_t} \quad (1)$$

$$ROI = \frac{\text{Total Cost of PV plant}}{\text{Annual Revenue from FIT}} \quad (2)$$

$$\begin{aligned} \text{Annual Revenue from FIT} &= \text{Produced annual energy} \times \text{FIT} \\ &= E \times \text{FIT} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{FIT} &= \text{Feed In Tariff} = 15 \text{ Algerian Dinars (Da)/kW h} \\ &= 0.123 \text{ Euros/kW h} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Revenue Lost} &= \text{Annual Revenue (without Soiling)} \\ &\quad - \text{Annual Revenue (with Soiling)} \end{aligned} \quad (5)$$

where the FIT in Algeria is warranted for 20 Years at a fixed rate of 15 Da (0.123 Euros) in case of PV power plants in the range of 1–5 MW.

3.2. Design and simulation of PV power plants installed in Algeria desert: Study cases of Adrar (1 MW) and Ouargla (5 MW)

The Adrar region is at 1400 km by road from the capital Algiers in south-west direction. This is a region of Algerian desert where the climate is very hot with temperatures reaching 55 °C in summer, in this region there is a reserve of water in the basement and rainfall is very low since the annual average rainfall barely reaches 14–15 mm, mainly falling in autumn or spring. For the PV plant design simulation, a temperature of 30 °C has been considered and it represents the yearly average temperature. The solar radiation is among the highest in the world and its average duration is about 3300 h per year (Hordon and Binkley, 2005). From March to June there are seasonal winds creating dust storms and causing major losses of energy production due to sand grains deposition on the glazing of solar panels. The levels of soiling losses have been varied in the range of 2–10% according to data collected on the basis of SKIRON model. Then, a site in this region is chosen and its perimeter delimited in the Helioscope software, as shown in Fig. 7. The modules type of bulk silicon from Yingli 250 W panda has been selected; it is noted that a PV Plant of 20 MW were already installed in July 2015 with the same type of module.

The software installs PV modules which are distributed according spacing to prevent the shadow from one row to another. Then, the next step is to moving the selection of operated inverters; In this design centralized inverters have been preferred, 04 in total of 250 kW each and are connected to feed into the network according to a wiring diagram of combiner boxes from the various branches of the PV fields. Then, a diagram as shown in Fig. 7 is generated by Helioscope software. For incorrect choice of the inverters the software gives an alert for inverters adjustment; like in case of permissible input voltages from the connection of PV modules by taking into account the over or under voltage obtained by reduction or increase in temperature. After adjustment of the inverter type, correcting and obtaining all acceptable levels, an adjustment is done to define the desired simulation conditions for the annual operating of the PV plant in the “Set Condition” page Fig. 8. Then, the setting temperature of 30 °C is introduced and the soiling level is varied from 0 to 10%. The value chosen for this study is estimated from Appels et al. (2013) and Jiang et al. (2011).

Similarly, the previous steps have been repeated for a second Saharan site in Ouargla, where average temperature levels are equivalent to 30 °C and with low rainfall. The capacity of the

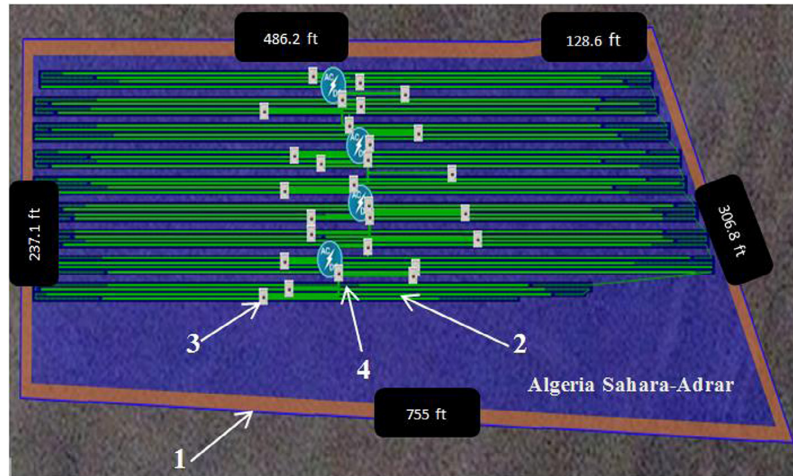


Fig. 7. Design and implementation of PV plants in desert sites, Algeria Sahara-Adrar. (1) Plant border, (2) String of PV Modules, (3) Combiner box, (4) Inverter.

