Energy Performance Analysis of On-Grid Solar Photovoltaic System- a Practical Case Study

*Mohamed R. Behiri**, ***Mohamed A. Mohamed****, Mohammed J. Al shammri**, *****Hegazy Rezk****‡

*Mechanical Engineering Department, Faculty of Engineering, Mutah University, Al-Karak, Jordan

**Mechanical Engineering Department, Faculty of Engineering, Benha University, Benha, Egypt

***Department of Electrical Engineering, Fuzhou University, Fuzhou 350116, China

****Electrical Engineering Department, Faculty of Engineering, Minia University, Egypt

*****College of Engineering at Wadi Addawaser, Prince Sattam Bin Abdulaziz University, KSA

(behiri@bhit.bu.edu.eg, dr.mohamed.abdelaziz@mu.edu.eg, hegazy.hussien@mu.edu.eg, eng_m_alshammri@hotmail.com)

‡ Corresponding author; Hegazy Rezk,11991, Tel.: 00966547416732, Fax:00966115882000, hegazy.hussien@mu.edu.eg

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Abstract- This research paper presents an experimental investigation for performance evaluation and energy efficiency estimation of a specific grid connected photovoltaic (PV) power system under real meteorological conditions. The basic installation and data of 10 MW Oryx photovoltaic plant (OPVP) installed in Ma'an, Jordan is introduced. The main objective of this research is to show and examine the obtained results and build a good database for Ma'an in particular and Jordan in general. In addition, promote the use of solar photovoltaic plants as a clean and cheap alternative energy source, whether on-grid or standalone. This approach relies on a genuine atmosphere conditions including, correspondence system and meteorological station. The weather data are obtained from three different weather stations in Ma'an, Jordan to compare and insure the accurate estimation. Last year, OPVP supplied the national electric power company in Jordan with 24.157 GWh. This integration was considered satisfactory during this period, where the annual energy efficiency of the OPVP was 12.1%, the average annual value of the performance ratio was 78.14%, and the average annual capacity factor was 26.34%. By comparing the obtained results with the actual values, it is ascertained that the proposed approach has the superiority over estimating the energy efficiency and performance of PV plants. Moreover, the obtained outcomes can be utilized as rules for the use of solar PV power plants in Jordan and other comparative climatic nations.

Keywords Renewable energy, solar photovoltaic, energy efficiency, on-grid, meteorological data.

1. Introduction

Nowadays, the world is searching the substitute of fossil fuels for a hygienic and cheap energy society, which is, depicted the consideration as clean electricity premise [1-3]. In addition, there are rising worries far and wide over the high fossil fuel costs, in light of the increased demand and the lineament to hold fuel to other generations. Therefore, incredible considerations through the world are drive towards renewable energy sources (RESs) [4-6]. In Jordan, the Ministry of Energy and Mineral Resources (MEMRs) aims to get 9% of Jordan's energy from RES [7].

Solar Photovoltaic (PV) energy is the best expanding RESs that maintain to develop every year in various countries. It is beholding as an exquisite technique to catch sun radiation and changes over it to electricity [8-10]. Therefore, solar PV energy has considered one of the technologies that helped MEMRs to achieve this goal. This technology has found great interest from the government as well Jordan has a convenient place with a suitable climate to create solar power plants, moreover, it tends to be utilized in various applications. However, PV systems in Jordan were mostly confined to residential housings where it was difficult to connect to the electricity grid. Grid-connected systems have not been widely developed in Jordan due to technical and economic obstacles without government support. Getting a franchise to feed energy in the grid was a relatively complex process for professional electricity producers.

However, in 2012, MEMR provided an exception to the regulations to make it easier for customers to feed energy in the grid. Jordan now has a complete framework of regulations, making it more useful and easier to purchase and install a grid-connected PV systems, which may give the required payment needed to create a healthier and mature PV. Hence, PV systems have acquired more particular considerations from researchers in terms of performance evaluation, improvements in the efficiency of systems and price of its equipment [11]. Many scientific researches worldwide have addressed the energy efficiency and performance of solar PV systems. Among them, the authors in [12] reviewed and analyzed the operational data of 993 residential PV plants installed in Belgium between 2007 and 2010 with total peak power of 4MW. The authors stated that the average commercial of an optimally arranged PV system, delivers an average yearly capacity of 892 kWh/kWp, while the average annual performance ratio (PR) is 78% and the average performance index is 85%. In addition, they reported that the energy delivered by this system is 15% sub-par compared to the energy delivered by a high-quality PV system. The real power of PV modules is reduced by 5% less than the relating nominal power declared on the manufacturer's data sheet. Micheli et al. [13] showed and compared the performance results of two grid-connected PV systems of the same size in northern, Italy over one year data. They relied on the PR and system yield indicators for performance evaluation and established that the impact of module temperature is more pronounced within the spring and summer months. The authors in [14] analyzed the experimental results of a grid-connected 2 kW PV system installed on the University of Malaga, Spain. The authors studied the effect of climate factors and reflector properties on the operation of the PV system. In addition, the authors analyzed this system to investigate the performance of grid-related PV systems in climatic variation in southern Spain. In [15] the authors evaluated the performance of a 36 kW grid-connected PV system in Abu-Dhabi, UAE, for one year data. The system performance was studied in terms of temperature effects and dust deposition. The authors in [16] predestined the yearly performance of a 5 MW grid-connected PV system in India. The performance analysis is performed in terms of array yield, system efficiency and system losses. In [17], the authors examined the procedures and drawbacks of open-air estimation of modules temperature coefficient. In [18], the authors estimated the temperature coefficients of twelve PV panels in two different areas under different radiations using various irradiation sensors. The impact of the inaccuracy in tracking maximum power point, are examined in [19]. The examination likewise assesses the computation models uncertainties for the cell temperature and tilted surfaces radiation. The impact of temperature on various sorts of panels operating losses have been examined in [20-22]. In [23] the impact of wind on the temperature of PV module is investigated by contrasting the experiential data and different literatures. Table 1 shows the performance of different PV systems around the world.

