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First Year Performance of a PV Plant in Jordan Compared to PV Plants in the Region

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Abstract- This paper presents the first year (2014) performance analysis of a 276 kWp grid-connected roof-type solar PV plant located at the campus of Al-Ahliyya Amman University in Jordan, using monitored data. The plant is installed on 3000 m2-roof of Arena building at the University campus. The array consists of 1176 modules with two orientations 10° and 15°. The PV array is configured in a way that the system includes 14 panels in parallel with 14 inverters. The plant is equipped with a monitoring system which is connected to the internet and gives the data on a daily basis. The study shows that the actual and estimated specific energy productions are 1639kWh/kWp-year, and 1726 kWh/kWp-year, respectively. The annual capacity factor and performance ratio are found to be 18.7% and 87.5%, respectively. The actual energy production is found to be 452406 kWh/year, whereas the estimated annual energy production is found to be 476467 kWh as calculated using the software PVsyst V6.32. The measured and estimated yields are in close agreement to each other with a relative error of about 5%. It is found that the maximum actual yields in July and minimum in January. Compared to PV plants worldwide, and particularly in detail to a PV plant in Syria, the analysed plant (the AAU plant) has an excellent overall performance.

Keywords—Photovoltaic Plant; Specific system Production; Performance Ratio; Capacity Factor; Jordan, Syria

1. Introduction

Al-Ahliyya Amman University (AAU) was established in 1990 as the first private university in Jordan. The University consists mainly of 7 Buildings, 5 Female Dormitories and the Cultural Foundation Forums (ARENA); the total built up area of university campus is 72,868 m^2. The average specific electrical energy consumption of the university is about 4.5 kWh/m^2 monthly. The annual electricity consumption is about 4 GWh [1]. The electrical usage breakdown is shown in “Figure 1”.

To reduce the electricity bill, the AAU decided to install a solar PV plant with a capacity of 276 kWp on the roof of Arena building which has an area of 3000 m^2 “Figure 2”.

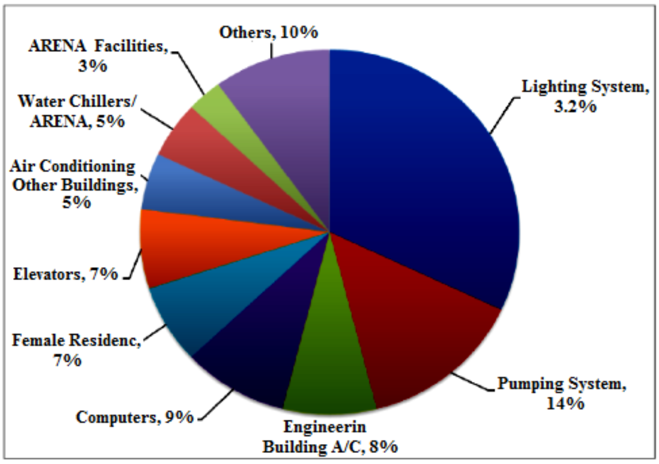

Figure 1. Electrical use breakdown of AAU [1]

Figure 2. PV plant on the roof of Cultural Foundation Forums Building (ARENA) in AAU, Amman, Jordan

Following the design stage, and after receiving the approval, the installation of the System took about 10 days. After installing the system it was inspected by JEPCO (The Jordanian Electric Power Company) who released the necessary approvals to connect the system to the grid. This paper presents the measured system data for the year 2014 and the performance analysis of these data. The objective of this analysis is to show if this project is promising and encouraging to determine whether the university would install more PV plants. Moreover, a comparison of the plant behaviour with other plants in the region and worldwide was performed. We have used the software PVsyst V6.32 for calculating the estimated parameters of the installed system and compared them with the actual parameters [2].

2. Technical Description of the System

The PV system is located in As-Sarw region (between Amman and As-salt city), Jordan with a Latitude of +32.05 (32°03'00"N); and Longitude of +35.72 (35°43'12"E). The used module is ET-P660235WW/ ET-P660235WB with its data shown in " Table 1".

