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Evaluation of the operational efficiency of 3 MWp photovoltaic power plant situated in the Sahara Desert of Algeria

Messaouda Chaib[1], Abdeldjalil Dahbi[2,3], Ali Benatiallah[1]
[1]Laboratory of Energy Environment and Information System (LEESI), Department of Material Sciences, University of Adrar, Adrar, Algeria
[2]Laboratory of Sustainable Development and Computing (LDDI), University of Adrar, Adrar, Algeria
[3]Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS), Centre de Développement des Energies Renouvelables (CDER), Adrar, Algeria

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ABSTRACT

The primary aim of this study is to examine the behaviour of the photovoltaic plant installed in Kabertene, Algeria, under desert climate conditions. Simulations and modeling have been carried out for the photovoltaic cell, panel, and array under standard test conditions as well as a range of different operating conditions. Furthermore, the photovoltaic (PV) plant has been simulated using measured data, PVsyst, and MATLAB Simulink. The aim was to assess the solar energy potential within the examined geographic area and evaluate the performance of the PV plant. The performance of the obtained results was compared in different cases. The real results closely match those of PVsyst and MATLAB software when using real data and the real performance ratio, because it takes into consideration the cleanliness state of the PV panels. The results indicate that environmental factors, especially solar radiation and temperature, exert a considerable effect on the operational capacity of the PV system. This leads to variations in the electrical energy output and the performance ratio of the system. The total yearly energy injected into the grid was 5028.21625 MWh. The annual average daily PV system performance ratio is 67%. Finally, the research concludes that the area has substantial solar potential, encouraging the development of new PV plants.

Corresponding Author:

Messaouda Chaib
Laboratory of Energy Environment and Information System (LEESI), Department of Material Sciences
University of Adrar
Adrar, Algeria
Email: chaib.messaouda@univ-adrar.edu.dz

1. INTRODUCTION

As the world becomes more aware of the dangers of climate change and efforts are made to curb the release of greenhouse gases [1], [2], the importance of renewable energy becomes more widely recognized. Governments and businesses are increasingly investing in renewable energy technologies, all of them are working for energy transition to obtain more sustainable energy systems. Renewable energies are energy sources that are replenished naturally and can be used indefinitely without depleting the Earth's resources. They include solar, wind, hydropower, geothermal and biomass energy.

Algeria has a considerable potential of renewable energies thanks to its location in the world [3], especially solar energy [4]-[8]. Photovoltaic energy holds particular significance in Algeria due to its vast solar deposit [8]. Algeria's energy strategy aims to accelerate the expansion of solar energy. The government has initiated multiple photovoltaic projects with a combined capacity of around 800 MWp by 2020. Additionally, further projects with a capacity of 200 MWp per year are planned for implementation within 2021-2030 [9]-[12]. Currently, Algeria has 23 photovoltaic (PV) power plants that have been set up by the company Electricity and Renewable Energy Company (SKTM) starting in 2014.

The plants are classified into three categories according to geographical location: the Eastern High Plateaux, the Western High Plateaux and the Southern. Six of these plants were installed in Adrar: 9 MW in Timimoune, 20 MW in Adrar, 6 MW in Zawiat Kounta, 5 MW in Aoulef and 5 MW in Reggan, 3 MW in Kabertene. This study will be focused on the photovoltaic power plant of Kabertene located in Adrar, which has not been studied yet. Most research works on photovoltaic stations were done using one simulation method and software, or they did not use real parameter (weather and electrical parameters), or they neglect the dust effect on the performance ratio [13]-[18]. However, this paper describes the performance Analysis of the photovoltaic system under desert climate using both (MATLAB, PVsyst) software with a comparison between simulation results and the real measured values. Moreover, this study explains the causes of differences between the real measurement values and those obtained from software or simulated model. The importance of cleaning PV panel has been also investigated to have good efficiency and accuracy. Based on the obtained results, it is recommended to use real performance ratio (PR) that makes the simulation results closer to real results, because it takes in account all climate parameters, electrical loses and even the cleaning stat of panels, otherwise this point should be taken in consideration.

This paper is divided into four sections. The second one is devoted to the system description (the site's geographic location, the PV power station, and its characteristics). The third section is devoted to the simulation using different software (PVsyst and MATLAB) with real data measurements. Results and discussions using are presented in this section with comparisons. The conclusion is given in the last part of this paper.

2. METHOD

2.1. Kabertene's photovoltaic power plant (3 MWp)

Kaberetene photovoltaic power plant extends over than six hectares with a capacity of 3 MWp. It is installed near KSAR Kabertene, about 60 km from the Wilaya of Adrar, Algeria (31° 50 Nord et 0° 78 Est). Figure 1 shows the PV plant from an aerial view. The modules utilized are polycrystalline photovoltaic panels. The plant comprises three sub-fields. It includes equipment to convert the DC power generated by the PV arrays into 30 kV AC power for grid injection.

