ENERGY AND ENVIRONMENTAL PERFORMANCE ANALYSIS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS UNDER SIMILAR OUTDOOR CONDITIONS IN THE SAHARAN ENVIRONMENT

Mohammed Amine DERICHE, Ahmed HAFIFA, Ali TAHHRI, Kamal MOHAMMEDI, Fatima TAHRI

URMPE/ MESO, M. Bougara University, Boumerdès-35000 Algeria
ma.deriche@univ-boumerdes.dz, mohammedi.kamal@univ-boumerdes.dz
LAADI, ZianeAchour University, Djelfa-17000 Algeria
hafaifa@hotmail.com

Electrical Engineering Faculty of the University of Science and Technology of Oran, Mohamed Boudiaf
USTO-MB, BP 1505 El M’naouer, Oran, 31000, Algeria.
alitahri.dz@gmail.com, fatimatahri.dz@gmail.com

Abstract

The aim of this paper is to present a one-year performance analysis of four grid-connected PV systems installed at Ghardaia city in Algeria’s Sahara. The grid-connected PV systems are based on four different PV module technologies which are: monocrystalline silicon (m-Si), multi-crystalline silicon (mc-Si), cadmium telluride (Cd-Te) and amorphous (a-Si) PV module technologies. The PV systems based on the thin film technologies have their performance ratio better throughout the year when the performance ratio of the mc-Si technology is better in the winter season. The a-Si PV system has its performance ratio about 6.13 % more better than mc-Si and 8.90 % better than m-Si. The AC energy produced with the a-Si PV system is 13.32 % more than what the mc-Si system produces. It was found that the a-Si PV system performs better than the other technologies under the Saharan climate conditions of Ghardaia city. The energy payback time (EPBT) and greenhouse gases (GHG) emissions of the different PV systems were analyzed. The EPBT and GHG emissions per year, vary from a minimum value of 2.8 years to a maximum value of 5.73 years and from 13.24 tons to 32.03 tons of CO2/kWh for CdTe and m-Si respectively. The CdTe PV system performs better in terms of EPBT and GHG emissions compared to the other technologies (m-Si, mc-Si and a-Si) due to its low life cycle energy requirement.

Keywords: Performance assessment, Saharan outdoor conditions, grid-connected PV, thin film photovoltaic modules, energy payback, greenhouse gases emissions.

1. INTRODUCTION

Renewable energy for sustainable development is now recognized as the key solution for the future generations. With the impact of global warming on the ecosystem and the human life, it is urgent to make more efforts for the energy transition [1, 2]. The photovoltaic energy can play important role in the long-term transition to a sustainable society [3–5].

In the recent years, the capacity of grid-connected systems is growing faster and continues to represent the most of PV installations worldwide [4]. Therefore, the performance assessment of PV solar installations is becoming more and more crucial analysis task for researchers, investors and policymakers to reach a global roadmap for developing and deploying PV systems [6–8].

In 2016, the global production capacity exceeded 80 GW for PV modules where thin film production increased by 11%, which represents 6% of total global PV production [6, 9]. The increase of production of thin film PV technologies and the use of the different thin film PV modules in grid-connected PV systems driven the worldwide researchers to establish a good knowledge of their energy performance under different outdoor conditions.

In Iran, Edalati et al. [10] investigated the performance of two types of 5.52 kWp grid-connected PV systems, the first one based on monocrystalline silicon (m-Si) PV modules and the second one on multi-crystalline silicon (mc-Si) PV modules. They found that the grid-connected PV system composed of mc-Si PV modules performs better especially in higher ambient and module temperature and they suggest to use mc-Si PV module technology in dry and hot regions. In southwestern of Malaysia, Humada et al. [11] evaluated the performance of two grid-connected photovoltaic (PV) systems (monocrystalline silicon, m-Si; copper-indium–diselenide; CIS). Their results show that efficiency of CIS technology was higher than the c-Si technology and the CIS technology exhibit higher performance in all evaluation parameters. Two power plants based on a-Si:H single-junction and c-Si PV modules were evaluated in the Republic of Korea by Myong et al.
[12]. The results of the energy evaluation showed that the a-Si:H single-junction PV plant energy output was 2.7% higher compared to the c-Si PV plant. A study and analysis of three on-grid PV systems were conducted under Izmit, Kocaeli weather conditions in Northwest of Turkey by Başoğlu et al. [13]. The three PV systems were installed by using crystalline (c-Si), multicrystalline (mc-Si) and cadmium–telluride (Cd-Te) modules. They concluded that PV system with (Cd-Te) module technology performs more better than the others technologies with higher system quality. Wang at al. [14] analyzed the performance of three grid-connected PV systems in Spain. The three PV systems are mc-Si, a-Si and CdTe PV technologies basis. They found that the PV system of mc-Si performs more better than the others technologies.

In the literature, there are some studies dealing with the analysis of the performance of grid-connected PV plants under desert climate conditions. In Oman, Kazem et al. [15] analyzed a 1.4 kW grid-connected PV system composed only of mc-Si PV modules for six months under desertic climate conditions. According to the results of their study, the performance factor, the capacity factor and the yield factor were 84.6%, 21% and 1875 kWh/kWp/year respectively. They also estimated the payback period which is about 11 years. In Chile, under a coastal desert climate conditions, Ferrada et al. [16] studied the performance of two on-grid PV systems composed of amorphous/microcrystalline silicon a-(Si/nc-Si) tandem thin films and monocrystalline silicon (m-Si) PV modules, respectively. They concluded that the PV system with m-Si performs more better than a-(Si/nc-Si) and gives some recommendations for cleaning a dust accumulation for each technology. Dabou et al. [17] investigated a 1.75 kWp grid-connected PV system installed in the Saharan city of Adrar located in the southwest of Algeria. The PV plant is composed only of m-Si PV modules. They analyzed the performance of the system in clear, cloudy and sandstorm days. They concluded that for such climate conditions of Algeria’s desert, the minimum values of reference yield, array yield, final yield were in sandstorm day due to low level of daily solar irradiation, and the minimum values of the performance ratio and efficiency of the PV module, system and inverter, and the maximum value of capture and system losses were in clear day due to high ambient temperature.

