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Evaluation of Grid-Connected PV Electricity Generation Systems using Experimental Approaches

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Abstract:

In this article, experimental measurements were conducted for a whole year to evaluate a 1.4 kW grid-connected PV power plant installed at Sohar University, Oman.The environmental data and system data were collected and the system parameters such as: yield factor, Capacity Factor, Cost of Energy, Payback Period were evaluated. Experimental results showed that the highest power generated for an array is 245.8 kWh, and the highest reference power ranged from 3.43 to 5.65 kWh, while the final yield ranged from 4.61 to 7.33 kWh/kWp-day. Also, it found that the capacity factor (CF), cost of energy (CoE), and payback period (PBP) were 21.7%, $ 0.045/kWh, and 11.17 years respectively.

***Keywords:** Deseret weather conditions; Grid connected PV system; PV performance*

Introduction

Photovoltaics have begun to take an appropriate share of the global energy markets and are considered the most popular renewable energies around the world [1]. However, questions continue to be raised about the impact of these units on the surrounding environmental conditions such as the solar radiationintensity, ambient temperature, relative humidity, wind speed and dust. Certainly, the performance of solar cells deteriorates over time due to these weather conditions, for example, the temperature of the PV unit increases by 10°C from its standard value (25° C) causing the deterioration of the electrical efficiency about 5% [2] [3]. Also, the accumulation of dust causes a deterioration of the generatedpower and this degradation is proportional to the amount of accumulated dust, the physical properties, and the quality of its chemical components [4, 5].

Several researchers have evaluated the performance of GCPV systems while studying the effect of environmental conditions on parameters such as electrical efficiency, life cycle costs, energy costs, and energy recovery period.

Reference [6] explained that the electrical efficiency of the photovoltaic cells ofgrid connected station is permanently degraded at an annual rate of 0.5% to 1%. The practical study of a number of photovoltaic unit technologies has demonstrated that the life of these photovoltaics units depends on the type of PV cell manufacturing technology.

Ref. [7] evaluated a photoelectric system connected to the grid with a capacity of 1006.74 kilowatts made of silicon (C-Si). The photovoltaic system operated in a semi-continental climate. The evaluation results showed that the efficiency of the system was deteriorating, from -0.30% to -0.17% starting from the third year of operation. The reference considered these limits acceptable according to the results of the two references [8, 9].

In this article, the possibility of operating a photovoltaic system in the Sultanate of Oman (GCPV) in practicewill be evaluated. The tested station has a generating power of 1.4 kilowatts and

May – June 2020
ISSN: 0193-4120 Page No. 1264 - 1270

is installed in the College of Engineering, Sohar University, north of the Sultanate. For the station evaluation purpose, data for this station was collected for the period from July 2017 to June 2018.

1. Experimental Setup

1.1 The used PV system

The Sultanate of Oman is one of the producing and exporting countries of oil and gas, so these two fossil fuels dominate the energy market in Oman [10]. The Sultanate's government has started to make clear efforts in the field of reducing carbon emissions and establishing projects, even if it is currently shy, but it is in the process of expanding to integrate renewable energies into electricity production. This trend is intended to diversify energy sources and reduce dependence on fossil fuels. It has become certain that renewable energies have the potential to achieve this goal [11]. Since Oman is located in the solar belt and has high solar brightness hours with high radiation intensity, the use of solar energy to produce electricity is the alternative and the best option. Omani government reports indicated that within its vision to produce electricity in 2030, PV plants are expected to reserve a few gigawatts [12].

One of the practical experiences in this field is the experience of the College of Engineering - Sohar University, as a photoelectric electrical system connected to the grid was established. Sohar city, north of Oman, is located at 24.3461°N, and longitude 56.7075°E. 140GH-2PU solar cells have been used that can produce 1.4 kW and 12 V DC voltages (under standard test conditions). Figure 1 shows a photo of the system installed in Sohar. The photovoltaic cells are installed at a fixed tilt angle (27° to the south) and equal to the latitude value of Sohar + 3 degrees, depending on the results of the reference [13]. To achieve the voltage required to be connected to the grid-connected inverter, the PV modules are connected in series. This system uses a Sunny Boy 1700 inventor. Table 1 lists the technical specifications for the PV cells and the reflector used in the system.