Numerous studies have been devoted to correlate among the actual and titular performances of PV systems and to the long term monitoring. A monitoring system is exhibited in [24], to incorporate a unit based-on field estimation of the *I-V* characteristics of the PV modules. In [25], an approach is exhibited to evaluate the electrical production of external test data, in light of an amended *I-V* curve paradigm and a novel expression for the output power maximization.

Many PV systems were installed in Jordan such as Shams Ma'an, (52.5 MW, 2016), Al Qweira (65 MW, 2015), Ardh Al Amal (10 MW, 2014), Al Zanbaq (10 MW, 2014), Zahrat Al Salam (10 MW, 2015), Al Ward Al Joury (10 MW, 2015) and Anwar Al Ardh (20 MW). This ensures that Jordan is increasingly using PV power systems. However, the available literature provides scarce data on energy efficiency and PV systems performance in Jordan. This research work, accordingly presents an experimental approach for performance analysis and energy efficiency estimation of a specific grid-connected PV power system under real meteorological conditions located in Jordan. The outcomes and data analysis of an experimental estimation of energy efficiency, performance and other parameters in actual meteorological conditions of the 10MW Oryx photovoltaic plant (OPVP) installed in Ma'an, Jordan have been presented. Moreover, the temperature variation and the rise of temperature impact on the performance of OPVP have studied both on the daily and yearly basis. On the other hand, daily datasets of one-minute average data have been used for in-depth analysis in this work. Customers or corporations that are eager to invest in the Jordanian PV strip can exercise several feasible data and aspects in this paper.

2. Site Description

This section presents general information and climatic descriptions of Ma'an city, Jordan. Ma'an is located between 30° 100 N and 35° 47 E at 1.060-1.2 km above sea level (ASL). The potential of solar energy in Ma'an is wide, where the sunshine hours is higher than in other areas in Jordan, moreover, it has low values of diffuse irradiation [35]. The annual average daily global irradiance is about 6 kWh/m^2/day, furthermore, it has wide flat lands which makes it suitable for a large-scale PV plants [36]. The state of the climate in Ma'an is the situation of the Eastern Mediterranean (i.e. the climate is cold and blustery in the winter; however, it is sweltering and dries in summer). Winter starts from Oct. to Apr. with yearly precipitation of (52 mm/year). The normal temperature values are - 6.0 ° C, 16.9 ° C, and 28.7 ° C in Jan., Apr., and July, respectively. The most extreme span of daylight happens in June with supreme qualities of 12.6 hours/day, while the normal daylight in winter is 7.0 hours/day. Normal relative humidity ranges from 46.5% to 62.4% amid winter and from 43.5 to 52.1% amid summer. Moreover, the direction of wind is usually from west to southwest [37].

Ma'an has many advantages makes it competitive in the field of solar energy. Among them, it has high direct solar irradiance (DNI) and gross solar irradiance (GHI) of 2700 kW/h/m^2/y and 2300kW/h/m^2/y respectively [38]. Moreover, it has a flat topography, moderate temperature, high sea altitude, and a relative decrease in humidity and dust. Meanwhile, it is geographically close to the national high/medium voltage network. Hence, Ma'an, Jordan clearly

Table 1. The performance of different PV system around the world

Author	Year	Location	Rated Capacity (kW$_P$)	Period of monitoring	Main finding (%)			Yield (kWh/kWp/day)	
					* η_{PV}	*PR	*CF	*YF	*YR
Milosavljević et. al [26]	2015	Serbia	2	January 2013 - January 2014	10.07	93.6	12.88	--	
Ayompe et. al [27]	2011	Dublin, Ireland	1.72	November 2008 - October 2009	12.6	81.5	10.1	2.41	2.85
Emmanuel et. al [28]	2009	Sitia, Crete	171.36	A year of 2007	-	58-73 (67.36)	-	1.96-5.07	-
Vikrant and Chandel [29]	2013	India	190	A year of 2003	8.3	55–83 (74)	9.27	1.45-2.84	2.29-3.53
Emilio et. al [30]	2013	Sardinia, Italy	395.61	Ground mounted installation	-	87.3	-	-	-
			1042.29	Building integrated rooftop installation	-	83.2	-	-	-
Pietruszko and Gradzki [31]	2004	Warsaw, Poland	1	2000-2001	8	50 - 80	-	-	-
Leloux et al. [32]	2012	Belgium	4MW	2007-2010	-	78	-	-	-
Sidrach and Mora [33]	1999	Spain	2	1997		64.5	-	2.7	-
Decker and Jahn [34]	1997	German	392	1991–1994		47.5-81 (66.5)		1.9	