This work presents an energy performance analysis and life cycle assessment (LCA) of four grid-connected PV systems based on four different PV module technologies which are: monocrystalline silicon (m-Si), multi-crystalline silicon (mc-Si), cadmium telluride (Cd-Te) and amorphous silicon (a-Si). The four PV plants are installed at Ghardaia city in the desert of Algeria. The period of the study includes twelve months of monitored data, from May 2015 to April 2016.

The paper is organized as follows: Section 2 shows a description of the PV power plants. The analysis method used to evaluate the performance of the PV plants and the LCA is described in Section 3. Section 4 shows the main results obtained and the discussion of the performance of each grid-connected PV system. Finally, in section 5, the most relevant conclusions are summarised.

2. PV POWER PLANTS DESCRIPTION

The PV power plants installed in Ghardaia city located in the desert of Algeria with the following geographical coordinates 574 m of altitude, latitude: 32°36’2.43”N of latitude and 3°42’6.32”E of longitude. Fig. 1, shows the geographical situation of Ghardaia city in Algeria’s Sahara and an overview of the PV power plants installation is depicted. The PV power plants are four grid-connected PV systems based on different PV module technologies that are monocrystalline silicon (m-Si), multi-crystalline silicon (mc-Si), cadmium telluride (Cd-Te) and amorphous (a-Si). The PV modules are set on a fixed support with 30° as tilted angle and faced to the south.

Fig. 1. The geographical situation of Ghardaia city in Algeria’s Sahara (on the left), and an overview of the installation of the four grid-connected PV systems (on the right)
The main characteristics of each PV module technology are given in Table 1 and in Table 2, the specification of the grid-connected PV systems are reported.

Table 1. Main characteristics of the different PV module technologies.

| Module technology | m-Si | mc-Si | Cd-Te | a-Si |
|-------------------|------|-------|-------|------|
| Maximum Power $P_{max}$ (Wp) | 250 | 235 | 80 | 103 |
| Short Circuit Current $I_{SC}$ (A) | 8.79 | 8.64 | 1.88 | 4 |
| Open circuit Voltage $V_{OC}$ (V) | 37.62 | 36.94 | 60.8 | 41.1 |
| $I_{oc}$ temperature coefficient (%/°C) | 0.03 | 0.04 | 0.04 | 0.08 |
| $V_{oc}$ temperature coefficient (%/°C) | -0.34 | -0.32 | -0.27 | -0.33 |
| $P_{max}$ temperature coefficient (%/°C) | -0.43 | -0.43 | -0.25 | -0.20 |
| Efficiency (%) | 15.35 | 14.43 | 11.1 | 7.1 |
| Area ($m^2$) | 1.63 | 1.63 | 0.72 | 1.45 |
| Weight (kg) | 21.5 | 21.5 | 12.0 | 20.8 |

Table 2. Specification of the grid-connected PV systems.

| Type | m-Si | mc-Si | CdTe | a-Si |
|------|------|-------|------|------|
| N. of modules | 420 | 420 | 1260 | 972 |
| Series | 20 | 20 | 12 | 18 |
| Parallels | 21 | 21 | 105 | 54 |
| $P_{max}$ (kWp) | 105 | 98.7 | 100.8 | 100.116 |
| $I_{oc}$ (A) | 173.04 | 170.1 | 173.25 | 200.88 |
| $V_{oc}$ (V) | 607 | 580.8 | 582 | 608.4 |
| $I_{oc}$ (A) | 184.59 | 181.44 | 197.4 | 222.48 |
| $V_{oc}$ (V) | 752.4 | 738.8 | 729.6 | 813 |
| area | 684.6 | 684.6 | 907.2 | 1409.4 |
| Capacity | 96 | 96 | 96 | 96 |

In order to measure the meteorological parameters such as irradiance, ambient temperature, relative humidity, speed and direction of wind and atmospheric pressure, a weather station was installed nearby the PV installation.

The monitoring system was set to measure and store the electrical and meteorological parameters every 1 hour. All meteorological sensors installed with the grid-connected PV systems were supplied by LSI LASTEM Company. The irradiance was measured using DPA053 Pyranometer with a total accuracy of 5W/m² for one day of measure and the ambient temperature and relative humidity were sensed by thermohygrometer DMA672.1 probe with temperature and relative humidity accuracy of ±0.15 °C and ±3% respectively. The wind speed and direction were measured by DNA 121# with an accuracy of ±0.07 m/s and ±0.3 degrees of wind direction and the atmospheric pressure was measured by DQA240.1#C with uncertainty of 1 hPa. The modules temperature were sensed using the platinum resistance thermometers PT100 type attached to the back surface of the modules with temperature range (-50 °C to +80°C) and an accuracy of 0.15°C. All parameters were recorded by a data logger.

Each grid-connected PV system is connected to the utility grid through an inverter equipped with a distributed control system and Profibus protocol communication.

3. ANALYSIS METHOD

3.1. Performance parameters

The collected monitored data of the four grid-connected PV systems are used to assess their performance and behavior in the Saharan climate conditions. The monitoring campaign includes twelve months of monitored data, from May 2015 to April 2016.

The data acquisition system allows collecting the sensed parameters that are in-plane irradiance, PV array temperature, array output voltage, current and power, output power inverter. The performance parameters used to perform the PV power plants analysis and their evaluation are calculated as recommended by the IEC 61724 standard [18].

