Chapter

# Performance Analysis of a 20 MW Grid-Connected Photovoltaic Installation in Adrar, South of Algeria

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## Abstract

This chapter presents the performance of a 20 MWp grid-connected PV system installed in a harsh environment, Adrar in the South of Algeria. The results were monitored over a period of 1 year, from January 2018 to December 2018. The PV system assessment includes final and reference yields, system efficiency, performance ratio, capacity factor, and total system losses. The total yearly energy delivered to the grid was 35892.22 MWh, and the monthly average reference and final yields of the system are in the range 5.92–8.1 (h/day) and 4.39–5.56 (h/day), respectively. Furthermore, the annual average daily PV system efficiency, performance ratio, capacity factor, and total losses were 10.82%, 71.71%, 20.76%, and 2.04 h/day, respectively.


**Keywords:** photovoltaic, grid-connected, final yield, PV system efficiency, performance ratio, total losses

## 1. Introduction

In recent years, Algeria has shown great interest in new and renewable energies. Therefore, on February 19, 2015, the first PV plant was commissioned in Djanet (stand-alone system) in the South-East of Algeria with a total power of 3 MW. In the same year, five PV plants with a total capacity of 48 MW were integrated into the national grid. Most of the photovoltaic plants were installed in the south of Algeria where the insulation time exceeds 3500 h/year. Evaluating the performance of the installed photovoltaic systems is indispensable; it gives researchers the required information regarding the technology (PV, inverter) used and its suitability for the installation site.

In the literature, many studies have investigated, evaluated, and analyzed PV grid-connected systems in different locations, such as India [1], Italy [2], Ireland [3], Ghana [4], Iran [5], Brazil [6], Mauritania [7], Korea [8], Greece [9], and Morocco [10].

In India (South India), the performance of 5 MWp photovoltaic grid-connected systems was presented in [11], by using the RETScreen software for the validation of the performance of the PV plant in real time. It was found that the annual average energy generated by the system is 24116.61 kWh/day, and observed that the annual average daily array yield is of 5.46 h/day, reference yield of 5.128 h/day, final yield of 4.810 h/day, module efficiency of 6.08%, inverter efficiency of 88.20%, and system efficiency of 5.08%. Moreover, a performance study of a 190 kWp grid-interactive photovoltaic plant was conducted by Sharma and Chandel [12], who found that the final yield, reference yield, and performance ratio vary in the range 1.45–2.84 h/day, 2.29–3.53 h/day, and 55–83%, respectively. In [13], the authors presented a grid-connected photovoltaic system installed on the rooftop of the Siksha 'O' Anusandhan University. The results showed the total energy generated during the period test was 14.960 MWh. The array yield, final yield, module efficiency, inverter efficiency, and performance ratio of the system were found to be 4.09 h/day, 3.67 h/day, and 13.42, 89.83, and 78%, respectively. In a different study, Doolla and Banerjee [14] analyzed the variation in the capacity factor of PV grid-connected systems around India. They found that the capacity factor varies between 16 and 20%, and lower values were observed in northeastern states of the country due to poor solar irradiance throughout the year.

In other studies, Ya'acob et al. [15] evaluated three different PV systems in Malaysia, namely concentrating PV system (CPV), PV sun tracking flat (TF), and fixed flat PV system (FF). It was concluded that the most suitable system is the tracking flat PV system with an average daily generation, system efficiency, power efficiency, average daily yield, and capacity factor of 4.7 kWh, 11%, 85%, 2.3 kWh/kWp, and 32%, respectively. Mpholo et al. [16] evaluated the performance of a 281 kWp grid-connected photovoltaic system in Lesotho, Roma (Italy). The results show a satisfactory performance, with a weighted performance ratio of 70%; a monthly yield for the array (YA), reference (YR), and final (YF) in the ranges (71.7–168.0), (161.6–199.3), and (64.4–151.4) kWh/kWp, respectively.