Table 1 Specifications of the proposed system

PV array (Kyocera KD140GH-2PU)	
PV module rated power (10 modules)	140 Wp (1.4 kWp)
Maximum voltage	17.7
Maximum current	7.91
Open circuit voltage	22.1
Short circuit current	8.68
PV module efficiency	13.9%
Temperature coefficient of Voc	-0.36 %/k
Temperature coefficient of Isc	0.06 %/k
Inverter	1
AC voltage	220-260
Inverter efficiency	94.1%

Figure 1.The studied Sohar University PV grid-connected system

2.3.Performance evaluation criteria

Table 2 summarizes the equations used in evaluating performance variables defined by IEC 61724 "International Electrotechnical Commission" 1998 to evaluate grid-connected PV systems.

Table 2:The equations used in evaluating the performance criteria for the studied system

Eq. No.	The variable calculated	Variable definition	Equation	Unit	Ref.
1	The daily/monthly yield	daily net AC energy output of the system divided by the peak power of the installed PV array at standard test conditions (STC)	$YF_d = \frac{E_{PV}(kWh/year)}{PV_{WP}(kWp)}$	h/d	20

2	Final Yield	The ratio of the electricity produced from the inverter (EAC) to the nominal power of the installed photoelectric array	$YF_F = \frac{E_{AC}(kWh/year)}{PV_{WP}(kWp)}$	h/d	21
3	Reference Yield	The ratio of the insolation (H) to the irradiance in STC conditions(G=1000W/m²)	$YR = \frac{G_T}{G_{STC}}$	h/d	20
4	Capacity factor	The ratio of AC electricity actually generated to the electricity that the system will generate in the case of a currency under nominal conditions	$CF = \frac{SY}{8760} = \frac{E_{PVannual}}{(P_R \times 8760)}$	%	22
5	performance ratio	the standard employed to evaluate the used PV system quality	$PR = \frac{SY}{Y_R}$	%	23
6	Life cycle cost		$LCC = C_{capital} + \sum_1^n C_{O\&M}.R_{PW} + \sum_1^n C_{replacement}.R_{PW} - C_{salvage}.R_{PW}$	USD	24
7	Present worth		$R_{PW} = F/(1+i)^N$	USD	25
8	Maintenance cost		$MC_r = MC_{0r} \times \left(\frac{1+f}{i-f}\right) \times \left[1 - \left(\frac{1+f}{1+i}\right)^N\right]$	USD	25
10	Total Maintenance cost		$MC = \sum_1^r MC_r$	USD	24
11	Cost of energy		$CoE = \frac{LCC}{\sum_1^n E_{PV}}$	USD	24
12	Replacement cost of the k^{th} component		$RC_k = IC_k \times \sum_{j=1}^{N_r} \left(\frac{1+FR}{1+IR}\right)^{\left(\frac{LP \times j}{N_r+1}\right)}$	USD	26
13	Total Replacement cost		$RC = \sum_{k=1}^{2} RC_k$	USD	26
14	PV generated power		$P_{PV}(t) = P_{peak}\left(\frac{G(t)}{G_{stc}}\right) - \alpha_T[T_c(t) - T_{stc}]$	kW	26
15	Cell temperature		$T_c(t) - T_{amb} = \left(\frac{NOCT - 20}{800}\right) G(t)$	ºC	24
16	Generated energy		$E_{AC,t1} = \sum_{t=1}^{N} E_{AC,t2}$	kWh	25
17	PV efficiency		$\eta_{PV} = \frac{E_{DC}}{G(t) \times A_c} \times 100\%$	%	21
18	System efficiency		$\eta_{sys} = \frac{E_{AC}}{G(t) \times A_c} \times 100\%$	%	21