The performance ratio is defined as the final yield $Y_f$ divided by the reference yield $Y_R$ [18, 19] :

$$ PR = \frac{Y_f}{Y_R} \times 100 $$

$Y_f$ is defined as the daily AC energy output $E_{AC}$ of the system divided by the rated power of the installed PV array PSTC at standard test condition (STC) and its unit is kWh/kWp [18]. It is expressed as follows:

$$ Y_f = \frac{E_{AC}}{P_{STC}} $$

$Y_R$ represents the number of hours per day during which the solar radiation would need to be at reference irradiance levels in order to contribute the same incident energy as was monitored [18]. It can be performed as follows:

$$ Y_R = \frac{\sum G_{meas}}{G_{STC}} $$

Where $G_{meas}$ is the measured irradiance (W/m²), GSTC irradiance under standard condition test (W/m²) and is the recording interval.

The AC energy generated by the PV system is obtained as:

$$ E_{AC} = \tau \sum P_{AC} $$

Where $P_{AC}$ is the power supplied by the inverter to the grid utility in kW and $E_{AC}$ is expressed in kWh.
The system efficiency is calculated as follows:

$$\eta_{sys} = \frac{E_{AC}}{S_A \tau \sum O_{meas}}$$  \hspace{1cm} (5)

Where $S_A$ is the surface of the PV array.

### 3.2. Life cycle assessment of the PV power plant - evaluation methodology

The PV power plant produces the electricity from the solar energy, but in the same time consumes the energy throughout its life cycle.

Many researchers and manufacturers collected different data of the all components of the PV system, (modules, and balance of system BOS) to update the database. The LCA is used to study the energy payback performance of PV system, and also the effect to the environment throughout the life cycle. According to the International Organization for Standardization (ISO). In step to the ISO 14041- 1998, ISO 14042- 2000 and ISO14043- 2000, the LCA methodology contains definition of goal and scope, inventory analysis, impact assessment and interpretation of results as is indicated in fig. 2.

The energy requirement of transportation of the equipment’s is not considered in this study.

![Fig. 2. Framework of life cycle assessment](image_url)

**Goal and scope**

The goal of this LCA study is to make an assessment of the environmental impact of the electricity generation by different grid-connected PV systems composed of different module technologies as detailed in section 2.

The monocrystalline silicon and the multicrystalline silicon PV modules are constitute of 60 cells with a total cell area of 1.46$m^2$ (0.156 x 0.156 x 60), total area of 1.63$m^2$ (1.645 x 0.990) and total cell area of the PV power plants (m-Si and mc-Si) are 613.27$m^2$. For the area of the cadmium telluride and amorphous silicon PV modules are 0.72$m^2$ and 1.45$m^2$ with a total cell area of the PV power plants are 907.2$m^2$ (0.72 x 1260) and 1409.4$m^2$ (1.45 x 972) respectively.

**Inventory analysis - LCA boundaries**

Each PV power plant are composed of two principal parts, the first is the solar PV modules, and the BOS parts. The details of different productions stages were reported in the literature [20, 22, 23]. The cell of silicon crystalline (m-Si and mc-Si) is fabricated from quartz mining, than it is introduced in an arc furnace to metallurgical-grade silicon (Mg-Si), and after this stage it will be purified into solar grade silicon (SoG-Si) the ingots of mc-Si will be cast and saw into wafers, and the m-Si goes through one more step which is Czochralski (CZ) recrystallization [20, 21] as is shown in fig. 3. The cells are encapsulated between glass panes and assembled by frame give as a PV module, and the number of the PV cell is according to the power of the PV module. For the CdTe module technology, it is made from the raw of material of Cu and Zn ores for Te, and Cd respectively, and in the end of the treatment process we obtain a module [20].

![Fig. 3. Process step of manufacturing of crystalline and thin film silicon module (m-Si, mc-Si and a-Si)](image_url)

In additional of the PV modules connecting in series and or in parallel placed on metallic structure, and the Balance Of System BOS (inverter, transformer, junction box, cabling, array support, concrete etc…), we obtained a PV power plant.

**Energy requirements in the life cycle of PV systems**

Many researchers and manufacturers seeking about the energy requirement of the PV power plants and creates a database for different reasons, among to reduce the energy necessary to produce modules, and as result, to decrease the Energy payback times (EPBT).
• **Solar PV modules**

Jinqing and Honxing [24], after the comparison study of the energy requirements between different PV technologies, monocrystalline silicon, multicrystalline silicon, cadmium telluride and amorphous silicon, the review of energy requirements during life cycle can vary from 2860 to 5253 MJ/m², 2699 to 5150 MJ/m², 790 to 1803 MJ/m² and 710 to 1990 MJ/m² respectively.

The energy requirement for crystalline silicon PV technology (m-Si and mc-Si) is taken as it is estimated in [21, 24]. The average of 3860 MJ/m² and 5253 MJ/m²; and the average of 3065 MJ/m², 3120 MJ/m² and 3940 MJ/m² respectively. There is one more step in the production process of multicrystalline PV module compared to the multicrystalline technology that is called Czochralski (CZ) recrystallization, this step gives a higher efficiency but consumes more energy in their manufacturing process, the reason of the higher value of energy requirement of m-Si compared to the mc-Si. For the thin film cadmium telluride and amorphous silicon the energy requirements are considered of 918 MJ/m², and 1202 MJ/m² respectively [25]. Each PV technology has its own energy requirement, which is different from one technology to another, this difference is remarkable and especially, between crystalline silicon and thin-film. The difference is due to the manufacturing process and the materials used for each technology. We selected this value because this energy requirement included frame.