* η_{PV} (Energy Efficiency), *PR* (Performance Ratio or Performance Factor), *CF* (Capacity Factor), *YF* (Final Yield or Yield Factor), and *YR* (Reference Yield or Reference Factor).

presents good conditions for utilizing solar energy and converting it into electrical or thermal energy.

Nowadays, many investors are concerned with installing large-scale PV projects in Ma'an. In 2011, the data of five small PV systems have been tested and analyzed to find out the suitable one for the Ma'an's weather condition [39]. The total capacities of solar PV projects were developed within Ma'an governorate is around of 170 MW.

3. Oryx PV Plant Description

The Oryx PV plant (OPVP) is located between a 30° 100' N and 35° 47' E. The project site is located about 17 km from Ma'an city, which is about 225 km from the capital city of Amman. The site is characterized by being a flat area with no sudden changes in topography and cliffs. The project area is located between two main valleys (the main natural drain of rain); the first is crossing the area in the northern part and the second is in the southern part. In addition, a non-developed drain system is not required in the central parts of the project area, but there is only a small channel connected to the main valley. The site is 1.220-1.240 km ASL and is situated in an arid climatic zone. The site has very little and scattered vegetation. The OPVP installation site has a normal slope with a level difference of about 5 m and there are rock outcrops in the site.

The PV modules of OPVP are installed on 10.3 acres, approximately 36 hectares. The plant has 34,320 Polycrystalline Silicon (Poly-Si) modules. Every string includes 20 series connected modules. The plant has 1716 strings and 13 inverters. The capacity of each inverter is 900 kW and the total plant capacity is 10 MWh. The strings are connected in parallel with generated voltage of 415V at the output of each inverter. Every two inverters are connected to a step-up transformer that raises the voltage from 415 V to 33 KV. Moreover, the power plant includes a control room and other facilities structures. The total electrical energy generated by OPVP during May 1, 2017 to April 30, 2018 was 24.157 GWh and sold to the National Electric Power Company (NEPCO). However, the expected yearly electricity production for OPVP was 21.712 GWh, 3.112 GWh more than forecasted. The main reason for the increase in energy production was because of high solar irradiance level compared to the expected ones as well as low temperature raise efficiency of PV modules. The shading caused by pollution is separated into soft shading, for example, air pollution and the harsh shading that happens when a solid object obscures the sunlight, especially in summer so the cleaning cycle for PV modules in summer was monthly, which contributed to increasing production.

4. Theoretical Study

The solar PV power plant characteristics parameters that have been studied in the present work are energy efficiency (η_{PV}), specific yield factor (*YF*), performance ratio (*PR)* and capacity factor (*CF)*. According to IEC [40, 41], these parameters can be defined as follows:

4.1 Energy efficiency

The energy efficiency of PV plant is defined as the relation of the generated energy and the solar energy dropping the surface of PV plant it at a certain time. The value of energy efficiency can be hourly, daily, monthly and yearly. In this paper, the monthly value of energy efficiency is considered that can be calculated as follows [42]:

$$\eta_{PV} = \frac{\sum_{i=1}^{n}\left(E_D\right)}{S \times \sum_{i=1}^{n}\left(G_{opt}\right)_i} \quad (1)$$

where η_{PV} denote the energy efficiency; n represents the month days number; E_D is a total energy generated from the solar PV system and transferred to the power grid within the day (Wh); S is a total PV array area, m^2 and G_{opt} is a total global solar energy dropping on one square meter of the solar PV plant modules during the day (Wh/m^2).

The above equation is used to calculate the PV plant η_{PV}, experimentally.

4.2 Specific yield factor

The specific yield factor (YF) denotes the relation of the energy generated from the solar PV system and transferred to the power grid at specific time (E_{ACout},Wh) and the total installed capacity of the solar modules ($P_{max,STC}$, W$_p$) as follows [43]:

$$YF = \frac{E_{ACout}}{P_{\max,STC}} \quad (2)$$

4.3 Performance ratio

The performance ratio is implies a relation of YF and the reference yield (YR) of the solar PV plant as the follows:

$$PR = \frac{YE}{YR} \quad (3)$$

$$YR = \frac{G_{opt}(\mathrm{w/m^2})}{1000(\mathrm{W/m^2})} \quad (4)$$

4.4 Capacity factor

The capacity factor denotes the relation of the yearly energy generated from PV solar plant and the energy that can be generated if it is operated with the total installed power as follows [44]:

$$CF = \frac{YF}{8760(\mathrm{h})} = \frac{E_{ACout}}{P_{\max STC} * 8760} = \frac{G_{opt} * PR}{P_{\max STC} * 8760} \quad (5)$$

