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Analysis of the performance evolution of a solar PV plant under harsh climatic conditions

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Abstract: This paper investigates the performance of a grid-connected photovoltaic (PV) system under harsh environmental climate condition of Djibouti, using monitoring data collected during four years of operation. The system was evaluated with IEC 61724 standard guidelines, the impact of climatic factors on the performance of the PV system has been assessed.
The total energy generated for the period of evaluation was 1.92 GWh. The monthly average daily reference yield, array yield and final yield were 5.6 h/d, 5.1 h/d, and 4.7 h/d, respectively. The monthly average daily system losses and capture losses were 0.37 h/d and 0.54 h/d, respectively. The average performance ratio for respective PV arrays and system are 90% and 84%. The monthly average daily PV module and system efficiency were 12.68% and 11.75% respectively. Funnel-shaped graphs have been observed according to the seasonal variation of the PV module efficiency. The maximum average capacity factor is reached for the first year with 16.77%, with four years average of 16.35%.
This research result will be beneficial for comparison to the other PV plants over the world and for investors of the future grid-connected solar PV power plant in Djibouti.

Keywords:
Grid-connected PV system, performance ratio, harsh environmental condition, Djibouti

1. Introduction

In 2014, the electrification rate of Djibouti was about 55%. The currently installed electricity generation capacity is 126 MW with an effective capacity limited to 57 MW, because of the unreliability of old power plants. The country does not own local fossil resources and is depending mainly on imports of the fossil fuel and its economy depends on the tertiary sector whose resources come mainly from the commercial and port activities in the country. Electricity consumption increased by 75% over the past decade, while electricity production increased over the same period by 57% **[1-2]**. This resulted in power outages during periods of peak demand during the summer months. Since 2011, the Djiboutian grid is interconnected to the Ethiopian grid. This reduced the grid outages but these sometimes occur when the interconnection faces a technical problem. Facing these issues and due to huge potential in renewable resources, Djibouti is interested in the diversification of its energy mix. This by developing renewable energy in its territory such as solar, geothermal and wind energy in order to reach its goal of 100% renewable energy by 2020 **[3]**. Also the country has committed to reduce by 40% its greenhouse gas emissions by 2030 at the United Nations Conference on Climate Change (COP21) held in Paris in 2015 **[4].**

Due to Djibouti's huge solar potential of about 2200 kWh/m^2 per year**,** PV systems arouse a great interest, mainly for the production of electricity on a large scale. The installed PV capacity in the country was about 12 kWp at the beginning of 1987 **[5]** and is estimated to date from about 800 kWp spread throughout the territory.

Mainly composed by this 302.4 kWp grid-connected and two other PV power plant in rural area, one of 100 kWp and another of 60 kWp. However, the massive deployment of this technology is currently facing economic, technological and scientific challenges related in particular to the none-well-known environmental conditions. Djibouti is located on the Horn of Africa at latitude 11°30' N and longitude 43°00' E. It is characterized by a desert maritime climate **[6]**, with high temperatures throughout the year. But there are two seasons: a "cool" season from October to April, with small periods of rain and temperatures of 21°C to 33°C and a hot season from May to September, with temperatures of 35 °C to 45 °C and dust-laden dry wind (Khamsin). The months of May and September are transition periods during which operate reversals of winds, which causes an increase in moisture. The rainfall is low and erratic. It mainly falls in the early cool and warm seasons.
The performance of PV power plants is linked to the on-site weather conditions such as irradiation, ambient temperature, humidity and wind speed.

In the past ten years a number of studies **[7-8-9-10]** have been reported on the performance evaluation of the grid connected solar PV power plants installed worldwide. Those studies review the performances of the grid connected PV systems under different climatic conditions, mounting configurations and PV technologies.

An analytical performance monitoring of a 142.5 kWp grid connected rooftop building integrated photovoltaics (BIPV) system under tropical climate of Singapore was carried out by Stephen Wittkopf et al **[11]**. The system was evaluated as per IEC 61724 standard guidelines. During this period the energy generation of the system was 217.8 MWh. The performance ratio was 81%, array yield and final yield was respectively 3.86 h/d and 3.12 h/d. The system and array efficiency were 11.2% and 11.8%. In order to examine the performance of an array under different irradiance conditions, a classification of daily irradiance from overcast to clear with temporal change of irradiance level (high-medium-low) are presented. In addition, the impact of shading, orientation, tilt and PV module temperature are also presented.