Table 1. Module data at STC

Model Type	ET-P660235WW, ET-P660235WB
Cells per module	60
Cell Type and dimension	Poly 156x156 mm
P_{max}	235 W
Module efficiency	14.44%
Power Tolerance	2%
V_{mp}	29.83 V
I_{mp}	7.88 A
V_{oc}	37.08 V
I_{sc}	8.5 A
Maximum System Voltage	DC 1000 V
NOCT	45.3°C
Voltage coefficient	- 0.34 %/°C
Current coefficient	0.04 %/°C
Power coefficient	- 0.44 %/°C

The array comprises 1176 modules configured as 14 sub-arrays. Each sub-array consists of 4 strings with 21 modules connected in series for each string. The system is equipped with 14 sub-array identical inverters SUN2000-20KTL from Huawei Technologies with technical specifications as shown in "Table 2". The array orientation is fixed as two orientations, vis. Mixed Tilt/Azimuth of 15°/0° and 10°/0°. The plant is equipped with a monitoring system which is connected to the internet and gives the data on a daily basis which can be followed in a website [3].

Table 2. Inverter specifications

Max. efficiency	98.5%
European efficiency	98.20%
Max. DC input	22.5 kW
Max. input voltage	1000 V
Max. input current per MPPT	18 A
Operating voltage range	250-850 V
MPP voltage range	480-800 V
Rated input voltage	620 V
Number of MPP trackers	3

"Figure 3" shows a schematic layout of one panel of the PV plant.

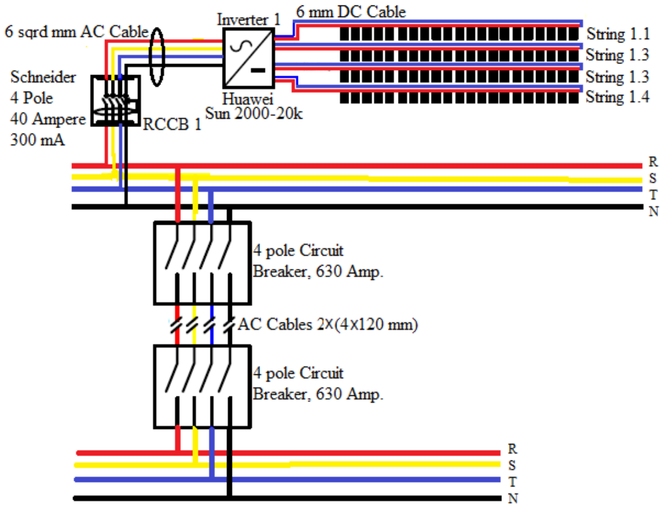

Figure 3. Layout of one panel of the AAU PV plant

3. Actual and Estimated Energy Production

According to the monitored data of the plant form January, 1st to December, 31st, 2014, the actual energy production was 452,506 kWh/year with a specific final yield (Yf) of 1639 kWh/kWp. The minimum value of 16,898 kWh was in January, whereas the highest value of 55,821 kWh was in July as shown in "Figure 4". The PV plant is simulated by the program PVsyst V6.32. The simulation results show that the expected energy fed into grid is found to be 476,467 with a specific final yield of 1726 kWh/kWp, which indicates a good agreement with the measured value with a relative deviation of about 5%. It is obvious from "Figure 4", that the actual values exceed the estimated values from April to August. The PV plant saves in 2014 about 331 tonnes of CO_2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity.