• **Balance of system (BOS)**

The Balance of system (BOS), defined all the equipment existing in the PV power plant, excepting the PV modules, like the array support structure, inverter, transformer, junction box, wiring, foundation concrete, etc… To obtain the total energy requirement of the PV power plant, it is necessary to know the energy requirement of the BOS components, and adding that of the PV modules. Therefore, the evaluated of energy required of each BOS components in MJ/kWp are, wiring 248 MJ/kWp, support structure 4459 MJ/kWp, foundation concrete 2352 MJ/kWp and 88402.17 MJ for the inverter of 100 kW, the embodied energy of the inverter includes the replacement of 10% of the equipment one every 10 years [26].

The energy requirement for each components of BOS and of the four PV modules technologies for each PV power plant is indicated in Table 3.

#### 3.3. Energy payback times (EPBT) and greenhouse-gas (GHG) emissions

**Energy payback times (EPBT)**

EPBT is defined as the years of operation of PV system to compensate the energy consumption from manufacturing of PV panels and the balance of system (BOS). The EPBT is expressed as follows:

\[
EPBT = \frac{E_{\text{input}}}{E_{\text{output}}} \tag{6}
\]

Where \( E_{\text{input}} = E_{PV} \cdot E_{BOS} \) \( (7) \)

\( E_{PV} \) is the energy requirement of the PV panels during life cycle containing many processes like manufacturing, installation, operation and maintenance, and energy for decommissioning. \( E_{BOS} \) is the energy input of the balance of system components including the energy requirement of all other components excepting the PV panels. \( E_{output} \) presents the electricity generated annually from a PV system, in term of primary energy, (MJ) [20, 27].

| Component                      | Energy required (MJ) |
|-------------------------------|----------------------|
| **Technology**                |                      |
| PV modules                     |                      |
| m-Si                          | 3119.38              |
| mc-Si                         | 2310.52              |
| CdTe                          | 832.81               |
| a-Si                          | 1694.099             |
| Inverter                      | 88.40                |
| Wiring                        | 26.04                |
| Support structure             | 468.19               |
| Fondation-concrete            | 246.96               |
| **Total**                     | 3949.98              |

| Component                      | Percentage (%)       |
|-------------------------------|----------------------|
| **Technology**                |                      |
| PV modules                     |                      |
| m-Si                          | 78.99                |
| mc-Si                         | 74.64                |
| CdTe                          | 51.01                |
| a-Si                          | 68.06                |
| Inverter                      | 2.24                 |
| Wiring                        | 0.66                 |
| Support structure             | 11.86                |
| Fondation-concrete            | 6.25                 |
| **Total**                     | 100                  |

**Greenhouse-gas (GHG) emissions**

The PV power plant produces electricity from solar radiation. This technology is friendly for the environment because no longer consume of fossil fuels, so as a result, no emissions of GHG. but if we take a consideration, the life cycle assessment of each component of the PV power plant (PV module and BOS), we find, that the PV power plant consumes energy and emits GHG during their lifetime.

In this study, GHG emission is considered as an equivalent of CO₂.

The emissions of CO₂ per kWh of electricity consumed is approximately 0.73 kg of CO₂/kWh [28]. The CO₂ emissions (kg of CO₂ per year) can be expressed as:

\[
CO₂ \text{ emissions per year} = \frac{E_{\text{input}} \times 0.73}{L_t} \tag{8}
\]

Where \( L_t \) is the life time of the system in years. The total CO₂ emissions (kg of CO₂) over the life time can be calculated as:
Total CO$_2$ emissions = $E_{input} \times 0.73$  \hspace{1cm} (9)

To calculate the CO$_2$ mitigation (kg of CO$_2$) per year:

The annual CO$_2$ mitigations

(kg of CO$_2$) = $E_{output} \times 0.73$  \hspace{1cm} (10)

The total CO$_2$ mitigations (kg of CO$_2$) over the life time is expressed as:

Total CO$_2$ mitigations over lifetime

= $E_{output} \times L \times 0.73$  \hspace{1cm} (11)

Using the equations (9) and (11), we obtain:

Net CO$_2$ mitigation over lifetime (kg of CO$_2$) = $(E_{output} \times L - E_{input}) \times 0.73$  \hspace{1cm} (12)

4. RESULTS AND DISCUSSION

4.1 Meteorological parameters

To understand the behavior of the grid-connected PV systems, the meteorological parameters recorded during the monitoring campaign are analyzed. To clearly analyzed the weather conditions that the PV systems were faced, the meteorological parameters were calculated during sun hours based on monthly daily average values.

Fig. 4, shows the percentage distribution of annual daily in-plane irradiation received on the PV arrays. The 85.46% of the daily in-plane irradiation occurs between 5.5 kWh/m$^2$ and 8.5 kWh/m$^2$. It is clear that the most frequent values of daily in-plane irradiation are concentrated around high values of irradiation which is typical of the Saharan climate.

![Figure 4: Percentage distribution of annual daily in-plane irradiation received on the PV arrays.](image)

In fig. 5, the percentage distribution of annual daily in-plane irradiation received on the PV arrays function of the daily average ambient temperature is depicted. The 67.66% of daily in-plane irradiation is located between 22.5 °C and 47.7 °C of ambient temperature.

![Figure 5: Percentage distribution of annual daily in-plane irradiation received on the PV arrays function of the daily average ambient temperature.](image)

Table 4 summarizes the monthly daily average and annual average meteorological parameters and their standard deviations. The monthly daily average irradiation ranges from 5.29 kWh/m$^2$ in September to 7.56 kWh/m$^2$ in May. The PV arrays received an annual daily average irradiation of 6.38 kWh/m$^2$. The ambient temperature and irradiation have a close correlation to the modules temperature. The monthly average ambient temperature varies from 17.81 °C in December to 44.70 °C in August with an annual average value of 29.57 °C. The monthly daily average wind speed reaches the lowest value of 1.07 m/s in November to the highest value of 5.51 m/s in April with an annual average value of 3.56 m/s. The monthly daily average relative humidity ranges from 9.48% in May to 47.49% in November with an annual average value of 29.91%. The monthly daily average atmospheric pressure varies from its lowest value of 943.08 hPa in April to its highest value of 964.74 hPa in December with an annual average value of 954.17 hPa.

