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تحليل أداء الأنظمة الشمسية الكهروضوئية: دراسة حالة لمحطة الطاقة الشمسية الكهروضوئية في جامعة فلسطين التقنية

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Performance Analysis of PV Systems: Case study of Palestine Technical University (PTUK) PV Plant

تحليل أداء الأنظمة الشمسية الكهروضوئية: دراسة حالة لمحطة الطاقة الشمسية الكهروضوئية في جامعة فلسطين التقنية

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Abstract: Performance ratio is one of the indicators used to describe the effectiveness of the PV systems. The sustainability of the PV system year after year as well as its reliability can be checked by measuring the performance ratio each year. This indicator will also enable us to carry out a comparison between the performances of different PV systems. In this paper, the performance ratios for five PV systems installed on the roof tops of some of PTUK university buildings have been calculated on monthly and yearly basis. The analysis has been carried out using the available data (energy production and solar irradiation) for the year 2019. It was found that the performance ratio has higher values for May and September in comparison with other months. On the other hand, its lowest values were obtained in winter months. This trend can be observed for all of the PV clusters on the five buildings. When taking into account the overall system, the highest value for the performance ratio was 0.89, which was for September, whereas its lowest value of 0.70 was obtained in January. The performance ratio, which was calculated on yearly basis for the overall system, was found to be 0.80. When considering each building separately, the lowest value was 0.44 for the "Services" building whereas the highest value was 0.94 for the Science building.

Keywords: PV plants, Plant Capacity, Performance Ratio, Global Irradiation, Irradiance.

المستخلص: نسبة الأداء هي أحد المؤشرات المستخدمة لوصف فعالية الأنظمة الشمسية الكهروضوئية. يمكن التحقق من استدامة النظام الشمسي الكهروضوئي عامًا بعد عام بالإضافة إلى موثوقيته عن طريق قياس نسبة الأداء كل عام. سيمكننا هذا المؤشر أيضًا من إجراء مقارنة بين أداء الأنظمة الشمسية الكهروضوئية المختلفة. في هذا البحث، تم حساب نسب الأداء لخمسة أنظمة شمسية كهروضوئية مثبتة على أسطح بعض مباني جامعة فلسطين التقنية على أساس شهري وسنوي. تم إجراء التحليل باستخدام البيانات المتوفرة (الطاقة المنتجة والإشعاع الشمسي) لعام 2019. لقد تبين أن نسبة الأداء لها قيم أعلى لشهري نيسان وايلول مقارنة بالأشهر الأخرى. من ناحية أخرى، تم الحصول على أدنى قيم لها في أشهر الشتاء. يمكن ملاحظة هذا الاتجاه لجميع الانظمة المثبتة على مباني الجامعة الخمسة. وعند الأخذ في الاعتبار كامل النظام المركب في الجامعة، كانت أعلى قيمة لنسبة الأداء 0.89 ، والتي كانت لشهر أيلول، في حين تم الحصول على أدنى قيمة عند 0.70 في كانون ثاني. نسبة الأداء التي تم حسابها على أساس سنوي للنظام كاملا كانت 0.80. عند النظر لكل نظام على حدة ، كانت أقل قيمة 0.44 لمبنى الخدمات الطلابية بينما كانت أعلى قيمة 0.94 لمبنى كلية العلوم.

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الكلمات المفتاحية: محطات الطاقة الشمسية الكهروضوئية، قدرة المحطات الشمسية الكهروضوئية، نسبة الاداء، الاشعاع الشمسي الكلي، التشعع.

INTRODUCTION:

Measure in productivity terms, the cumulative size of photovoltaic (PV) systems around the world by the end of 2019 was approximately 580.1 GW (IRENA 2020). According to the same report, the overall increase in renewable energy sources in 2019 (worldwide) was about 176 GW. Nearly 98 GW of this was from solar systems. **Figure (1)** shows the trend in the growth of renewable energy sources, including solar systems, during the past 5 years.