A performance assessment of different PV technologies arrays, polycrystalline silicon (p-Si) hetero-junction with intrinsic thin layer silicon (HIT) and amorphous single junction silicon (a-Si) under similar composite climate (cold in winter and hot and humid in summer) conditions in Gurgaon, India is carried out by Sharma et al. **[12]**. The performance comparison shows that HIT and a-Si PV arrays have performed better than p-Si array at this location.

Several studies on performance evaluation have been undertaken under tropical and hot climatic conditions **[13-17]**. K. Padmavathi et al. **[13]** evaluated the performance of a 3 MWp grid-connected solar PV power plant in Karnataka, India for the years 2010 and 2011. The performance ratio ranges between 78% and 61% respectively for February and June 2011; it remains lower than 60% during four months (August to November 2010). The annual reference and final yield were respectively 5.36 kWh/ kWp-day and 3.73 kWh/kWp. The capacity factor for this PV power plant is 12.38% for 2010 and 15.69% for the year 2011. The lower value of the capacity factor for the year 2010 is due to inverter failure and grid failure losses. A comparative study on the performance of two different technologies amorphous silicon and multi-crystalline of 500 kWp grid-connected PV power plants located in Gujarat, India has been related by Brijesh Tripathi et al. **[14]**. The study shows that the final yield of p-Si power plant ranges from 2.79 hour/day (h/d) to 5.14 h/d and the a-Si power plant ranges from 2.62 h/d to 4.84 h/d. The performance ratio (PR) varies from 57.1 to 93.14% for p-Si power plant and for a-Si it varies from 53.72 to 87.64%. It was also found in this study that the a-Si solar PV power plant has high capture losses than p-Si PV power plant. In **[15-16]** the performances of PV systems have been evaluated under hot and desertic climate condition of Sohar, Oman and Abu Dhabi, United Arab Emirates. According to these researches the final yield is respectively 5.14 h/d for Sohar and ranges between 4.5 h/d and 5.571 h/d for Abu Dhabi. Also, in the same region of Arabic peninsula, A. Al-Otaibi et al **[17]** presented 12-month performance evaluation of two (85.05 kWp and 21.6 kWp) rooftop grid-connected PV systems in Kuwait. The performance ratio ranges between 74% and 85% and the annually averaged daily final yields of the PV systems were 4.5 h/d. To maintain those performances the PV module was equipped with automated cleaning system, this minimize the effect of soiling. The table 1 resumes the performance parameters of PV systems under different climatic conditions.

In order to understand the performance of solar photovoltaics and impact of the local climate, a grid connected 302.4 kWp PV pilot plant was installed since 2012 at the "Centre d'Etudes et de Recherche de Djibouti" (CERD) by Japan International Cooperation Agency (JICA). This installation is unique in this region and represents a tool for research and development for the Laboratory of New and Renewable Energies of CERD.

Since this 302.4 kWp PV power plant is the first PV plant connected to the grid in Djibouti, no data are available regarding the actual performance of PV systems in Djibouti or in the same climate conditions of the horn of Africa's coastal regions. The aim of this paper is to understand how a grid connected PV power plant is performing under harsh climate conditions (arid, dusty and very low rainfall) of Djibouti. Data have been monitored during four consecutive years (2012 to 2015) and was analyzed on hourly, daily and monthly basis in order to evaluate the performance trends.

2. The CERD 300kW demonstration PV facility in Djibouti

A solar photovoltaic power plant was installed at the CERD as part of cooperation between Republic of Djibouti and the Japanese government for a project to promote solar PV. This solar PV power plant is tied to the power grid of Djibouti. The solar park occupies an area of 2138.4 square meters with 1,440 photovoltaic panels (KYOCERA-polycrystalline silicon). Each panel is characterized by a peak power of 210 Wp. All panels deliver a total power of 302.4 kWp. The panels are arranged in thirty arrays. Each array consists of forty eight panels, 10 kWp per array. The PV arrays are directed to the South and tilted at 12°.

Fig.1. PV system installation

The plant includes junction boxes which are placed upstream of the PV inverter. Their function is to parallelize PV strings. Three inverters that allow the conversion of direct current (DC) output of the solar panels into alternative current (AC) power and synchronization with the grid. Each inverter supports 100 kWp. The plant is also equipped with measuring instruments such as an ambient temperature sensor and a pyranometer. All data from the different measuring instruments are routed to a data logger and recorded by: minute, hour, day, week, month and year.