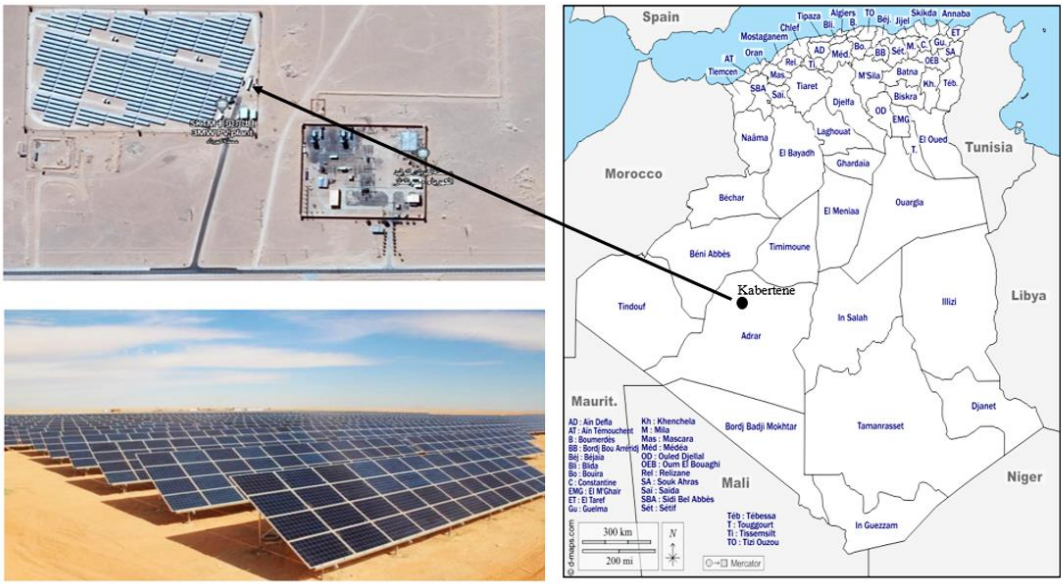


Figure 1. Geographic location of photovoltaic plant

2.2. Solar plant overview

Kabertene's PV plant consists of 3 sub-fields, each producing 1 MWp. It utilizes 93 matrices, with 44 panels per matrix arranged in two strings of 22 serially-connected panels each. Every eight strings (four matrices) link to a combiner box, three combiner boxes are linked to a single parallel box. Subsequently, four of these parallel boxes are interconnected to a general box situated within a shelter. This shelter houses two general boxes and two inverters. Each general box is then coupled to an inverter (DC/ AC), which in turn is connected to a step-up transformer that raises the voltage from 315 V to 30 kV. Via this transformer, the inverters inject energy into the electrical network via a busbar. Figure 2 provides a diagram of the Kabertene photovoltaic plant. The meteorological data, as well as the AC power provided to the electrical network, are monitored continuously and measured at frequent intervals of every quarter-hour by the SKTM service team. The key parameters and specifications of the photovoltaic system are shown in Table 1.

The photovoltaic panels used in the PV plant are polycrystalline. It is branded YINGLI SOLAR, by a Chinese manufacture. The characteristics of the panels in standard test conditions (STC, (T = 25 °C, G = 1000 W/m^2)) are shown in Table 2. The polycrystalline cells are made from multiple crystals. The low manufacturing cost is among its advantages compared with Monocrystalline. But its drawback is the lower yield relatively.

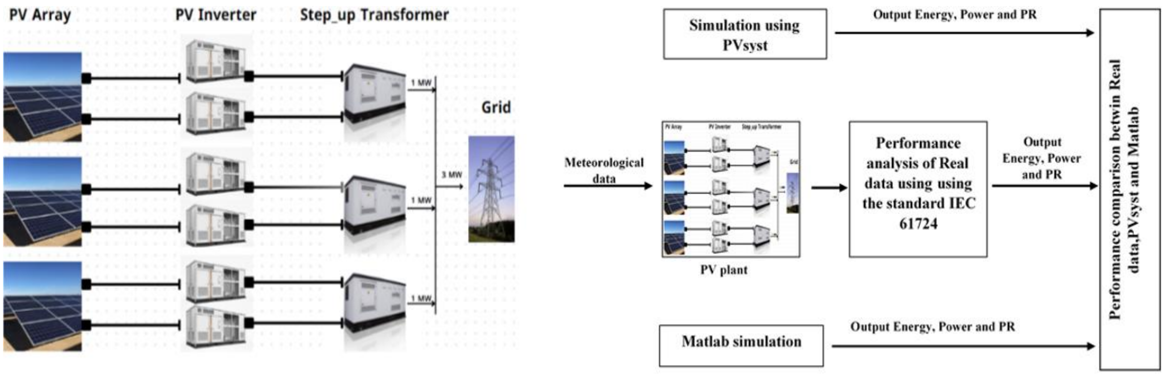


Figure 2. Description diagram of proposed grid-tied PV plant study

Table 1. Specifications of the analyzed PV plant

Design parameter	Characteristics
Power output	3 MW
Sub-array count	3
Total modules	12276
Modules per sub-array	4092
Strings per sub-array	186
Modules per string	22

Table 2. Photovoltaic module specifications

Parameters	Specification
Manufacturer	Yingli Solar YL245-29b
Cell technology	Polycrystalline
Power at STC (W)	245
Vmp (V)	29.6
Imp (A)	8.28
Voc (V)	37.5
Isc (A)	8.83

2.3. Theoretical modelling of the PV system

2.3.1. Modelling of the solar PV cell

The photovoltaic panel is solar cell is compound from solar cells integrated, either in a series or parallel. The PV solar cells can be represented by an electrical circuit model [19], [20], as in Figure 3. In this diagram, the current generator translates the luminous flux, the diode represents the polarization phenomena. While, the two resistors (serial and shunt) represent respectively the contact and connection resistance and the leakage current at the cell junction [21]-[24]. The output current from a photovoltaic cell can generally be expressed through the following mathematical (1). This mathematical form shows the relationship between the output current and other parameters that impact the cell's performance:

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

Knowing that: I_{ph}: depicts the current produced by the PV cell under illumination; I_{sh}: represents the current flowing in the resistor Rsh; I_d: represents the current of the diode. This later is written as (2).

$$I_d = I_s \left(exp \left(\frac{V+I \cdot R_s}{aV_T} \right) \right) \tag{2}$$

Knowing that: 'I_s' represents the diode's reverse saturation current, which is expressed by (3).

$$I_s(T) = I_{sn} \left(\frac{T}{T_{STC}} \right)^{\frac{3}{a}} exp \left[\left(\frac{qE_g}{a \cdot K} \right) \left(\frac{1}{T_{STC}} - \frac{1}{T} \right) \right] \tag{3}$$

The current that represents the diode reverse saturation current in STC is expressed as (4).