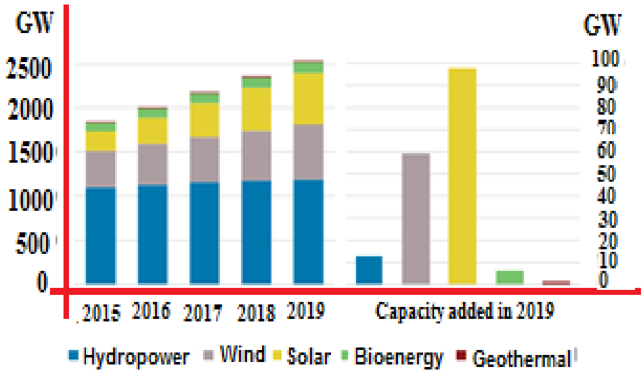

Figure (1):Power capacity growth of renewable energy sources (IRENA 2020).

Regarding solar systems and according to the same report, Asian countries continued to dominate the global solar photovoltaic expansion with an increase of 56 GW, which accounts for about 60% of the global solar systems in 2019. China, India, Japan, Republic of Korea and Viet Nam were identified to have most new capacity in 2019 .

In the context of Palestine, the energy sector is really different in comparison to neighbor countries. This is mainly due to the non-availability of natural resources and thus, its dependency on other countries to provide its needs of various energy sources. It is worth noting that, nealy all of Palestine fossil fuels needs come from others and about 87% of its electricity has been imported (Juaidi, Francisco, Ibrik and Francisco 2016). A shortage of electricity supply in the Palestinian territories has been noticed during recent years. As expected, this inadaquate supply had a detrimental effect on the majority of life activities around the country. According to the chairman of the Palestinian Energy and Natural Resources Authority, and unless this matter is rectified, the negative effect will worsen, especially with an expected 6% increase in demand for electric power over the next decade or so (Milhem 2020). Diversifying the energy sources and investing in the renewable energy may reduce the dependency on others and thus decrease this shortage .

Palestine has high potentials of solar energy as it has more than 3000 of sunshine hours per year and high yearly averages of solar radiation. This yearly average may take values in the range 5.4 to 6.0 kWh/m2/day for most of the locations around Palestine (Ismail, Moghavvemi and Mahlia 2018). Although other renewable energy sources have less potential around Palestine, there are many promising investments in these fields.

The Palestinian government and through the Palestinian Energy Authority issued a renewable energy strategy in 2012. The first stage of this initiative aimed to achieve 10% of electricity need from renewable energy sources by 2020. A new national renewable energy strategy (from 2020 to 2030) was also released. This plan aims to achieve about 500 MW from renewable sources. According to this extended strategy, 80% of the 2030 target will be provided by PV systems (Milhem 2020) .

Similar strategies have been adopted by many countries around the world. Most focused-on PV systems as this is an abundunt source with variations in its potential from country to another. The great interest in investing in this type of renewable energy source makes all players in this field (manufacturers, installation companies, and owners) do their best to achieve the maximum energy production. This includes the technologies used in manufacturing the components used to construct the PV systems, the installation design, and efficient operation management .

One of the indicators used to assure the efficient and reliable operation of any PV project is its performance ratio (PR). This is the ratio between the actual energy produced by a certain PV plant and the theoretical energy expected. The greater the PR value for a certain PV plant, the more efficient the plant will be. It is an important indicator as it informs us as to how much the PV plant is reliable and efficient. In addition to measuring the the reliability and productivity level of any given PV plant, the PR value can also be used to compare different plants performances and over a period of time.

If the measured PR value was found to be below the normal value (which could be determined by the manufacturer or the PR supplier), it indicates that there is a fault in the PV plant. Of course, PR value can never reach the 100% as there are unavoidable losses during the operation of the PV plant, such as thermal and conduction losses. The incomplete harvesting of the sun radiation can also lead to lower PR values (Nils et al. 2012). There are other reasons that affect the performance of PV systems, some of which had been conducted in the study of (Usman, Tah, Abanda, and Nche 2020). These factors include: geographical location, solar irradiance, dust, and shading. Their work incorporated mathematical computations in order to prove that the different methods used in the design of PV systems may also lead to significant diffrences between their performances.

Three separate PV systems from various technologies were analyzed to calculate their performance ratio in different locations in Peru for a period extended to three years (Irene et al. 2019). It was found that two monocrystalline PV systems showed a performance ratio value of 83% over a three-year period, whereas the performance ratio for the polycrystalline system ranges from 70% to 77%.

Another study conducted for European countries in the Netherlands, it was found that the Performance ratio reached 80% for the two consecutive years (2014 and 2015), followed by a 79% ratio for 2016 (Bala, Panagiotis and Wilfried 2018). In this study, it was also found that the performance ratio decreases as the age of the installed system increases.