Condition Set: Condition Set 5												
Description	Condition Set 5											
Weather Dataset	TMY, 10km Grid, meteonorm/nrel medium resolution (meteonorm) (download)											
Solar Angle Location	Meteo Lat/Lng											
Transposition Model	Perez Model											
Temperature Model	Sandia Model											
Temperature Model Parameters	Rack Type	a		b		Temperature Delta						
	Fixed Tilt	-3.56		-0.075		3°C						
	Flush Mount	-2.81		-0.0455		0°C						
Soiling (%)	J	F	M	A	M	J	J	A	S	O	N	D
	5	5	5	5	5	5	5	5	5	5	5	5
Irradiation Variance	5%											
Cell Temperature Spread	4° C											
Module Binning Range	-2.5% to 2.5%											
AC System Derate	0.00%											
Module Characterizations	Module						Characterization					
	YL245C-30b (Panda) (Yingli Solar)						Default Characterization, PAN					
Component Characterizations	Device						Characterization					
	Sunny Central SC 250U (SMA)						Default Characterization					

Fig. 8. Set condition window in Helioscope software for soiling levels input and study (details of conditions sets).

designed PV plant has been increased to 5 MW and two types of PV panels have been selected which are monocrystalline Silicon (Yingli-Panda 250 W) and thin-film CdTe (First-Solar 117.5 W). The technical specifications of these modules are shown in the

Table 3; the difference of these two panel types are the superior efficiency for monocrystalline silicon counterbalanced by the lower power loss versus the temperature in the case of thin film technology ($-0.29\%/^{\circ}\text{C}$). Therefore, we will make comparisons

Table 3
Technical specifications of applied PV modules.

Module type			Mono-Si	Thin film CdTe
Identification name	Parameters	Unit	YL250C-30b-Yingli panda 250 W	FIRST SOLAR FS-4117-2
Power output	P_{max}	W	250	117.5
Open-circuit voltage	V_{oc}	V	38.1	88.2
Short-circuit current	I_{sc}	A	8.71	1.79
Temperature coefficient of Voc	βV_{oc}	$\%/^{\circ}\text{C}$	-0.31	-0.29
Dimensions	(L/W/H)	mm	1650 mm/990 mm/40 mm	1200/600/6.8
Cell type		mm	Monocrystalline-Si	Thin-film CdTe

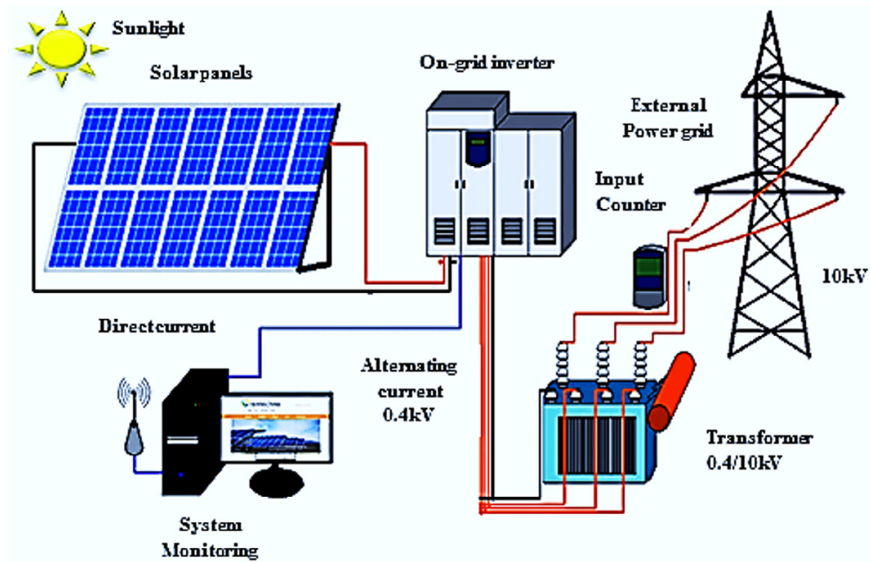


Fig. 9. Wiring diagram of installed PV plants (Adrar 1 MW, Ouargla 5 MW).

and synthesis in Section 4. Fig. 9 shows the principle diagram for the wiring of PV plants of Adrar 1 MW and Ouargla 5 MW.

