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Articles and Statements

Simulation Study of Three Solar PV Grid-Conected Systems

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Abstract

In this paper, a performance analysis of three grid-connected PV systems in Beni Mellal weather conditions was carried out using PVsyst software and the monitored data. The PV system consists of polycrystalline silicon (pc-si), monocrystalline silicon (mc-si) and amorphous (a-si) solar cell technologies. The predicted annual production is found to be around 3733.1 kWh, 3716.5 kWh and 3543.8 kWh for the mc-si, pc-si and a-si technologies, respectively. The performance analysis has showed that the predicted annual average value of PR ratio for the a-si is nearly 83.8 %, 80.5 % for mc-si and 80.1 % for pc-si plant. The analysis of actual operating data has revealed that the annual average value of PR of pc-si, mc-si and a-si technologies are quantifiable at 86.80 %, 84.87 % and 83.60 %, respectively.

Keywords: PV systems, mc-si, pc-si, a-si, performance analysis, performance ratio, final yield, system losses, PVSyst.

1. Introduction

Solar energy is a free and inexhaustible source of energy that can provide alternative energy without polluting the environment. Therefore, its use reduces the rate of decrease in energy reserves. Solar energy has a huge energy potential that exceeds fossil fuels and can meet the world's energy needs many times over.

Recently, research in the field of photovoltaic solar energy has been increasingly active. Most of the conducted researches are focused on two main areas. The first one is to improve the conversion of solar radiation into electrical energy, while the second one is associated with DC to AC conversion at inverter level. As a result, the Photovoltaics become a fast growing market. The Compound Annual growth rate of PV installations was 24 % between years 2010 to 2017. Photovoltaic module production is in continuous growth. In 2017, China and Taiwan took a share of 70 %, followed by the rest of Asia-Pacific and Central Asia with 14.8 %. Europe contributed by 3.1 %. The United States and Canada accounted for 3.7 %. The record lab cell efficiency is 26.7 % for mono-crystalline and 22.3 % for multi-crystalline silicon wafer-based technology. The highest

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lab efficiency in thin film technology is 21.7 % for CIGS and 21.0 % for CdTe solar cells. PV system performance has strongly improved. Before 2000, the typical Performance Ratio was about 70 %, while today it is in the range of 80 % to 90 % (Philipps et al., 2018).

The performance analysis of photovoltaic installations is very important because it ensures the monitoring of the installations by detecting anomalies that may appear. It reveals the impact of weather conditions, especially, temperature and dust, as well as losses at the level of inverters and cables... For example, the works conducted in (Monokroussos et al., 2011; Huld et al., 2011; Zinßer et al., 2008; Strobel et al., 2009) show that the global irradiance, ambient temperature and the solar radiation spectrum are parameters that most affect energy production. All of these parameters affect the operating conditions of PV modules, however the cells temperature is the major factor affecting electricity production. In fact, the effect of the temperature on operating solar cells is related to the temperature coeffcient of each PV technology (Makrides et al., 2009). The work in paper (Radziemska et al., 2003) showed that for the crystalline silicon modules (c-Si), the performance, decreases when the temperature increases, while the paper (Makrides et al., 2012) showed that the modules realized with single or multi-junction amorphous silicon cells (a-Si) are able to improve the electrical performance in high temperature conditions.

The electrical performance analysis of the grid-connected photovoltaic system is based on the international IEC 61724 (Anon et al., 1998) standard published by the International Electro Technical Commission (IEC). It describes the performance parameters of photovoltaic installations including the final yield (Yf) and the Performance Ratio (PR). It is noted that final yield is used to compare the performance of PV systems installed at the same place using the same or differing mounting structure. Performance Ratio (PR) is widely used to analyze the performance and to compare PV systems located in different regions. Several studies are carried out to analyze the performance of photovoltaic installations based on the performance ration. It has been shown in paper (Leloux et al., 2012) that the average value of the performance ratio of 993 residential PV systems in Belgium was found to be 78 %. In island, the performance ratio (PR) of a photovoltaic park, with a peak power of 171.36 kWp, has ranged from 58 to 73 %, giving an annual PR of 67.36 % (Kymakis et al., 2009). In paper (Sharma et al., 2013), a correction to the efficiency module results a reducing in the absolute percentage error between measured and predicted annual energy yield and performance ratio values to 4.89 %, 4.94 %, 1.16 % and 4.34 %, 4.93 %, 1.88 % for p-si, HIT and a-si arrays respectively. The performance comparison shows that HIT and a-si arrays have performed better than p-si array at this location. The energy yield of a-si modules is found to be 14% more in summer months and 6 % less in winter months in comparison to p-si modules. The HIT modules are found to produce 4-12 % more energy consistently than p-si modules. In Meknes (Morocco), a performance analysis and economical/environmental assessment of two grid-connected PV systems, including pc-Si and mc-si technologies, were carried out. The results showed that, for the same rated capacity, pc-si modules have higher monthly total average final yield than mc-Si modules. The leveled cost of electricity ranges between 0.073-0.082 $/kW h. The Payback time found to be in the range 11.10-12.69 years for this analysis. Furthermore, it was shown that the installed PV system has the potential of reducing approximately 5.01 tons of CO_2 emission per year (Allouhi et al., 2016). The performance analysis of three PV plants installed in Marrakech city has shown that in winter, pc-si yields achieve 11 % more than a-si/μc-si but it generates 7 % less than mc-si. In summer, pc-si yields perform 4 % less than a-Si/μc-Si, but 7 % more than mc-si. Relative performance of a-si/μc-si increases by nearly 0.6% per 1°C against its two other bulk-silicon competitors, supporting that a-si/μc-si cells operate with a positive temperature power coefficient. Analysis of the daily data shows that the a-Si/μc-si cells daily performance degrades 1.1 % faster that the mc-si one. The a-si/μc-si cells daily performance degrades 0.2 % faster that pc-si one, while the pc-si cells daily performance degrade 0.9 % faster that mc-si one. Cumulative yearly PV yields show that the a-si/μc-si solar cells AC yearly yield performs around 1.5 % more than the mc-si one but degrades yearly nearly 1.5 % faster than the former, and that a-si/μc-si solar cells AC yearly yield performs around 2.2 % less than the pc-si ones and degrades yearly nearly 0.8 % faster than the former. In addition, the pc-si solar cells AC yearly yield performs around 3.8 % more than the mc-Si ones but degrades yearly nearly 0.8 % faster than the former (Aarich et al., 2018).