5. Experimental Study

A single axis tracker grid-connected 10 MW solar PV plant was installed in Ma'an, Jordan in April-2017.The experimental estimation of performance and energy efficiency of OPVP was carried out from May 1, 2017 to April 30, 2018. The following sections detailed the measurements instruments and the PV system components used in this plant:

Fig. 1 The Anemometer installed on OPVP

5.1 Measurements instruments

In order to measure the wind speeds and their directions, Kriwan type anemometer has been used on OPVP as shown in Fig. 1. Moreover, the measurements of horizontal solar and direct solar radiation have been taken on OPVP by SMP10 Pyranometer as shown in Fig. 2. The measurements of the ambient temperature, air humidity, rain intensity, rain amount, and atmospheric air pressure have been taken by Clima multi-sensor instrument as shown in Fig. 3. The measurements of the backside module temperature have been taken by the Platinum Silicone Patch Sensors (PSPS). The module temperature sensors and fittings installed on OPVP are shown in Fig. 4. The meteorological parameters measurements in OPVP have taken by this mini weather station. Moreover, the same meteorological data has been collected from another two stations in different locations behind OPVP site to compare and ascertain the measured data. The numeric values of the parameters and meteorological data have been directly recorded on SCADA server by fiber optics communication cable as well as transferred to excel file for further numerical and graphics processing.

5.2 OPVP components

The total capacity of the plant is 10.468 MWh$_{DC}$. The plant consists of 34,320 Polycrystalline Silicon (Poly-Si), (BYD P6C-36 Series-3BB), and each one is 305 W. The modules are series connected and installed on metal tempered steel with the establishment inclined at 0º toward the South as shown in Fig 5. Every string have 20 series connected modules and the plant has 1716 strings assemble into DC distribution boxes for steady perform of OPVP. The plant contains 13 Sunny Central 900CP XT kind three-phase inverter each of 900 kW capacity.

The main components of OPVP can be summarized as the following:

1. The number of PV modules is 34320 and 305 W of each and every 20 modules have one string;
2. The number of strings is 1716 and every 22 strings have one DC box;
3. The number of boxes is approximately 78 boxes and every 6 boxes have one inverter;
4. The number of inverters is 13, each 3-Phase inverter is 900 kW, every 2 inverters have one transformer and the number of transformer is 7.