In Algeria, although different photovoltaic systems were installed around the country, they were poorly investigated. Only some efforts were found in the literature to evaluate the performance of mini-systems connected to the power grid [17, 18].

For the first time, this chapter attempts to predict the performance of a grid-connected system installed in a desert area in the Adrar region, South of Algeria, and a performance evaluation of a 20 MW PV system over a 1-year period (January 2018 to December 2018) is presented. The IEA 61724 standard (International Energy agency) guidelines were used to analyze the performance of the system. The PV system assessment includes final and reference yields, system efficiency, performance ratio, capacity factor, and total system losses.

## 2. PV plant description

The 20 MW grid-connected PV plant of Adrar comprises 20 subfields of 1 MWc each and divided into two subsystems. In total, the numbers of modules per subfield are 4092. The modules are mounted at an angle of 28° and oriented southward. The type of module is polycrystalline with a maximum power of 245 Wp and total module area of 132,538,775 $m^2$. The manufacture characteristic of the PV module is shown in **Table 1**. The station was put into service on October 28, 2015, and was expected to produce annually 36,414 MWh, with an economy of about 10,080 $m^3$/year of natural gas. However, the results presented in this study consist of the measured data over a period of 1 year (January 2018 to December 2018). A block scheme of the considered photovoltaic system is illustrated in **Figure 1**.

The in-plane global solar radiation, wind speed, ambient temperature, and the output AC power were measured and recorded after every 15-min interval.

| Parameters | Specification |
|---|---|
| Manufacturer | Yingli Green Energy Holding Co. Ltd. |
| Cell type | Polycristallin |
| PV Model | YL245P-29P |
| Maximum power, $P_p$ (W) | 245 |
| Maximum power voltage, $V_p$ (V) | 29.6 |
| Maximum power current, $I_p$ (A) | 8.28 |
| Open circuit voltage, $V_{oc}$ (V) | 37.5 |
| Short circuit current, $I_{sc}$ (A) | 8.83 |
| Number of cells | 60 |
| Module dimensions (mm) | 1640*990*35 |
| Module efficiency (%) | 15.1 |
| Maximum system voltage (V) | 1000 |
| Temperature coefficient of $P_p$, $\alpha_{Pp}$ (%/°C) | −0.42 |
| Temperature coefficient of $I_{sc}$, $\alpha_{Isc}$ (%/°C) | 0.05 |
| Temperature coefficient of $V_{oc}$, $\alpha_{Voc}$ (%/°C) | −0.32 |

