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ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

Techno-economic assessment of on-grid solar PV system in Palestine

Imad H. Ibrik[1]*

Abstract: This paper presents the analysis of obtained result from continuous data monitoring of a 41 kWp solar PV system installed on the rooftop of faculty of medicine building at An-Najah National University, Nablus, Palestine (32°13′43.67° N and 35°13′15.72° E). The system was monitored for three years 2016–2018 and it consists of 128 PV panels, an inverter DC/AC, and a grid-connected gross meter. The output electricity feeding to the grid solar electricity is compared and verified with the results from the simulation software program (PVsys) by adopting the installed component specifications, operation conditions, and weather data of the site. The energy generated was fed into the existing power grid and the respective building loads through SMA inverters. The performance parameters of the plant evaluated and compared with other Mediterranean countries, Final Yield (FY) was 1684 kWh/kWp, Reference Yield (RY) was 2046.507 kWh/kWp, and Capacity Utilization Factor (CUF) was found to be 18.5%. The annual average monthly Performance Ratios (PR) for three operating years were 0.88, 0.86 and 0.85, respectively. These indicators provide good feedback for system designers, contractors and energy providers with the actual capacity and feasibility of the system that they can offer the end-users.

Subjects: Power & Energy; Clean Tech; Electrical & Electronic Engineering

Keywords: grid-connected PV system; long term assessment; performance indicators; techno-economic feasibility

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PUBLIC INTEREST STATEMENT

Renewable energy sources have become the choices of future energy supply, chiefly due to energy security and the sustained emissions emanating from conventional energy sources leading to global warming. In this line, rooftop grid-connected PV system rooftop can help solve power shortages in public buildings. The energy assessment of the PV power systems is carried out by using different types of performance indicators that benchmark the long-term output of these systems against the PV panel maximum output at hypothetical operation conditions. Hence, the present paper determines the long-term performance assessment of grid-connected PV systems in Palestine and comparing it with other countries.

1. Introduction

Solar energy now it's one of the best options for future energy demand in terms of availability, cost feasibility, accessibility, different capacities, and efficient output compared to other types of renewable energy (RE) sources. In Palestine, as other countries are facing the growth of energy needs, especially in electrical energy, and unfortunately the country facing a big problem with the shortage of conventional supply across all sectors. Therefore, RE sources and especially solar energy in Palestine are necessary nowadays and in the future, to cover the growth of demands and support sustainable development.

Solar Photo-voltaic (PV) systems are a good alternative and feasible solution for generating electricity in Palestine, especially for grid-connected systems. The potential of solar radiation is about 5.4 kWh/m^2/day with about 3000 sunshine hours a year (Mason & Mor, 2009). One of the best advantages of rooftop solar PV systems is that they can be granted and installed faster than other types of renewable energy sources. They are cost savings, secure investment, increasing access to energy, supporting from government, reducing carbon footprints, and needs low maintenance costs (Ibrik, 2019; Ibrik & Hashaika, 2019).

Few papers in the literature reported analyzing the long-term performance of rooftop solar PV systems connected to the grid in different Mediterranean countries. Ghouari, Hamouda, Chaghi, and Chahdi (2015) analyzed the PV performance with the capacity of 1.6 kWp at Batna University, in Algeria. The average solar radiation was 5.21 kWh/m^2.d., the PV system was monitored for 1 year of operation in order to evaluate the performance of PV on-grid system. The performance ratio ranged between 51% and 61% and the total energy delivered to the grid was 1705 kWh/year. The annual yield was 1065 kWh/kWp, and all output energy from this mentioned PV system was delivered into internal electrical network of the University.

Al-Otaibi, Al-Qattan, Fairouz, and Al-Mulla (2015) presented a 12-month-long performance evaluation of the first 85.05 kWp and 21.6 kWp systems, with copper indium gallium selenide (CIGS) thin film, these two systems installed on the rooftop of two schools in Kuwait. The performance ratio was maintained for both systems between 0.74 and 0.85, the annual energy yield of PV systems was about 1642.5 kW h/kWp.

Kazem, Albadi, Al-Waeli, Al-Busaidi, and Chaichan (2017) presented a system design and techno-economic evaluation of a Grid-connected PV system in Adam city, Oman with a size of 1 MW. The numerical simulation was made using MATLAB developed code. The system has a payback period of 10 years and a cost of energy 0.2258 USD/kWh. The system considered as feasible and shows great promise for the city of Adam.