The aim of this work is to this program by simulating, using PVsyst software, and comparing the production of the three photovoltaic plants based on the three silicon technologies, including monocrystalline (mc-si), polycrystalline (pc-si) and amorphous (a-si) silicon technologies. The associated analysis is made using performance parameters being specified by International Energy Agency (IEA) (Eltawil et al., 2010). The dealt with parameters are the performance ratio (PR), the system losses (Ls), the capture losses (Lc), the final yield (Yf) and the capacity factor (FC). Actual production and weather data are also given and analyzed.

1. PV Plants Description

1.1. PV Plants

The photovoltaic system was installed on the rooftop (Fig.1) of the Faculty of Science and Technology, Beni Mellal, Morocco. It consisted of three mini-stations of 2kWp photovoltaic for each one, distinguished by the three silicon technologies: Monocrystalline (mc-si), Polycrystalline (pc-si) and Amorphous (a-si). Each mini-station of both monocrystalline and polycrystalline types formed by eight panels of Sunmodule plus SW 255 Wp from Solarworld. The modules, which are included 60 solar cells connected in series, have a yield of 15 % under standard test conditions. Every string is connected to the 3-phase Sunny Boy 2500HF inverter. The Amorphous Silicon mini-station consists of 12 panels of POWER NT_155AF 155 Wp forming two strings joined in parallel. Each string is formed by connecting 6 modules in series. Both strings are linked to a 3-phase Sunny Boy 2500HF inverter. The unshaded modules were fixed with an tilt angle of 30°, facing south at an azimuth angle of 0°. More details can be illustrated in Table 1 and Figure 2.

Fig. 1. The three PV plants

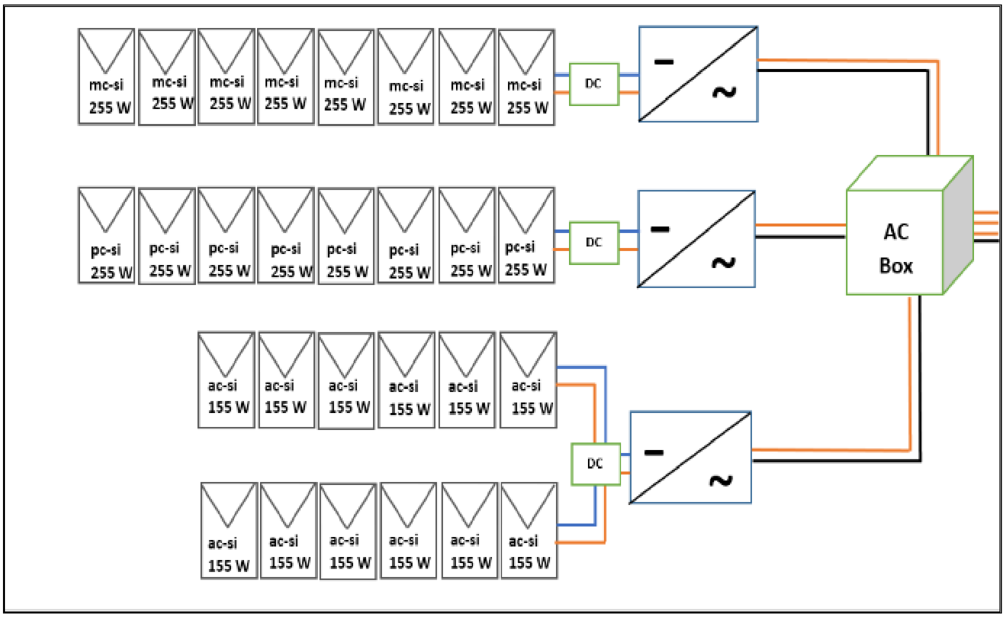


Fig. 2. PV plants illustrative schematics

Table 1. Electrical characteristics

Modules	mc-si	pc-si	a-si
Module nominal power (W)	255	255	155
Module nominal open circuit voltage (V)	37.8	38	85.5
Module nominal voltage at maximum power (V)	31.4	30.9	65.2
Module nominal short circuit current (A)	8.66	8.88	2.56
Module nominal current at maximum power (A)	8.15	8.32	2.38
Temperature coefficient of power (per K)	-0.450 %	-0.410 %	-0.280 %
Temperature coefficient open circuit voltage (per K)	-0.300 %	-0.310 %	-0.320 %
Temperature coefficient short circuit current	0.004 %	0.051 %	0.070 %

1.2. The weather Station

The photovoltaic power generated is directly related to the climatic conditions including solar radiations and the ambient temperature. To follow the changes of the meteorological parameters and their influence on the production of the photovoltaic field, we have installed a meteorological station that measures the horizontal solar irradiations, the irradiation inclined by 30°, the ambient temperature, the photovoltaic panel temperature, the wind speed and the wind direction.