$$I_{sn} = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{a.V_T}\right)-1} \tag{4}$$

For the improvement of (3) by substituting (5), it becomes:

$$I_s(T) = \frac{I_{sc}+K_I.\Delta T}{exp\left(\frac{V_{oc}+K_V.\Delta T}{a.V_T}\right)-1} \tag{5}$$

Where ΔT is defined by (6).

$$\Delta T = T - T_{STC} \tag{6}$$

The photo-current I_{ph} is defined by (7).

$$I_{Ph} = \left[I_{Ph,STC} + K_I (T - T_{STC}) \right] \frac{G}{G_{STC}} \tag{7}$$

with: $I_{ph,STC}$: Corresponds to the photocurrent produced by the PV cell under the reference temperature. T_{STC}: represents the nominal temperature obtained in STC, T_{STC} = 25 °C; G: represents the solar irradiance given in W/m^2; G_{STC}: represents the nominal solar irradiance obtained in STC at G_{STC} = 1000 W/m^2.

The equation of current generated by the PV cell is as (8).

$$I = I_{Ph} - I_S \left[exp \left(\frac{V+IR_S}{aV_T} \right) - 1 \right] - \left[\frac{V+IR_S}{R_{sh}} \right] \tag{8}$$

Manufacturers do not provide the values of five critical parameters (Is, Iph, a, Rs, and Rsh) Instead, they only supply some experimental values measured under (STC). These values include the open-circuit voltage (V_{oc}), short-circuit current (Isc), the voltage (Vmp) and current (Imp)respectively at MPP. The open circuit voltage/temperature coefficient kv), short circuit current/temperature coefficient (ki) and the maximum experimental peak output power (Pmax_e). These parameters are always used in the model.

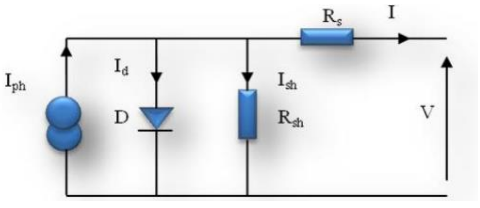


Figure 3. Electrical circuit model equivalent to photovoltaic cell

2.3.2. Modelling of the photovoltaic module

A photovoltaic module is an assembly of interconnected solar cells. The schematic module equivalent circuit include a series arrangement of Ns cells and a parallel configuration of Np cells, as in Figure 4. The general equation describing the output current of a PV array can be represented as (9).

$$I = N_p \times I_{ph} - N_p I_S \left[exp\left(\frac{\frac{V}{N_S} + \frac{I \times R_S}{N_P}}{K \times T_C \times A} \right) - 1 \right] - \frac{\left(\frac{N_P \times V}{N_S} + I \times R_S \right)}{R_{sh}} \quad (9)$$

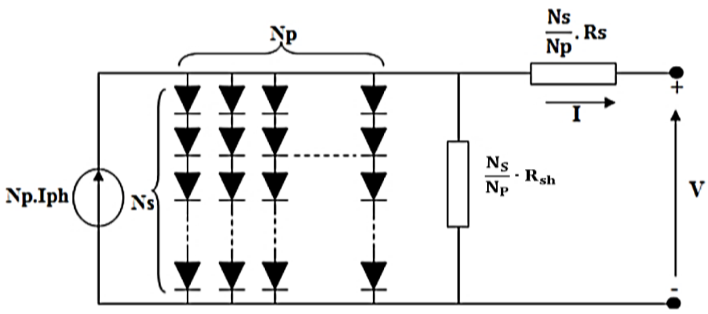


Figure 4. General model of a photovoltaic panel

2.4. PV system specifications for performance assessment

The International Energy Agency (IEA) has established performance parameters to analyze grid-connected photovoltaic systems. These parameters provide a comprehensive pre-feasibility analysis of the PV system, encompassing: array yield, reference yield, final system yield, array capture losses, system losses, capacity utilization factor, performance ratios, inverter efficiency, system efficiency, and energy injected into the grid as exhibited in Table 3 [14], [25]-[32].

Table 3. Evaluation metrics for photovoltaic (PV) plant performance

Evaluation metrics	Equations	Comments
Array yield (YA) and final yield (YF)	$Y_A = \frac{E_{DC.d}}{P_{rated}}; Y_{F.d} = \frac{E_{AC.d}}{P_{rated}}$ $Y_{F.m} = \frac{1}{N}\sum_1^N Y_{F,d}; Y_{R.d} = \frac{\tau * \sum G_t}{G_{STC}}$	P_{rated}: rated power produced by the photovoltaic plant
Reference yield (YR)	$Y_{R.m} = \frac{1}{N}\sum_1^N Y_{R,d}$	G_t: The incident solar radiation (kW/m^2) G_{STC}: Reference solar radiation (1 kW/m^2)
Performance ratio (PR) and system losses (Ls)	$PR = \frac{Y_F}{Y_R}; L_s = Y_A - Y_F$	
Array losses (L_C) and total energy losses (L_T)	$L_C = Y_R - Y_A; L_T = Y_R - Y_F$	
Capacity factor (CF)	$CF_y = \frac{E_{AC,y}}{P_{PV,rated} * 8760}; CF_m = \frac{E_{AC,m}}{P_{PV,rated} * 24 * N}$	y: is the yearly period
System efficiency	$\eta_{sys,\, m} = \frac{E_{AC,m}}{H_{t,m} \times A_a}; H_{t,m} = \sum_1^N (\tau \sum_1^{96} G_t)$	$H_{t,m}$ the monthly total in-plane irradiation (kWh/m^2)