Hassan and Elbaset (2015) presented a rooftop grid-connected PV system installed at Minia University, Egypt. Energy output and techno-economic analysis was determined and evaluated.

Ayadi, Al-Assad, and Asfar (2018) determined the performance analysis of grid-connected photovoltaic system at University of Jordan, the final yield of system ranged from 1600–1715 kWh/kWp and the payback period was around 3 years.

Kamal Attari and Elyaakoubi (2016) presented an evaluation of a grid-connected photovoltaic (PV) system installed on the roof of a government building located in Tangier, Morocco. The experimental data were recorded from 1 January 2015 to December 2015 based on real-time observation. The final yield (Yf) ranged between 1645 kWh/kWp, the performance ratio (PR) ranged from 58% to 98% and the annual capacity factor was found to be 14.84%.

Shahhoseini, Abbasi, and Abbasi (2018) investigated in a conference paper the technical and economic feasibility of implementing a grid-connected photovoltaic system in an auto parts manufacturing company located in Iran, in this paper, the economic analysis, the parameters of initial cost, net present value, internal rate of return, payback, discounted payback period, and levelized cost of energy have been calculated.

Almarshoud (2017) conducted feasibility study utilizing real-time solar irradiance data for a 1 MW grid-connected PV system in Qassim region in the middle of Saudi Arabia. The analysis has been done using both technical and economic indicators. Technical performance indicators are; Yield Factor around 1710.

Pillai and Naser (2018) analyzed the economic performance of a 1 MW grid-connected photovoltaic (PV) system optimised for matching the daily peak load in Bahrain in terms of levelised cost of electricity (LCOE), net present value (NPV), payback period (PBP) and energy payback time (EPBT).

Ahmadi et al. (2017) performed an experimental study on two different PV systems with amorphous and polycrystalline technologies. Two platforms of the same equipment considered for this study are installed in the South West and the North of Tunisia. In the South west, the annual final yield is 1887 kWh/kWp/year, while for the amorphous module is about 1902 kWh/kWp/year. These results constitute an attractive factor for the investor in PV industry especially in the South West of Tunisia.

Oudah (2017) analyzed the solar radiation aspects, the performance and the cost-effectiveness of designing a proposed utility scale, grid-connected PV Power Plant of 4 MW capacity to enhance the energy demand at AL-Mahmudiyah region in Iraq. The average of in-plane global solar radiation of (2130.8) kWh/sq.mt/day. The PV Plant supplied the grid with an average of 6767 MWh/year at an annual performance ratio (PR) 79.2%. The final yield (Yf) ranged from 3.53 to 5.45 kWh/kWp/day with an annual capacity factor 19.4%. The array yield (Yr) with an average value of 4.7 kWh/kWp/day. The AC output power 3.162 MW at an average system efficiency of 15.5%. The power losses were calculated and displayed in a diagram loss.

Therefore, the main goal of this paper is to determine the long-term performance assessment of grid-connected PV systems in Palestine and comparing it with other countries, analyze the performance of the grid-connected photovoltaic system in medicine faculty at An-Najah university from 2016 to 2018, for specific case-study. The monthly amount of energy fed to the grid was concluded from the energy bill and analyzed against total solar irradiation measured by a local weather station.

2. Solar PV plant at medicine building at ANNU "A case study"

The PV power plant was installed on the rooftop of medicine building, at An-Najah National University, Nablus—Palestine, Figure 1, which shows the rooftop solar PV power plant. The grid-connected system consists of 128 polycrystalline silicon solar modules 320 Wp each one with an overall installed capacity of 41 kWp, covering a total surface area of 249 m^2 and inclined at 30°. The PV modules are arranged in

Figure 1. View of rooftop solar PV power plant.

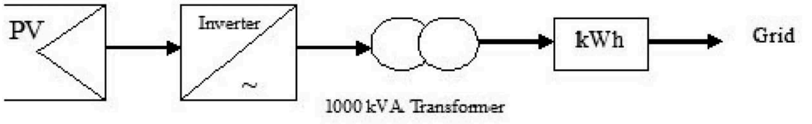

Figure 2. One-line diagram of the PV system.