Fig. 2 SMP10 Pyranometer installed on OPVP

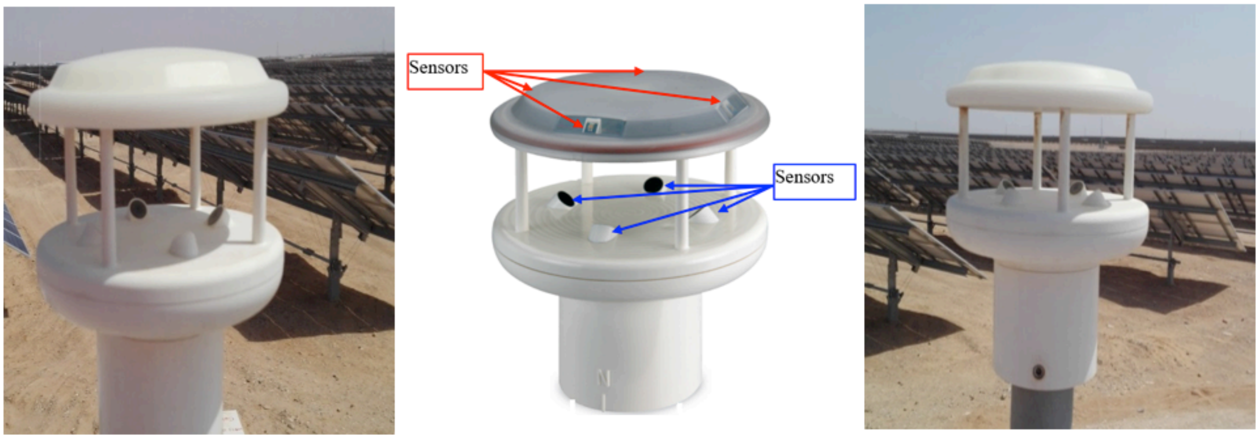

Fig. 3 The Clima sensor installed on OPVP

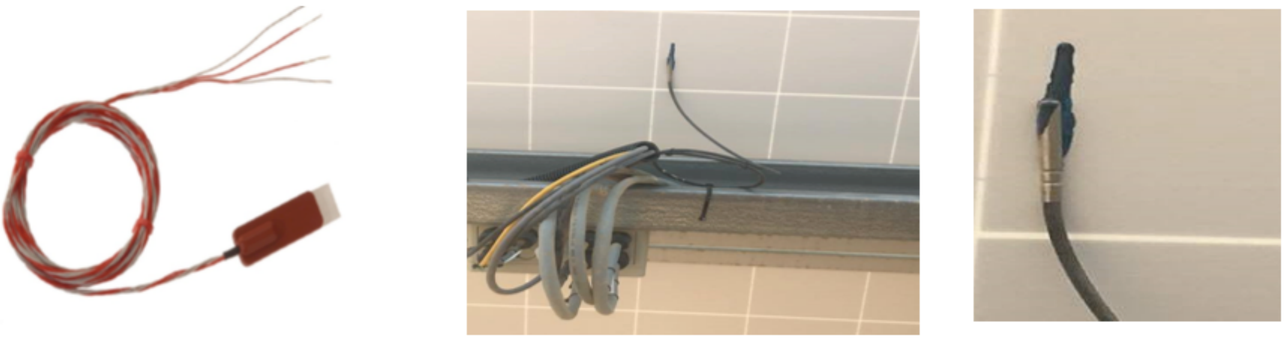

Fig. 4 The module temperature Sensors (PSPS) installed on OPVP

Fig. 5 Overview of OPVP

6. Results Analysis and Discussion

The experimental outcomes concerning the meteorological and performance parameters of the 10 MW OPVP installed in Ma'an for annual period from May 1, 2017 to April 30, 2018 have been analyzed and discussed in this section. The daily ambient temperature (T_{amb}), backside of module temperature (°C), and daily values of the humidity from May 1, 2017 to May 1, 2018 are shown in Fig. 6. Fig. 6 also shows the daily amount of electrical power generated (MWh) and G_{opt} falling on one square meter of a single axis tracker South-oriented surface, at the angle of 0º. The daily values of the wind speed, rain intensity and rain amount are given in Fig 7. Fig. 7 also presents the daily solar radiation of the reference clean and dirty cell, respectively.

The average daily ambient temperature (T_{amb}), back side of module temperature (°C), and average daily values of the humidity from May 1, 2017 to May 1, 2018 are shown in Fig. 8. The yearly average, maximum, and minimum values of the ambient temperature were 17.1ºC, 38.3ºC (in Aug. 1, 2017), and -1.9 ºC (in Nov. 25, 2017), respectively. The yearly average, maximum, and minimum values of the back side module temperature were 18.4 ºC, 66 ºC (in Aug. 16, 2017), and -1.9 ºC (in Jun. 28, 2017), respectively. Furthermore, the yearly average, maximum, and minimum values of the humidity were, 35.79 %, 78.7 % (Dec. 24, 2017), and 10.7% (Nov. 25, 2017), respectively. Figure 8 also shows the average daily amount of electrical power generated (MWh) and the G_{opt} falling on modules**.** The daily average, maximum, and minimum values of G_{opt} were were 340 W/m^2, 441 W/m^2 (in Jul. 2017), 213 W/m^2 (in Dec., 2017), respectively. The average, maximum, and minimum values of the daily active energy feed were 66.2 MWh, 97.5 MWh (in May. 24, 2017), and 9.5 MWh (in Dec. 24, 2017), respectively.

The 10 MW OPVP installed in Ma'an generated 24.157 GWh of electrical energy from May 1, 2017 until April 30, 2018. The best measure of generated energy from the OPVP was 2.548 GWh in July and the G_{opt} was 10.575 kWh/m^2. Notwithstanding, in a similar period, the best measure of electrical energy (97.485 MWh/day) was produced on May 18, 2017. The monthly η_{PV} of the OPVP versus ambient temperature (T_{amb}) is appeared in Fig. 9.

It is obvious from Fig. 9 that with the reduction of the ambient temperature, there is an expansion of the exploratory η_{PV}. However, with the expansion of the wind speed there is a slight increment in η_{PV} as a reason of cooling of solar modules, brought about by wind in summer months. However, if speed reaches 12 m/s the module will turned horizontal so the η_{PV} will decrease also another factor like soling rate decrease efficiency.

The monthly average values of *PR* and *YF* of the OPVP are shown in Fig. 10 and 11, respectively

Based on the experimental estimation of η_{PV} and the other performance parameters of OPVP plant, the following results can be summarized:

1. The total annual amount of the global solar energy dropping on one square meter on single axis tracker, is 2983 kWh/m^2.
2. The value of *YF* and *YR* was 2307.7 kWh/kWp and 2983 h, respectively.
3. The annual mean value of *PR* of the OPVP was 78.14% and varied between 72 %- 86%.
4. The annual value of *CF* of OPVP was 26.34% in period May 1, 2017 to April 30, 2018.
5. The annual η_{PV} of the OPVP was 12.1%, in period May 1, 2017 to April 30, 2018.