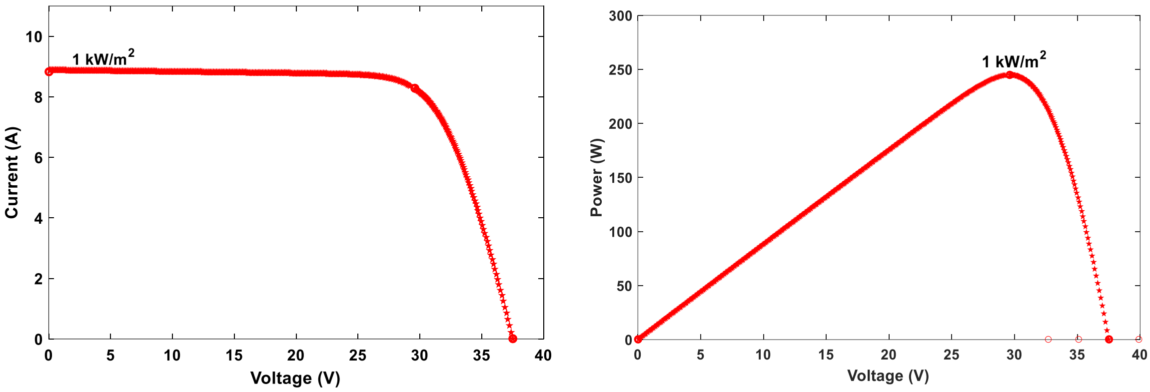
3. RESULTS AND DISCUSSION

3.1. Simulation using different software with real data analysis

3.1.1. Simulation results of PV modules using MATLAB Simulink

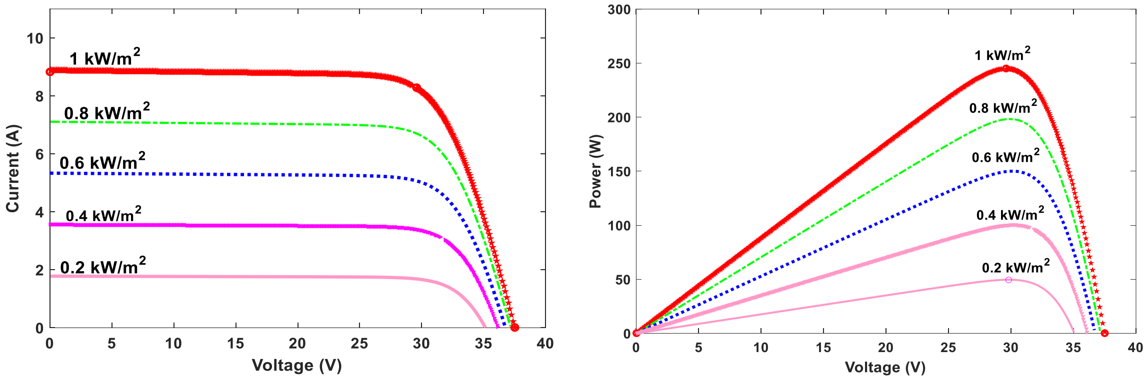
The following section represents the simulation results using MATLAB for the real PV module (YL245-29b) characteristics in STC condition, then for various irradiations and temperatures, as in Figures 5-7. The simulated I(V) and P(V) curves of the examined 245 W polycrystalline PV panel under standard test conditions (25 °C, 1000 W/m²) are presented in Figures 5(a) and 5(b) respectively. The short circuit current is 8.83 A, and the open circuit voltage V_{oc} is around 37.5 V, matching the values from the real characteristics. Figure 6(a) depicts how the current-voltage profile changes with varying irradiation levels. Clearly, the current scales linearly with irradiation, while the voltage is not heavily influenced.

Figure 6(b) illustrates the impact of irradiation changes on the power characteristic. Higher irradiation leads to increased power output levels. From Figure 7(a), it can be seen that voltage rises proportionally with temperature, but current remains roughly constant. Consequently, maximum power output varies with the voltage and current changes. Figure 7(b) shows that at 1000 W/m² irradiation, temperature does not affect power output as significantly as irradiation itself. After simulating and analyzing the panel's performance under different conditions, the polycrystalline photovoltaic plant was simulated using MATLAB and PVsyst.



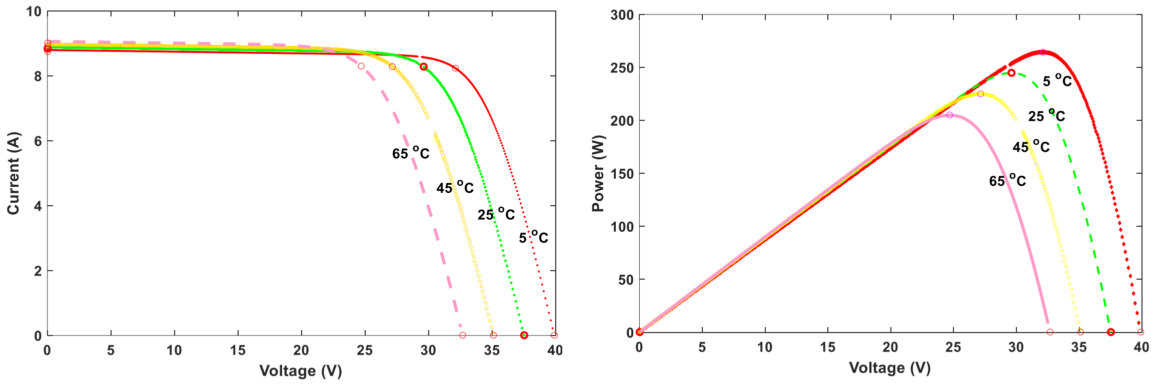
(a) (b)

Figure 5. I-V and P-V curves of YL245-29b module in STC conditions: (a) current-voltage (I-V) curve PV panel and (b) power-voltage (I-V) curve PV panel



(a) (b)

Figure 6. Influence of solar irradiation on the I-V: (a) and P-V and (b) curves of PV panel



(a) (b)

Figure 7. Influence of temperature on the I-V: (a) and P-V and (b) curves of PV panel

3.1.2. Simulation using PVsyst

The PVsyst software tool was used to simulate the photovoltaic system, inputting the same specifications as the real-world PV system. This simulated model incorporated PV modules, inverters, and a grid interface network, the details of which are presented in Table 4. The data presented in Table 5 reveals a promising level of solar energy availability in Kabertene. The solar potential fluctuates from 3.34 kW/m^2 during the month of December to a higher value of 7.36 kW/m^2 in July. Across the entire year, the average solar energy potential stands at 5.52 kWh/m^2 per day. Photovoltaic panels can advantageously utilize this solar potential when their tilt angle is optimally set at 30 degrees. The monthly variations of climatic data in Kabertene photovoltaic power plant are shown in Table 5.