Concerning the solar irradiation, we have used two polycrystalline silicon modules. This solar module is belonging to Pheasant "Sun plus 20".

In order to get information about the PV panels' ventilation, we have used an anemometer measuring the speed and the direction of the wind. Its characteristics are accuracy: ± 0.3 m/s from 1 to 60 m/s and ± 1.0 m/s from 60 to 100m/s.

To measure the temperature of three photovoltaic technologies and the room temperature, we have exploited four temperature sensors PT100 modules.

For the room temperature, the sensor is in direct contact with air, however it is protected from the sun and the rain. The Data of different measurement sensors and inverters are stored at five-minute intervals by PCDUINO cards. These cards save the data as CSV files and send them by mail.

2. Performance parameters

In this section we will introduce the expression and the definition of each performance parameter.

1.2. The reference yield (Yr)

The reference yield is the ratio of the total solar radiation Ht (kWh/m2) arriving at the surface of PV solar panels and the reference radiation quantity G0 (1kW/m2). This parameter represents the number of hours during for which the illumination is equal to that of the reference. It is recalled that Yr defines the solar resource for the PV system.

$$Yr = Ht/G0 \quad (1)$$

1.3. The array yield (Ya)

The PV field efficiency is defined as the ratio between the total energy EDC (kWh) generated by the PV system for a defined period (day, month or year) and the rated power P0 (kWp) of the system respect to the standard conditions (STC: irradiation: 1000 W/m2, 25° C, Ambient temperature and the reference spectrum AM 1.5-G). Algebraically, it is given by

$$Ya = E_{DC}/P0 \quad (2)$$

1.4. The final yeild(Yf)

The final yield is the total energy produced by the PV system, EAC (kWh) with respect to the nominal power installed P0 (kWp). This quantity, which represents the number of hours during which the PV field operates at its nominal power, reads as

$$Yf = EAC/P0 \quad (3)$$

1.5. Losses

- The various losses (LC): The various LC losses are defined as the difference between the reference efficiency and the PV field efficiency. They represent losses due to Panel temperature, partial shading, spectral Loss, staining, errors in research maximum power point, conversions (DC/AC), etc.

$$Lc = Yr - Ya \quad (4)$$

- Avoid system losses by conversion (LS): The losses of the system are due to the converting losses of the inverters (DC-AC). They are defined by the difference between the PV field yield (Ya) and the final yield (Yf.) as follows

$$Ls = Ya - Yf \quad (5)$$

1.6. The performance ratio (PR)

The performance ratio PR indicates the overall effect of losses on the energy production of the PV system. The PR values indicate how a PV system approaches the ideal performance under actual operating conditions. PR, which is a dimensionless quantity, is defined by the ratio between the final yield and the reference yield.

$$PR = Yf/Yr \quad (6)$$

1.7. Solar PV plant energy efficiency

Solar PV plant energy efficiency is the relation between the electrical energy generated by the solar PV plant and the solar energy falling on the solar modules. Monthly energy efficiency of the solar PV plant is calculated using the relation

$$\eta = \frac{\sum_{i=1}^{n}(E_D)i}{S\sum_{i=1}^{n}(G_{opt})i} \quad (7)$$

n is the number of days in a month. ED is a total amount of the electrical energy generated by the solar PV plant and transmitted to the power grid during the day (Wh), Gop is a total amount of global solar energy falling during the day on one square meter of the solar PV plant modules (Wh/m2). S is a total solar module surface (PV array area) (m^2).

1.8. Solar PV plant capacity factor (CF):

Capacity Factor (CF) is the relation between the real annual electrical energy generated by PV system and the electrical energy which could be generated if the PV solar plant operated with its total installed power 24 h a day over a year. Solar PV plant capacity factor is calculated using the following equation

$$CF = \frac{Y_f}{8760(h)} \times 100 \qquad (8)$$

2. Simulation results and discussion

We have used PVsyst as a simulation tool to analyze the three grid-connected PV systems. PVsyst is a good software package, widely used for the study, design and data analysis of different PV systems including stand-alone, grid-connected, pumping and DC-grid PV systems.

2.1. Meteorological conditions

Fig. 3 shows the monthly ambient temperature and the monthly horizontal solar radiation. The reported average annual ambient temperature is 19.11°C. The recorded maximum value of temperature is 29.21 in July and the lowest value was 9.24°c in January. The monthly global horizontal irradiance ranged from 98.9 kWh/m2 in January to 240.4 kWh/m2 in July.