3. Results and discussion

3.1.Experimental results

Figure 2 shows the solar radiation intensity and the average daily ambient temperature for April 2018. The diffuse and global solar radiation intensity for Sohar cityare 3289 Wh/m^2 and 6182 Wh/m^2, respectively. The average ambient temperatures in the measured days were less than 40°C. The maximum global solar radiation measured was at 12

May – June 2020
ISSN: 0193-4120 Page No. 1264 - 1270

AM and 1 PM while the diffuse maximum values achieved at 2 PM.

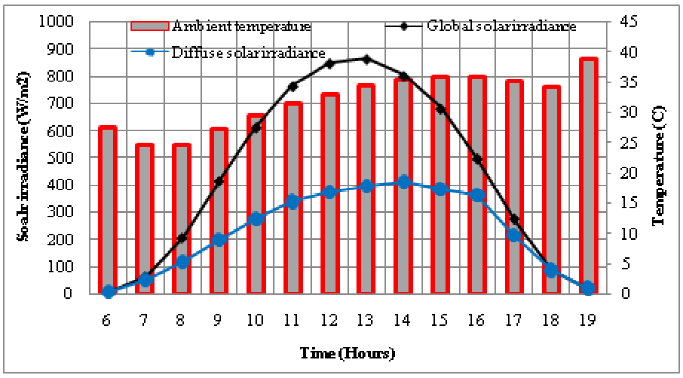

Figure 2:Sohar profiles for solar irradiation and ambient temperature.

The variables of the photoelectric system connected to the network were measured using a set of sensors that were connected to different parts of the system. The measurements of these devices were taken at 15-minute intervals. Figure 3 shows the electric power generated by a constant current (DC) and that converted to AC by the inverter. This power was measured during January 2018 for a period of 30 days (winter season in Oman). The DC and AC powers are close to each other as shown by the curves of the figure due to the high efficiency of the inverter used in the system, which reduces losses. The measurements were made during the winter (January), which is a season with more clouds and less sunshine, and with all this, the productivity of the plant was relatively high.

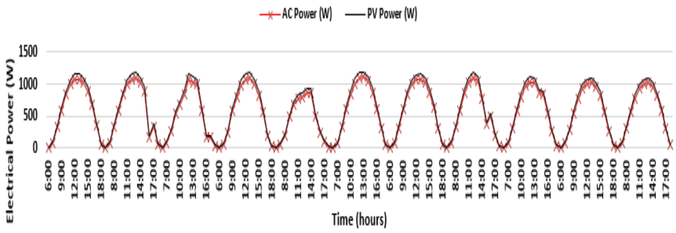

Figure 3:One-month(January) power generatedbythe studied system

Figure 4 shows the high consistency between the AC voltage and the system frequency. The curves in the figure show that the average AC frequency has a daily value of 49.98 Hz (± 0.02%) while the average AC voltage has reached 248.58 V (± 0.21%). These values are well suited to the frequency and voltage of the Omani national network.