Table 4. Parameters of the polycrystalline PV power plant

Category	Parameter	Value
Geographical location	Latitude	28°27'06" North
	Longitude	0°02'52" West
	Altitude	279 meters
PV field orientation (Fixed)	Tilt angle/Azmuth	30°/ 0
System input	PV module	12276 units (Yingli Solar _YL245-29b)
	Unit power	245 Wc
	Lenght	1650 mm
	Width	990 mm
	Number of inverters	06
	Model	Sungrow_SG500MX
	Unit power	500 kWc
	Operating voltage	500-850 V
	Report Pnom (DC: AC)	1.00

Table 5. Monthly variations of climatic data in Kabertene PV plant

	Global horizontal irradiation Wh/m^2/day	Horizontal diffuse irradiation Wh/m^2/day	Temperature °C	Wind velocity m/s	Link turbidity [-]	Relative humidity %
January	3.74	1.22	12.4	5.20	3.917	37.5
February	4.60	1.62	15.6	5.69	4.644	29
March	5.53	2.22	20.9	5.99	6.595	21.7
April	6.50	2.68	25.3	6.10	7	18
May	6.81	3.03	30.8	6.30	7	13.2
June	7.36	3.34	34.8	5.80	7	12
July	7.35	3.23	38.4	5.90	7	10.8
August	6.62	3.19	37.5	5.70	7	11.7
September	5.57	2.58	33.1	5.30	7	20.4
October	4.62	2.07	27.3	5.20	7	26.5
November	4.07	1.31	18.5	5.10	4.731	36.1
December	3.43	1.19	13.7	5.30	4.037	43.3
Year	5.52	2.31	25.7	5.6	6.037	23.3

3.1.3. Real measured data analysis

This study also evaluates the efficiency of the installed grid-tied photovoltaic power plant, aiming to identify promising solar PV technologies and guide deployment strategies in Southern Algeria. Figure 8 presents monthly weather data during the hours of sunshine in 2022 to analyze the behavior of the PV system under desert conditions. The plotted monthly average weather parameters include global solar irradiation (G) and ambient temperature (Ta) to understand the system's performance.

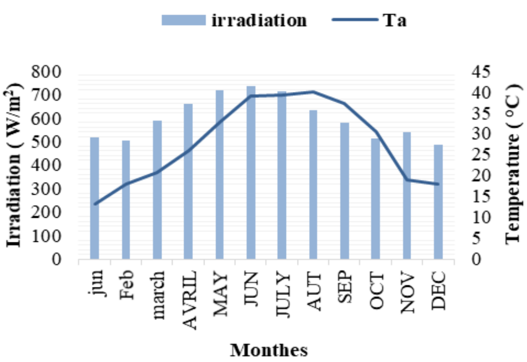


Figure 8. Monthly average temperatures and solar irradiation evolution in Kabertene, (Algeria)

The received solar radiation quantity ranges from a low of 485 kWh/m^2 per month in December 2022 to a high of 737 kWh/m^2 per month in June 2022. The average ambient temperature at this site is 28 °C. The maximum ambient temperatures occur during June, July, and August when solar radiation is also at its peak.

The reduced solar radiation levels in other months result from the sun's position as well as sky cloudiness and dust from sand winds, which can significantly impact the radiation reaching the solar PV modules

3.2. Comparison between simulation results and real data

This section detailed a comparison between the real photovoltaic plant measured data and software simulation results using PVsyst and MATLAB.

3.2.1. Real measured data with PVsyst

Figures 9 and 10 present respectively the comparison between real measured data and PVsyst simulation results of monthly average temperature and global horizontal irradiation (GHI). It is noted that the direction of the variations of the quantities (T, G) is the same in the both real and PVsyst cases. However, there are small differences in temperature and others in illumination. These differences are mainly due to the estimation methods of the areas where there are no measurement stations because of the high cost of this solution. As well as the method used for data estimation (Metronome, NASA, PVGIS, and TMY), and the given years of the data bases. These parameters give reasonable results but their differences cause some errors.

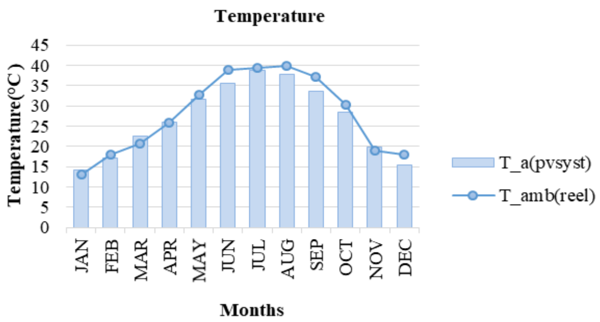


Figure 9. Evaluating the monthly average temperature between real data and PVsyst

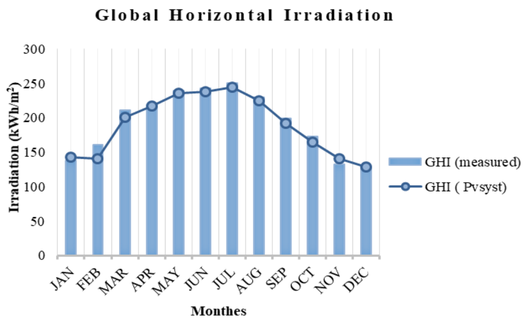


Figure 10. Comparing the monthly average global horizontal irradiance between real data and PVsyst

Figure 11 presents the comparison between real performance ratio and simulated PR using PVsyst. According to the provided information from SKTM about the months where the cleaning was performed in (April, November), Figure 11. It is clear that when the PV panels are cleaned, the real PR increases strongly and becomes closer to Pvsyst PR. Then, it decreases gradually due to dust and the increasing of temperature. The PR of Pvsyst is reasonable, but it does not take all the parameters of the PV system and the state of the PV panels; especially the cleaning, which makes differences between (PR Pvsyst and real PR), Figure 11.