The high values of irradiation and ambient temperature are recorded in the months of May and August respectively. The Saharan environment is renowned by low values of relative humidity, high irradiation and high values of ambient temperature recorded usually in August that can exceed 45°C as maximum value.

4.2. Performance parameters results

Data recorded from May 2015 to April 2016 were used to compute the monthly average daily performance parameters of each PV system technology. Fig. 6, shows the monthly average daily performance ratio of the grid-connected PV systems. The PV system based on m-Si technology has a performance ratio that varies from 74.77% in August to 82.95% in March. The performance ratio of mc-Si PV system ranges from 76.06% in September to 87.92% in February. For the PV
systems based on the thin films technologies, Cd-Te and a-Si, their performance ratios vary from 79.81 % in August to 88.37 % in February and from 82.02 % in April to 89.99 % in July respectively.

Table 4. Monthly daily average and annual daily average meteorological parameters and their standard deviations

| Year/Month | Irradiation (kWh/m²) | Ambient temperature (°C) | Relative humidity (%) |
|------------|----------------------|--------------------------|-----------------------|
|            | Mean | STD | Mean | STD | Mean | STD |
| 2015/05    | 7.56 | 0.10 | 39.48 | 6.77 | 3.40 | 1.46 |
| 2015/06    | 6.95 | 0.46 | 34.06 | 4.78 | 5.44 | 2.10 |
| 2015/07    | 7.11 | 0.10 | 38.70 | 4.66 | 3.96 | 1.73 |
| 2015/08    | 6.50 | 0.69 | 44.70 | 5.54 | 3.51 | 3.32 |
| 2015/09    | 6.06 | 0.54 | 35.04 | 3.77 | 3.03 | 1.98 |
| 2015/10    | 7.09 | 0.28 | 33.38 | 5.69 | 3.53 | 2.05 |
| 2015/11    | 5.29 | 1.45 | 25.68 | 3.67 | 1.07 | 37.79 |
| 2015/12    | 6.06 | 0.55 | 17.81 | 5.44 | 1.66 | 1.05 |
| 2016/01    | 5.00 | 0.86 | 20.68 | 5.47 | 4.06 | 2.81 |
| 2016/02    | 6.03 | 1.18 | 20.19 | 5.23 | 2.89 | 2.17 |
| 2016/03    | 6.90 | 0.89 | 21.33 | 5.71 | 4.43 | 2.09 |
| 2016/04    | 5.88 | 2.23 | 24.32 | 5.76 | 5.51 | 2.75 |
| **Annual Avg** | 6.41 | 0.78 | 29.61 | 5.21 | 3.54 | 5.11 |

| Year/Month | Wind speed (m/s) | Relative humidity (%) | Atmospheric pressure (hPa) |
|------------|------------------|-----------------------|---------------------------|
|            | Mean | STD | Mean | STD | Mean | STD |
| 2015/05    | 3.40 | 1.46 | 9.48 | 6.54 | 954.34 | 3.15 |
| 2015/06    | 5.44 | 2.10 | 22.43 | 6.40 | 953.63 | 1.42 |
| 2015/07    | 3.96 | 1.73 | 20.31 | 6.60 | 954.28 | 2.06 |
| 2015/08    | 3.51 | 3.32 | 12.94 | 6.08 | 951.29 | 1.71 |
| 2015/09    | 3.03 | 1.98 | 20.64 | 8.48 | 951.17 | 1.15 |
| 2015/10    | 3.53 | 2.05 | 31.81 | 12.11 | 955.05 | 3.52 |
| 2015/11    | 1.07 | 37.79 | 47.49 | 11.98 | 957.67 | 2.58 |
| 2015/12    | 1.66 | 1.05 | 48.22 | 17.25 | 964.74 | 1.26 |
| 2016/01    | 4.06 | 2.81 | 34.32 | 12.39 | 954.25 | 4.56 |
| 2016/02    | 2.89 | 2.17 | 38.63 | 10.74 | 961.12 | 2.42 |
| 2016/03    | 4.43 | 2.09 | 29.07 | 14.96 | 948.69 | 4.88 |
| 2016/04    | 5.51 | 2.75 | 39.09 | 18.00 | 943.08 | 5.12 |
| **Annual Avg** | 3.54 | 5.11 | 29.54 | 10.96 | 954.11 | 2.82 |

The PV systems of the thin film technologies perform better through the year when the mc-Si technology performs better in the winter season.

It can be noticed that a seasonal trend of the grid-connected PV systems monthly average daily performance ratio is observed and it is different from technology to another. This seasonal trend in performance ratio was also observed in tropical desert maritime climate conditions by Daher et al. [29] and in the south of the Mediterranean climate by Phinikarides et al. [30].

In fig. 7, the monthly average daily final yield and reference yield are depicted. The reference yield varies from its high value of 7.56 hours in May to low value of 5.29 hours in September. The final yield of all technologies follow the same trend as the reference yield. The thin film technologies Cd-Te and a-Si have a better final yield in all seasons. The a-Si technology has its final yield better in the summer when the Cd-Te in the spring and the winter.

The monthly average daily AC energy output is shown in fig. 8. Both thin film technologies have their AC energy outputs vary from their lowest values in September to their highest values in August. The Cd-Te final yield ranges from 452.16 kWh to 627.49 kWh when the a-Si final yield varies from 437.56 kWh to 665.59 kWh.

The grid-connected PV systems based on thin film module technologies generate more AC energy than the PV systems based on silicon technologies through the year except in December and January where the m-Si system generates more AC energy than all the others technologies.
Despite its low efficiency, the a-Si PV system performs better than the other technologies under the Saharan climate conditions of Ghardaia city.