**Table 1.**
*Photovoltaic module specifications.*

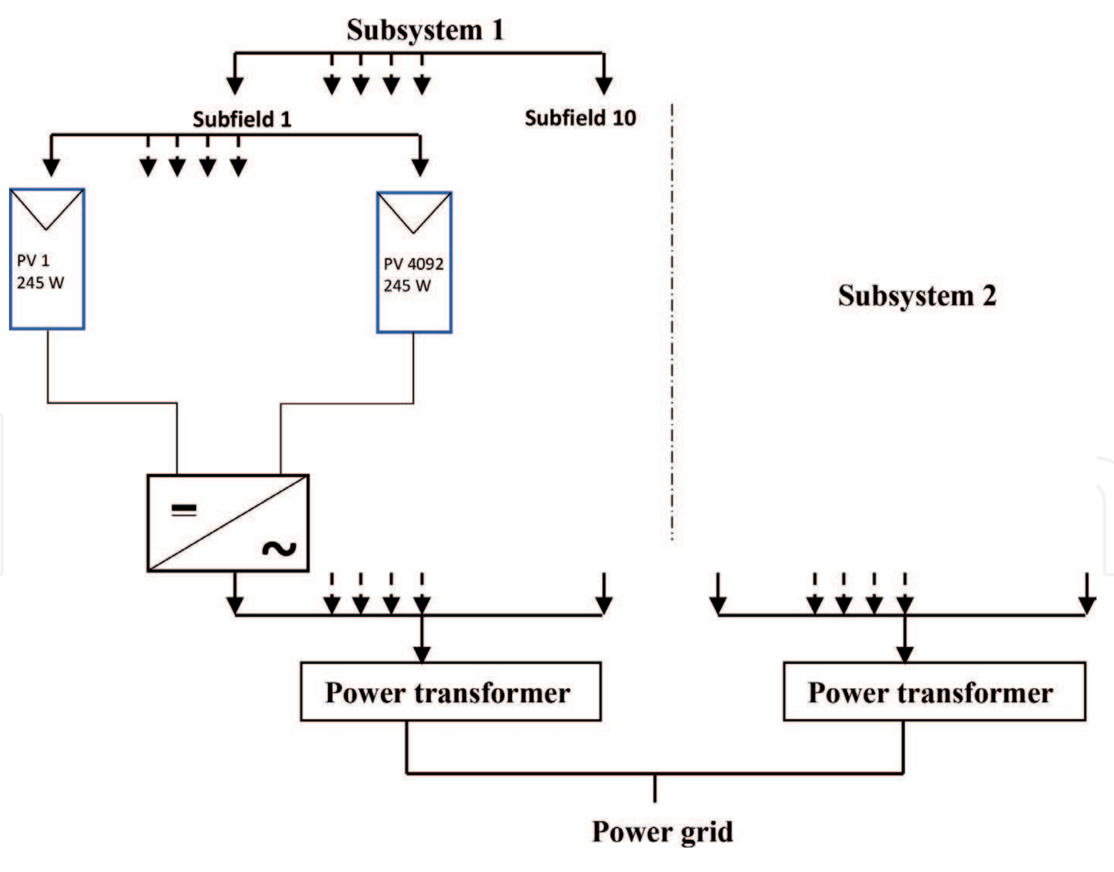


**Figure 1.**
*Schematic representation of the considered PV system.*

We observe a few days missing in the months of: January (2-day data is missing for both subfields), July (5-day data is missed for the second subsystem), and October (3 days are missed concerning the two subsystem).

## 3. Performance analysis

Equations (1)–(9) are applied in accordance with the IEC 61724 standard to investigate the performance of the grid-connected PV system.

### 3.1 Final yield ($Y_F$)

Final yield ($Y_F$) is the total AC energy generated by the PV system over the monitored period divided by the rated output power of the PV system:

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PV,rated}} \tag{1}$$

$$Y_{F,m} = \frac{1}{N}\sum_{1}^{N} Y_{F,d} \tag{2}$$

The total daily and monthly AC energy generated by the system was obtained as:

$$E_{AC,d} = \tau \cdot \sum_{1}^{24} P_p \tag{3}$$

$$E_{AC,m} = \sum_{1}^{N} E_{AC,d} \tag{4}$$

where N is the number of days per month, $\tau$ is the recording interval ($\tau$ = 15mn), $P_p$ is the AC power in kW, and $E_{AC}$ is expressed in kWh. The terms *d* and *m* indicate the daily and monthly period.

### 3.2 Reference yield ($Y_R$)

Reference yield is the ratio of total in-plane solar irradiation $H_t$ (kW/m$^2$) and the reference irradiance $H_{STC}$ (=1 kW/m$^2$). It can be calculated as follows:

$$Y_{R,d} = \frac{\tau \cdot \sum G_t}{G_{STC}} \tag{5}$$

The monthly average daily reference yield is obtained as:

$$Y_{R,m} = \frac{1}{N}\sum_{1}^{N} Y_{R,d} \tag{6}$$

### 3.3 Performance ratio (PR)

The performance ratio is a dimensionless quantity which provides important information concerning the system losses (modules, inverters, cables, weather conditions, loss due to non-STC temperature) in the PV systems. This quantity defined as the ratio of the final yield ($Y_F$) and the reference yield ($Y_R$). It indicates the percentage of the real energy supplied by the system [19, 20] and can be expressed as follows:

$$PR = \frac{Y_F}{Y_R} \tag{7}$$

### 3.4 Total energy losses ($L_T$)

The total energy loss ($T_L$) of the system is obtained from the difference between the reference yield $Y_R$ and the final yield $Y_F$. The total losses represent the PV losses due to irradiance level and array temperature and quality module, ohmic wiring, mismatch, and total inverter losses [21]:

$$L_T = Y_R - Y_F \tag{8}$$

### 3.5 Capacity factor (CF)

The capacity factor (CF) is the ratio of the actual energy output of the PV system and the PV system energy generates operating at full rated power. The yearly and monthly capacity factors were calculated by Eqs. (9) and (10), respectively:

$$CF_y = \frac{E_{AC,y}}{P_{PV,rated} \times 8760} \tag{9}$$

$$CF_m = \frac{E_{AC,m}}{P_{PV,rated} \times 24 * N} \tag{10}$$

where the term $(y)$ indicate the yearly period.

### 3.6 System efficiency

The monthly system efficiency is given as:

$$\eta_{sys,m} = \frac{E_{AC,m}}{H_{t,m} \times A_a} \tag{11}$$

where

$$H_{t,m} = \sum_1^N \left( \tau \sum_1^{24} G_t \right) \tag{12}$$

where $H_{t,m}$ monthly total in-plane insolation (kWh/m$^2$).

## 4. Results and discussion

The monthly average daily ambient temperature and wind speed over the monitored period is shown in **Figure 2**. The monthly average daily ambient temperature varies from a minimum of 14.05°C in December to a maximum of 40.8°C in July. The months of May, June, July, August, and September (summer months) show higher ambient temperature compared to the other months. The monthly variation of daily average wind speed is from a minimum of 3.59 m/s in October to a maximum of 5.14 m/s in April. **Figure 2** shows that the wind speed over the monitored period (during all the months) is higher.

The monthly total AC energy generated to the grid and in-plane irradiation over the monitored period is shown in **Figure 3**. The total in-plane irradiation varies from a minimum of 171.7 kWh/m$^2$ in January to a maximum of 251.2 kWh/m$^2$ in May. The highest values were recorded in the months of March, April, May, June, July, and August (Spring and Summer). The monthly total variation of the AC energy generated to the grid ranged from 2725.15 MWh in July to 3447.5 MWh in March. As shown in **Figure 3**, there is a correlation between the total AC energy and the total in-plane irradiation. As the total irradiation increases, the total energy likewise increases. In July, a 5-day loss of energy value data for one of the subsystem was observed. This explains the low energy value in the month of July despite high irradiation. From **Figures 2** and **3**, it is evidently clear that increases in ambient