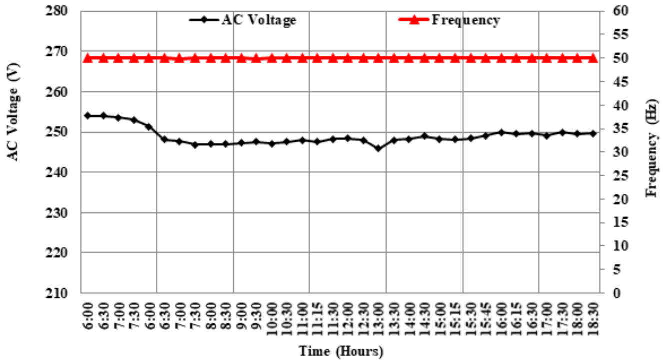

Figure 4:AC voltage and frequency for the GCPV System studied

Figure 5 shows the relationship between the power generated by the photovoltaic system studied in kWh and the power of the photovoltaic unit in kW and their relationship to the intensity of solar radiation. The measurements were made on a day in June 2017 (Summer of Oman). In this month (June) the intensity of solar radiation peaks in the middle of the day and has reached, according to practical measurements, 1158 W/m^2. Also, the ambient air temperature was high (45°C) during the day, and this will definitely cause a clear reduction in the generated power and electrical efficiency of the PV modules. The curves of the figure show a clear dependence of the power generated by the PV unit or by the station directly on the intensity of the solar radiation. From 9:30 AM until 15:30 PM, the power curve generated by the station is flat, which means that the station's productivity is stable during this period.

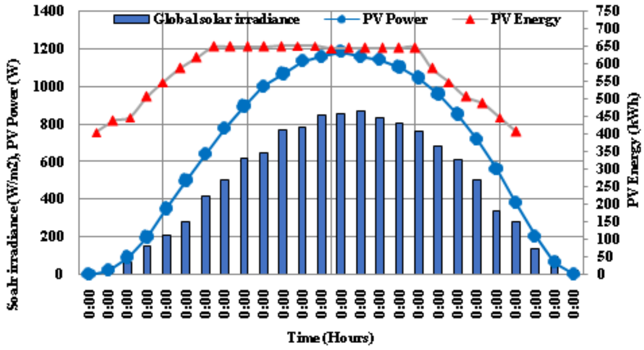

Figure 5: PV system power, energy and solar irradiance

Figure 6 shows the yield of the studied system for a full year. The array yield ranged between 3.43 to 5.65 kWh/kWh, the reference yield ranged between 4.61 to 7.33 kWh / kWh, and the final output ranges between 3.24 and 4.82 kWh/kWh. This yield is directly proportional to solar radiation. The yield of the studied system is relatively high when compared to other systems of literature [16, 17 and 18]. For the studied system, CF accounted for 21.7%, CoEof the system was $ 0.045/kWh, and the payback period(PBP) amounted to 11.17 years.

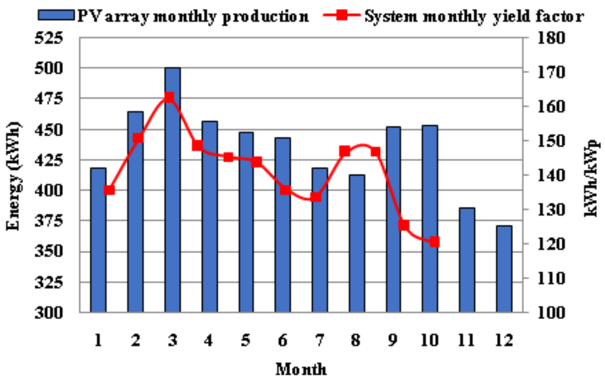

Figure 6: Grid-connected PV system and monthly performance

Figure 7 shows the change in the efficiency of the PV array and inventor for each month of the studied period. The ration of performance fluctuates between 0.53 in June to 0.71 in January, with an annual average of 0.67. This performance is relatively low in summer due to the losses in voltages caused by the high temperature of PV modules in summer, and it is high in winter due to the low temperature of the PV modules during this season. The electrical efficiency of the GCPV plant array in Sohar fluctuates from 9.1% to 10.8%, as the maximum efficiency was in December and its minimum was during July. The solar radiation intensity during the month of July is higher than the month of December, but this month in Oman is characterized by a high rate of dust in the atmosphere and a high temperature of the photovoltaic cells, so the outcomes of the GCPV station are lower than the case of the December. As for the inventor, its efficiency ranges from 91% to 94% throughout the year.