The PV cells temperature is measured by 6 K-type thermocouples over four PV modules of one array. Four thermocouples are on the front side of the panels and two on the rear side of the PV panels. Wind speed and direction are measured by an anemometer and a weather vane and installed on a mast to 6 m above the ground.

The plant has several modes of operation. It usually works in "grid-connected" mode. The surplus energy produced is injected to the grid of electricity of Djibouti. In case of power failure or load shedding, the plant switches to the "standalone" operating mode .This mode involves stopping inverters 1 and 2, the inverter 3 provides power to CERD and this if sunshine condition is favorable. During this phase inverters 1 and 2 are pending that the grid supply is restored. Once the network is restored the PV system restart normally (grid-connected operation).

3. Environmental conditions of the PV installation

In order to understand the environment in which the solar PV plant evolves, **Fig.2** illustrates the monthly average hourly global solar radiation on the plane of the array (G_t) and ambient temperature (T_{amb}) averaged over daylight hours during the monitoring period of the solar power plant (February 2012-August 2015). G_t is measured by a (broad spectral sensitivity) thermopile pyranometer. On this graph, we observe an alternation between seasons with an increase of Tamb and decrease of I_{POA} in summer period and decrease of T_{amb} and an increase of G_t in cool season. The temperature ranges between a minimum of 29.4°C in January 2015 and a maximum of 40.6 °C in July 2013. The quantity of solar radiation received ranges between 4.6 kWh/m^2 per day for July 2013 and 6.4 kWh/m^2 per day for the month of April 2015. The average on-site ambient temperature and POA irradiance are respectively 34 °C and 5.6 kWh/m^2 per day. With a respective seasonal variation is of the order of 11°C for T_{amb} and 1.8 kWh/m^2 per day for G_t. During the months from June to August dust uplift caused by the Khamsin induces opacity of the sky which reduces the rate of solar radiation reaching the solar PV.

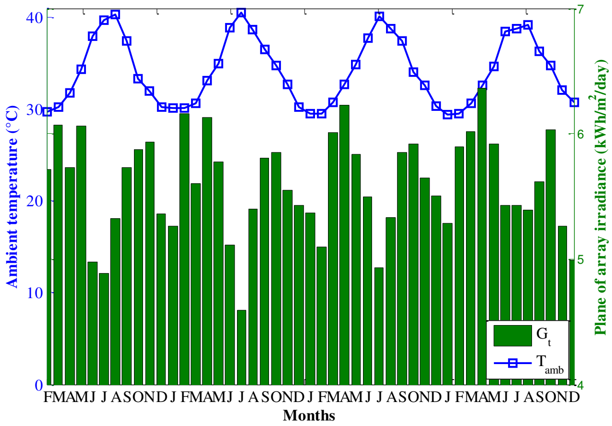

Fig.2. Monthly average daily plane of array irradiance and daylight ambient temperature

4. Methodology

In order to analyze the performance of a 302.4 kWp grid connected solar PV plant, data collected during four years continuous monitoring (1st February 2012 to 31st December 2015) are used. Those data are recorded 1-min steps and contain such electrical (E_{DC} and E_{AC}) and environmental parameters (G_t and T_{amb}). Prior to their analysis, these data were preprocessed to remove all outliers that do not correspond to the proper functioning of the solar plant. Such anomalous behavior includes instrumentation failure, grid outages, and voluntary stoppages of the PV plant for maintenance or other in voluntary interruptions. The calculated performance parameters are normalized on a daily basis.

4.1. Performance evaluation

In order to analyze the performance of a solar PV system, performance parameters have been specified by the International Energy Agency (IEA) and are described in the standardized norms (International Electrotechnical Commission) IEC 61724 **[18]**. These parameters are the reference yield (Y_r), array yield (Y_a), final yield (Y_f), the performance ratio (PR), system losses (L_S) and array capture losses (L_C). These parameters are used to define the system performance as a whole in relation to energy production, solar resources and the overall effect of the PV system losses. The set of performance measures considered in this study is summarized in table 1.