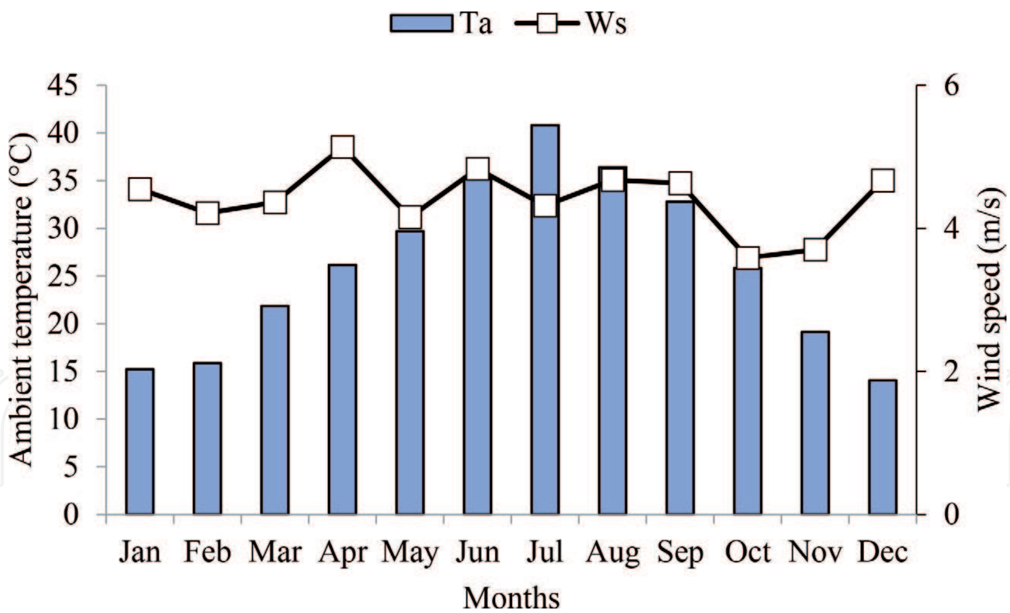


**Figure 2.**
*Monthly average daily ambient temperature and wind speed over the monitored period.*

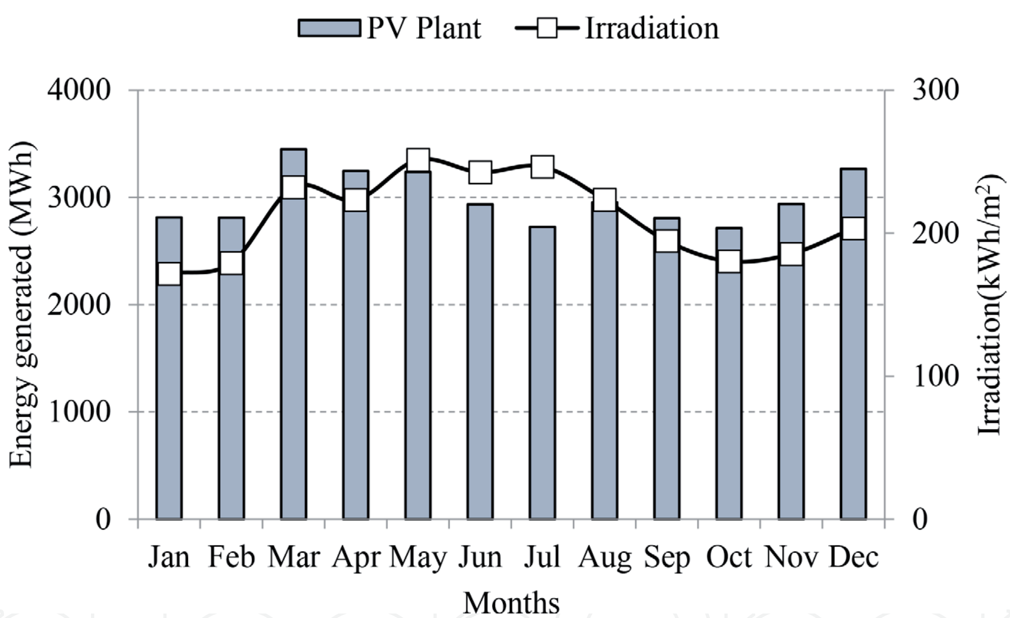


**Figure 3.**
*Monthly total AC energy generated to the grid and in-plane irradiation over the monitored period.*

temperature have a negative effect on the energy produced by the system due to the increased PV modules temperature, although the wind flow on the photovoltaic modules contributes to reducing the PV cell temperature [7, 19]. Generally, the irradiation had a greater impact on energy generation than ambient temperature [22].

**Figure 4** shows the average monthly performance ratio and efficiency of the PV system over the monitored period. The results show that the performance ratio varies from a min. of 55.29% in July to a maximum of 81.96% in January, with an annual average of 71.71%. Similarly, the efficiency varies from 8.34% in July to 12.37% in January. The performance ratio and efficiency refer to the level of losses in the photovoltaic solar system. There are three main reasons for losses of performance are dust, ambient temperature, and solar radiation. In [22], the authors indicated that ambient temperature had a greater impact on the performance ratio and efficiency than irradiation, and high values for both parameters were observed during days with low ambient temperature.