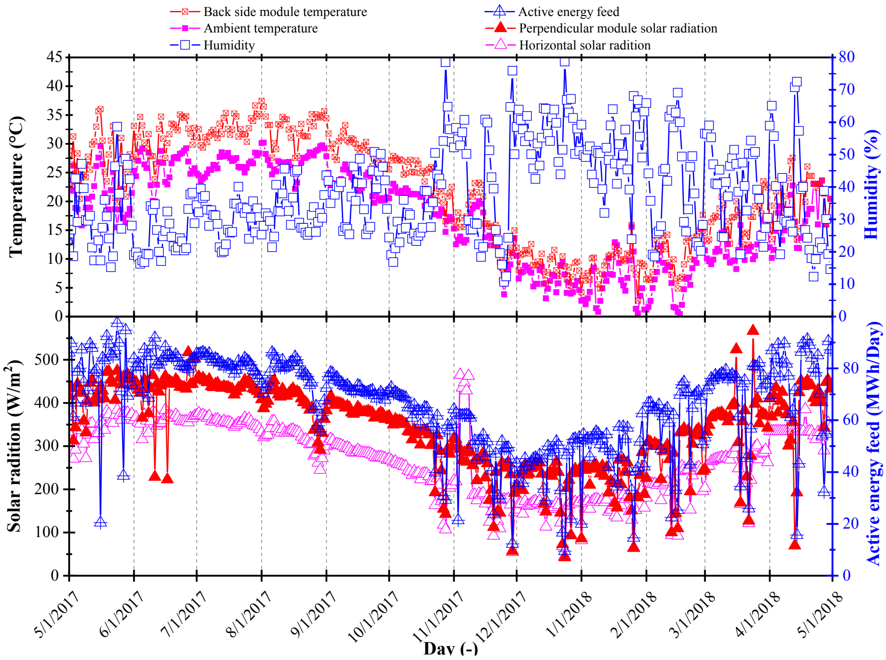

Fig. 6 The daily ambient temperature, daily back side module temperature, daily values of the humidity, daily values of the global solar energy (G_{opt}), and daily electric power generated.

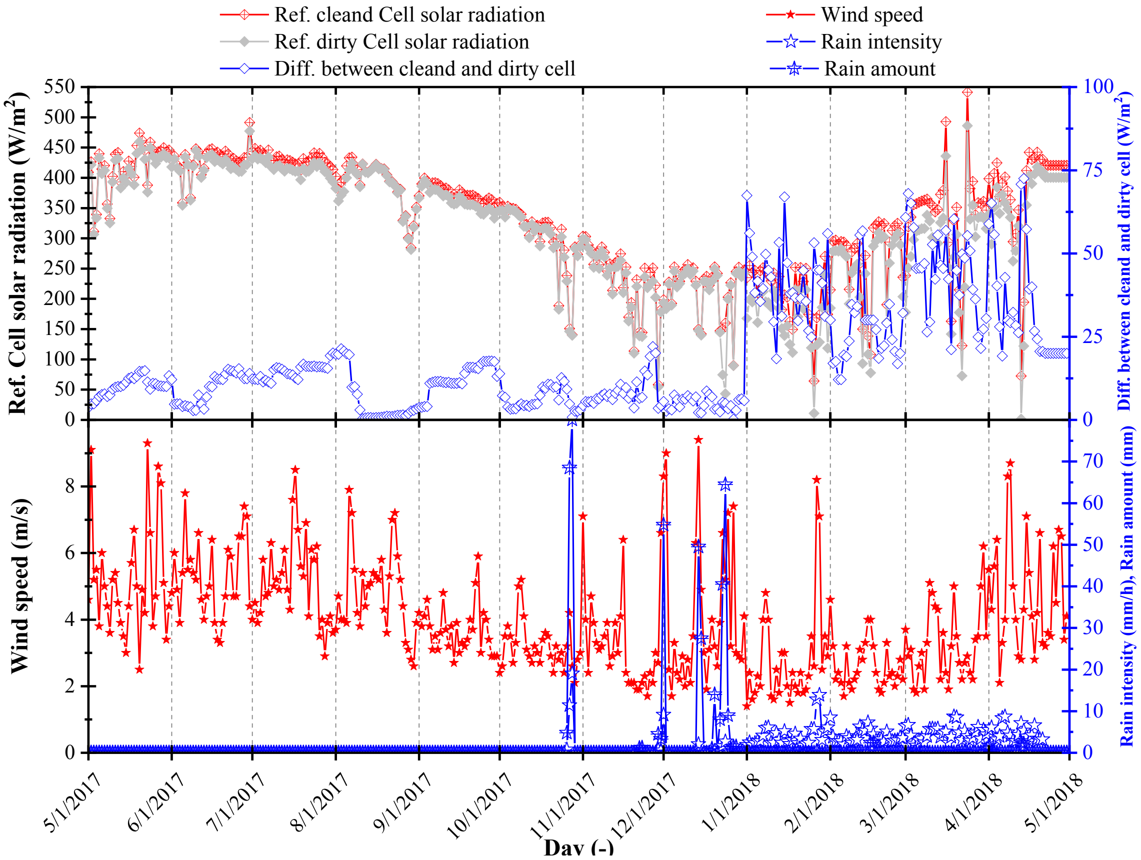

Fig. 7 The daily values of the wind speed, rain intensity, rain amount, daily solar radiation of the reference clean and dirty cell.