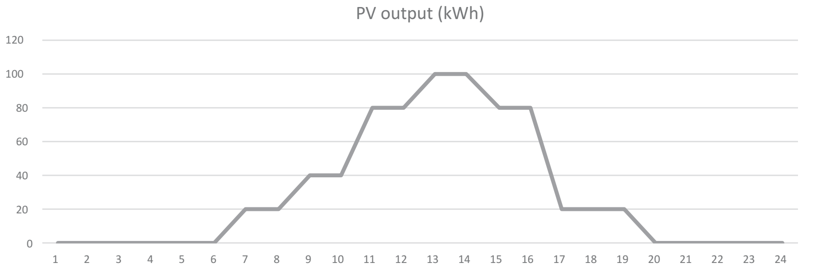

Figure 3. Typical daily load curve—medicine faculty.

8 parallel strings, with 16 modules in each string and connected to SMA inverters with capacity 45 kVA, the MPP tracker used to ensure that the inverter is adjusted to the MPP point and the greatest possible power is fed into the mains electricity grid. Figure 2 shows a schematic block circuit diagram of the PV system.

2.1. Energy consumption

The typical daily load curve of electrical consumption at the faculty of medicine is illustrated in Figure 3:

From measured data, the monthly building energy consumption as average = 26,734 kWh/year and the annual building consumption as average = 320,795 kWh/year.

2.2. Location and specification of illustrated PV system

The PV power plant constructed at the faculty of medicine located at the new campus of An-Najah National University with coordination 32°13′43.67”N, 35°13′15.72”E. The specification of installed solar PV modules illustrated in Table 1.

Table 1. The specification of solar PV modules

	Medicine faculty
Number of panel	128
PV Brand	Amerisolar
Model No.	AS-6M 320
Wp/panel	320 Wp
System capacity	40.96 kWp
Voltage at Maximum Power (Vmpp)	37.1
Current at Maximum Power (Impp)	8.63
Open Circuit Voltage (Voc)	45.7
Short Circuit Current (Isc)	9.00
Panel Efficiency (%)	16.49
Cell Type	Poly-crystalline
Panel dimension (m)	1.956 × 0.992 × 0.05 m
Panel area (m2)	1.94
Panel weight (Kg)	27

Table 2. The specification of used inverters

	Medicine faculty	
System capacity	41 kW	
Brand	SMA	
Model No.	Sunny 2000TL	Sunny 5000TL
NO. of independent MPP inputs/string per MPP	1/6	2/2
DC MPPT Range/Input voltage range	580–800 V	245–800 V
Max input current (DC)/string	36 A	17 A/15 A
Rated AC power (W)	20,000	5000
AC voltage range	160-280	230/400
Max output current	29 A	7.3 A
Efficiency (%)	98.5%	98.0%
Weight	45 kg	37 Kg
No. of inverter per project site	2	1

The PV array in all sites are connected to inverter through a DC junction box, the solar inverter convert DC energy which generated by the photovoltaic array to AC, the specification of used inverters illustrated in Table 2.

For this on-grid system, a grid-tie inverter was used which is taking the reference input voltage, phase angle, and frequency from the grid. The site has its own monitoring system to collect the data of solar radiation in W/m2, the temperature of the module (°C) and the ambient temperature (°C) and energy output. The data is recorded and collected remotely using the SMA portal.

2.3. Simulation results of PV system

A software program PVsys have been used for design and simulation of the above mentioned system. The simulated results are illustrated in Table 3, and the expected energy output from PV simulation is illustrated in Figure 4.

2.4. Comparison between simulation results and real data

The energy values resulted from PVsyst packages are compared with the actual values derived from the Sunny Portal internet site. Real-time energy measurements using SMA inverters for the transformation of DC coming out of the solar panels arrays to AC have been taken during the last three years 2016–2018. The measured PV system output comparing with expected simulated energy output is illustrated in Table 4.

Table 3. Simulated results

PV system	
PV Generator Output	41 kWp
Spec. Annual Yield	1,684.33 kWh/kWp
Performance Ratio (PR)	78.4 %
Yield Reduction due to Shading	1.3 %/year
Grid Feed-in	68,990 kWh/year
Grid Feed-in in the first year (incl. module degradation)	68,990 kWh/year
Stand-by Consumption	37 kWh/year
CO_2 Emissions avoided	41,372 kg/year

Figure 4. Monthly energy expected output.