**Figure 5** shows the monthly and annual capacity factor of the PV system. The monthly capacity factor can be seen to vary between 18.31% in July and 23.17% in March. The annual capacity factor is 20.77%, with an overall monthly average of 20.76%. The capacity factor of other PV plants based on existing literature: in India [1], it ranged from 15.4 to 20%, Oman from 13 to 20% [23] and 21% [24], and Morocco from 6.55 to 21.42% in [10] and for a polycrystalline PV technologies the CF ranged from 20.014 to 23.799% [25].

**Figure 6** shows the monthly daily average variation of the final yield, reference yield, and total energy losses. As shown in **Figures 3** and **6**, the reference yield is directly proportional to the irradiation, respectively; they vary from a minimum of 5.92 (h/day) and 171.69 kWh/m$^2$ in January to a maximum of 8.1 (h/day) and 251.19 kWh/m$^2$ in May.

In the present study, the annual monthly average daily final yield of the PV plant is 4.98 (h/day). The reason for this high value is the high irradiation and the extended

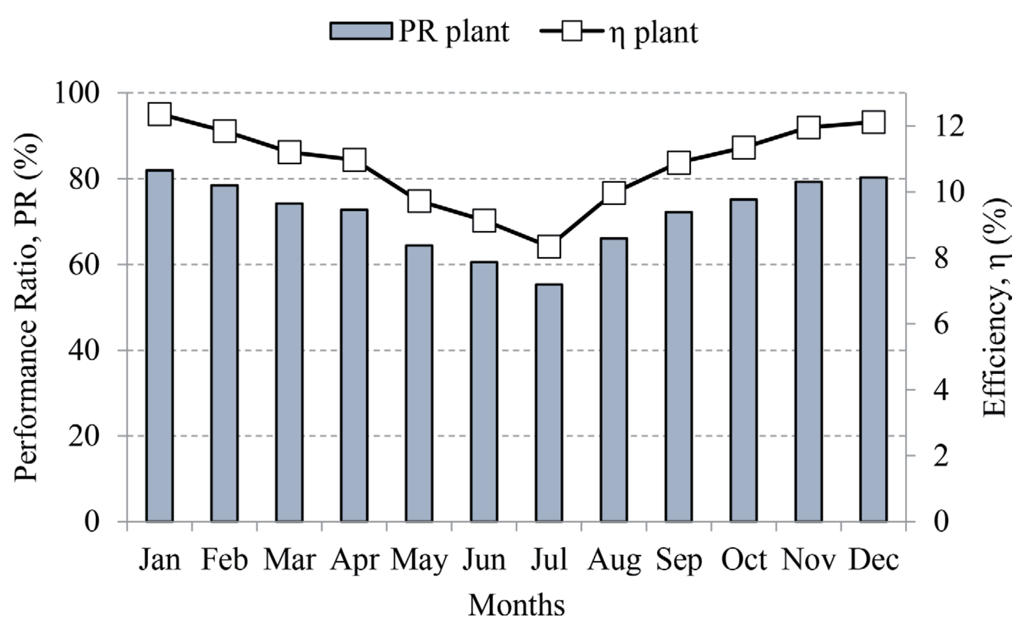


**Figure 4.**
*Performance ratio and efficiency of the PV system over the monitored period.*

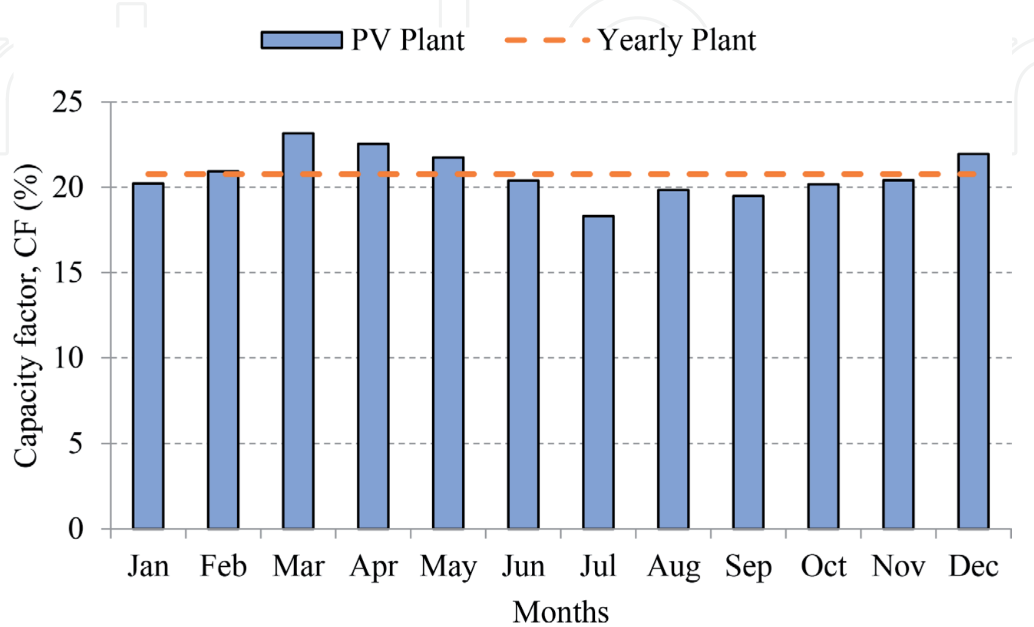


**Figure 5.**
*Monthly and annual capacity factor over the monitored period.*

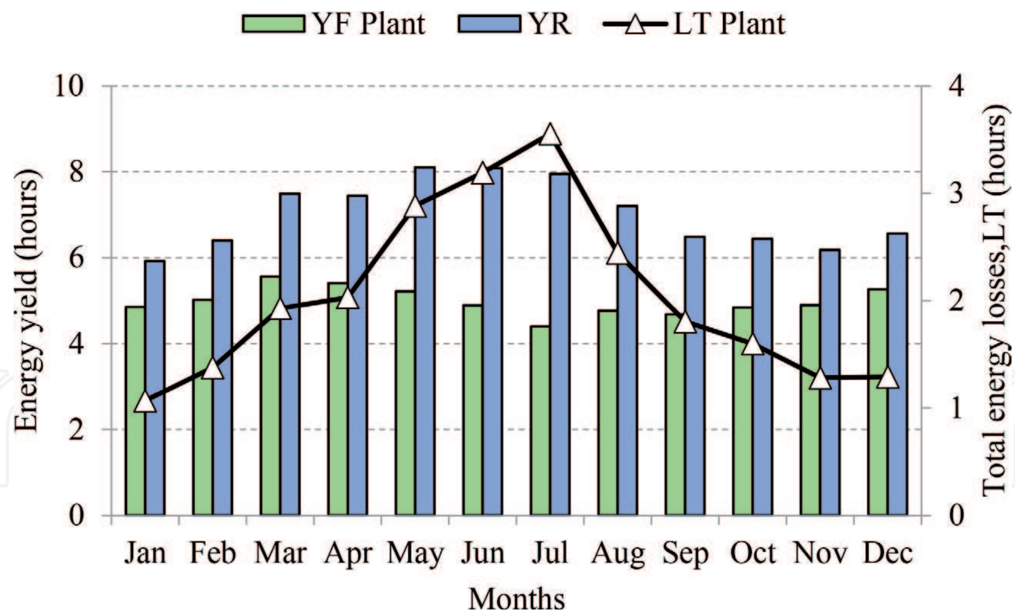


**Figure 6.**
*Monthly average energy yield and energy losses over the monitored period.*

sunshine duration in Adrar [10]. This value is close to other final yields of different PV systems found in the literature such as that of Oman (Sohar) 5.1 (h/day) [24], and higher than in Kuwait 4.5 (h/day) [26], in Oman (Muscat) 4.1 (h/day) [23] and in Morocco 4.45 (h/day) [10]. The monthly daily average yields (final and reference) increase during the months from May to August due to higher irradiation and more sun hours.

