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

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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 İzmit, Kocaeli weather conditions in Northwest of Turkey by Başoğlu et al. [13]. The three PV systems were installed by using crystalline (c-Si), multi-crystalline (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 kW h/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/lc-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/lc-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 titled 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_M (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_{sc} 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_M 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
Pmax (kW_p)	105	98.7	100.8	100.116
I_{pm} (A)	173.04	170.1	173.25	200.88
V_{pm} (V)	607	580.8	582	608.4
I_{sc} (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 pression, 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-connedted 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 ÷ +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] :

$$PR = \frac{Y_F}{Y_R} \times 100 \tag{1}$$

YF is defined as the daily AC energy output EAC 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:

$$Y_F = \frac{E_{AC}}{P_{STC}} \tag{2}$$

YR 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:

$$Y_R = \frac{\tau \sum G_{meas}}{G_{STC}} \tag{3}$$

Where Gmeas 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:

$$E_{AC} = \tau \sum P_{ACi} \tag{4}$$

Where P_{ACi} 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:

$$\eta_{sys} = \frac{E_{AC}}{S_A \tau \sum G_{meas}} \quad (5)$$

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 Standarization (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.

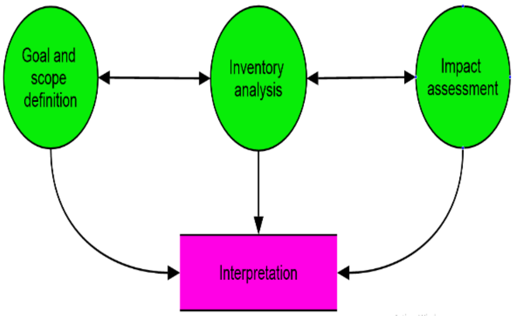

Fig. 2. Framework of life cycle assessment

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

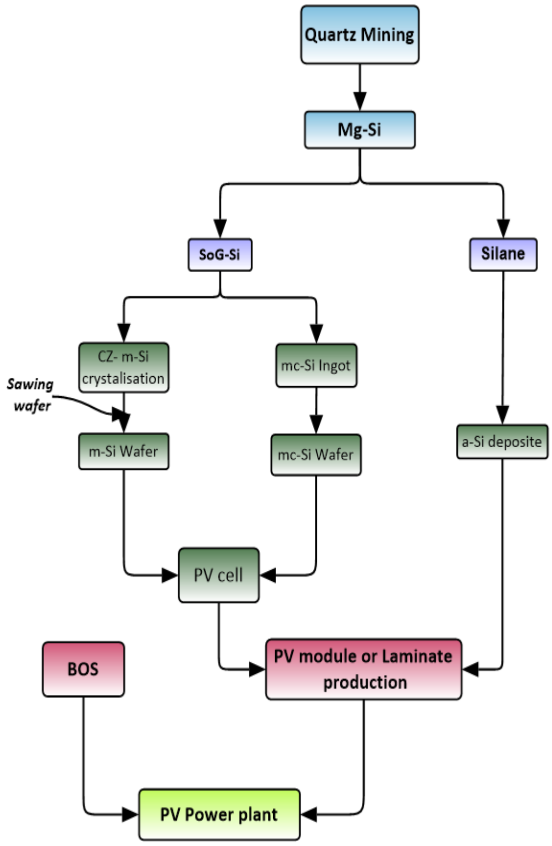

Fig. 3. Process step of manufacturing of crystalline and thin film silicon module (m-Si, mc-Si and a-Si)

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/m^2, 2699 to 5150 MJ/m^2, 790 to 1803 MJ/m^2 and 710 to 1990 MJ/m^2 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/m^2 and 5253 MJ/m^2, and the average of 3065 MJ/m^2, 3120 MJ/m^2 and 3940 MJ/m^2 respectively. There is one more step in the production process of monocrystalline 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_p/kW_p are, wiring 248 MJ_p/kW_p, support structure 4459 MJ_p/kW_p, foundation concrete 2352 MJ_p/kW_p 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:

$$EPBT = \frac{E_{input}}{E_{output}} \tag{6}$$

Where $E_{input} = E_{PV} E_{BOS}$ (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].