Table 5. Annual daily average performance ratio, final yield, AC energy output and system efficiency and their respective standard deviations.

| PV system | Daily PR (%) | Mean | STD  | Daily final yield (kWh/kWp) | Mean | STD  |
|-----------|-------------|------|------|-----------------------------|------|------|
| m-Si      | 79.41       | 2.69 | 5.00 | 0.58                        |
| mc-Si     | 81.83       | 2.42 | 4.91 | 0.60                        |
| CdTe      | 84.41       | 2.36 | 5.41 | 0.65                        |
| a-Si      | 87.17       | 2.17 | 5.58 | 0.65                        |

Fig. 8. Monthly average daily AC energy generated.

Fig. 9 shows the efficiencies of PV systems. The efficiency of m-Si PV system varies from 12.10 % in August to 13.43 % in March, when the mc-Si PV system efficiency ranges from 11.57 % in September to 13.38 % in February. For the thin film technologies Cd-Te and a-Si, this PV systems' efficiencies vary from 8.87 % in August to 9.82 % in February and from 5.83 % in April to 6.39 in July respectively.

The Cd-Te, m-Si and mc-Si technologies have their efficiencies better in the winter and in the other hand the a-Si technology efficiency is better in the summer.

4.3. EPBT and GHG emissions results

Table 6 shows the energy payback time for each grid-connected PV systems, and the different parameters of CO2 emissions, the results obtained in the present study concerned the EPBT was calculated using the Eqs.(6) and (7) and from the eqs (8) to (12) are used to calculate CO2 emissions, total CO2 emission, CO2 mitigations, CO2 mitigation over lifetime and net CO2 mitigation over lifetime respectively.

Table 6. The energy payback time for each PV system and CO2 results.

| PV system | EPBT (years) | CO2 emissions (tons of CO2/year) | Annual CO2 mitigation (tons of CO2) | Net CO2 mitigation over life time (Tons) |
|-----------|--------------|----------------------------------|-------------------------------------|----------------------------------------|
| m-Si      | 5.73         | 32.03                             | 139.77                              | 2693.5                                 |
| mc-Si     | 4.86         | 25.11                             | 129.03                              | 2598                                   |
| CdTe      | 2.8          | 13.24                             | 145.26                              | 3300.5                                 |
| a-Si      | 3.39         | 20.19                             | 148.85                              | 3216.5                                 |

From the results obtained in Table 6. It is observed that the EPBT is low for CdTe PV technology with value of 2.8 years compared with others PV technologies of 3.39 yrs, 4.86 yrs and 5.73 yrs for a-Si, mc-Si and m-Si respectively. This difference between different PV technologies is due mainly to the amount of energy consumed during the manufacturing process, when the m-Si consumes more energy compared to the mc-Si and the thin film technology (a-Si and CdTe). The CO2 emissions (tons of CO2/year) is inversely proportional to the CO2 mitigation (tons of CO2), when the CdTe PV technology has a low value of the CO2 emissions of 13.24 (tons of CO2/year) with high value of net CO2 mitigation of 3300.5 (tons).
5. CONCLUSION

The evaluation of four grid-connected PV systems based on different PV module technologies is conducted under Saharan environment climate conditions at Ghardaia city in Algeria. Two technologies are based upon the following silicon based technologies: monocrystalline silicon (m-Si) and mc-Si (multi-crystalline) and two other ones are thin film technologies, cadmium telluride (Cd-Te) and amorphous (a-Si).

The PV array of the grid-connected systems are faced to a high annual daily average irradiation of 6.38 kWh/m² and a high annual daily average ambient temperature of 29.57 °C. The ambient temperature in such area can reach 45 °C especially in August. It was observed that a 67.66% of daily plane irradiation occurs between 22.5 °C and 47.7 °C of ambient temperature.

Data recorded during the monitoring campaign from May 2015 to April 2016 were used to assess the performance of the PV systems. The PV systems based on the thin film technologies have their performance ratio better through the year when the performance ratio of the mc-Si technology is better in the winter season. The Cd-Te and a-Si technologies have a better final yield in all seasons. The a-Si technology has its final yield better in the summer when the Cd-Te in the spring and the winter.

The Cd-Te, m-Si and mc-Si technologies have their efficiencies better in the winter and in the other hand the a-Si technology efficiency is better in the summer. The a-Si PV system has the better annual average daily performance ratio of 87.17 %, the higher final yield of 5.58 kWh/kWp and the better AC output energy of 558.64 kWh.

The a-Si PV system has its performance ratio about 3.17 % better than the Cd-Te, 6.13 % better than mc-Si and 8.90 % better than m-Si.

The AC energy produced with the a-Si PV system is 13.32 % more than what the mc-Si system produces. Despite its low efficiency, it can be concluded that the a-Si PV system performs better than the other technologies under the Saharan climate conditions of Ghardaia city.

The EPBT is higher for thin film than the crystalline PV technology, it vary between 2.8 and 5.73 years for CdTe, 3.39 for a-Si, 4.86 yrs for mc-Si and 5.73 for m-si). Hence, the EPBT will be higher if the process of manufacture of the BOS of the grid-connected PV system and especially PV modules consumed more energy.

The CO₂ emissions, range from 13.24 (tons of CO₂/year) for CdTe to 32.03 (tons of CO₂/year) for m-Si.

REFERENCES

1. Holden E, Linnerud K, Banister D. Sustainable development: Our Common Future revisited. Global Environmental Change 2014; 26: 130–139.