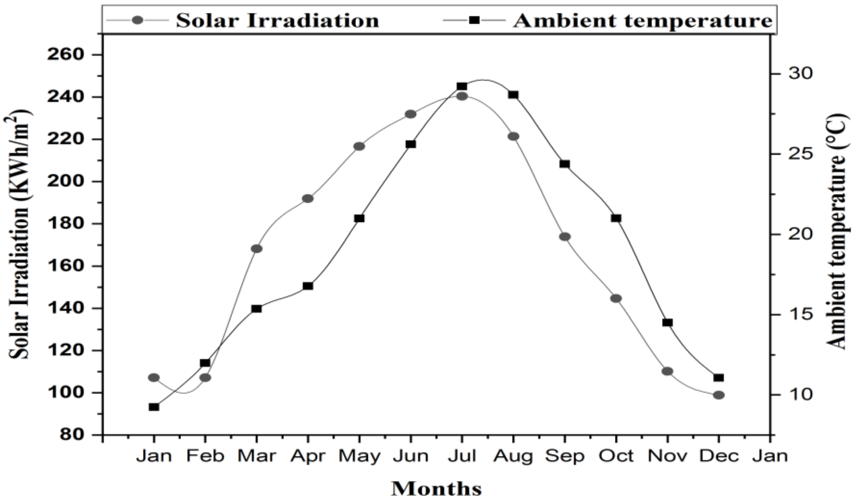


Fig. 3. The monthly ambient temperature and horizontal solar radiation

2.2. PV plants production

Figure 4 shows the comparison between the three photovoltaic systems in terms of the monthly energy fed into the grid. It can be seen that the mc-si plant produce more energy than pc-si and a-si plants. The annual energy injected into the grid by mc-si, pc-Si and a-Si photovoltaic plants was found to be 3733.1 KWh, 3716.5 KWh for and 3543.8 KWh, respectively.

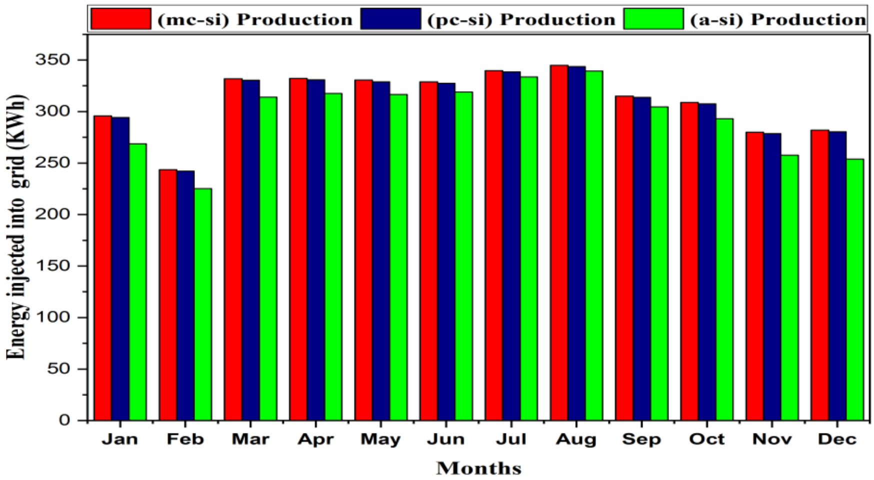
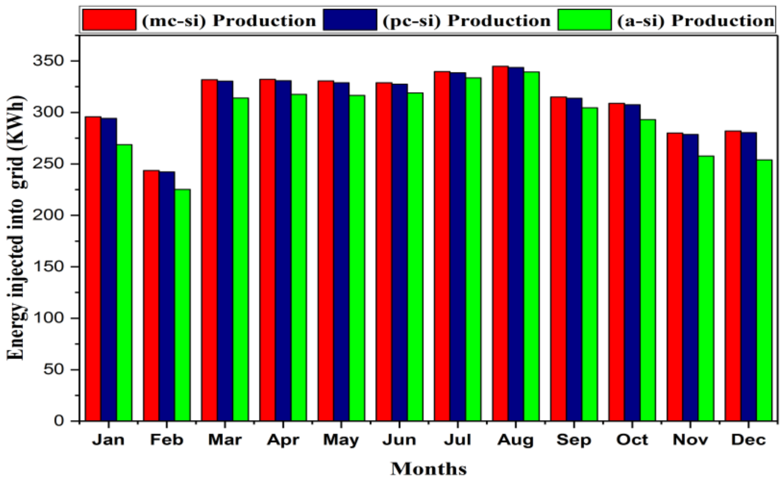


Fig. 4. Power injected into the grid

2.3. Performance comparison

Figure 5 shows that the annual average value of performance ratio for the a-Si is nearly 83.8 %, 80.5 % for mc-Si and 80.1 % for pc-Si plant. The highest values of PR are observed in the month of December and January. We can explain this feature by the decreasing in temperature that minimizes the system losses. However, in the hottest months, amorphous silicon (a-Si) photovoltaic plant seems to be the least infected by the high temperature. As presented in Table 1, the three types of PV modules have a different temperature coefficients of power (TCP). The TCP provides a measure of the decrease in produced power due to temperature increase. The TCP for the mc-Si modules and pc-Si modules are -0.45 %/K and -0.41 %/K, respectively. While for a-Si modules, it is -0.280 %/K. According to the lower negative value of the TCP of a-Si panels, the a-Si has shown a higher performance compared to mc-Si and pc-Si fed into the grid. It can be seen that the mc-si plant produce more energy than pc-si and a-si plants. The annual energy injected into the grid by mc-si, pc-Si and a-Si photovoltaic plants was found to be 3733.1 KWh, 3716.5 KWh for and 3543.8 KWh, respectively.



