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Performance analyses of grid-connected photovoltaic power system

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Abstract - *Grid-connected photovoltaic systems are required to introduce photovoltaic solar energy into urban areas. To analyze these systems, a 15 MWp power system has been installed at the site of Oued Keberit a town and commune in Souk Ahras, province in North-Eastern Algeria. The array power output was estimated by using measured I – V curves for the installed modules with minimization of mismatch losses. The supplied grid energy and main performances are described. Results show an annual performance of 83.9 % and the energy production is 23 735 MWh/year, which is sufficient energy to Power approximately 5 000 homes with clean renewable energy.*

Résumé - *Des systèmes photovoltaïques connectés au réseau sont nécessaires pour introduire l'énergie solaire photovoltaïque dans les zones urbaines. Pour analyser ces systèmes, un système d'énergie de 15 MWc a été installé sur le site de l'Oued Keberit, une ville et une commune de la province de Souk Ahras au Nord-Est de l'Algérie. La puissance de sortie du réseau a été estimée en utilisant des courbes I - V mesurées pour les modules installés, avec une minimisation des pertes de désadaptation. L'énergie de la grille fournie et les principales performances sont décrites. Les résultats montrent une performance annuelle de 83.9 % et la production d'énergie est de 23 735 MWh / an, ce qui représente une énergie suffisante pour alimenter environ 5 000 foyers en énergie renouvelable propre.*

Mots-clés: Photovoltaïque - Grid - Connecté - Ratio de performance - Logiciel PVsyst.

1. INTRODUCTION

Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts.

Hence they are used for a power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even megawatt-scale power plants [1].

The solar photovoltaic systems have been installed in various parts of the globe for power generation where the grid connectivity is neither feasible nor possible due to inaccessible locations. Generation of electricity through solar photovoltaic (PV) system is clean, reliable and environment-friendly. Solar PV systems have the potential to become a major source of electricity generation in future due to rapid reduction of fossil fuel.

Electricity generation through solar PV system has shown an impressive growth around the globe with an annual total new addition of 50 GW during 2015. China added the highest of 15.2 GW while India added 2 GW during 2015 among the top ten solar power producing countries [2]. The global PV installed capacity at the end of 2015 was estimated as 227 GW as compared to 3.4 GW in 2004. This shows a tremendous growth of solar PV installation for power generation over the last ten years.

Algeria is a country with a privileged solar resource, which has already implemented stand-alone photovoltaic power systems in isolated areas [3]. In 2012, Algeria began a process of green power by launching an ambitious program of development of renewable energy and energy efficiency.

This program consists of installing a renewable power of nearly 22 000 MW between 2012 and 2030, will be dedicated to cover the national demand for electricity. In April 2014, a law concerning the energy feed-in tariff for photovoltaic installations over 1MW was promulgated. By 2030, about 40 % of the production of electricity for domestic consumption is from renewable sources [4].

In this paper, we will use the coefficients of performance established by the International Atomic Energy, Agency Photovoltaic Power Systems Program and described in IEC61724 [5]. We assess three performance parameters of this standard to define the overall system performance compared to the impact of energy production, solar resources, and all system losses. These parameters include the final PV system yield, reference yield, and performance ratio.

2. GEOGRAPHICAL LOCATION OF THE SITE

Oued Keberit is a town and commune in Souk Ahras, Province in North-Eastern Algeria. It is located at latitude 35°55'28 North and longitude 7°55'1" East, figure 1. The temperature ranges from 22.9 °C to 26.3 °C the summer and reaches to as low 10.2 °C in the winter.

This provides an ideal environment for any Photovoltaic power plant projects [6]. Therefore, it is a perfect location for implementing the PV power plant for our study.

Fig. 1: Geographical location of the site

3. DESCRIPTION OF THE SOLAR PV- GRID SYSTEM

A grid-connected PV system consists of solar panels, inverters, a power conditioning unit and grid connection equipment. It has effective utilization of power that is generated from solar energy as there are no energy storage losses.