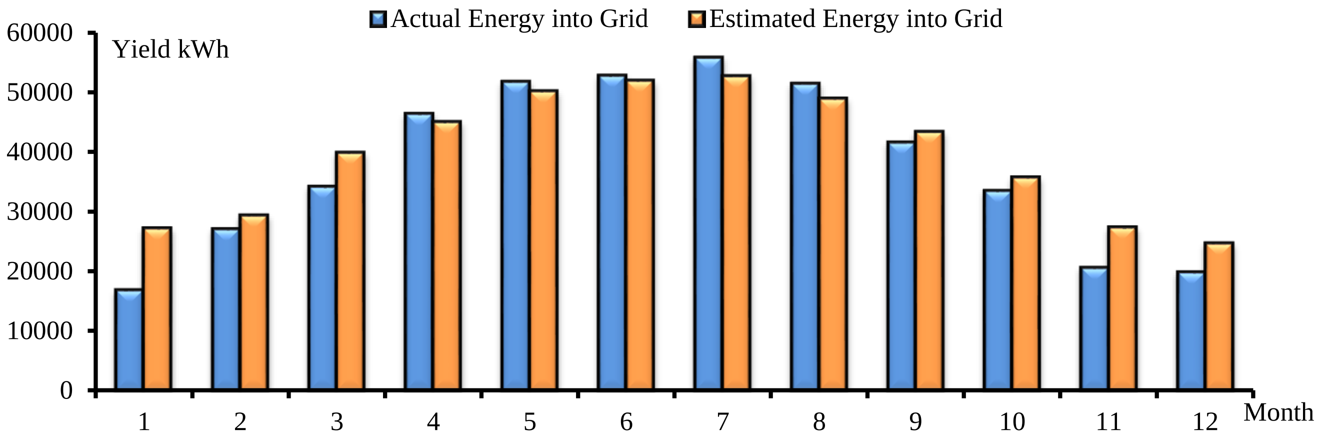

Figure 4. Measured and estimated energy production for January-December 2014

The measurement and estimation (simulation) of photovoltaic energy production is a fundamental issue in PV system engineering. Measurement and monitoring is generally simpler than estimation which is dependent upon weather. Monitoring and estimation of PV can be used for various purposes including, financial analysis. Whatever the goal, the processes and methods are critical to the technical and financial viability of PV technology and its integration into the utility grid. Simulation of PV systems differs from monitoring. The input may be either measured or calculated. The output is not measured but calculated. Simulation is a two part process entailing use of a set of input parameters and a model or transfer function of the physical plant used to calculate performance of a PV system [4].

4. Performance Ratio

4.1. *Definition*

One of the key evaluation criteria of the PV system is the Performance ratio (PR) of a grid-connected PV plant. PR is an indicator of the effectiveness of the plant in transforming the solar energy captured by PV array into AC energy delivered to utility grid. PR is defined for a period of time (usually a month or a year) as the ratio of the measured generated AC energy fed into the point of common coupling (PCC) to the potential array output DC energy under Standard Test Conditions (STC). The calculation of annual and monthly PR% can be performed by "Eq. (1)" and "Eq. (2)", respectively [5,6,7,8]:

$$\text{Annual PR\%} = \frac{\text{Measured Energy at PCC}\left[\frac{\text{kWh}}{\text{year}}\right]}{\text{Insolation}\left[\frac{\text{kWh}}{\text{m}^2.\text{day}}\right] \times \text{active array}\,[\text{m}^2] \times 365 \times \eta_{\text{module}}} \times 100\% \qquad (1)$$

$$\text{Monthly PR\%} = \frac{\text{Measured Energy at PCC}\left[\frac{\text{kWh}}{\text{Month}}\right]}{\text{Insolation}\left[\frac{\text{kWh}}{\text{m}^2.\text{day}}\right] \times \text{active array}\,[\text{m}^2] \times 30 \times \eta_{\text{module}}} \times 100\% \qquad (2)$$

4.2. Performance Ratio Calculation

- Active array area

$$\begin{aligned}(\text{Area of module cells}) &= 0.156 \times 0.156 \times 60 \times 1176 \\ &= 1717.148\ \text{m}^2\end{aligned}$$

- The solar data of plant location is assumed to be as of Amman and is adopted from NASA-SSE Satellite included in the database of software PVsyst V6.32. Based on horizontal values, the global monthly average insolation in collector plane is computed using the software PVsyst V6.32; the results are represented in "Figure 5". The yearly average global insolation in collector plane is 5.71 kWh/m^2.day.