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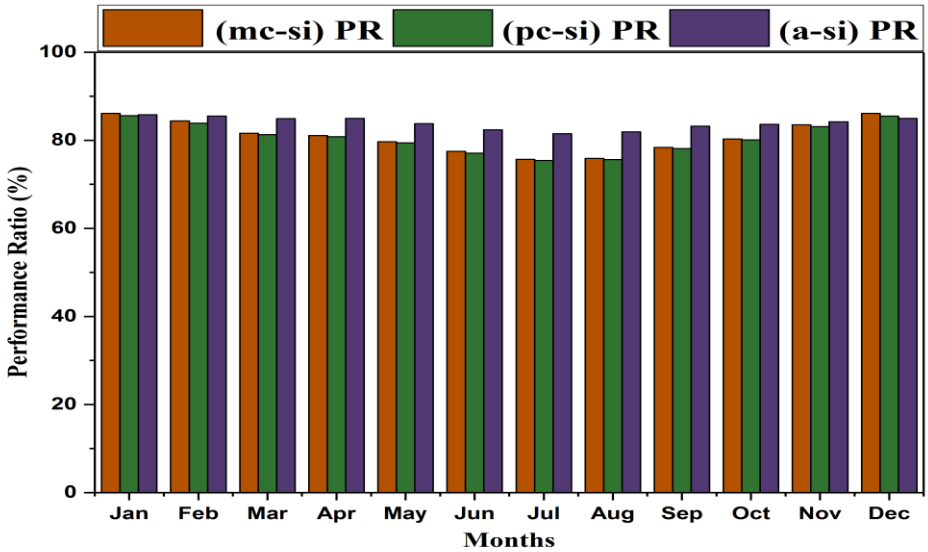