When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load to the utility grid.

The proposed model is illustrated in figure 2 by the PVsyst software.

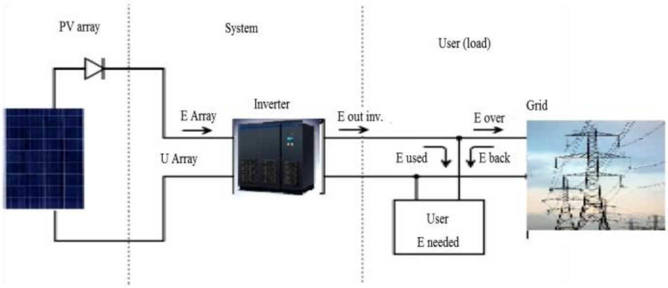


Fig. 2: Schema of PV Grid –Connected System

4. SYSTEM SPECIFICATIONS

4.1 Module used in the system

Table 1 depicts the characteristics of PV module used in our study which is the maximum power at STC (Pmax) is 250 W.

Table 1: Characteristics of PV module used in the system

Manufacturer	Yingli Solar
Model	YL250-29b
Technology	Si-poly
Maximum power at STC, Pmax	250 W
Short-circuit current, Isc	8.837 A
Open circuit voltage, Voc	37.73 V
Optimum Operating voltage, Vmpp	30.23 V
Optimum operating current, Impp	8.273 A
Efficiency	17.13 %
Module area	15.40 m^2

4.1.1 Modeling of photovoltaic panels

Recently, researchers have proposed various models for simulation and modelling of photovoltaic systems. It is invaluable effort as it may lead us to the real model. In this study, single diode model is employed as it is simpler and closer to the actual model.

Figure 3 depicts single diode model of a photovoltaic cell. [7, 8].

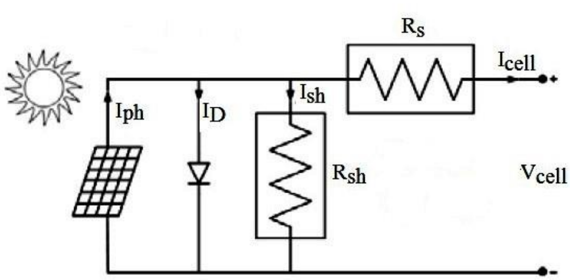


Fig. 3: One-diode equivalent circuit for a PV cell [9]

If the Kirchhoff current law is applied to the circuit in figure 3 [10].

$$I_{cell} = I_{ph} + I_D + I_{sh} \tag{1}$$

The net electron, hole, and diode current with Boltzmann distribution are:

$$I_e = I_{e0}\left(e^{\frac{qV_D}{KbT}} - 1 \right) \quad (2)$$

$$I_h = I_{h0}\left(e^{\frac{qV_D}{KbT}} - 1 \right) \quad (3)$$

$$I_D = I_e + I_h = I_0\left(e^{\frac{qV_D}{KbT}} - 1 \right) \quad (4)$$

Where q is the electron load (1.602 x 10^{-19} C), and k is the Boltzmann constant (1.381 x 10^{-23} J/K). The source current expression of the solar cell equivalent circuit shown in figure 2 is obtained in {Eq. (5)} by applying Kirchhoff's voltage law [11, 12].

$$I_D = I_0\left(e^{\frac{qV_D}{MkT}} - 1 \right) = I_0\left(e^{\frac{(qV)_{PV} + IR_s}{MkT}} - 1 \right) \quad (5)$$

N_{pc}, Number of parallel panels in connected series with others constitutes the PV panels. Total voltage of the series PV array can be evaluated by adding the voltages of each PV. Total current of the shunt PV array is also calculated by adding currents of each PV for the fixed voltage [13].