2. Leach G. The energy transition. Energy Policy 1992; 20: 116–123.

3. Süsser D, Döring M, Ratter BMW. Harvesting energy: Place and local entrepreneurship in community-based renewable energy transition. Energy Policy 2017; 101: 332–341. https://doi.org/10.1016/j.enpol.2016.10.018

4. Moosavian SM, Rahimi NA, Selvaraj J, Solangi KH. Energy policy to promote photovoltaic generation. Renewable and Sustainable Energy Reviews 2013; 25:44–58. https://doi.org/10.1016/j.rser.2013.03.030

5. Solé J, García-Olivares A, Turiel A, Ballabreria-Poy J. Renewable transitions and the net energy from oil liquids: A scenarios study. Renewable Energy 2018; 116:258–271. https://doi.org/10.1016/j.renene.2017.09.035

6. Renewables 2017: Global Status Report. Montreal, QC, CA: REN21, 2017.

7. Lai CS, Jia Y, Lai LL, Xu Z, McCulloch MD, Wong KP. A comprehensive review on large-scale photovoltaic system with applications of electrical energy storage. Renewable and Sustainable Energy Reviews 2017;78:439–451. https://doi.org/10.1016/j.rser.2017.04.078

8. Freitas S, Santos T, Brito MC. Impact of large scale PV deployment in the sizing of urban distribution transformers. Renewable Energy 2018; 119: 767–776. https://doi.org/10.1016/j.renene.2017.10.096

9. Fraunhofer Institute for Solar Energy Systems, ISE, Ed., “PHOTOVOLTAICS REPORT,” Jul. 2017.

10. Edalati S, Ameri M, Irannanesh M. Comparative performance investigation of mono- and polycrystalline silicon photovoltaic modules for use in grid-connected photovoltaic systems in dry climates. Applied Energy 2015;160:255–265. https://doi.org/10.1016/j.apenergy.2015.09.064

11. Humada AM, Hojabri M, Hamada HM, Samsuri FB, Ahmed MN. Performance evaluation of two PV technologies (c-Si and CIS) for building integrated photovoltaic based on tropical climate condition: A case study in Malaysia. Energy and Buildings 2016; 119: 233–241.

12. Myong SY, Park YC, Jeon SW. Performance of Si-based PV rooftop systems operated under distinct four seasons. Renewable Energy 2015; 81: 482–489. https://doi.org/10.1016/j.renene.2015.03.055

13. Başoğlu ME, Kazdaloğlu A, Erfidan T, Bilgin MZ, Çakır B. Performance analyzes of different photovoltaic module technologies under Izmit, Kocaeli climatic conditions. Renewable and Sustainable Energy Reviews 2015; 52: 357–365. https://doi.org/10.1016/j.rser.2015.07.108

14. Wang H, Muñoz-García MA, Moreda GP, Alonso-García MC. Seasonal performance comparison of three grid connected photovoltaic systems based on different technologies operating under the same conditions. Solar Energy 2017; 144: 798–807. https://doi.org/10.1016/j.solener.2017.02.006

15. Kazem HA, Khatib T, Sopian K, Elmenreich W. Performance and feasibility assessment of a 1.4kW roof top grid-connected photovoltaic power system under desertic weather conditions. Energy and Buildings 2014; 82: 123–129.

16. Ferrada P, Araya F, Marzo A, Fuentealba E. Performance analysis of photovoltaic systems of two different technologies in a coastal desert climate zone of Chile. Solar Energy 2015; 114: 356–363. https://doi.org/10.1016/j.solener.2015.02.009
17. Daroub R, Bouchafa F, Hadj Arab A, Bouriau A, Draou MD, Neçaiba A, Mostefaoui M. Monitoring and performance analysis of grid connected photovoltaic under different climatic conditions in south Algeria. Energy Conversion and Management 2016;130:200–206. https://doi.org/10.1016/j.enconman.2016.10.058

18. IEC 61724: Photovoltaic system performance monitoring - guidelines for measurement, Data Exchange and Analysis. [Online] Available: https://global.ies.com/doc_detail.cfm?gid=CEFDCAAAAAAA, Accessed on: Feb, 05 2018.

19. Khalid AM, Mitra, Warmuth W, Schacht V. Performance ratio – Crucial parameter for grid connected PV plants. Renewable and Sustainable Energy Reviews 2016; 65: 1139–1158. https://doi.org/10.1016/j.rser.2016.07.066

20. Kim HC, Fthenakis VM. Life cycle energy demand and greenhouse gas emissions from an amorphous high concentrator photovoltaic system. IEEE 4th World Conference on Photovoltaic Energy Conference 2006; 628–631.

21. Leccisi E, Raugei M, Fthenakis V. The energy and environmental performance of ground-mounted photovoltaic-systems-a timely update. Energies 2016; 9: 622. https://doi.org/10.3390/en8080622

22. Sherwani AF, Usmani JA, and Varun. Life cycle assessment of solar PV based electricity generation systems: A review. Renewable and Sustainable Energy Reviews 2010; 14: 540–544.

23. Van Overstraeten RJ. Advances in silicon solar cell processing. In Photovoltaic Solar Energy Conference: Proceedings of the International Conference, Held at Cannes, France, 1980. W. Palz, Ed., Dordrecht: Springer Verlag; 2013: 257–262.

24. Peng J, Lu L, Yang H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews 2013; 19: 255–274. https://doi.org/10.1016/j.rser.2012.11.035

25. Ito M, Kato K, Komoto K, Kichimi T, Kurokawa K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules. Prog. Photovolt: Res. Appl. 2008; 16: 17–30.

26. Alsena EA, Frankl P, Kato K. Energy pay-back time of photovoltaic energy systems: Present status and prospects.(en) https://dspace.library.uu.nl/bitstream/1874/7943/1/98053.pdf. 1998.

27. Wu P, Ma X, Ji J, Ma Y. Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study. Energy Procedia 2017; 105:68–74. https://doi.org/10.1016/j.egypro.2017.03.281

28. Brander M, Sood A, Wylie C, Haughton A, Lovell J. Technical Paper Electricity-specific emission factors for grid electricity. Ecometria, Emissionfactors. com, 2011.