Fig. 5. Annual average value of performance

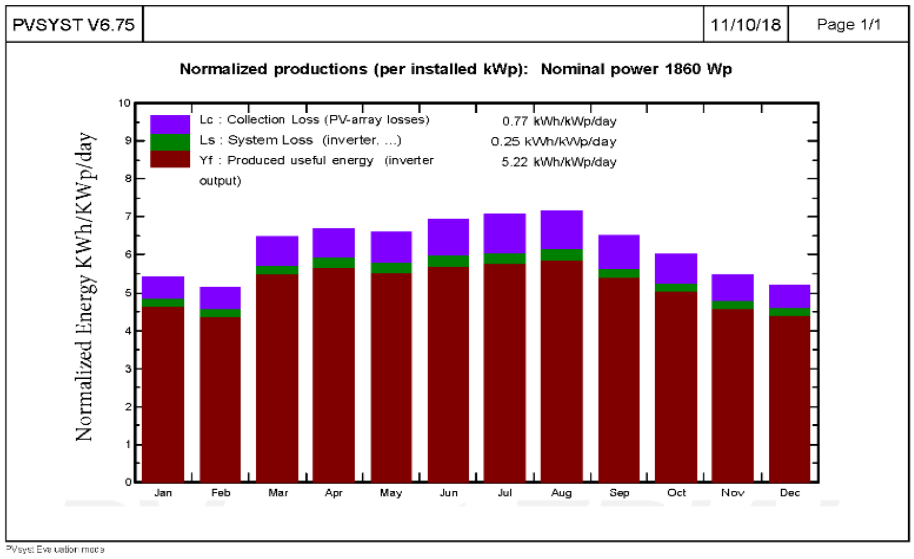

Fig. 6. The final yield and the total losses of the a-Si PV system

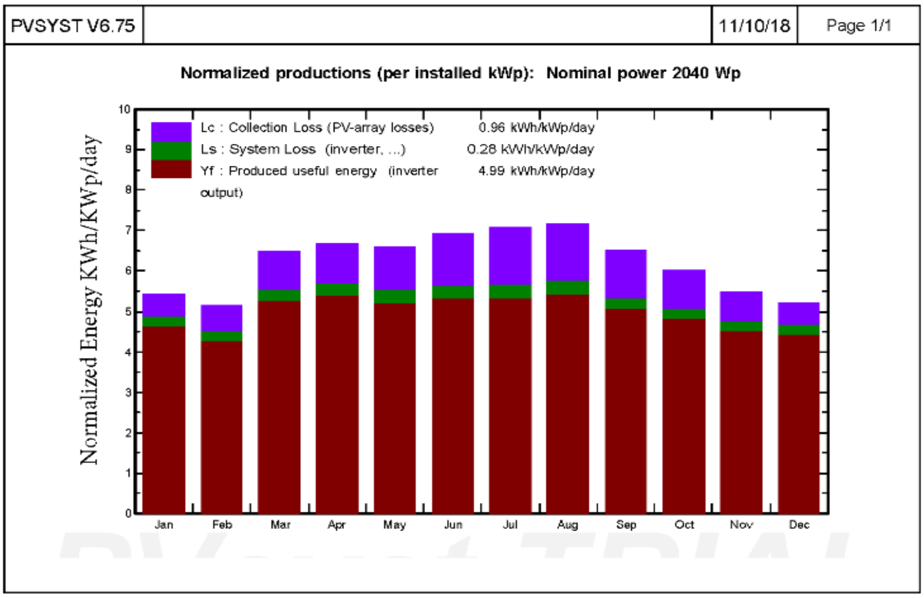

Fig. 7. The final yield and the total losses of the pc-Si PV system

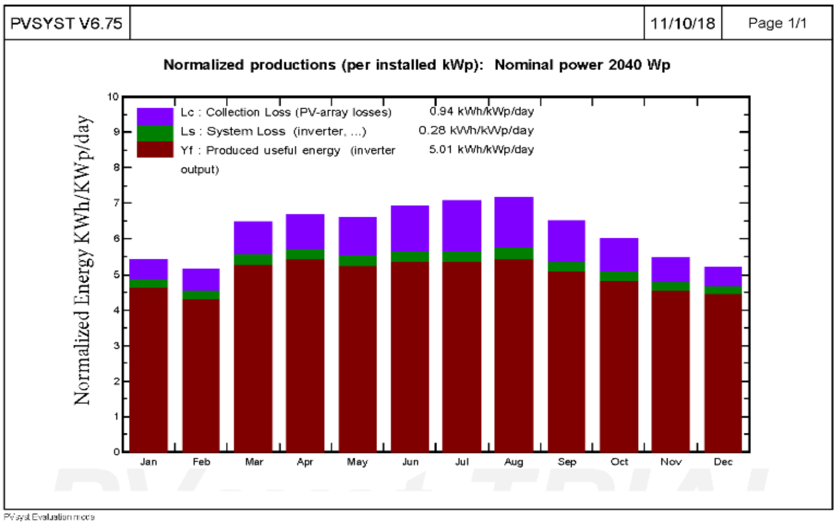

Fig. 8. The final yield and the total losses of the mc-Si PV system

Figures 6, 7 and 8 quantify the system losses and the capture losses. It is shown that the average daily energy losses are more important during the hottest months (summer) that explains the decreases of PR in this period. Concerning the system losses, the annual average value is about 0.28 KWh/KWp/day for pc-si and mc-si, and 0.25 h KWh/KWp/day for a-Si plant. The annual average value of the capture losses is found to be 0.77 KWh/KWp/day, 0.96 KWh/KWp/day and 0, 94 KWh/KWp/day for the a-Si, pc-Si and mc-Si, respectively. It can be seen that the most important losses of the three systems reside at the capture level caused by the irradiance and the array temperature.

The average final yield (YF) predicted for the a-si, mc-si and pc-si PV systems, during a period of one year, was 5.22 KWh/KWp/day, 5.01 KWh/KWp/day and 4.99 KWh/KWp/day, respectively.

2.5. Monitered data

It seems essential to introduce the meteorological parameters recorded during the year of 2017, to analyse the results of the present work. In particular, Figure 9 represents the variation of the solar radiation on the module plane and the ambient temperature.

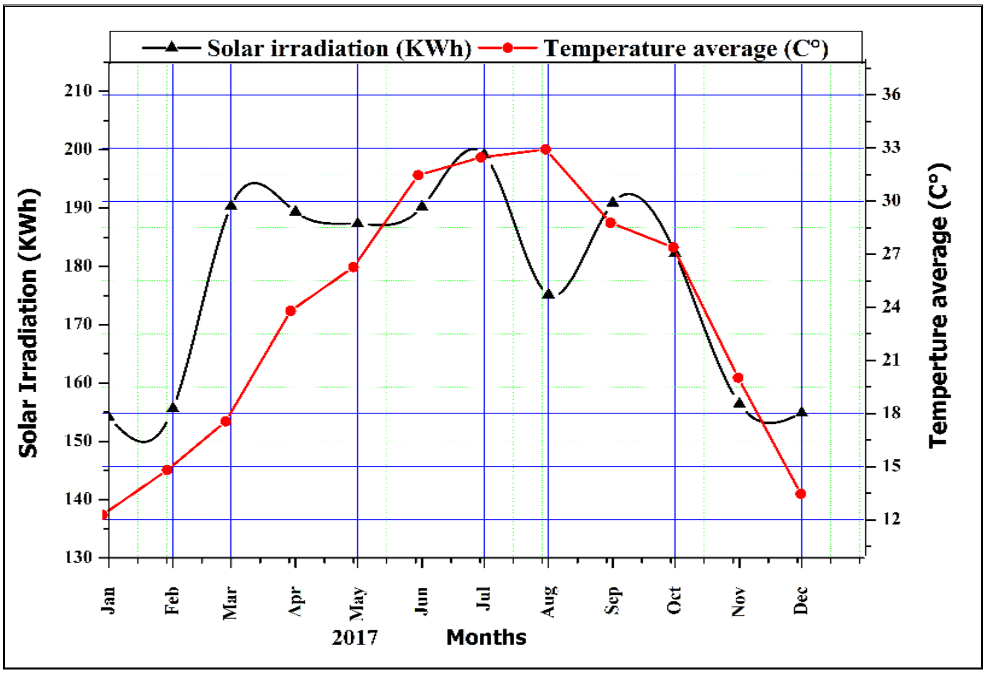

Fig. 9. Monthly solar irradiation on the module plan and average temperature

It follows from Figure 9 that the monthly irradiation on the module plan ranges from 154 kWh/m2 to 199 kWh/m2. The highest irradiance is witnessed in the months of July 2017, while the lowest one is recorded in January 2017. It is observed that the average monthly ambient temperature ranges from 12.27 ° C in January 2017 to 32.9 ° C in August during the trial period.

In what follows, we will discuss each performance parameter of our system. It is recalled that our PV system is built from three PV plants according to the silicon technologies. Taking such PV systems installed in the same location and using the same or different mounting structures, the Final Yield (Yf) is a sufficient indicator to compare their performance.

Concretely, Figure 10 shows the evolution of the Yf during the year of 2017.