V_m, the voltage applied to the end of the module; I_m, module current

$$V_m = N_{sc} V_{new} \quad (6)$$

$$I_m = N_{sc} V_{new} \quad (7)$$

$$I_{ph} = \left(I_{sc} + \alpha(T_c - 25) \right) \frac{G}{G_{ref}} \quad (8)$$

$$I_{cell} = I_{ph} - I_0\left(e^{\frac{(qV_D)_{pv} + IR_s}{mkT}} - 1 \right) - \frac{(V_{pv} + IR_s)}{R_s} \quad (9)$$

Change in current-voltage characteristics of the panel used in the PV generator and change in power-voltage characteristics depending on the radiation are shown in figure 4 and 5, respectively. While the panel generates 250 W at a temperature of 25 °C and radiation of 1000 W/m^2, it generates 201.1 W for 800 W/m^2 and 150.8 W for 600 W/m^2 [14].

4.1.2 Inclination and orientation

PV panels are optimized for the best orientation according to the solar path in Oued Kebrit, fFigure 6 to gain maximum solar irradiation and the result is that the tilt angle is 35° and Azimuth angle is 00, figure 7.

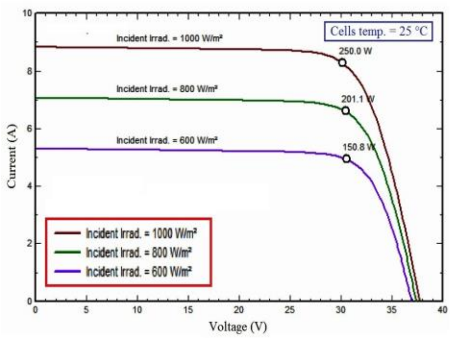


Fig. 4: Change in current-voltage characteristics depending on the radiation

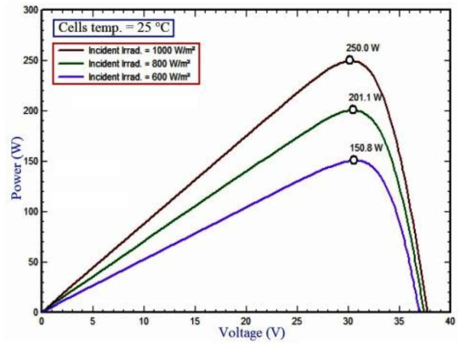


Fig. 5: Change in power-voltage characteristics depending on the radiation

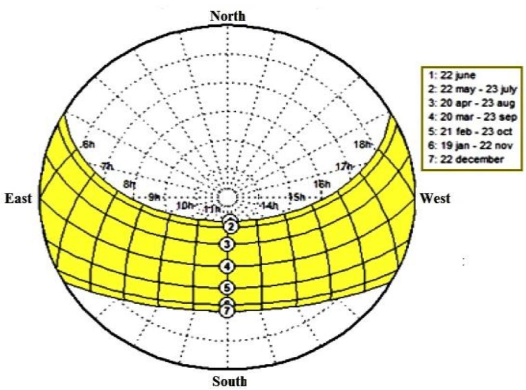


Fig. 6: Solar paths at Oued Keberit, (Lat. 35.9°N, Long. 7.9°E, Alt. 623 m). solar time

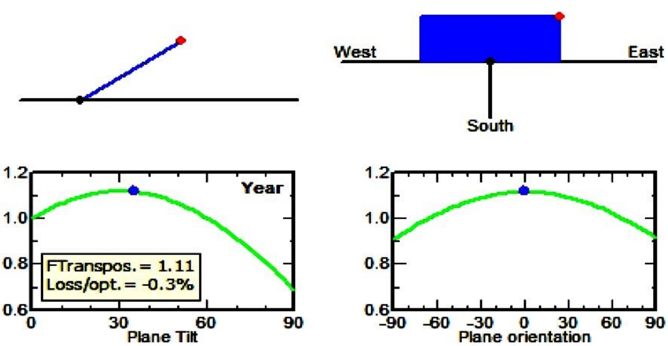


Fig. 7: Inclination and orientation of PV modules used in the system

4.2 Specification of inverter used in the system

This study uses 30 units of 500 kW to get a total of 15 MW (**Table 2**). The output is set to 400 V at 50 Hz for grid compatibility in Algeria [15].