Table 3. Energy required by the principal components of the four PV power plants technologies

Component	Energy required (GJ)			
Technology	m-Si	mc-Si	CdTe	a-Si
PV modules	3119.38	2310.52	832.81	1694.099
Inverter	88.40	88.40	88.40	88.40
Wiring	26.04	24.48	25	24.83
Support structure	468.19	440.10	449.47	446.42
Fondation-concrete	246.96	232.14	237.08	235.47
Total	3948.98	3095.65	1632.76	2489.22
Component	Percentage (%)			
Technology	m-Si	mc-Si	CdTe	a-Si
PV modules	78.99	74.64	51.01	68.06
Inverter	2.24	2.86	5.41	3.55
Wiring	0.66	0.79	1.53	0.99
Support structure	11.86	14.22	27.53	17.93
Fondation-concrete	6.25	7.50	14.52	9.46
Total	100	100	100	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 CO_2.

The emissions of CO_2 per kWh of electricity consumed is approximately 0.73 kg of CO_2/kWh [28]. The CO2 emissions (kg of CO_2 per year) can be expressed as:

$$CO_2 \text{emissions per year} = \frac{E_{input} \times 0.73}{L_t} \tag{8}$$

Where L_t is the life time of the system in years.

The total CO_2 emissions (kg of CO_2) over the life time can be calculated as:

$$TotalCO_2\text{emissions} = E_{input} \times 0.73 \quad (9)$$

To calculate the CO_2 mitigation (kg of CO_2) per year:

$$\text{The annual } CO_2 \text{ mitigations } (\text{kg of } CO_2) = E_{\text{output}} \times 0.73 \quad (10)$$

The total CO_2 mitigations (kg of CO_2) over the life time is expressed as:

$$\text{Total } CO_2 \text{ mitigations over lifetime} = E_{\text{output}} \times L_t \times 0.73 \quad (11)$$

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

$$\text{Net } CO_2 \text{ mitigation over lifetime (kg of } CO_2) = \left(E_{\text{output}} \times L_{\text{t}} - E_{input}\right) \times 0.73 \quad (12)$$

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.

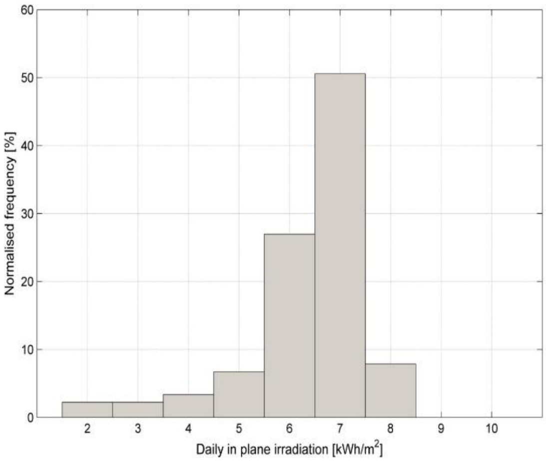

Fig. 4. Percentage distribution of annual daily in-plane irradiation received on the PV arrays.

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.

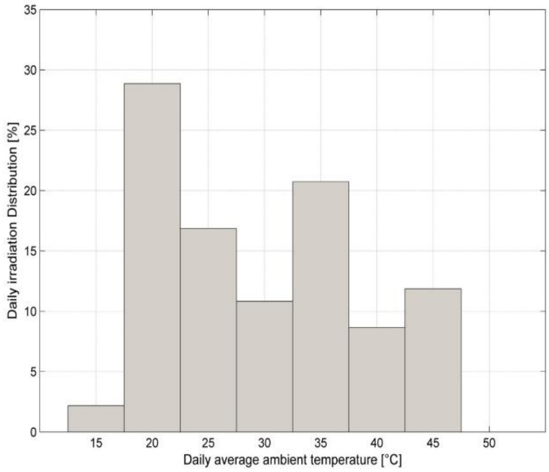

Fig. 5. Percentage distribution of annual daily in-plane irradiation received on the PV arrays function of the daily average ambient temperature.

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 crucial influence on the PV plants outputs, knowing that they have a close correlation to the modules temperature. The monthly daily average ambient temperature varies from 17.81 °C in December to 44.70 °C in August with an annual daily 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	5.50	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 technolgy 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].