4. Results and discussions

4.1. Impact of soiling level on generated revenue from 1 MW PV plant at Adrar

The cost of 1 MW PV plant in Adrar including furniture and installation is estimated to 1 millions Euros. Table 4 gives an overview of each items allowing this calculation and taking in account the actualized prices from Photovoltaic market.

The study of the effect of soiling on the energy production in the photovoltaic power plants of a chosen site is done using the two software's SKIRON and HelioScope. The link between the two programs is made by forecasting soiling level data using the SKIRON software, which provides a database of the level of soiling of the studied site which is introduced by the user in the HelioScope software through the Condition set window. This allows calculation of

the energy losses in the photovoltaic power plants caused by dust accumulation and introduced as soiling level.

In Adrar site, the level of soiling is varied from 0 to 10% to study its impact on power plant output parameters as: produced energy yearly, annual revenue from FIT and ROI. The plotted curves in Figs. 10–12 demonstrate important decreases for all of these parameters when level of soiling increases. It was noticed that for a soiling losses level of 10% a reduction of energy production of 180 MW h per year corresponding to a revenue losses about 20,000 Euros by year were calculated this is translated in a much longer time for Return On Investment (ROI) with plus of 6 months. These parameters are applied to study the economic benefit that could support cleaning and its process in numbers of cycles by year in Section 4.3.

The obtained results for losses in annual energy production, is explained by the irradiance losses which is proportional to the level of soiling.

The results obtained in this section show how the level of soiling decreases the energy production in the PV power plant of

Table 4
Components specification of designed PV plant 1 MW & 5 MW.

Item	Equipment name	Specification	Cost \$/unite	Qty	Cost \$
1	PV modules	250 W	0.61/W	4056	618,540
2	Inverts	500 kW	70,000/500 kW	2	140,000
3	Combiner boxes	10 input, 1 output	1300/Comb box	20	26,000
4	Mounting system	Galvanized Al	100/kW	1	100,000
5	Dc power distribution cabinet lightning protection		10,000/cabinet	2	20,000
7	Boosting transformer	0.4/11 kV	25,000	1	25,000
8	Environment monitor		40,000	1	40,000
9	Monitoring system	SCADA System	25,000	1	25,000
10	Cable and protective material		25/kW	1	25,000
11	AC and DC cable		20/kW	1	20,000
12	Communication cable		30/kW	1	30,000
13	Study project design	Site visits, measurements, satellite data and power calculation software			88,500
Total cost of PV plant (1 MW)		USD 1,158,040 ≈ Euros 1,000,000			

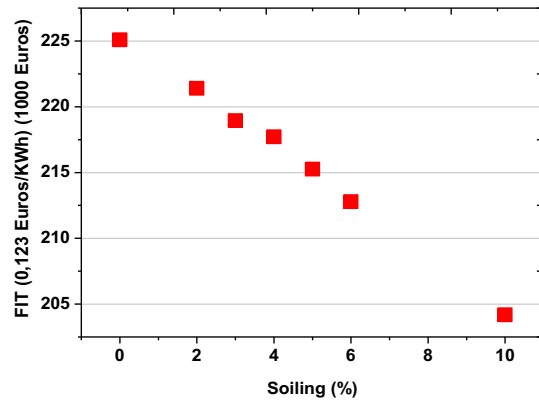


Fig. 10. Variation of generated revenue versus level of soiling: Adrar 1 MW PV plant of Mono-Silicon panels type.