In another study, the performance of a number of residential PV systems in Japan was analyzed. The systems covered by this study have different internal constructions and configurations as well as different manufacturers. The results showed a range of values for the performance ratio in the range 66.1% to 81.6 % (Yuzuru et al. 2007) .

A more recent study was conducted in 2017 in southern Spain, where the performance ratios for three, geographically different systems were measured on daily basis (Isabel et al. 2017). The study revealed that while one location had a daily performance ratio in the range 40% to 92%, the second location had a ratio in the range 42% to 93% for and the third location in the range 39% to 86%. The daily performance ratio for these three locations had high values in March and April, whereas its lowest value in December. It is worth noting here that the performance ratios in the summer season were lower than those obtained in spring.

In 2020, Dhimish conducted an extensive study in England aimed at measing monthly performance ratio of 8000 PV systems distributed across the country. The analysis was conducted over a 5-year period. The results indicated that the average monthly performance ratio was 0.8574 (Dhimish 2020).

A 41 kWp PV system installed on the rooftop of the faculty of Medicine building at An-Najah National University (Nablus, Palestine) was also a subject of investigation to measure its PR. The study revealed that the average yearly performance ratio was 0.88, 0.81, 0.83 for 2016, 2017, 2018 respectively (Ibrik 2020). In another study for a PV system installed on the roof of the Engineering building at same university, the monthly averages of the performance ratio showed values between about 0.80 and 0.89 (Ibrik 2019) .

The main purpose of this paper is to evaluate the performance of a grid-connected PV system installed in a location near the coast of the Mediterranean in Palestine (Tulkarm City) and compare the results with other locations in different countries. The monthly energy production of the PV system obtained by the inverters' data loggers and the solar irradiation measured by the metrological station were utilized in the analysis to obtain the performance ratio .

DATA AND ANALYSIS METHOD

The data used in this study has been gathered from PV arrays installed on the roof tops of five buildings in Palestine Technical University (PTUK), over the period from January, 2019 till December 2019. Details of the PV systems used are included in Table 1, whereas figure 2 shows part of the installation. Figure 3 shows the meteorological station on the roof of one of PTUK buildings. It is worth noting that all panels are tilted by an angle of 22º.

Table (1): Details of PV systems installations on PTUK buildings roofs

Building	Installed Capacity (kWp)	No. of PV panels	No. ofinverters
Engineering Building - Old	46.72	146	2
Services Building	48.1	148	2
Main Building	133.25	410	6
Library Building	110.5	340	5
Science Building	146.25	450	7
Total	484.82		

Figure (2): PV installed systems on roof tops of some of PTUK buildings.

Figure (3): The metreological station – Engineering Building

Table (2) includes readings of the energy generated by inverters for each building in each month of year 2019. These data are obtained from data loggers integrated with the inverters. Table 3 includes the data of the total irradiation per month.

Table (2): Monthly energy output from the inverters on each building for 2019.

Month	Amount of energy generated (kWh) each month				
	Engineering Building	Services Building	Main Building	Library Building	Science Building
January	5030	2763	12341	10668	13678
February	5056	5245	13108	10367	13630
March	6080	6265	14336	10524	17601
April	6975	7458	19257	15403	21751
May	7522	8146	21141	16057	25654
June	7383	7724	21196	17666	24128
July	6982	7399	20164	16949	24140
August	7147	6292	16819	14829	21392
September	6750	6716	18159	15080	20606
October	6024	6071	15640	13418	17082
November	4307	5548	14772	11854	14460
December	3262	4211	11157	9048	11021
Total Energy for each building (kWh)	**72518**	**73838**	**198090**	**161863**	**225143**
Overall Energy (kWh)	**731452**				

Table (3): Total irradiation per month

Month	Total Irradiation (kWh/m^2)
January	131.251
February	128.463
March	153.652
April	177.149
May	186.123
June	200.042
July	192.203
August	171.626
September	156.479

October	143.762
November	133.378
December	108.012
Total	**1882.14**

Performance Ratio Calculation:

As mentioned earlier, the performance ratio is that between the actual energy generated by the PV plant and the theoretical energy produced. There is more than one formula that can be used to calculate the performance ratio.