4.3 System components summary

The equipment used to construct the grid-connected PV system for our case study consists of 60 060 polycrystalline modules, 2730 strings in parallel and 22 modules in series to generate 15 000 kWp of power (figure 8). The area required for fixing the panels is 97 513 m^2. The annual energy of the system is 23 735 MWh/year [16].

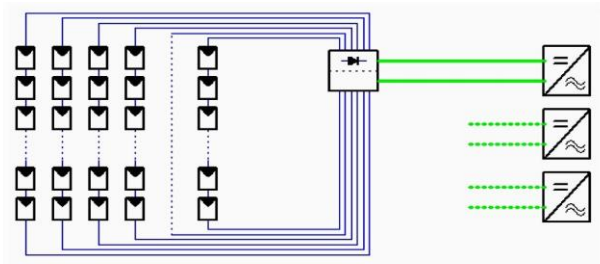


Fig. 8: Global system configuration

5. PERFORMANCE ANALYSIS METHODOLOGY

5.1 Performance parameters

To analyze the performance of a grid-connected system, a number of performance parameters are being developed by the International Electro technical Commission [5] under reference IEC 61724.

These parameters include final yield, reference yield, performance ratio, system efficiency, and capacity factor. The Final yield refers to the total energy generated by the system for a defined period of time (day, month, and year). The annual final yield is given by the expression [17, 18]. (10)

Where E_{AC}, is the total AC energy output (kWh) and $P_{PV,rated}$, is the nominal power of the installed PV array at standard test conditions (STC).

The reference yield Y_R [19, 20] is the total in-plane insolation or global in-plane , horizontal insolation divided by the reference irradiance under standard temperature conditions which is 1 kW/m^2. It is a measure of the theoretical energy available at a specific location over a specified time period. The reference yield can be calculated by:

$$Y_R = H_t / G_0 \qquad (11)$$

5.2 Array and system energy losses

The array capture losses L_A represent the losses due to array operation that highlights the inability of the array to fully utilize the available irradiance [21]. The array capture losses are the difference between the reference yield and the array yield. It is given as:

$$L_A = Y_R - Y_{A}\frac{\text{kWh}}{(\text{kW}_p)} \qquad (12)$$

The system losses L_S areas due to losses in converting the DC power output from PV to AC power by the inverter. It is given as:

$$L_S = Y_A - Y_{F}\frac{\text{kWh}}{(\text{kW}_p)} \qquad (13)$$

Array capture losses are the difference between the reference yield and the array yield.

$$L_C = Y_A - Y_{F}\frac{\text{kWh}}{(\text{kW}_p)} \qquad (14)$$

Finally, the total energy loss (L) from this system is obtained from the difference between the reference yield and the final yield as:

$$L = Y_R - Y_{F\frac{kWh}{(kW_p)}} \tag{15}$$

Concerning the performance ratio (PR), it represents the ratio of energy fed to the grid (final yield) to the energy that the system could have produced had it operated at its rated conditions (STC) of 1 kW/m^2 (reference yield). PR represents the fraction of energy actually available after deducting energy losses [22]. PR is given by:

$$PR = Y_F / Y_R \tag{16}$$

The annual capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it operated at full rated power for 24 h a day for a year and is expressed as [23]:

$$CF = \frac{Y_F}{24 \times 365} = \frac{PR \times Y_R}{8760} \tag{17}$$

5.3 System efficiencies

The efficiency of a PV system can be grouped into PV array efficiency, system efficiency, and inverter efficiency. The array efficiency is based on the DC power output while the system efficiency is a function of the AC power output. The array efficiency η_{PV} represents the mean energy conversion efficiency of the PV array, which is the ratio of daily array energy output (DC) to the product of total daily in-plane irradiation and area of the PV array [21]. The PV module efficiency is calculated by the following equation.