Table 1. Performance measures

Performance measure	Definition	comments
Reference yield (Y_r)	$Y_r = \frac{G_t}{G_0}$	(1)
Array yield (Y_a)	$Y_a = \frac{E_{DC}}{P_0}$	(2)
Final yield (Y_f)	$Y_f = \frac{E_{AC}}{P_0}$	(3)
Performance ratio (PR)	$PR = \frac{Y_f}{Y_r}$	(4)
System losses (L_S)	$L_S = Y_a - Y_f$	(5)
Array capture losses (L_C)	$L_C = Y_r - Y_a$	(6)

Array efficiency	$\eta_{PV} = \frac{E_{DC}}{G_t \times A_a} \times 100\%$	(7)
system efficiency	$\eta_{SYS} = \frac{E_{AC}}{G_t \times A_a} \times 100\%$	(8)
inverter efficiency	$\eta_{inv} = \frac{E_{AC}}{E_{DC}} \times 100\%$	(9)
Capacity factor	$CF = \frac{E_{AC}}{P_0 \times 24 \times 365} = \frac{Y_f}{8760} = \frac{Y_r \times PR}{8760}$	(10)

(1)- The reference yield is the ratio between the total amount of solar irradiance G_t (kWh/m^2) reaching the surface of the solar PV panels and the reference irradiance G_0 (1kW/m^2). Y_r defines the solar resource for the PV system. It represents the number of hours during which the irradiance is equal to the reference.
(2)- The array yield is defined as the ratio of the total energy generated E_{DC} (kWh) by the PV arrays for a defined period (day, month or year) and arrays rated power P_0 (kWp) under standard conditions (STC: irradiation 1000 W/m^2, 25°C ambient temperature and reference spectrum AM 1.5-G).
(3)- The final yield is the total energy produced by the PV system, E_{AC} (kWh) divided to the rated power P_0 (kWp). This amount represents the number of hours the PV field should operate at its rated power. It expressed in kWh/kWp or h/d.
The above measures are combined to provide a second set of performance indicators.
(4)- The performance ratio PR quantifies the overall effect of losses on the rated output. PR values indicate how a PV system approaches the ideal performance under actual operating conditions. PR is defined by the ratio between the final yield and the reference yield, it is a dimensionless quantity.
(5)- The system losses L_S due to losses from inverter conversion (DC to AC current) and are defined by the difference between the array yield (Y_a) and the final yield (Y_f).
(6)- Array capture losses (L_C) are defined as the difference between the reference yield and PV array yield. L_C represents the losses due to: temperature of the panels, mismatch, wiring, partial shading, spectral losses, soiling, errors in seeking the maximum power point and other losses.
The efficiency of the facility can be evaluated in terms of distinct array, system and inverter efficiencies.
(7)- The PV array efficiency (η_{PV}) is the ratio of DC energy output to the product of plane of array irradiance and overall PV array area.
(8)- The system efficiency (η_{SYS}) is the ratio of AC energy output to the product of plane of array irradiance and overall PV array area (A_a).
(9)- The inverter efficiency (η_{inv}) is the ratio of AC energy output to the DC energy generated by the PV arrays.
(10)- Finally the capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the solar PV power plant would generate if it operated at full rated power (P_0) for 24 h per day for a year.

5. Results and discussions

The monthly and cumulative energy generated from the PV system is represented in **Fig.3.** The peak energy generation is reached for the month of October 2015 with 46.7 MWh and the least energy was generated for the month of July 2013 with 31.3 MWh. The maximum energy generated is 1.5 times the least energy generated. The average monthly energy generation was 41 MWh. The accumulated energy generation for the first 12-month was 494 MWh, while the overall accumulated energy generation for the 47 months of operation was 1.92 GWh. During the prefeasibility study, energy generation was estimated at 460 MWh, compared to the first 12 months of operation, the plant generated 7.4% more than originally planned. The low energy generated for the period from June to August each year is related to the decrease of the amount of irradiation on PV arrays and on-site temperature increase (**Fig.2**).