29. Daher DH, Gaillard L, Amara M, Ménéo C. Impact of tropical desert maritime climate on the performance of a PV grid-connected power plant. Renewable Energy 2018;125:729–737. https://doi.org/10.1016/j.renene.2018.03.013

30. Phinikarides A, Makrides G, Zinsser B, Schubert M, Georgiou GE. Analysis of photovoltaic system performance time series: Seasonality and performance loss. Renewable Energy 2015; 77: 51–63. https://doi.org/10.1016/j.renene.2014.11.091

Received 2020-02-18
Accepted 2020-05-05
Available online 2020-05-06

Mr. DERICHE
Mohammed Amine. He received his state engineer degree in Electrical Engineering from the Faculty of Hydrocarbons and Chemistry, University of Boumerdes, Algeria in 2011, his Master degree in Mechanical Engineering / Modelling and Simulation in Mechanics from the Faculty of Engineering, University of Boumerdes, Algeria in 2012. After having completed his Master project, he joined the Modelling Simulation and Optimization of Alternative and Sustainable Systems Division of Materials, Processes and Environment research Unit (MESO/URMPE) where he is preparing his PhD studies in the Faculty of Engineering, University of Boumerdes, Algeria. He is the author of many scientific papers in the field of renewable energy, photovoltaic power plants performances. He is a consultant for the industry since 2012 as a coordinator of many PV power plants projects in Algeria. He is also involved in Renewable energy training courses at the national company of electricity center in Blida, Algeria. E-mail: ma.deriche@univ-boumerdes.dz

Professor Ahmed HAFIFIA was born in Algeria in 1974, he received the State Engineer degree in 2000 on Applied Automation, the Magister degree in 2004 on Applied Automation and control systems and the PhD on Applied Automation and Signal Processing in 2010 from the UMBB Boumerdes University. He received the Habilitation from the University of Sciences and Technology Houari Boumediene - USTHB - Faculty of Electronics and Computer Science, Department of Instrumentation and Automation on 2012. He is a PhD and Full Professor in Industrial Process: Automation / Diagnosis and Reliability Engineering at the Science and Technology Faculty of the University of Djelfa, Algeria, where He is actually the president of the scientific committee of Technical Sciences Department (CSD) since 2014 and he is pursuing his researches as a researcher at the Applied Automation and Industrial Diagnostic Laboratory of the University of Djelfa. Professor Ahmed HAFIFIA has participated in several international research projects and has led several national research projects. Currently he is the Director of the Applied Automation and Industrial Diagnostic Laboratory of the University of Djelfa. Professor Ahmed HAFIFIA is the founder of the Applied Automation and Industrial Diagnostic Laboratory at the University of Djelfa. He is the supervisor of many PhD Students in Algeria and he is the coordinator of several industrial research projects within
the applied automatic and reliability of industrial systems. His research area of interests includes the modelling and control in industrial systems, the diagnosis and new reliability engineering, fault detection and isolation in industrials process, intelligent system based on fuzzy logic and neural networks. He is acting as an expert in several national and internationals commissions and collaboration research activities. He has supervised several Master students and published many national/international conferences and journals papers.

E-mail: a.hafaifa@univ-djelfa.dz

Ali TAHRI was born in El Biodh Naama in Algeria in 1967. He received the Ingeniorat d’Etat, the M.Sc. and the PhD degrees from the University of Sciences and Technology of Oran, Algeria in 1992, 1997 and 2006 respectively all in electrical engineering. His main research interests are in the field of analysis, modeling and simulation of power converters, the advanced static VAR compensation, FACTS and photovoltaic systems. He is now a professor at electrotechnics department of the University of Sciences and Technology (Oran, Algeria) and member of the electrical engineering laboratory of Oran.

E-mail: alitahri.dz@gmail.com

Kamal MOHAMMEDI is a Professor in Energy Conversion since 1993, at M. Bougara University, Boumerdes/ Algeria. His research topics focuses on Multiphase Flows, Desalination processes, Solar Thermal Energy, Renewable Energy and Sustainable Development. He received his M Sc. degree in Mechanical Engineering from Boumerdes National Institute of Mechanical Engineering (INGM) Algeria, in 1985 and his Diplôme d’Etudes Approfondies and PhD degrees in Process Engineering from the INSA de Lyon, France, in 1992. Head of the Modelling Simulation and Optimization of Alternative and Sustainable Systems Division of Materials, Processes and Environment research Unit (MESO/URMPE), he has been involved in 2 FP6 European projects in Desalination with Renewable energy in Remote areas (RESYSproDESAL, OPEN-Gain) and 10 national projects in the fields of hybrid renewable energy systems, Renewable Energy Desalination, CSP, Sustainable Industrial parks, Carbone Dioxide mitigation, Energy Efficiency, Decision making, etc. He is the author and co-author of more than 40 published papers; book chapters and 100 conference articles in the fields of Concentrated Solar Power, Desalination, Hybrid Renewable Energy Systems, Low Carbone industry and multiphase flows interface tracking. He is a member of scientific committees and a reviewer of national and International journals. He is a member of advisory boards of national and international conferences where he chaired sessions. He supervised Master/ Engineer/Magister and PhD theses and consults for industry.

E-mail: mohammedi.kamal@univ-boumerdes.dz

Fatima TAHRI was born in Oran in Algeria. She received the Ingeniorat d’Etat, the M.Sc. and the PhD degrees from the University of Sciences and Technology of Oran, Algeria in 2002, 2006 and 2014 respectively all in electrical engineering. She is now working on projects dealing with power electronics converters in renewable energy. She is now a senior lecturer at High School of Electrical Engineering and Energetics of Oran, ESGEE, Algeria and member of the electrical engineering laboratory of Oran.

E-mail: fatimatahri.dz@gmail.com