$$\eta_{PV} = (100 \times E)_{DC} / (H_t \times A_m)\,(\%) \tag{18}$$

Where $A_m = \text{array area}\,(m^2)$. The overall system efficiency represents the performance of the entire PV system installed and it is given as:

$$\eta_{PV} = (100 \times E)_{AC} / (H_t \times A_m)\,(\%) \tag{19}$$

The inverter efficiency is given as:

$$\eta_{PV} = (100 \times E)_{DC} / E_{DC}\,(\%) \tag{20}$$

6. RESULTS AND DISCUSSION

Figures 9, 10 and 11 depict the current and voltage generated from the photovoltaic array for a day which the current is 51 003 Ah/day.

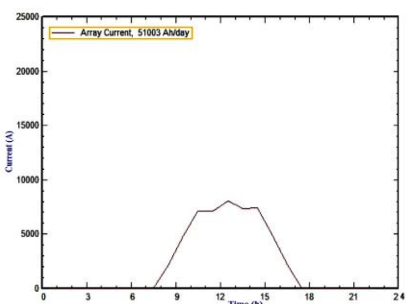


Fig. 9: Current generated from the photovoltaic array for a day

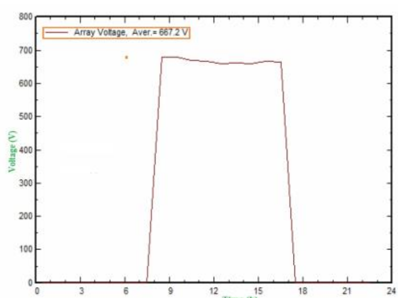


Fig. 10: Array average voltage generated from the photovoltaic array for a day

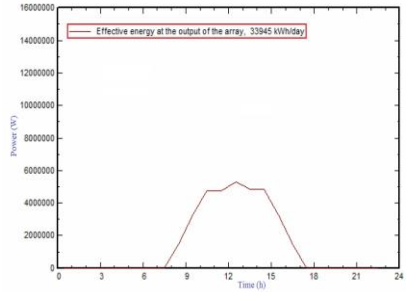


Fig. 11: Daily effective energy at the output of the array

The average voltage is 667.2 V and the effective energy at the output of the array is 33 945 kWh/day.

Our PV system’s nominal power output is 15 015 kWp. Due to various factors such as site location and system losses. The power capacity of the system is reduced figure 12.

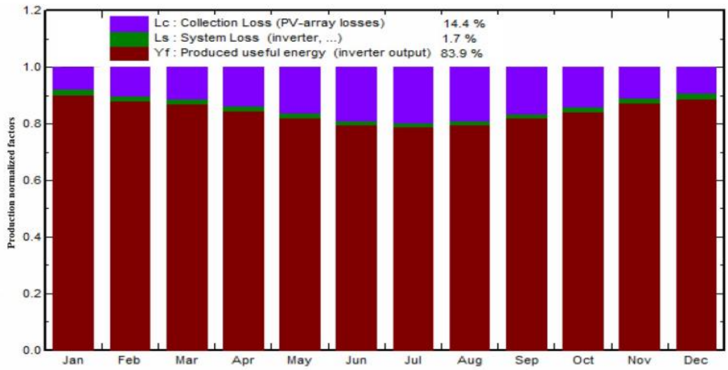


Fig. 12: Monthly nominal power graph for 15015 kWp system

Figure 13 is a graphical representation of the reference incident energy for each month of the year.