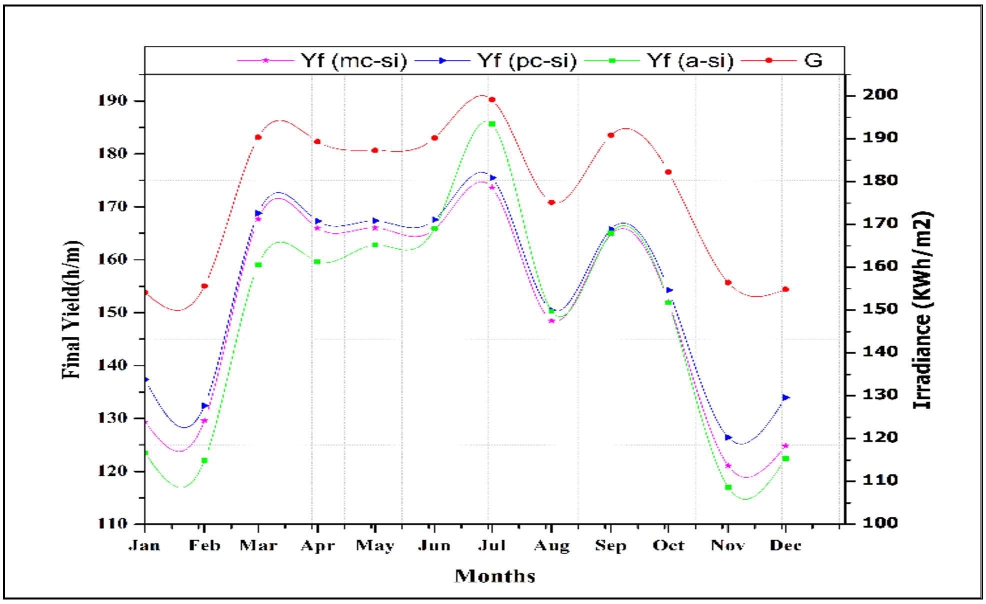

Fig. 10. Monthly Final Yield variation with solar irradiation

We can remark that the monthly average value of Yf is nearly 153 h/year for pc-si, 150 h/year for mc-si and 148 h/year for a-si. The highest value of Yf is found to be 175 h/m in the month of

July (the more irradiated month) and the lowest Yf is 126 h/m in the month of November (the less irradiated month) for pc-si. In the same months for mc-si the highest value of Yf is 173 h/m and the lowest is 121 h/m making an average value in the order of 150 h/year. concerning the a-si plant, the highest value of Yf is 185 h/m recorded in July, and the lowest one is 117 h/m in January, the annual average value is 148 h/year. so, under the same meteorological and geographical conditions, Polycrystalline silicon Photovoltaic technology showed the highest Final Yield value, it operates in its rated output power for 1847 hours in 2017 compared to 1809 h/year and 1785 h/year of monocrystalline and amorphous, respectively. It would seem interesting to mention that the Amorphous silicon technology has recorded, in July, the highest number of hours, it was of about 185 h of operation in its rated output power, which is unexpected.

To investigate the PV plant efficiency, we illustrate the associated calculations in Figure 11.

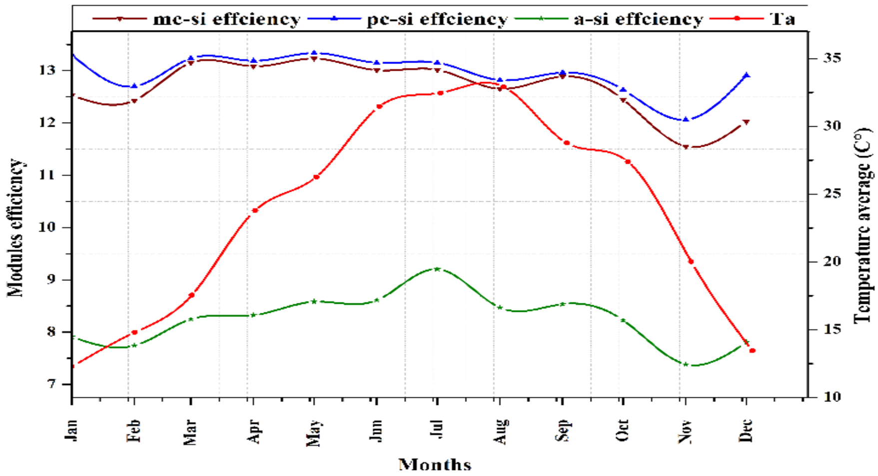

Fig. 11. The modules efficiency evolution with the ambient temperature

Figure 11 shows that mc-si PV array efficiency varies between 11.5 % in November and 13.23 % in May with higher values during more irradiated months. pc-si PV array efficiency took the values between 12.06 % and 13.33 % recorded in November and May, respectively. While, the a-si PV array efficiency was found to be confined between 7.38 % and 9.21 %. These values were recorded in January and July, respectively.

In this analysis, the most efficient of the three PV technologies is the pc-si modules, with average efficiency value of 12.9 %. The next one was the mc-si modules, with average value of 12.65 %. The lowest efficiency is observed for the a-si technology with average value of 8.2 %.

Next, we discuss the Capacity Factor in terms of the temperature. It is recalled that the Capacity Factor shows the fraction during one year, when the PV system is operating at it rated power. The associated calculations, for our systems, are given in Figure 12.

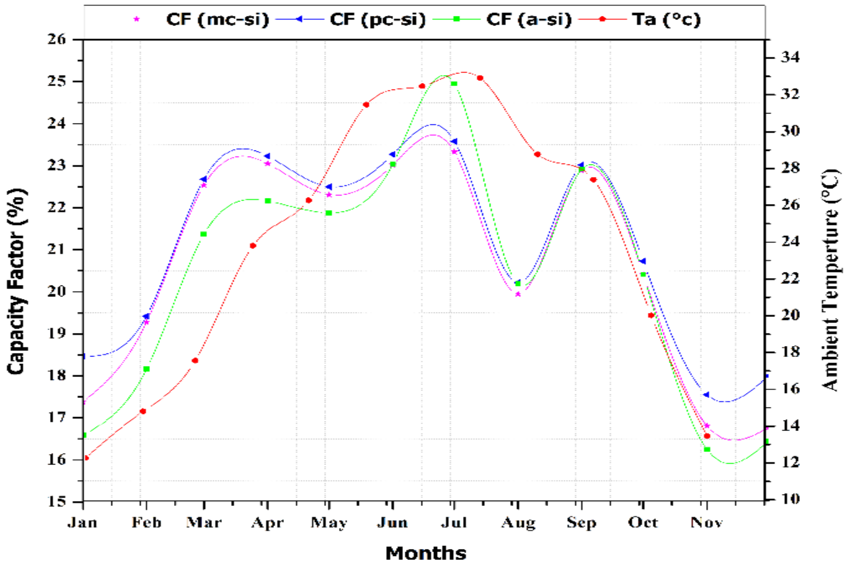

Fig. 12. The monthly capacity factor variations with the ambient temperature

It can be seen from Figure 12 that the Maximum values are 24.95 %, 23.58 % and 23.33 % for the a-si, pc-si and mc-si, respectively, which were recorded in July which coincides to the more irradiated month. While, the minimum values found to be 16, 25 %, 17,55 % and 16,77 % in November for the a-si, pc-si and mc-si, respectively.