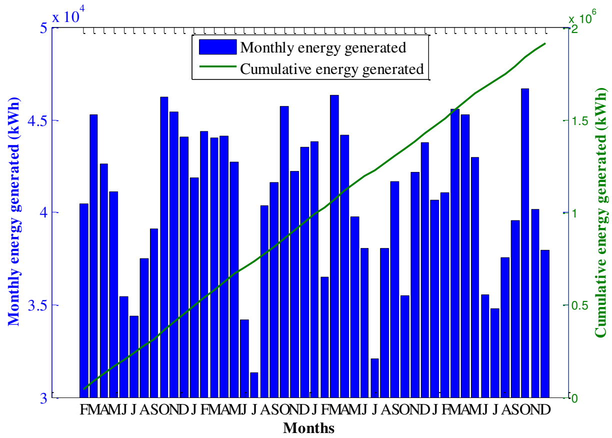

Fig.3. Monthly and accumulated energy generation from 302.4 kWp PV power plant

Fig. 4 illustrates monthly average daily final yield (Y_f), system losses (L_S) and PV array capture losses (L_C) subdivide in the four years of operation of the PV power plant. Y_f, L_S and L_C are expressed in hour per day (h/d). The monthly average daily final yield varies with a minimum of 3.68 h/d in July 2014 and a maximum of 5.43 h/d in February 2013 with an average of 4.69 h/d. Y_f being related to the energy production of the plant is very influenced by solar radiation. Also, we note that Y_f is low during the summer months of June, July and August over the operation period (2012-2015). Although not shown the variability of reference yield (Y_r) is similar to Y_f, due to the dependence of Y_f to sunlight. The reference yield ranges from a minimum of 4.59 h/d (July 2013) to 6.36 h/d (April 2015).

The system losses L_S are relatively stable with an average of 0.37 h/d, ranging from a minimum of 0.31 h/d in July 2013 to a maximum of 0.41 h/d in February 2013. The difference between maximum and minimum system losses is about 0.1 h/d, this shows that the power inverters of the PV system are performing on the DC-AC conversion.

The monthly average daily array capture losses L_C is much more pronounced and ranges from 0.12 h/d in December 2012 to 1.22 h/d in July 2015 with an average of 0.54 h/d. These losses are greater than 0.6 h/d for about 20 months on the 47 months of operation of the solar PV plant. They are directly linked to the losses due to the dustiness of the PV panels, high module temperatures during the summer period, wiring and partial shadowing.

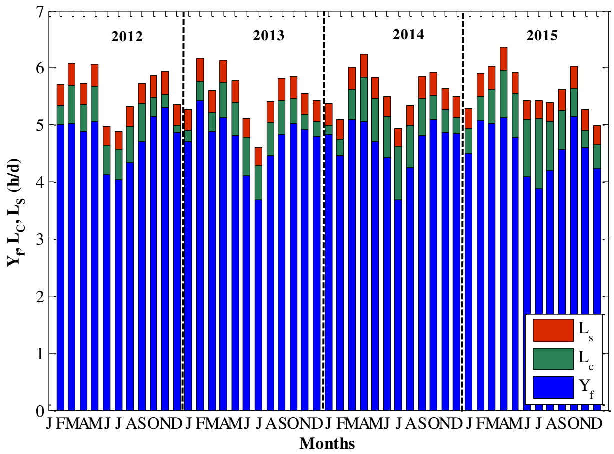

Fig.4. Monthly average daily final yield (Y_f), system losses (L_S) and PV array capture losses (L_C)

In order to analyze the performances of the 302.4 kWp grid-connected photovoltaic system in array and system level, **Fig.5** illustrates the monthly average daily array and final yield versus reference yield. It is also representing the performance ratio of the PV array (PR_{PV}, red circle) and the system (PR_{sys}, blue cross). The PR was assessed on a monthly basis for four years, 2012 to 2015. It is between 100% and 70% as reported in **Fig.5**. The maximum value of PR is reached in December 2012 with respective values of 98% for PRpv and 91% for PRsys. The minimum is reached in July 2015, with respective values of 77% for PRpv and 71% for PRsys.

In connection with the previous figure (fig.2), we can see the months that performance ratios are highest correspond to the lowest capture losses and inversely.

Most of months we have a performance ratio relatively stable and over a value of 80%. The averages PR through the operation period for respectively the PV arrays and the system are 90% and 84%**.** It is high compared to the results of the work cited in the first section **[17]**. As mentioned Jaebum by Lee et al. **[19]** a PR greater than 80% corresponds to a system with performance approaching the ideal performance under STC and a system with a PR lower than 70% should be suspected of failure or malfunction of components from the system (panels, inverters, etc.) or environmental factors (shade nearby, excessive dust panels, etc.). For this plant installed in Djibouti, the decline in the normalized performance ratio in July 2015 is certainly due to climatic factors such as higher temperatures and dust due to Khamsin which is a hot, dry and dusty wind. This uprising dust induces opacity of the sky which reduces the rate of sunlight reaching the solar panels.