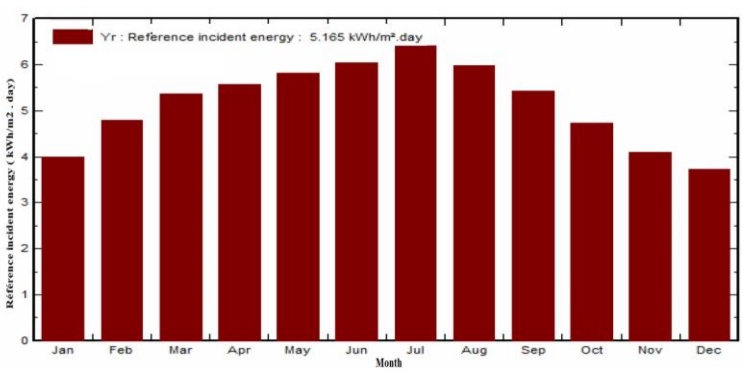


Fig. 13: Monthly incident energy graph

Figure 14 is a graphical representation of the Performance Ratio of the incident energy for each month of the year.

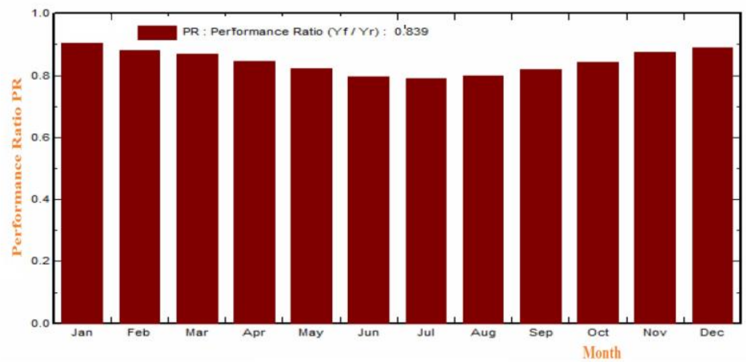


Fig. 14: Performance ration PR

Table 3 provides detailed simulation results performed using measured and Metronome derived climate data sets. It shows the input and output energy for the system, plus the associated energy losses [17].

Table 3: Comparison of the performance of different ground mounted grid-connected PV system

Location of PV technology	Installed capacity	Monitoring duration	PR	Refs
Port Elizabeth, South Africa	3.2 KWp	2015	84	[17]
India	10 MWp	2015	86.12	[6]
Western india	5.05KWp	2016	74	[24]
Southern Italy	960KWp	2017	84.4	[25]
Northeastern Brazil	2.2kWp	2017	82.9	[18]
Soukahras,Algeria	**15MWp**	**2018**	**83.9**	**Present Study**

Figure 15 shows the daily system output energy generated from our system for a day which the energy injected into the grid is 33 153 kWh/day.