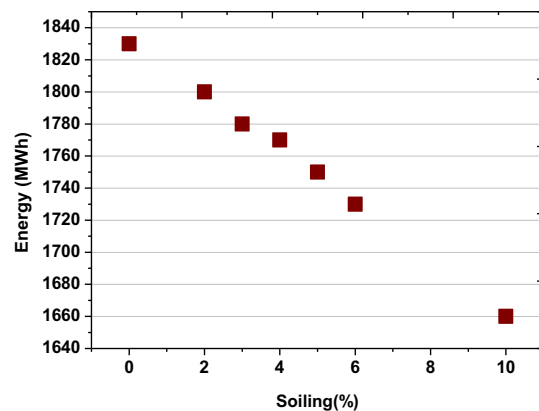


Fig. 11. Annual Energy production versus soiling level: Adrar 1 MW PV plant of Mono-Silicon panels type.

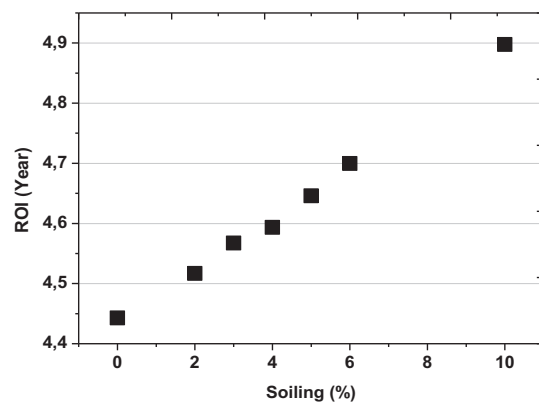


Fig. 12. Evolution of ROI versus soiling level: Adrar 1 MW PV plant of Mono-Si panels type.

Adrar. Indeed, this is due to the light transmission reduction of the PV module glazing (Jiang et al., 2011), which directly affects the index of performance and the annual revenues from FIT.

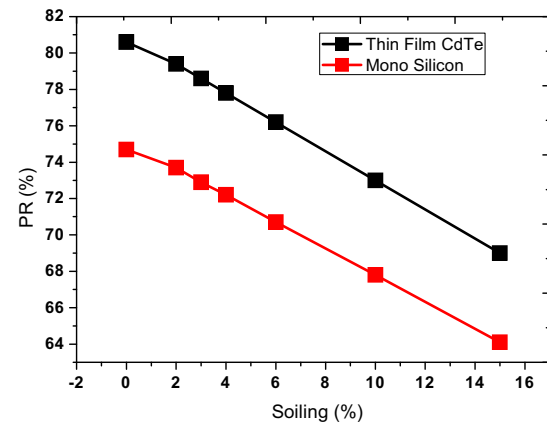


Fig. 13. Impact of PV Module technology on Performance index (PR) versus level of Soiling in Ouargla site.

4.2. Impact of PV panels technology on the performance index and revenues: Study case of 5 MW PV plant at Ouargla

In this second part of the study of PV plants grid connected in the Algerian desert, some analyses are done for revealing the effect of the technology of PV panels on the performance index PR of PV plant, its annual energy production and the return on investment ROI all by varying the level of soiling. For this, it was proceeded by Helioscope simulator the case study of 5 MW PV power plant installed in Ouargla site and comparing the application for two keys technologies of solar panels namely monocrystalline silicon (mono structure Panda crystalline type silicon) and thin films (CdTe). On Fig. 13 it is noticed a higher PR with a permanent gap of 6% favorable for thin film CdTe comparatively to Mono-Si solar panels' technology in any soiling level. In case of thin film panels, the PV plant performance index PR is beginning at 81% for as cleaned PV fields and dropping to 69% in the case 15% of soiling level. This superior performance is reflected in a higher level of energy production with more income resulting in a faster return on investment in the case of thin films. As already shown in the literature (Fathi et al., 2015; Steven, 2013), for the study of the application of thin-film technologies in areas with high temperatures, a better performance stability and thus profitability of the investment is shown for this technology type. However, it is important to remark that land area needed for installation of PV plants by using thin films panels is higher because of their lower efficiency comparatively to crystalline silicon (Chu and Meisen, 2011). This last point has no negative impact in the arid regions as like in southern region of Algeria where lands are available and sold by local governments to potential investors for modest prices to support local and sustainable development of the Algerian southern regions.