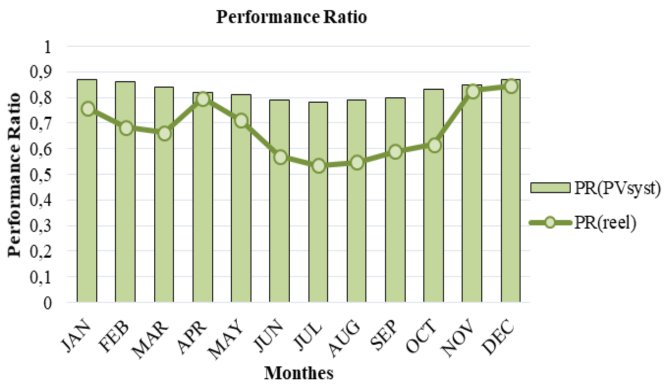


Figure 11. Comparison of PR between real data and PVsyst

3.2.2. Real measured data with MATLAB

Figure 12 shows the comparison between real and simulated power. While Figure 13 clarifies the importance of the consideration of the cleaning state of panels. It is noticed that the values of the product between the power simulated by MATLAB software and PR (real) are almost equal the real measured power, which opens several possibilities to make the model more efficient for the estimation of the energy production as well as the fault detection in the photovoltaic system.

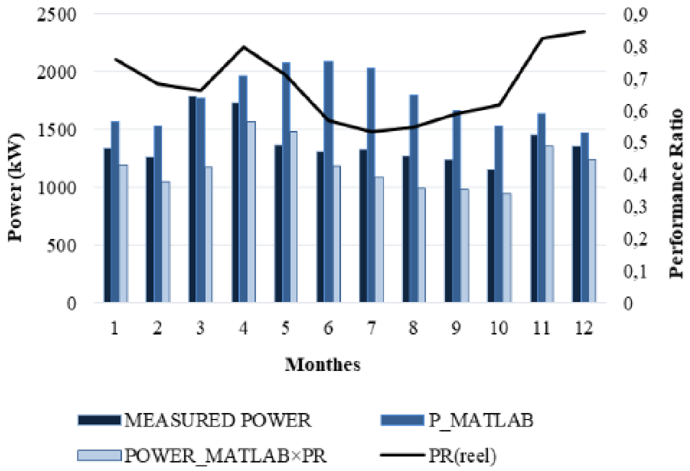


Figure 12. Performance ratio and power of the PV system in 2022

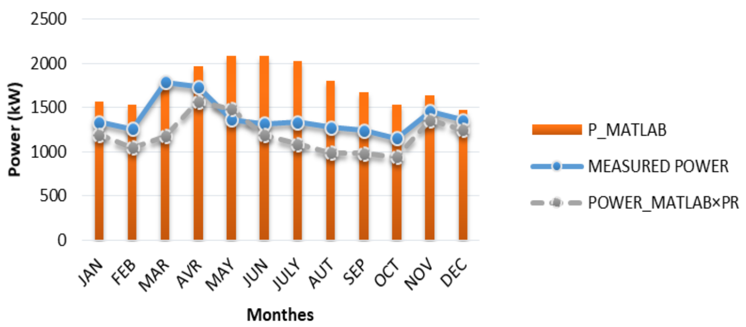


Figure 13. Comparison of different terms of power

3.2.3. Energy field output

Figure 14 shows the comparison of energy field output between MATLAB and PVsyst software. It is noted that the produced energy calculated by PVsyst and MATLAB using the real data are almost equal, especially in months when the panels are cleaned (April, November), because the real performance index becomes almost like that of PVsyst when the panels are clean. Figure 15 presents the daily produced energy. While Figure 16 shows the annual production rate. The data illustrates a reduction in energy generation during summer months, due to elevated temperature that impacts the panels efficiency, Figure 16. However, an upward trend is observed in the spring season.

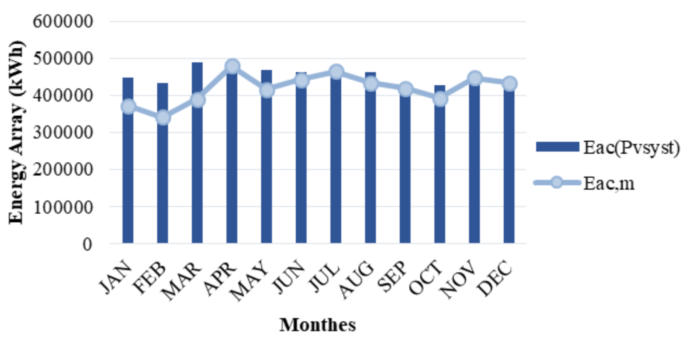


Figure 14. Comparison of energy field output between MATLAB (E_{ac}, m) and PVsyst software (E_{ac}, PVsyst)

Figure 17 illustrates both the energy input and output, accompanied by a detailed breakdown of losses. It serves as a valuable instrument for assessing plant efficiency. The total energy injected into the grid amounts to 5561 MWh. The nominal energy of the array is approximated at 6591 MWh. Consequently, the variance of 1030 MWh represents the comprehensive losses within the system, as indicated in Figure 17. The energy produced constitutes roughly 84.4% of the nominal energy of the array under STC conditions, with losses making up about 15.6%. These losses, such as temperature effects, ohmic wiring losses, electric connections, and component losses, collectively contribute to the overall reduction in energy output.