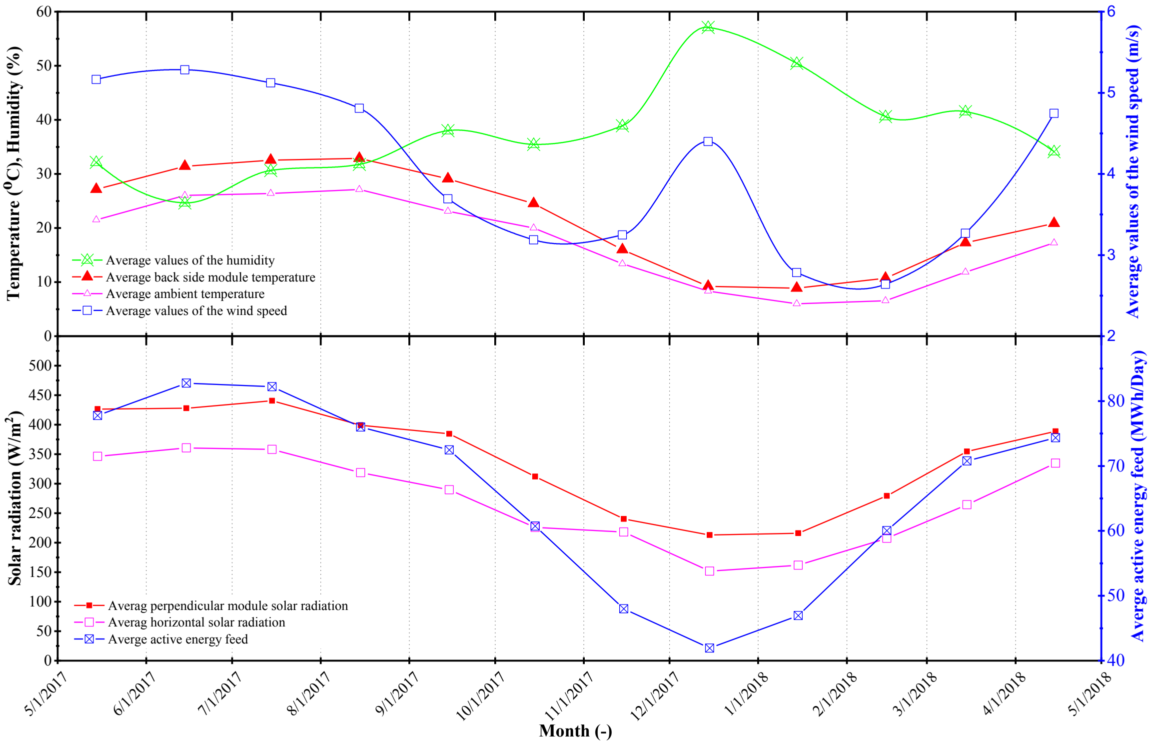

Fig. 8 The average daily ambient temperature, average daily back side module temperature, average daily values of the humidity, average daily values of G_{opt}, and average daily electric power generated.

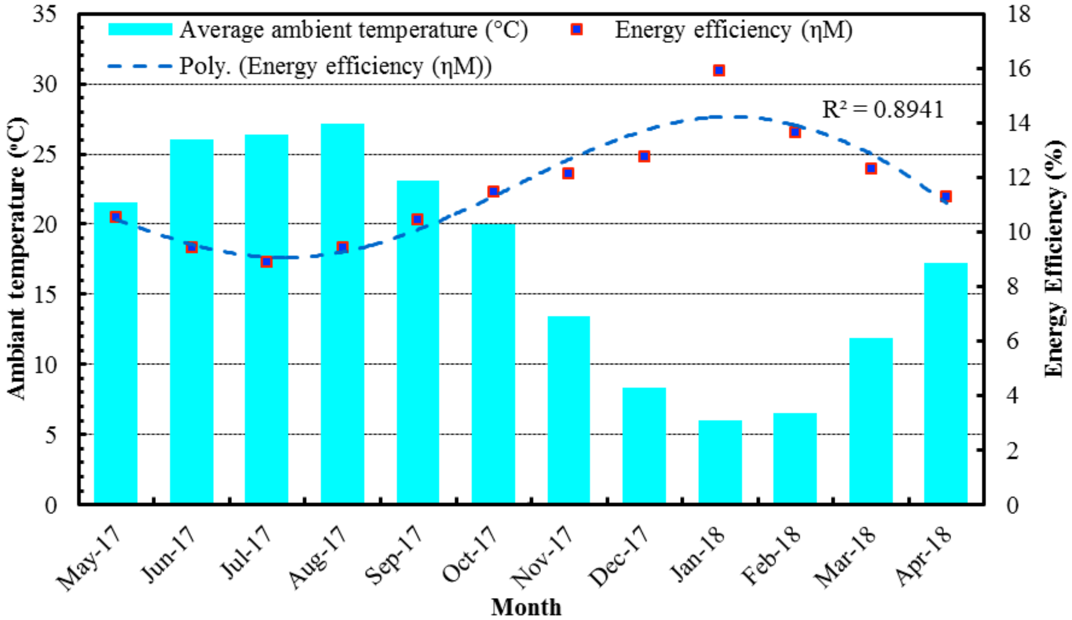

Fig. 9 The monthly η_{PV} of the OPVP versus ambient temperature (T_{amb}).