It is noticed from Fig. 14 that when the soiling level reaches 15%, the income of the PV power plant in thin films becomes equivalent to income in case of a mono-Si PV plant with 7% of soiling. Likewise, when a PV power plant of mono-Si is clean its revenue is equivalent to a thin film PV plant of same power capacity when it is soiled at 8%. Which shows that PV power plants having solar modules of thin films are more robust and productive in dusty environments. This result is confirmed by the real choices of Topaz PV power plant, one of the largest power plants installed in the world, at the USA in California desert with a capacity of 550 MW with thin films technology of CdTe (Marinopoulos and Bakas, 2014).

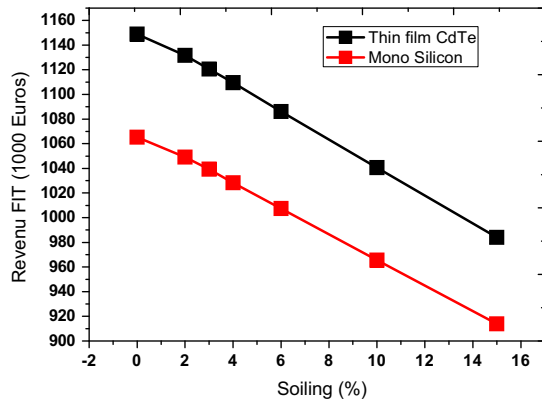


Fig. 14. Impact of PV module technology on annual revenue from FIT versus level of soiling in Ouargla Saharan site.

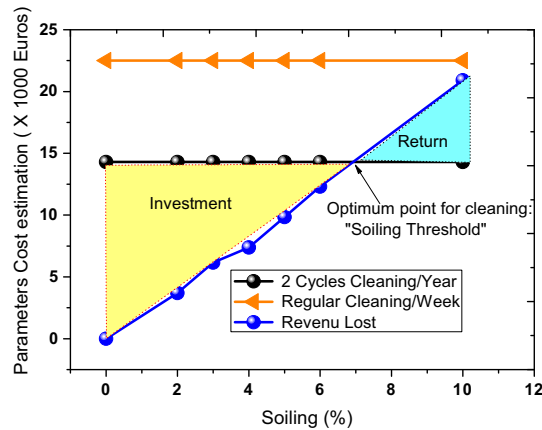
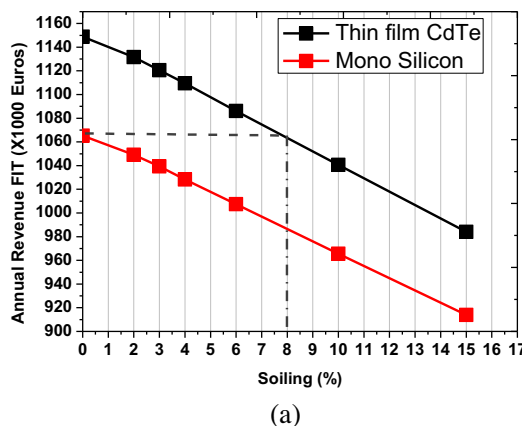


Fig. 15. Profitability analysis of the cleaning protocol for 1 MW PV plant at Adrar Saharan site.



4.3. Analysis of the profitability in the PV cleaning process

In order to minimize the soiling effect on the profitability of PV plants, the cleaning of PV module could become necessary or not; by taking in account the affiliated fees, the Fig. 15, illustrates two cleaning protocols. In the first one, the cleaning is regularly practiced (weekly), its cost have been previously estimated at 22,500 Euros per MW (Fathi et al., 2017) and for the second protocol, PV modules fields are cleaned totally twice a year for an estimated amount of 14,300 Euros per MW (<http://www.solarplaza.com/channels/asset-management/11400/pv-module-cleaning-does-it-pay-back>). In this last protocol, cleaning becomes profitable if soiling is superior to 7%. This lets you designate what can be called the soiling threshold for profitability of cleaning protocol where it is beneficial to perform it. Otherwise, for cleaning regularly practiced each week, the cost of cleaning can be recovered in case of soiling over 10%. It should be noticed that if no cleaning is taking place at least one time a year, the dust accumulation could be difficult to remove in next times.