In what follows, Figure 13 shows the average monthly ambient temperature and Performance Ratio of the three PV technologies tested over the monitoring period.

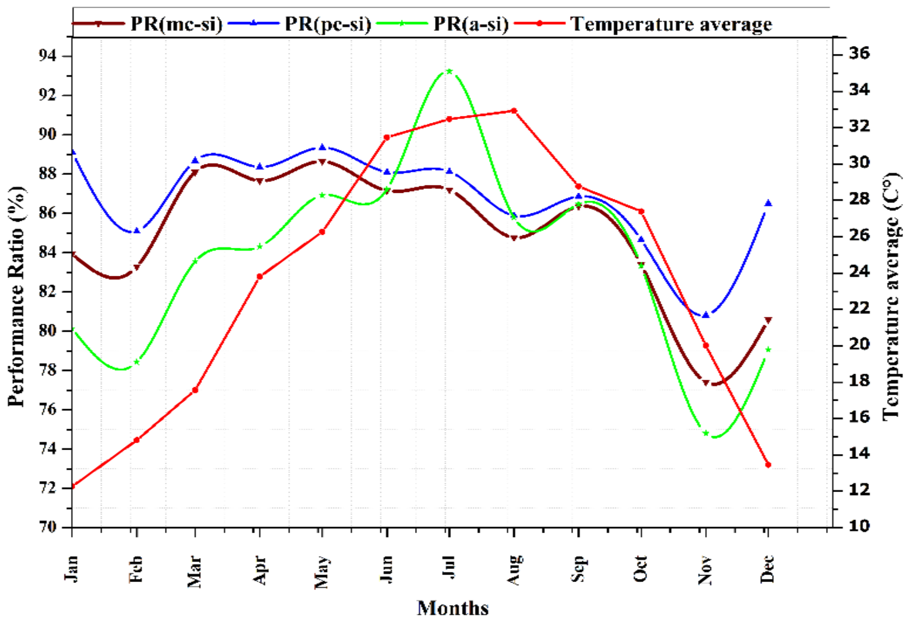

Fig. 13. The performance ratio evolution with the ambient temperature

The PR of the modules made of pc-si cells undergoes the smallest fluctuations over the monitoring period. It falls between 89.35 % and 80.81 %. The fluctuations of the monthly performance of the mc-si technology is slightly higher, where it falls between 88.65 % and 77.41 %. The PR of the modules made of a-si cells have been fluctuated widely between 93.24 % and 74.8 %. The average monthly PR of pc-si, mc-si and a-si technologies are quantifiable at 86.80 %, 84.87 % and 83.60 %, respectively.

The PR of the pc-si, mc-si and a-si modules, generally, decreases when the ambient temperature increases. In June, July and august when temperature reach high values, the PR of the mc-si and pc-si technologies reach the minimum values. On the contrary, a-si modules are characterized by low temperature coefficients on power and that why it is affected only slightly by the increase of the operating temperature in the warmer months. The a-si module, at high temperatures, it can recover some of the efficiency initially lost due to light-induced degradation that what we can see in Figure 13 and Figure 14.

As result it achieves superior performance over other technologies during the warmer months in December, January and February when temperature reach the lowest values, the Performance Ratio of the pc-Si and mc-si technologies reach the Maximum values with a large fluctuation. in March, April and May when temperature ranges from 18°C to 29°C the Performance Ratio of pc-si and a-si modules records high values with small fluctuations.

The Performance Ratio represents the overall losses on the rated output of the PV plant which can be resulted from the module temperature effects, the wiring, the inverter inefficiencies, the component failures etc. The effect of the Capture Losses on the Performance Ratio can be illustrated in Figure 14.

Fig. 14. The capture losses effect on the performance ratio

Figure 14 shows the effect of Capture Losses (Lc) on each Photovoltaic plants' performance. The low PR values observed for Amorphous technology are due to high Capture Losses. It is easy to see that Polycrystalline technology records the lowest values of Lc especially during the cold months. Monocrystalline technology shows the same behavior as Polycrystalline technology but with more losses. In contrast with the Polycrystalline and the Monocrystalline, the Amorphous technology records high losses values during the cold and less insolated months, and it gains energy during the wormer months.

4. Conclusion

In this paper, we have simulated the electrical production behavior of three mini photovoltaic installations based on silicon technology. This study forecasts an annual production of around 3733.1 kWh, 3716.5 kWh and 3543.8 kWh for the mc-Si, pc-Si and a-Si technologies, respectively. The performance analysis is carried out showing that the annual average value of PR for the a-Si is nearly 83.8 %, 80.5 % for mc-Si and 80.1 % for pc-Si plant. The annual average value of the system losses is about 0.28 KWh/KWp/day for pc-Si and mc-Si, and 0.25 KWh/KWp/day for a-si plant. The annual average.

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