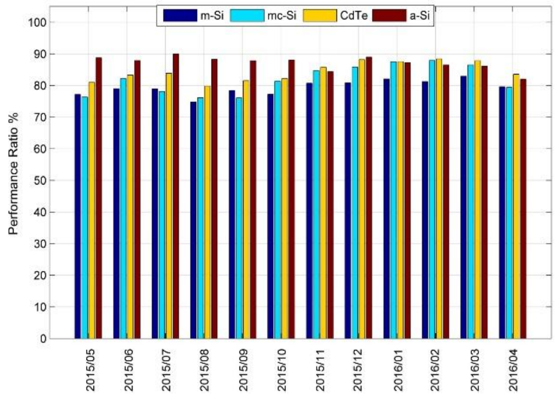

Fig. 6. Monthly average daily performance ratio

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.

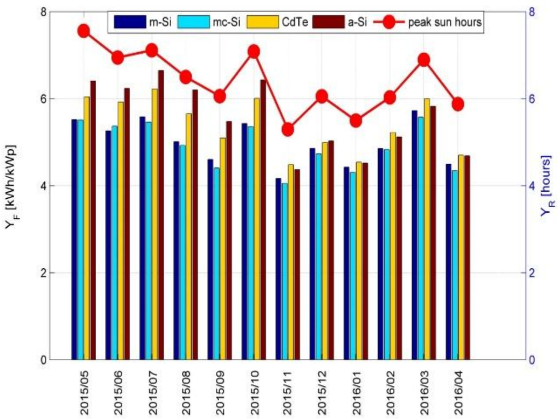

Fig. 7. Monthly average daily final yield and reference yield.

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.

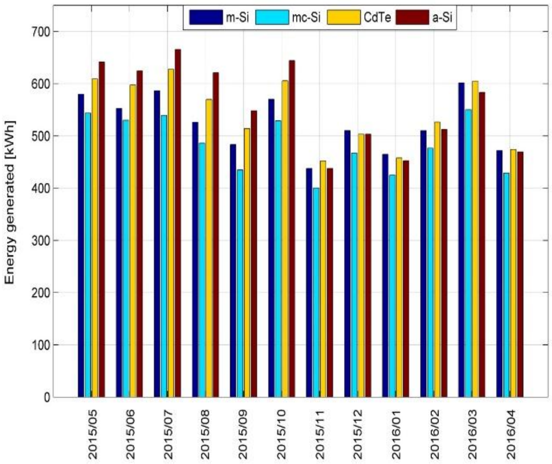

Fig. 8. Monthly average daily AC energy generated.

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, their 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.

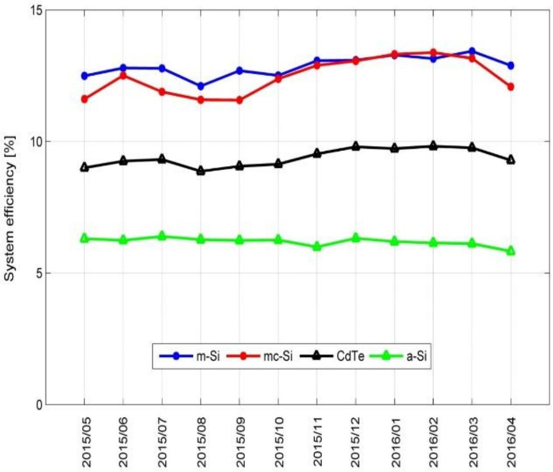

Fig. 9. Monthly average daily systems efficiency.

Table 5 summarizes the annual daily average performance parameters and their respective standard deviations. 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 % more better than the Cd-Te, 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.

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 (%)		Daily final yield (kWh/kWp)	
	Mean	STD	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
PV system	Daily AC energy (kWh)		Daily system efficiency (%)	
	Mean	STD	Mean	STD
m-Si	524.56	60.50	12.86	0.43
mc-Si	484.25	59.31	12.45	0.37
CdTe	545.17	65.61	9.38	0.26
a-Si	558.64	65.08	6.19	0.15

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)	CO_2 emissions (tons of CO_2/year)	Annual CO_2 mitigation (tons of CO_2)	Net CO_2 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 CO_2 emissions (tons of CO_2/year) is inversely proportional to the CO_2 mitigation (tons of CO_2), when the CdTe PV technology has a low value of the CO_2 emissions of 13.24 (tons of CO_2/year) with high value of net CO_2 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/m^2 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 in-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 asess 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 technolgy 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 (2.8 yrs 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 CO_2 emissions, range from 13.24 (tons of CO_2/year) for CdTe to 32.03 (tons of CO_2/year) for m-Si.

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