To analyze the incidence of technology type for PV panels on profitability of cleaning PV plant, Fig. 16 shows the same analyzes in case of thin film CdTe and Mono-Si panels. It is noticed that the income of the thin films power plant is always superior for same installed power peak capacity and therefore can afford to recover the extra costs of cleaning earlier than mono-Si panels' type. Then, it is found that the optimum point to cover extra cost for PV cleaning is advanced in thin films at 6.8% soiling level while for mono-Si the optimum point is 7.3%. Therefore, it seems that the technology of thin film could be advised for sites with higher levels of dust.

To cover the cleaning costs in the case of the mono-Si PV plant, soiling level must reach 7.3%, after this cleaning the plant will produce energy equivalent to that of its clean initial state with an annual revenue from FIT of 1,060,000 Euros which corresponds to thin film PV plant with 8% of soiling. In this case, the thin film PV plant could be let soiled up to 8% while remaining at a level of income higher than mono-Si power plant. Also, this result is predictable from performance index (PR) of power plants of thin films higher than mono-Si type showed in Fig. 13. This interesting result will make it possible to plan the cost of maintenance and operation of the PV plants from the study phase to make the right choice of PV module technology. Also, the knowledge of the threshold will allow making a profitable cleaning of the PV panels according to the site studied. It should also be noted that in countries with

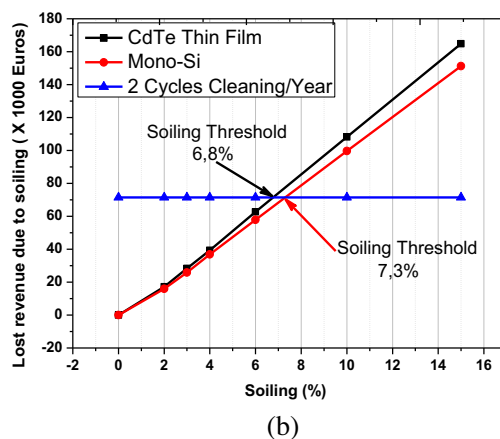


Fig. 16. Panels' technology effect on profitability of cleaning of PV plant 5 MW at Ouargla Saharan site. (a) Annual revenue from guaranteed FIT. (b) Annual lost revenue due to soiling and estimation of cleaning profitability from soiling threshold.

regular rainfall, it is generally not economical to clean the panels because the level of soiling is low between 5 and 7% as shown by previous studies in urbanized areas. In the simulation of the photovoltaic power plants, the soiling parameter is introduced and must be updated regularly according to the chosen site and this becomes possible by connecting with the SKIRON software.

5. Conclusion

The application of large scale PV plants in desert regions necessitates taking in consideration the effect of soiling which is an important factor for Operating & Maintenance cost. In Sahara regions, the average soiling levels (10–15%) shows the importance of cleaning process optimization. The main characteristics of PV plants have been studied as function of soiling level. The studied PV power plant of thin films (CdTe) have a performance index PR that is starting at 81% for zero soiling and dropping to 69% in the case 15% of soiling. Also, PV module technology impact on Performance index and Revenues have been studied in Algerian Sahara. In the case of thin films module technology, superior performance index (PR) is reflected by a higher level of energy production. In this case, more income resulting in a faster return on investment has been demonstrated. Also, it have been noticed that the optimum point for the cleaning of PV plants is at 6.5% of Soiling for solar panels of thin films which is slightly lowers comparatively to monocrystalline Silicon technology. Thus, in the case of solar panels of thin films technology, the profitability for managing the cleaning of PV power plant is recovered more quickly because of superior revenue due to better Performance index (PR) comparatively to Mono-Si technology. This obtained results showed the importance of need to acquire the environmental data of soiling levels of the studied site for the installation of a PV power plants and to simulate their influence on the energy production and revenue from FIT. This became possible by linking data from SKIRON tool for forecasting soiling levels and Helioscope software for modeling of PV plants operation parameters. A particular attention should be paid to the increase in operating costs owing to soiling level from which will depends the best choice of the PV module technology and the threshold level of soiling allowing to recover the costs of the cleaning protocol.

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