$$PR = \frac{Measured\ Energy}{Plant\ Capacity \times Total\ Tilt\ Irradaition \times Availability\ Factor} \quad (1)$$

where the Measured Energy is the actual energy (in kWh) obtained from the inverters, measured over a certain period of time (i.e the energy delivered to the grid), Plant Capacity is the DC rated power in (kWp) for this plant, Total Tilt Irradiation (kWh/m2) is the total yearly irradiation measured by a pyranometer fitted in the plane of the PV panels for a certain period of time, and the availability factor (%) is the ratio between the time at which the plant is available in certain period of time to the total time of this period. In this paper, the avialbility factor is assumed to be 100% (no electricity Interruptions)

The total yearly irradiation in a certain year is equivalent to the summation of peak sun hours during the year.

Equation (2) below is equivalent to **Equation (1)** but with the terms are written explicitely in terms of their constituting parameters.

$$PR = \frac{Measured\ Energy}{Total\ Tilt\ Irradaition \times Total\ PV\ modules\ Area \times PV\ Modules\ Efficiency \times Availability\ Factor} \quad (2)$$

where the Total PV Modules Area is the area (in m2) of one PV module as given by manufacturer multiplied by the total number of modules, the PV Modules Efficiency is also as given by the manufacturer.

The data logger integrated with the pyranometer is usually configured to store samples of the measured irradiance (W/m2) at each sample time. These measurements can be treated to obtain hourly average values of the irradiance. The hourly average values - after multiplying each of them by a time equivalent to 1 hour - can be added to obtain the daily irradiation (kWh/m2). If these daily irradiation values in a certain month are summed up, one can obtain the total irradiation in this month. These month values are shown in **Table (3)**. The summation of the monthly values will give the total yearly irradiation.

If the pyranometer sensor is installed on a horizontal surface, then these values will be referred to as the total horizontal irradiation, whereas if the pyranometer is installed on the plane of the tilted PV modules, then we have the total tilt irradiation. In our case, the pyranometer is installed in the plane of the tilted modules.

RESULTS AND DISCUSSION:

Performance Ratio Results:

Utilizing the data available in **Tables (1, 2) and (3)** and by using **Equation (1),** the performance ratio per month for each building has been calculated. The yearly performance ratio as well as the overall performance ratio of the whole plant are also calculated. All of these values are included in **Table (4).**

Table (4): Performance Ratio for each of PV plant in each month of year 2019.

Month	Monthly Performance Ratio (%) for each of PV plants mounted on				
	Engineering Building	Services Building	Main Building	Library Building	Science Building
January	0.82	0.44	0.71	0.74	0.71
February	0.84	0.85	0.77	0.73	0.73
March	0.85	0.85	0.70	0.62	0.78
April	0.84	0.88	0.82	0.79	0.84
May	0.87	0.91	0.85	0.78	0.94
June	0.79	0.80	0.80	0.80	0.82
July	0.78	0.80	0.79	0.80	0.86
August	0.89	0.76	0.74	0.78	0.85
September	0.92	0.89	0.87	0.87	0.90
October	0.90	0.88	0.82	0.84	0.81
November	0.69	0.86	0.83	0.80	0.74
December	0.65	0.81	0.78	0.76	0.70
Yearly Performance Ratio (%)	0.82	0.82	0.79	0.78	0.82
Overall Yearly Performance Ratio	0.80				

The average daily solar irradiation for each month has been calculated based on the total irradiation measured for each month. These month averages are shown in figure 4. The average for each month is calculated by dividing the total irradiation for this month by number of days for the month in question. For comparison purposes, these averages may be more indicative and informative. The month of June has the highest average, which is about 6.9 kWh/m2/day.