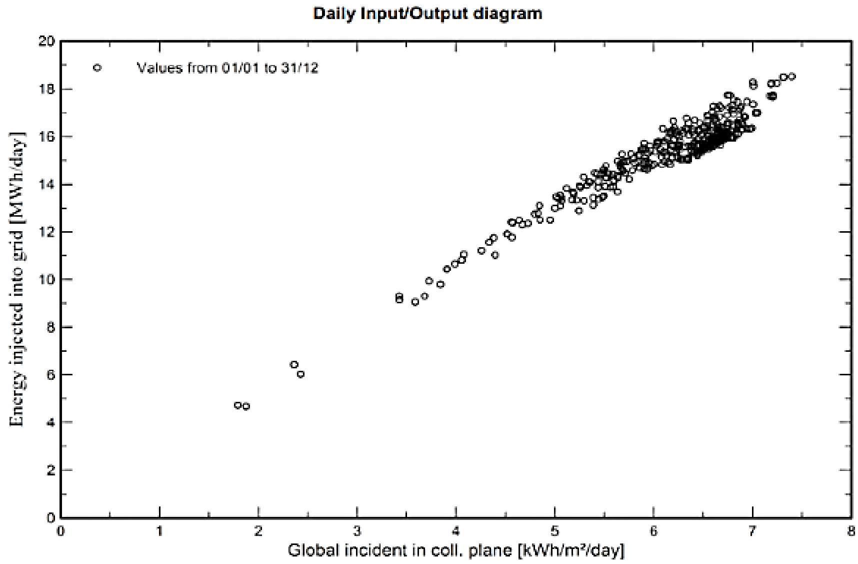


Figure 15. Daily produced energy

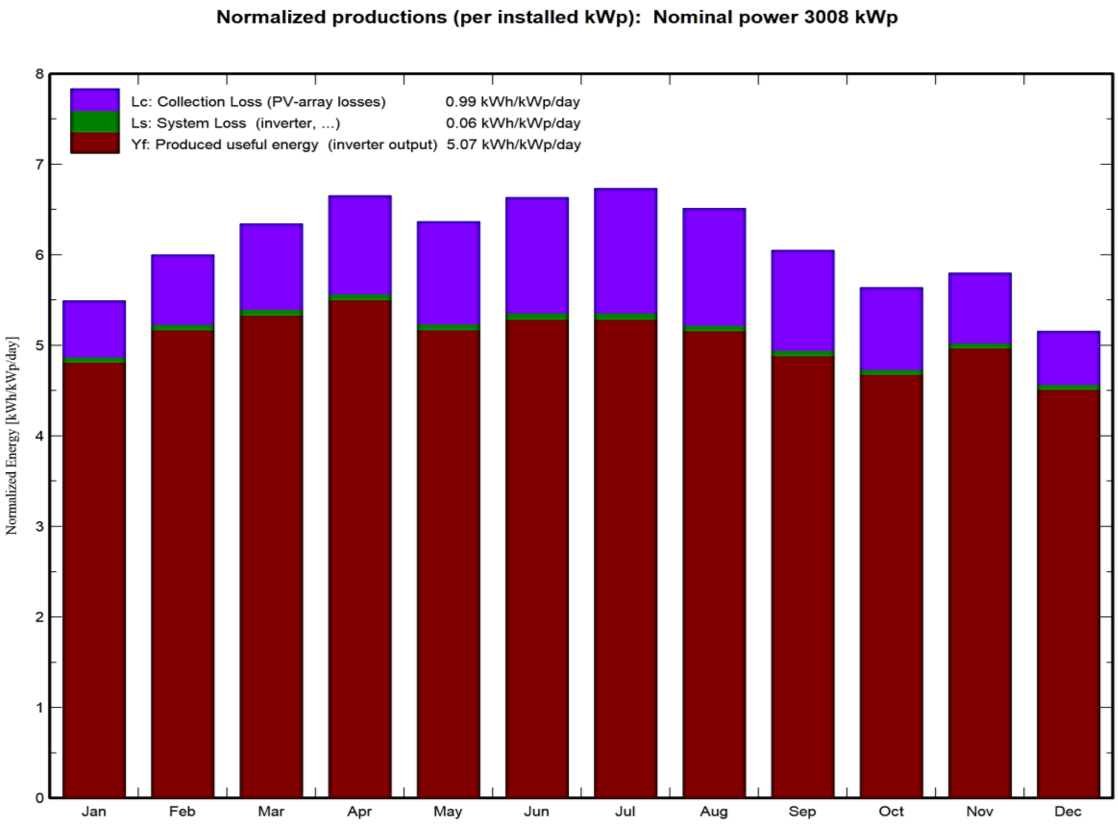


Figure 16. Histogram of annual production rate

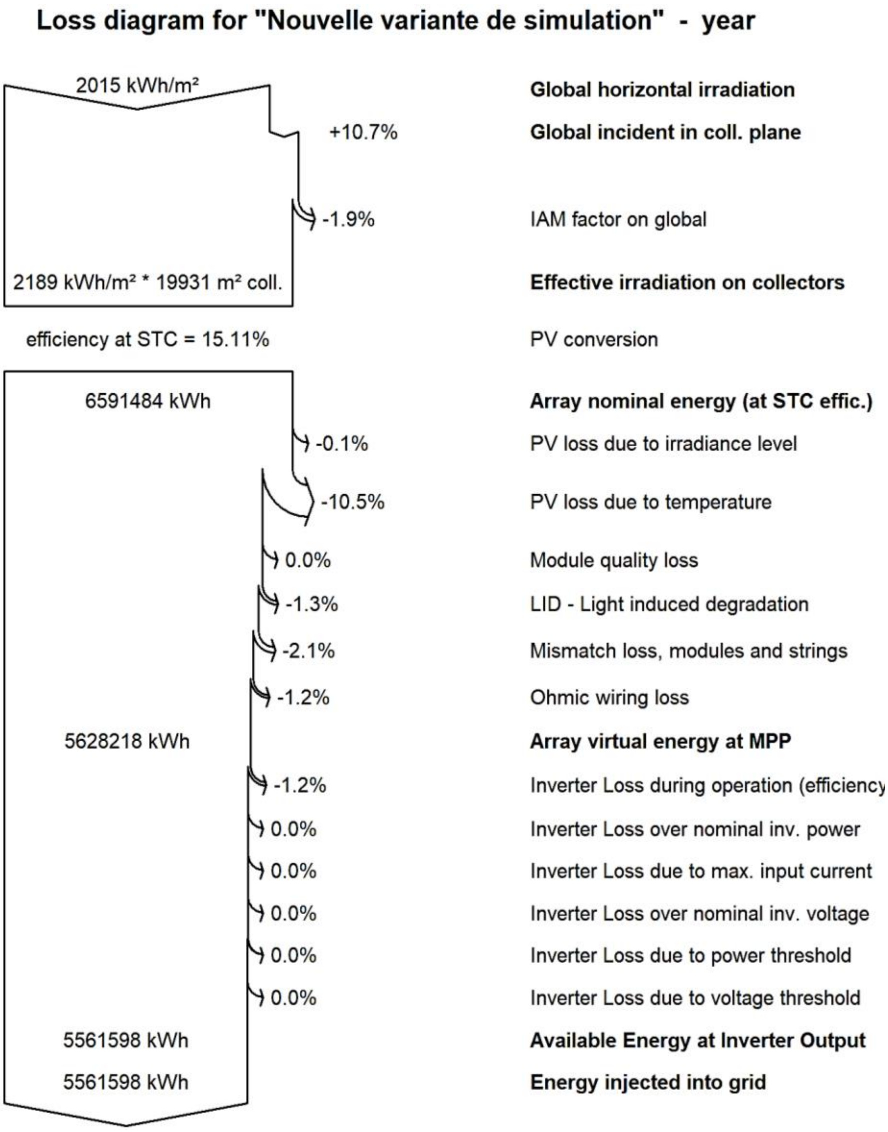


Figure 17. Loss diagram over the year

4. CONCLUSION

The paper analyzes and simulates a real polycrystalline photovoltaic (PV) plant located in the desert region of Kabertene, Adrar, Algeria. The main goals are to assess the solar energy potential of this area and evaluate the performance of the PV plant under desert conditions. The analysis was conducted using both MATLAB and PVsyst software, allowing for a comparison between simulation results and real data. It is observed that the major advantage of PVsyst is its ability to generate an installation reports and examine the output power and losses with weather estimation. However, MATLAB is more suitable for the simulation studies in small time intervals. In both cases, the cleanliness state of the PV panels should be taken into consideration when calculating the performance ratio (PR) to obtain accurate approximations.

The studied PV plant has been simulated using climate data from the same region. The findings reveal a favorable solar potential in the studied area (GlobHor: 128.8 kWh/m2 in December to 245 kWh/m^2 in July) and extended solar durations reaching up to 15 hours. However, it is observed that variations in climate conditions, particularly temperature and irradiance, have a significant impact on the output energy. The energy injected into the grid is directly proportional to the irradiation levels, ranging from a minimum of 421.4 MWh in December to a maximum of 497.5 MWh recorded in March. Furthermore, the output energy is influenced by other parameters especially dust accumulation. The simulations in MATLAB and PVsyst were more accurate when considering panel cleanliness. Excluding dust accumulation led to increased errors. The results encourage solar investments in the region but emphasize researching dust mitigation strategies to improve yield and efficiency.

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BIOGRAPHIES OF AUTHORS