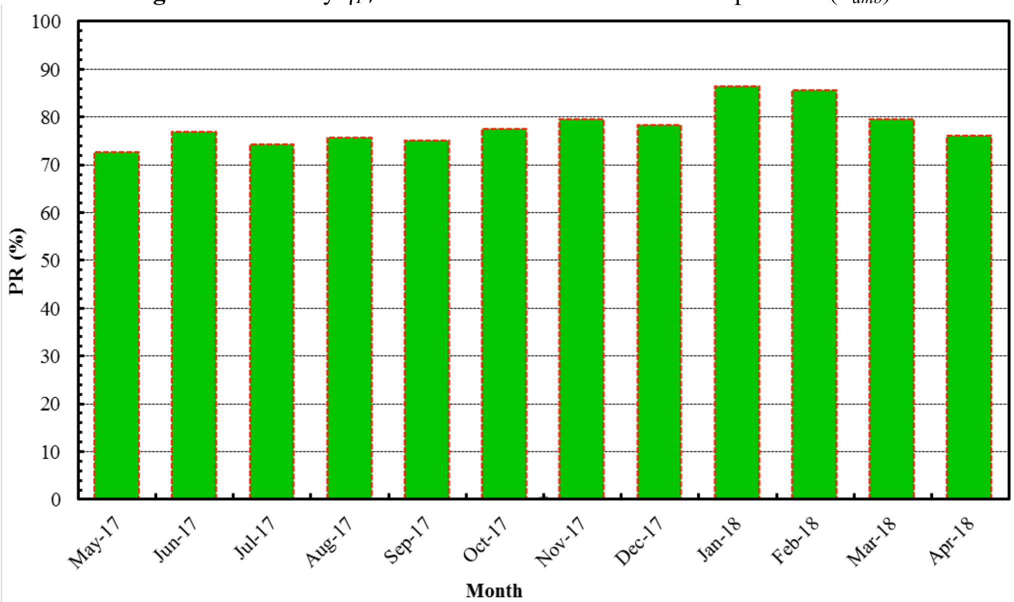

Fig. 10 The monthly average value of *PR* of OPVP.

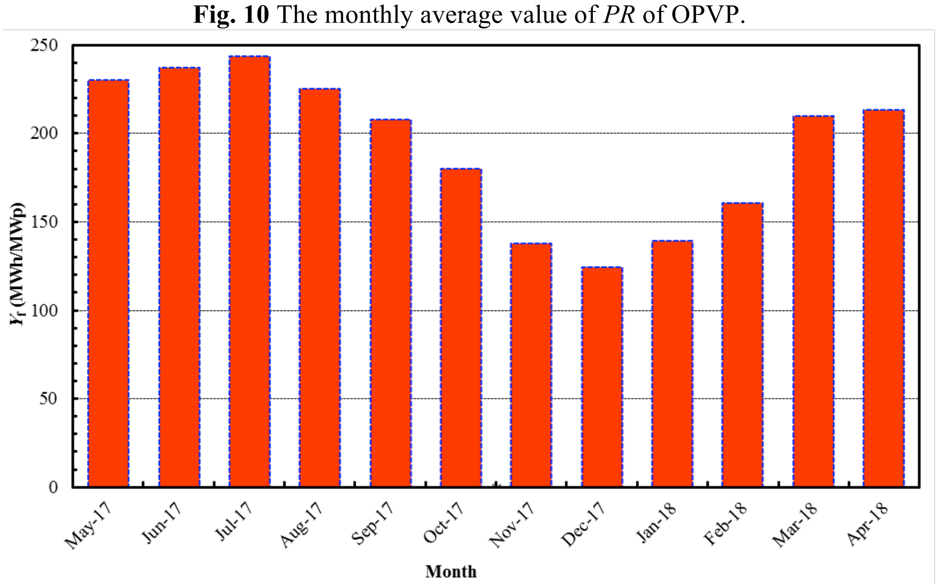

Fig. 11 The monthly average value of *YF* of OPVP.

6. Conclusion

In this paper an experimental approach based long term monitoring of data has been introduced to estimate and analyze the performance characteristics of 10 MW grid-connected OPVP installed in Ma'an, Jourdan. Based on what has been previously mentioned, one can infer that Ma'an is one of the genuinely most favorable locales for utilizing sun oriented PV plants are progressively being utilized for individual and business purposes. Nonetheless, accessible literature gives rare data about the energy efficiency of the solar PV plants in Jordan. The data introduced in this research are valuable for contrasting the compelling energy generation of the PV solar plants located in various districts of the world. The data can likewise be helpful in arranging and operation studies about went for anticipating the effect of the renewable sources on distribution systems beginning with genuine data and sensible power generation patterns within various time spans.

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