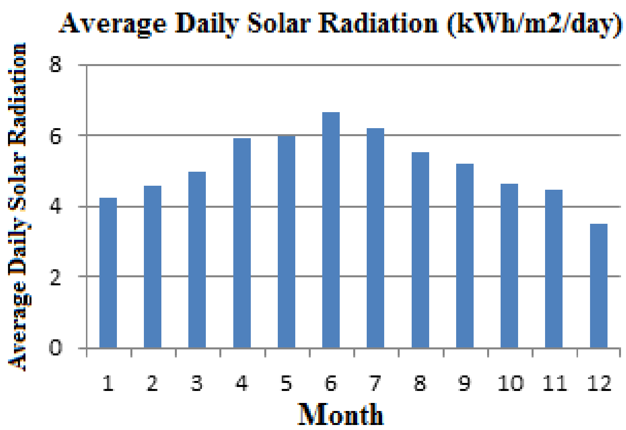

Figure (4): Average daily solar irradiation – Tulkarm

Graphical representations of the performance ratio for the overall PV system and the PV system installed on the roof of the Science building for each month are shown in figures 5 and 6 respectively. It can be observed that May and September have higher performance ratio in comparison with other months, despite that June has the highest average daily solar radiation and the highest total irradiation. The reason for this trend is due to the fact that June, in Palestine, has usually higher temperatures in comparison with May and September. This increase in temperature has a negative effect on the energy generation from the PV modules. This confirms the fact that the power generation from PV modules (which reflects their harvested energy) is proportional to the sun radiation but is negatively proportional to the module temperature (Ismail, Moghavvemi and Mahlia 2013) .

Referring to the data available in Tables 2 and 3, one can notice that, when compared with June or July, May had the highest energy generation, whereas the total irradiation is lower. For September, one can notice that despite the energy generation in this month is less than June, July, or August, the total irradiation is much smaller in comparison with these months. This means that low value of total irradiation in this month is capable of generating enough amount of energy that makes the performance ratio high. Similar trends can be observed for other months, as can be seen in the performance ratio figure.

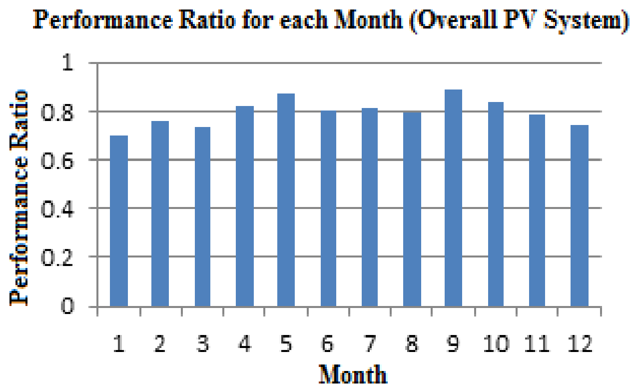

Figure (5): Performance ratio for the whole PV system in each month

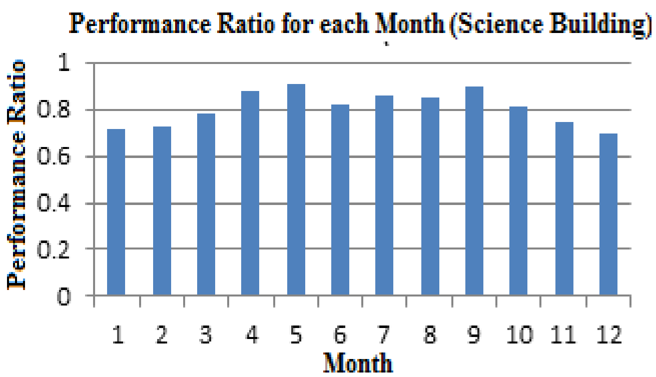

Figure (6): Performance ratio for the PV system in each month – Science Building

From **Figure (5)**, one can observe that highest value of the overall performance ratio occurs in September and it takes a value of 0.89, whereas the lowest value is 0.70 and occurs in January. This is when considering the whole PV system. Taking into account the PV system installed on the roof of Science building and observing the performance ratio values appeared in figure 6, the highest value is 0.94 in May, whereas the lowest value is 0.70 in December .

Performance ratio values for other buildings are presented in **Table (4).** One can notice that the different PV systems installed on the five buildings take different values for the performance ratio during the same period. Theoretically, as these systems are installed in the same geographical location and subjected to the same conditions, they are expected to have equal (or nearly equal) values. This isn't actually the case. It is worth noting, though, that not all of the different PV systems on the five buildings are oriented to the south. Furthermore, the spacing between the PV rows isn't the same for the different PV systems and they are actually exposed to different shading conditions. These factors are thought to be the reason for performance ratio taking different values for different buildings .