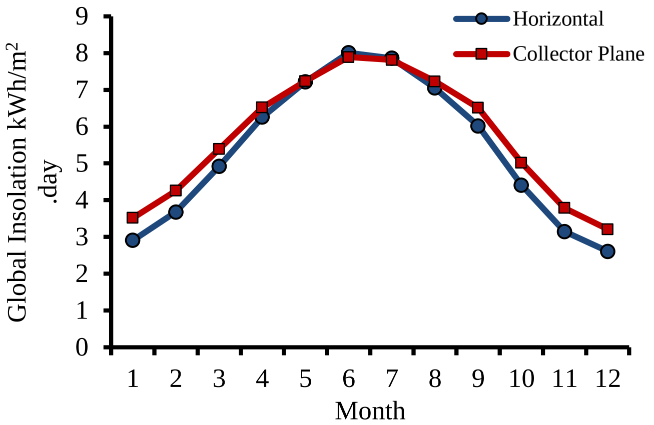

Figure 5. Global monthly average insolation at AAU

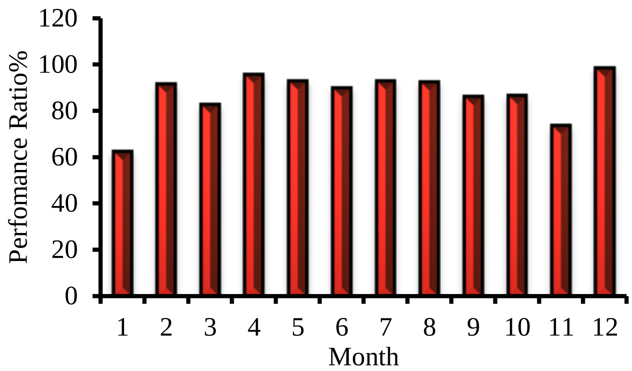

Figure 6. Monthly Performance Ratios, January-December 2014

The plant annual PR is calculated using "Eq. (1)":

$$\text{Actual Annual PR\%} = \frac{452405.92 \times 100\%}{5.71 * 1717.148 \times 365 \times 0.1444}$$

$$= \frac{452405.92}{516777.854} \times 100\% = 87.544\%$$

In modern solar PV plants, the performance ratio should typically be about 80% at starting year. According to the National Renewable Energy Laboratory (NREL), the standard performance ratio for a new PV system is about 77%, and over time, PR will degrade [9]. So, the PR value of over 87 % for the new university PV system shows an excellent quality of the system. The PR value indeed evaluates the total losses of the system which are less than 13% for our system. These losses account for mismatched modules, differences in ambient conditions, dirty collectors, inverter efficiency, wiring losses, system availability, diodes and connections … etc.

It is a good practice to calculate the monthly PRs in order to be aware of the losses for each month what it helps in deciding the suitable measures for reducing them. The calculation process is illustrated by an example for March,2014:

$$\text{PR\%, March} = \frac{34251 \times 100\%}{5.39 \times 1717.148 \times 31 \times 0.1444}$$

$$= \frac{34251}{41431.04} \times 100\% = 82.67\%$$

The results are shown graphically in "Figure 6".

It is obvious from "Fig. 6" that PR is minimum for January (62.45%), maximum for December (98.40%), and over 90% over 6 months. The performance ratio for the whole year is found to be 87.544% as calculated above.

4.3. Performance ratio Levels worldwide [10]

Many studies have been conducted [11,12.13,14] to analyze the performance of PV systems installed in different countries for different times. It has been observed an increasing trend of the annual PR values has been observed over the years as shown in "Table 3". The average PR values increased from about 65% in the 1990s to over 80% in the 2000s. Compared to average PR levels for PV plants worldwide, AAU plant belongs to plants of highest PR.