Chaib Messaouda is a Ph.D. student in Material's Sciences Department at the University of Adrar, Algeria. She received her B.Math. in 2016 then, licence degree in physics of material from University of Adrar, in 2019. After that, she obtained the master degree in Energetic Physics and Renewable Energy from the same university, in 2021. Her research interests include the field of engineering physics, renewables energy, environmental engineering, artificial intelligence, and intelligent control. She can be contacted at email: chaib.messaouda@univ-adrar.edu.dz.

Abdeldjalil Dahbi presently serving a principal researcher at the Research Unit in Renewable Energies in the Saharan Medium (URER-MS), Adrar, Algeria. He holds degrees in Electromechanical Engineering, Technical English, Electrical Controls, Energetic Physics, and a Ph.D. in Electric Controls. He became a professor in June 2023. His expertise includes renewable energy systems, wind energy, electric smart control, photovoltaic systems, remote control, meteorology, and IoT. He has published several papers, patents, and books. He also reviews for international conferences and journals, including IEEE and Elsevier. He can be contacted at email: dahbi_j@yahoo.fr.

Ali Benatiallah is currently a professor (hydrocarbure and renewable energy) and head of Faculty Scientific Council at Adrar University, Algeria. He received his engineering in Physics in 1991. He received another diploma of master in energy (physics) in 1994. He received his doctorate degree in Electric Controls in 2006. He has many posts in University of Adrar over his career: a member of the Science and Technology Faculty Scientific Counsel in 2007, head intensive Language Centre (SM) in 2011, president Science and Technology Faculty Scientific Counsel in 2014, head of energy environment laboratory in 2016. Furthermore, he realized many scientific events. He was a head of a doctorate project, chair of International Conference (ICHREME'23) Adrar. He authored numerous scholarly works, which have undergone presentation and publication processes at both international and national conferences. He can be contacted at email: ali.benatiallah@univ-adrar.edu.dz.