The total energy losses varied between 1.06 h in January and 3.55 h in July. The higher total energy losses were observed in the hot months, i.e., May to August. The reasons for the losses are generally due to dust and ambient temperature (heating of the photovoltaic cells which reduce the power provided by the photovoltaic modules). And in these conditions, periods of downtime of the system were observed (2 days in January, 5 days in July and in October stopped for 3 days with 1-day data incomplete).

## 5. Conclusion

The present chapter investigates the performance analysis assessment of ground-mounted large-scale grid-connected PV plant in Adrar, South of Algeria. The PV system is made up of 20 MW of polycrystalline silicon modules produced by Yingli Green Energy Holding Co. Ltd. and monitored between January 2018 and December 2018.

The PV system assessment includes final and reference yields, system efficiency, performance ratio, capacity factor, and total system losses. The main findings are the followings:

- The monthly total variation of the AC energy generated to the grid ranged from 2725.15 MWh in July to 3447.5 MWh in March, and the total yearly energy delivered to the grid in the year 2018 was 35892.22 MWh, which is close to the expected energy (36,414 MWh).

- The monthly average reference and final yields of the system are in the range 5.92–8.1 (h/day) and 4.39–5.56 (h/day), respectively, and the annual monthly average daily final yield is 4.98 (h/day). The monthly daily average yields (final and reference) increase from May to August due to higher irradiation and extended sunshine duration.

- The minimum and maximum efficiency and performance ratio were 8.34 and 55.29% in July, and 12.37 and 81.96% in January, respectively. The minimum capacity factor was 18.31 in July and the maximum was 23.17% in March. The minimum total energy losses was 1.07 h in January and the maximum was 3.55 h in July. Furthermore, the annual average daily PV system efficiency, performance ratio, capacity factor, and total losses were 10.82%, 71.71%, 20.76%, and 2.04 h/day, respectively.

- The reasons for the losses are generally due to dust, ambient temperature and solar radiation.

The results obtained show that the installation of photovoltaic stations in Adrar in Southern Algeria gives good results encouraging investments in this field and region.

## Conflict of interest

The author has no conflict of interest statement.

## Appendices and nomenclature

| | |
|---|---|
| $P_{mp}$ | maximum power (W) |
| $V_{mp}$ | maximum power voltage (V) |
| $I_{mp}$ | maximum power current (A) |
| $V_{oc}$ | open circuit voltage (V) |
| $I_{sc}$ | short circuit current (A) |
| $\alpha_{Pmp}$ | temperature coefficient of Pmp (%/°C) |
| $\alpha_{Isc}$ | temperature coefficient of Isc (%/°C) |
| $\alpha_{Voc}$ | temperature coefficient of Voc (%/°C) |
| STC | standard test condition (25°C and 1 kW/m$^2$) |
| $T_a$ | ambient temperature (°C) |
| $W_s$ | wind speed (m/s) |
| $P_p$ | AC power (kW) |
| $E_{AC}$ | AC energy generated (kWh) |
| $Y_F$ | final yield (h) |
| $Y_R$ | reference yield (h) |
| $T_L$ | total energy losses (h) |
| CF | capacity factor (%) |
| PR | performance ratio (%) |
| $H_t$ | total in-plane solar irradiation (kW/m$^2$) |
| $H_{STC}$ | reference irradiation (=1 kW/m$^2$) |
| $\eta_{sys}$ | system efficiency (%) |
| N | number of days per month |
| d, m, and y | daily, monthly, and yearly period |

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