Table 3. Performance ratio values for reported PV systems worldwide [10]

Installation time	Country	PR Range	MeanPR
1990s	Germany	0.38 - 0.88	0.67
2000s	France	0.52 - 0.96	0.76
2000s	Belgium	0.52 - 0.93	0.78
2000s	Taiwan	<0.3 - >0.9	0.74
2000s	Germany	0.70 - 0.90	0.84

5. Capacity Factor

5.1. Definition

The other key parameter for evaluating PV plants is the capacity factor (CF). CF of a power plant is the ratio of its actual generated energy over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity. The main difference between PR and CF is that CF ignores the environmental conditions affecting the plant, while PR accounts for these conditions. Capacity factor may be, however, a value which serves as comparison criterion for evaluating power stations with different fuels. Renewable Power plants and/or conventional power plants of high fuel cost that usually are operating at peak load periods, have relatively low capacity factors. "Table 4" shows average CFs for different power plants in UK [15].

Table 4. Average Capacity Factor for different power plants in UK

Type	Average CF (2007-2012)
Nuclear	62%
Combined cycle	57%
Coal-fired	45%
Hydroelectric	34%
Wind	28%
PV	9%

According to National Renewable Energy Laboratory (NREL), Golden, Colorado, USA, the CF of PV plants over a year is calculated as:

$$Annual\ CF\%\ (according\ to\ NREL) = \frac{Actual\ produced\ kWh}{DC\ Rated\ power \times 8760} \times 100\% \quad (3)$$

$$Monthly\ CF\%\ (according\ to\ NREL) = \frac{Actual\ produced\ kWh/month}{DC\ Rated\ power \times 24 \times month\ dayes} \times 100\% \quad (4)$$

5.2. Calculation of AAU plant Capacity Factor

The annual capacity factor of AAU plant is calculated using "Eq. (3) ":

$$\text{CF\% of AAU plant } = \frac{452405.92\ kWh}{276\ kW \times 8760} \times 100\% = 18.7\%$$

Monthly CFs are calculated and represented graphically in "Figure 7", which shows that CF is minimum in January (8.23%) and maximum in July (27.18%). The average CF the entire year is 18.7%.

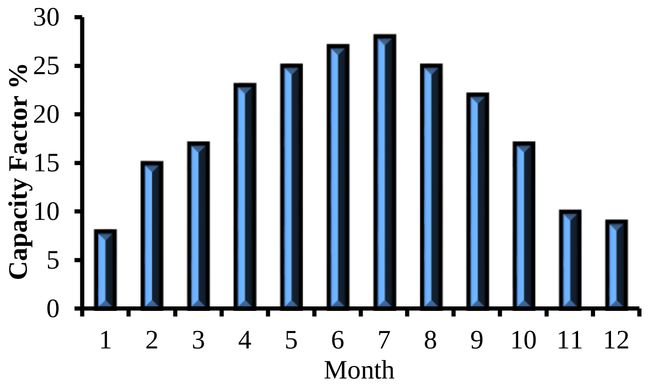

Figure 7. Monthly CFs for AAU Plant

According to [16], the capacity factors of reported PV plants in USA and UK are as follows: PV solar in Massachusetts 13-15%, PV solar in Arizona 19%, PV solar in UK 8.6%. The Annual CF of a PV plant in Egypt is 18.12% [17]. Compared to these CF values in some countries, our plant has a very high capacity factor, which again indicates an excellent performance.

The main reason of the very high CF value is the very high insolation in Jordan, which is about 2-times that in European countries, for example. The insolation value effects the numerator of CF relationship (Actual Yield).