In comparison with other studies already presented in the introduction section of this paper, one can notice that the results are approximately similar. For instance, the PR obtained by Irene et al. from Peru was in the range 0.70 to 0.77 (Irene et al. 2019), whereas that published by Bala and Panagiotis from the Netherlands was between 0.79 and 0.80 (Bala and Panagiotis 2018). Yuzuru et al. from Japan reported a PR in the range of 0.661 and 0.816 (Yuzuru et al. 2007). It is worth noting here that these studies had been carried out yearly and for more than one year. The Spanish study, on the other hand, had been based on daily data, showing PR values in the range 0.40 to 0.92 for one location, 0.42 to 0.93 for the second location, and 0.39 to 0.86 for the third location under investigation .

The results of the study conducted for a 41 kWp solar PV system installed at An-Najah National University (Nablus, Palestine) (Ibrik 2020) and presented in the introduction showed close values for performance ratio compared with the results of our study. Similarly, the results of the study conducted for a PV system installed on the roof top of the Engineering building at PTUK appeared to have close monthly averages (of performance ratio) to the monthly averages calculated for the PV system installed on the roof of the Engineering building at An-Najah National University (Nablus, Palestine) (Ibrik 2019) .

The PVSYST is one of famous software packages used to simulate the operation of PV systems. This software has been used to simulate each of the five PV system installed on the roofs of the PTUK buildings .

Figure (7) shows part of the results obtained using this software to simulate the operation of the PV system installed on the roof of PTUK's Engineering building. The value of this performance ratio – using this software - as shown in the figure below is 0.803. It is interesting to note that the actual value of this parameter obtained from real measurement (see table 4) is 0.82. Assuming our measurements are as accurate, the system must have produced better actual performance than expected.

PVSYST V6.84		24/08/20	Page 4/6

Grid-Connected System: Main results

Project : **Engineering building 46.72 - PTUK**

Simulation variant : **The existing situation**

Main system parameters	System type	**Sheds on ground**		
Near Shadings	Detailed electrical calculation	(acc. to module layout)		
PV Field Orientation	tilt	22°	azimuth	0°
PV modules	Model	TSM-320PD14	Pnom	320 Wp
PV Array	Nb. of modules	146	Pnom total	**46.7 kWp**
Inverter	Model	Blueplanet 20.0 TL3	Pnom	20.00 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**40.0 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**72.49 MWh/year**	Specific prod.	1552 kWh/kWp/year
	Performance Ratio PR	80.31 %		

Figure (7): Simulation of the Engineering Building using PVSYST.

Simple Economic Analysis of the Project:

The simple payback period (SPBP) is a technique used to analyze the economic feasibility of overall given PV project. The simple payback period is defined as the period at which the system will recover the capital cost of the project (the investment). It is equal to the ratio between the total capital cost and the yearly saving. The SPBP can be calculated using **Equation (3**) below.

$$SPBP = \frac{Total\ Capital\ Cost}{Saving\ per\ Year} \quad (3)$$

The total capital cost of this project was $487,100. The total energy generted per year was 731452 kWh. The cost of one unit of energy (in kWh) in the city of Tulkarm is $0.2. So, the saving for the year 2019 was $146,290. Consequently, using equation (3), the SPBP for PTUK is 3.33 year.

The SPBP for the PV suystem at Najah National University – as reported by (Ibrik 2020) was found to be 4.25, 4.35, 4.4 for the years 2016, 2017, 2018 respectvely. The reason why the payback period of the PTUK PV project is less than the payback period of Najah National University PV project is due to the high cost of the PV system per kWp for Najah National University project ($ 1268 per kWp for Najah National University, compared to $ 1005 per kWp for PTUK).

CONCLUSIONS:

The purpose of this study is to evaluate the performance ratio of 5 PV systems recently installed on the rooftops of 5 buildings in PTUK University, Palestine.

This analysis has been implemented for the whole system as well as for individual buildings, on monthly and yearly basis. The results showed a certain pattern with the highest values of the performance ratio appearing in May and September. The average annual performance ratio of the overall system was found to be 0.80. Furthermore, a comparison with other PV systems installed at other locations worldwide has been conducted.

This study had enabled us to confirm that the actual performance of the PV plant (reflected in the annual PR factor) is comparable to the expected theoretical (simulated) value. In fact, the actual result obtained for some buildings is better than the simulated value.

Such results could be useful in providing the policy makers in PTUK (and any other interested party) with the essential data about the performance of the PV systems in PTUK and Palestine, as a whole, and as such help in determining the feasibility of future PV projects.

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