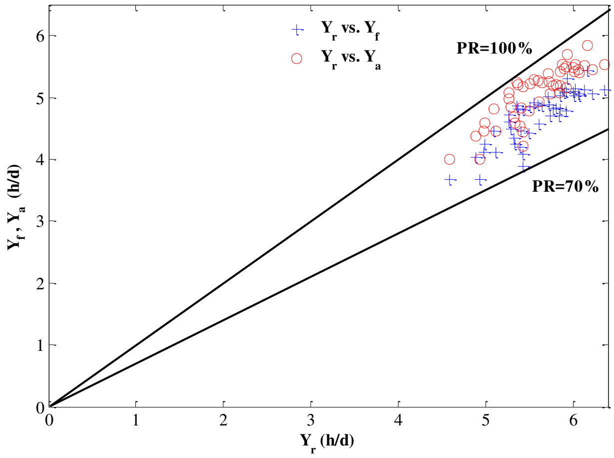

Fig.5. Array and system Performance Ratio

Fig. 6 shows four years monthly average daily PV module efficiency. It ranges between 10.87% in July 2015 and 13.82% for December 2012 with an average mean value of the PV efficiency of 12.68%. The nameplate PV module efficiency is 14.14% at STC, compared to the extremum of PV module efficiency we observe a gap of 0.32% with the maximum (Dec-12) , 3.27% with the minimum (Jul-15) and 1.46% with the average PV efficiency. Apart August 2012, the lowest values of the efficiency of PV modules are recorded in July, 12.3%, 10.95%, 10.87% respectively for 2013, 2014 and 2015. The lowest value of PV efficiency recorded for the month of July 2015 is linked to the dust deposition rate on PV arrays that was higher per comparison to the other months of july. According to the fig.1 July 2015 has lower temperature (T_{amb}= 38.82°C) and higher irradiance level (G_t= 5.43 kWh/m^2/d) than July 2012 (T_{amb}= 39.7°C; G_t= 4.89 kWh/m^2/d), July 2013 (T_{amb}= 40.57°C; G_t= 4.59 kWh/m^2/d) and July 2014 (T_{amb}= 40.17°C; G_t= 4.93 kWh/m^2/d). Apart from the first year when efficiency remains substantially constant during the hot season, the seasonal variation remains similar every year with funnel-shaped graphs.

Although not shown, the variability of the system efficiency is similar to array (PV modules) efficiency and its value varies between 10.02% (Jul-15) and 12.83% (Dec-12) with an average of 11.75%. Inverters efficiency ranges between 92.12% in July 2014 and 93.14% in November 2012.

During the four years of monitoring, we found a decrease in different efficiencies. Because we went from 12.96 % to 12.35 %, from 12.03 % to 11.43 % and from 92.81 % to 92.6 % between 2012 and 2015, respectively for the efficiencies of PV modules, PV system and the inverters.

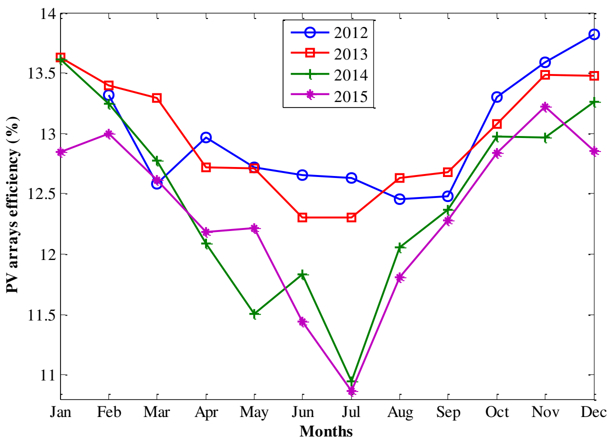

Fig.6. Monthly average daily PV efficiency

The performance of grid connected solar power plants is best defined by the capacity factor, which is the ratio of its actual AC output over a period of time, to its potential output if it were possible for it to operate at full-nameplate capacity continuously over the same period of time. **Fig.7** shows the monthly average daily capacity factor for the four year of operation of the 302.4 kWp solar PV plant. CF varies between 12.76 % in July 2014 and 22.11% for the month of October 2014 with four-year CF average of 16.35%. The maximum average is reached on the first year with 16.77%. This CF value is higher in comparison to other solar PV plants in other countries **[13]**. CF decline is observed for the harsh summer period from June to August and almost the lowest values of over the four year of operation is recorded for the months of July and are 14.32%, 13.09%, 12.76%, 13.11% respectively for 2012, 2013, 2014 and 2015. The CF is a parameter strongly impacted by the seasonal variation this is illustrated in fig.5 by a gap of about 3% between the summer months (June to August) and the other months of the year. Since the CF depends on the in plane solar irradiance and the ambient temperature, the period from June to August corresponds to the periods when temperatures are highest and the irradiance are lowest (Fig.1).This is the reason why CF decreases for this period. Also a factor such as the dustiness of the PV plant can also contribute to this decrease.