6. Effect of Ambient Temperature on Power Output of Array and Inverter

Cell temperature changes not only because variation of ambient temperatures, but also due to insolation change on the cells. Manufacturers often provide a parameter called nominal operating cell temperature (NOCT), which can be used for considering the changes in cell performance with temperature. The NOCT is cell temperature in a module under the following conditions: Ambient temperature 20◦C, Solar irradiance 0.8 kW/m^2 and Wind speed 1 m/s. To account for other ambient conditions, the following expression may be used [18]:

$$T_{cell} = T_{amb} + \frac{NOCT - 20°}{0.8} \times S \quad (5)$$

where T_{cell} is cell temperature (°C), T_{amb} is ambient temperature (°C), and S is actual solar irradiance (kW/m^2).

The approximate calculation of *Power Output of Array (PDC)* and *Power Output of inverters (PAC)* can be carried out as follows:

– From given monthly average ambient temperatures, average T_{cell} is determined for each month using "Eq. (5)".

– $P_{DC} = 276\,[1 - 0.0044(T_{cell} - 25)]\ \text{kW}$ (6)

– $P_{AC} = \eta_{conversion} \times P_{DC}\ \ \text{kW}$ (7)

The results are shown in "Fig. 8".

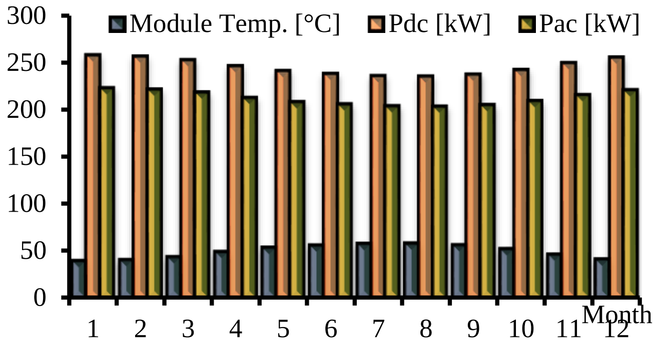

Fig. 8. Module temperature effect on power output of PV array (P_{dc}) and inverter (P_{ac})

As can be seen in "Fig. 8", when cells heat up and consequently cell temperature increases, both maximum DC power available and AC output power decrease. The minimum value takes place in August with 14.5% less than rated power, and the maximum one is found to be in January with 6.4% rated power drop. Given this significant variation in performance as cell temperature changes, it should be quite apparent that temperature needs to be included in any estimate of array performance.

7. AAU PV Plant Versus a Syrian PV Plant

To compare the quality of our plant with PV plants in the region, a grid-connected PV system in Syria is briefly analyzed and compared to AAU PV plant. The considered Syrian PV plant is a grid-connected plant operating since November, 9, 2010. It is installed in Damascus on the roof of one of the Electricity Ministry buildings. The PV array consists of 45 modules with a rated power of 90 W each. The module made in Syria has an efficiency of 13.56% and 36 cells connected in series. The cell area is 156.25 cm^2 . The array orientation is fixed at a tilt angle of 35°. Based on measured solar insolation on horizontal surface in Damascus [19], the monthly values on tilted collector are computed and represented in "Figure 9" with the insolation in Amman as well. The yearly average insolation in Damascus is 5.56 kWh/m^2.day, whereas the figure is 5.71 in Amman.

According to the measured data of the Syrian PV plant [20], the energy production in 2013 (the third year of operation) is 6177 kWh and the specific yield is 1525 kWh/kWp which is less than the specific yield of our Jordanian plant by about 7%. The lowest specific yield is found to be in January (92.59 kWh/kWp) while the highest value is in May (150.12 kWh/kWp). The specific yield of the Syrian plant exceeds that of Jordanian plant in November and winter months as shown in "Figure 10". This result is due to the higher array tilt angle (35°) of the Syrian plant relative to 10°-15° of the Jordanian plant.