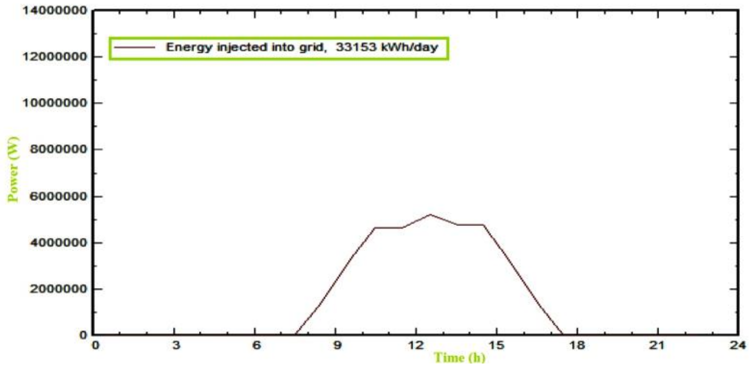


Fig. 15: Daily energy injected into the grid

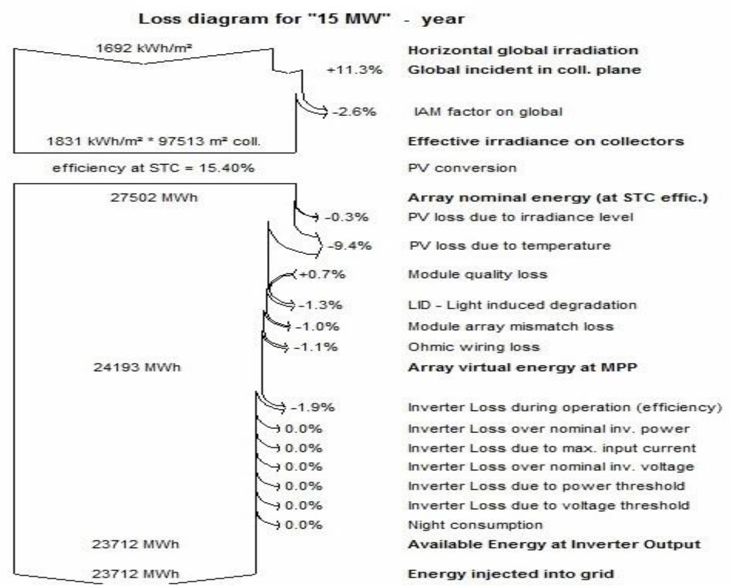
Table 4 shows the balances and main results of Grid-connected PV system. Yearly global horizontal irradiation is 1691.8 kWh/m^2. The yearly global incident energy on the collector plane is 1855.1 kWh/ m^2. Energy available at the output of the PV array is 24 215 523 kWh. The energy injected into the grid is 23 734 872 kWh.

The EffArrR is the efficiency of the PV array/rough area and the yearly average efficiency is 13.17 %. The yearly average efficiency of the system is 12.91 %. The average ambient temperature is 17.230C [6].

Table 4: Balances and Main Results

	GlobHor KWh/m²	T Amb °C	Globnc KWh/m²	GlobEff KWh/m²	Earray KWh	E-Grid KWh	EffArrR %	EffsysR %
January	76.9	6.40	123.9	120.9	1716465	1679828	14.21	13.91
Februry	94.9	8.00	134.2	131.2	1811085	1772767	13.84	13.55
March	137.0	11.30	166.1	161.9	2213699	2168962	13.67	13.39
April	162.6	15.10	167.0	162.4	2163199	2118735	13.28	13.01
May	197.2	20.60	180.2	174.4	2270280	2226028	12.92	12.67
Jaune	207.0	25.80	181.1	175.1	2209599	2168312	12.51	12.28
July	223.5	28.70	199.0	192.7	2404795	2361661	12.39	12.17
August	188.2	28.30	185.3	180.2	2260770	2218686	12.51	12.28
September	144.3	23.30	162.8	158.5	2043788	2004798	12.87	13.63
October	111.6	18.40	146.8	143.3	1893724	1855854	13.23	13.96
November	79.8	12.30	123.1	120.1	1649387	1614588	13.75	13.46
December	68.8	7.89	115.7	112.9	1578732	1544652	14.00	13.70
Year	**1691.8**	**17.23**	**1885.1**	**1833.7**	**24215523**	**23734872**	**13.17**	**12.91**

The loss diagram over the whole year, figure16 shows that the largest losses come from the array losses around 12.1 % and the inverter loss reach 2 %. The horizontal global irradiance is 1692 kW/m² and the effective irradiance on collectors is 1834 kWh/m². The energy injected into the grid is 23 735 MWh with the efficiency of the system equal to 15.40 %.



7. CONCLUSION

In this work, a 15MW photovoltaic grid-connected system situated in the site of Oued kebrite Souk Ahras in Algeria was modelled and simulated in PVsyst software to evaluate the energy performance.

The results show that the maximum solar irradiation was achieved at a tilt angle of 35° with a value of 1834 kW/m². Furthermore, the system is composed of 60 060 solar panels of 250 W and 30 inverters of 500 kW. The energy production was 23 735 MWh/year with a performance ratio of 83.9 %. This shows that Oued Kabarite has great potential for solar energy utilization due to its strategic location.

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