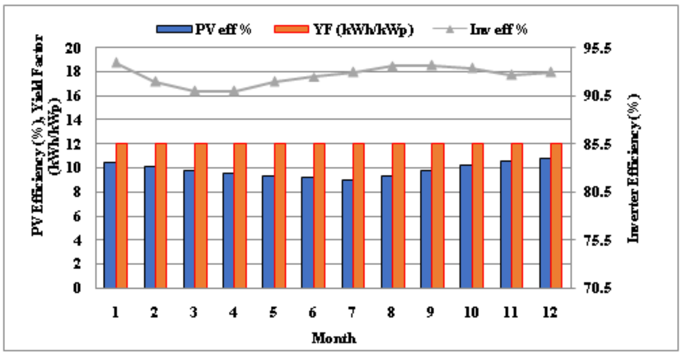

Figure 7: PV and inverter average monthly efficiencies.

4. Conclusion

In this study, the yield of the grid-connected photoelectric power station installed at the College of Engineering, Sohar University, Oman was evaluated. The GCPV booster generates a power of 1.4 kW. The measurements were monitored and recorded for a full year, starting from July 2017 until June 2018. In this study, the effects of hot climatic conditions of the study area on the system revenues were discussed. The results of the study showed that the highest final productivity is 3.24-4.82 "kWh / kWh per day, the reference yield ranged from 4.61-7.33" kWh / kWh, the matrix yield was from 3.43-5.65 "kWh / kWp-day", The production power is around 245.8 "kWh". As for power costs, it was 0.045 USD / kWh, the payback period reached 11.17 years.The results of the study proved that the reliability of using grid-connected PV systems for residential, commercial and industrial applications is relatively high. Also, the orientation of the Omani government to deploy such systems is an appropriate option.

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May – June 2020
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Nomenclature

PV	Photovoltaic	$P_{loss}(t)$	The instantaneous power losses
GCPV	Grid-Connected Photovoltaic	P_{PV}	The PV module power
V_{OC}	Open Circuit Voltage	P_{peak}	The PV peak power
I_{SC}	Short Circuit Current	$C_{salvage}$	The net worth of the system at the final year of project lifetime
$P_{in}(t)$	The instantaneous input power	P_R	Rated power
P_{Inv}	The inverter power	RC_k	The replacement cost of the k^{th} component (USD)
COE	Cost of Energy	R_{PV}	Performance factor
LCCA	Life Cycle Cost Analysis	t_1	The hour, day, month
SY	Specific Yield	$-t_2$	The minute, hour, day
CF	Capacity Factor	T	Temperature
STC	Standard test conditions	T_c	The cell temperature
YF_d	The daily/monthly yield	$T_{standard}$	The temperature of (25°C) at standard test conditions (STC)
YF	The yield factor	G	The incident solar irradiance (W/m^2)
YF_F	Final yield	WS	Wind Speed
YR	Reference yield	RH	Relative Humidity
MC	The system total maintenance cost	E_{AC}	Alternating current energy
MC_{or}	The maintenance cost of the rth component in the first year (USD)	E_{DC}	Direct current energy
MC_r	The maintenance cost (USD)	$G_{standard}$	solar irradiation (1000 W/m^2) at standard test conditions
PBP	Payback period	ICI	Total constant cost, including the cost of installation and civil works (USD)
A_c	The collector area (m^2)	IC_k	The initial cost of the k^{th} component (USD)
c_1, c_2 and c_3	The PV module coefficients	IC_r	The initial cost of the rth component (USD)
k_r	A constant refers to the maintenance cost as a percentage of the initial cost of the rthcomponent	K	Value of 1 and 2, which are equivalent to the inverter and pump, respectively.
N	Number of years	CA_i	The capacity of the i^{th} component of SAPV, SAPVT nanofluid and nano-PCM
N_r	The number of components replaced over the lifetime of the system	$C_{capital}$	The capital cost of a project
$C_{replacement}$	The cost of all equipment replacement and repair	$C_{O\&M}$	The yearly operation and maintenance costs