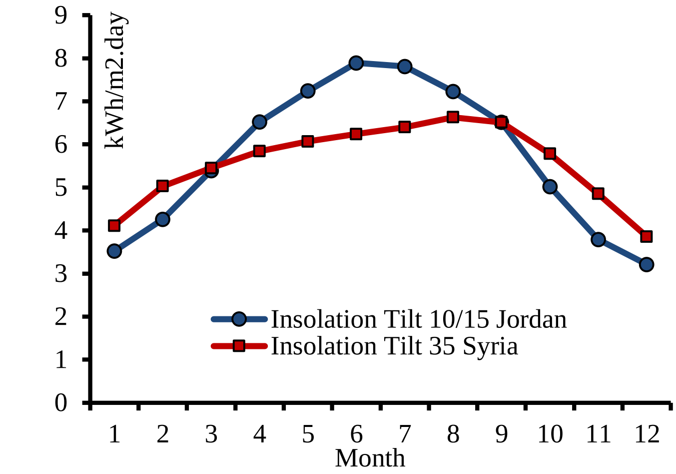

Fig. 9. Insolation on tilted array for Damascus and Amman

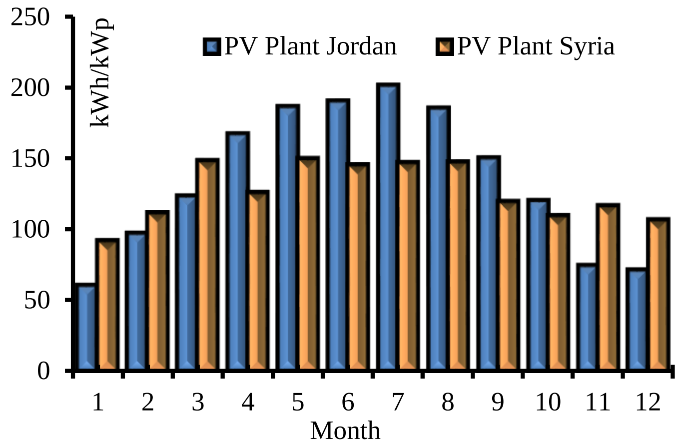

Fig. 10. Comparison between the two plants in terms of specific final yield

The annual performance ratio of Syrian plant is 88.2%, which is a little greater than PR of Jordanian plant (87.5%). It is calculated using "Eq.(1)":

$$\text{Actual annual PR\%} = \frac{6177 \times 100\%}{5.56 \times 36 \times 0.0156 \times 45 \times 365 \times 0.1365} = 88.2\%$$

The capacity factor of The Syrian plant is 17.4%, which is less than CF of the Jordanian plant by about 7%. It is calculated using "Eq. (3)":

$$CF\%\ of\ Syrian\ plant\ = \frac{6177\ kWh * 100\%}{4.05\ kW \times 8760} = 17.4\%$$

The comparison results are summarized in “Table 5”

Table 5. Comparison results in terms of main parameters

	Yearly Insolation; kWh/m2.day	**Specific final yield; kWh/kWp**	**PR%**	**CF%**
PV plant Jordan	5.71	1639	87.5	18.7
PV plant Syria	5.56	1525	88.2	17.4

8. Conclusions

The performance analysis of the 276 kWp grid-connected PV plant at AAU in Jordan is carried out in terms of main performance criteria such as specific final yield (Yf), performance ratio (PR%), and capacity factor (CF%). The values of Yf, PR, and CF are found to be 1639 kWh/kWp, 87.5%, and 18.7%, respectively. The Plant is simulated using the program PVsyst V6.32. The estimated energy injected into grid is found to be in good agreement with the actual energy production with a relative deviation of about 5%. Comparison of these values with evaluation parameters of reported PV plants in some countries, reveals that our plant is one of the best ones. A relatively extended comparison is conducted with a grid-connected PV plant in the region (Syria), which is briefly analyzed, shows that performance of both plants are approximately similar. Thus, the overall performance of AAU PV plant is found to be excellent during the first year of operation, and the studied PV system demonstrates a successful project in Jordan and in the region, what it helps to install more plants at the university and elsewhere.

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