Also CF proves significant in the design of solar power plant because it can estimate if a solar photovoltaic system at a given site is potentially exploitable.

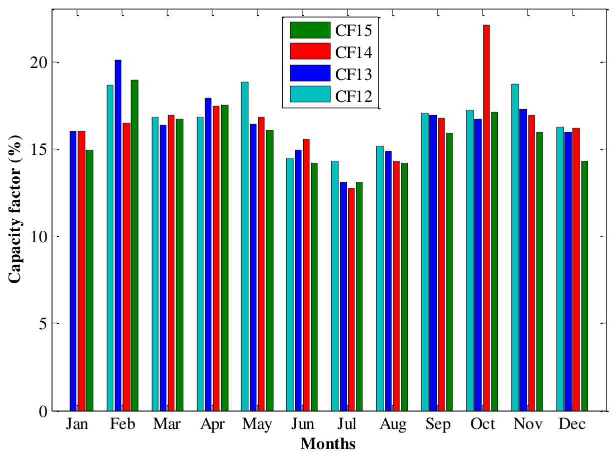

Fig.7. Capacity factor (2012 to 2015)

The comparison of operating results of the present work to the above-mentioned studies in part 1 indicates that PV system in Djibouti was comparable to those with highest performance parameters located in Oman and Abu-Dubai. A decrease in performance has been observed for all PV power plant installed in tropical and hot climate in harsh summer period from June to July. Several climate factors are responsible of the performance decrease in this period such the received quantity of irradiation, temperature and PV modules soiling.

6. Conclusion

In this study the performance of a 302.4 kWp grid-connected PV system is evaluated and the impact of climatic factors has been assessed. The performance parameters of this PV power plant are resumed as following:

- The accumulated energy for period of assessment (February-12 to December 2015) was 1.92 GWh. The energy generation for the first 12 months of the PV plant was 7.4% higher than originally estimated in the pre-feasibility study.
- The monthly average daily reference yield, array yield and final yield were 5.6 h/d, 5.1 h/d, and 4.7 h/d, respectively.
- The monthly average daily system losses and capture losses were 0.37 h/d and 0.54 h/d, respectively. The lower value of system losses shows that the power inverters are performing during power conversion.
- The average performance ratio for respective PV arrays and system are 90% and 84%.
- The monthly average daily PV module and system efficiency were 12.68% and 11.75% respectively, with a variation between 10.87% (Jul-15) and 13.82% (Dec-12) for PV module efficiency and 10.02% (Jul-15) and 12.83% (Dec-12) for system efficiency. Funnel-shaped graphs have been observed according to the seasonal variation of the PV module efficiency.
- The capacity factor ranges between 12.76% (Jul-14) and 22.11 (Oct-14). The maximum average is reached for the first year with 16.77%, with four years average of 16.35%.

Per comparison to the results presented in the first part, the PV system evolving in desert maritime climate conditions shows huge performances.

According to these performance parameters, it has been observed that the Solar PV power plant performed efficiently most of the month during the period of assessment. Apart for the months of June July and August that corresponding to harsh summer period. For this period it has been observed that the performance decrease is correlated to the decrease of irradiation (due to the khamsin's dust uprising) and increase of on-site temperatures and dust accumulation on PV modules.

The outcome of this research shows that this 302.4 kWp PV system works efficiently under harsh environmental conditions of Djibouti. This could be an incentive for investors for the future development of grid-connected solar PV plant. The data provided in this work will be a baseline for comparison to further PV power plant installed in same climatic conditions (coastal region of the Horn of Africa) and over the worldwide.
In ongoing work, the PV performance degradation for the climate of Djibouti will be estimated, and the thermal and electrical behavior of the PV system shall be investigated with the aim of developing an improved numerical model and estimate.

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