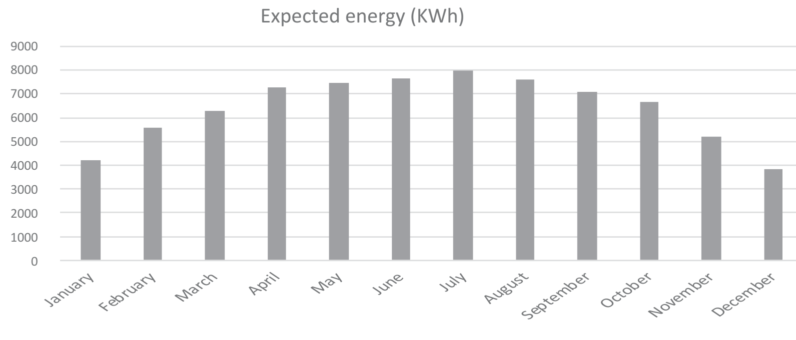

Table 4. Monthly measured PV system output comparing with expected PV simulated output

Capacity = 40.96 kWp		Year 2016	Year 2017	Year 2018
Month	Expected energy (kWh)	Measured energy (kWh)	Measured energy (kWh)	Measured energy (kWh)
January	4202.48	3943.158	3836.881	3611.824
February	5579.12	5048.368	4853.305	4843.547
March	6303.18	5595.386	5462.372	5373.743
April	7287.71	6541.716	6402.78	6341.07
May	7449.63	6611.957	6572.494	6525.632
June	7638.06	6753.963	6741.37	6615.435
July	7981	6960.995	6671.756	6738.932
August	7627.84	6824.333	6569.277	6474.095
September	7107.61	6072.589	5941.428	5912.634
October	6661.27	5714.166	5607.134	5577.569
November	5218.74	4457.883	4444.563	4377.528
December	3815.85	3296.241	3221.812	3176.727
Total	76,719.51	67,820.76	66,325.17	65,568.74

The comparisons of simulation and measurements showing small differences between them, the average difference around 12%. Therefore, the results of this investigation can be taken into account when expected calculations are needed.

3. Methodology of performance analysis of on-grid PV system

Performance analysis can be determined by calculating different parameters describing energy quantities for the PV system and its components and comparing it with the standard (Photovoltaic system performance monitoring- Guidelines for measurement, data exchange and analysis, 2010).

The electrical performance for the above installed PV system was analyzed and the main investigated parameters were calculated: such as system yields, system efficiency, CUF and performance ratio of the system.

3.1. System yields

The on-grid PV system yields is categorized into three types which are Array Yield (YA), YF, and YR.

The YA can be calculated as the ratio of daily, monthly, or yearly energy output from a PV system array to the rated capacity of PV array power (Adaramola & Vagnes, 2015; Elhadj Sidi et al., 2016). It is given as mentioned in Equation (1).

$$Y_{A=}\frac{E_{DC}}{P_{PV,rated}}(kWh/kWp) \tag{1}$$

where E(DC) is the DC energy output (kWh) from the PV array, its equal 74,552 kWh/year

YA ~ 1820 kWh/kWp/year

The final yield can be calculated as the total AC energy output during a given period divided by the rated capacity of PV array power. (Sharma & Chandel, 2013). And given as in Equation (2):

$$Y_{F=}\frac{E_{AC}}{P_{PV,rated}}(kWh/kWp) \tag{2}$$

E (AC) is the AC energy output in kWh.

YF~1684 kWh/kWp/year

The reference yield "YR" can be determined as a total in-plane irradiance divided by the reference irradiance under standard temperature (1 kW/m^2). It is calculated as in Equation (3)

$$Y_{R=}\frac{H_T}{H_R}(kWh/kWp) \tag{3}$$

where HT is the plane solar irradiance, and HR is the reference irradiance.

YR = 2046.507 kWh/kWp/year

The monthly measured solar plane insulations illustrated in Figure 5.

3.2. Energy losses

The array captured losses (LA) due to PV array losses (Wittkopf, Valliappan, Liu, Ang, & Cheng, 2012) can be calculated as the following, Equation (4):

$$L_{A=}Y_R - Y_A(kWh/kWp) \tag{4}$$

LA = 226.5 kWh/kWp/year

And system loss (Ls), due to inverter inefficiencies and is calculated as Equation (5):

$$L_{S=}Y_A - Y_F(kWh/kWp) \tag{5}$$

Ls = 136 kWh/kWp/year

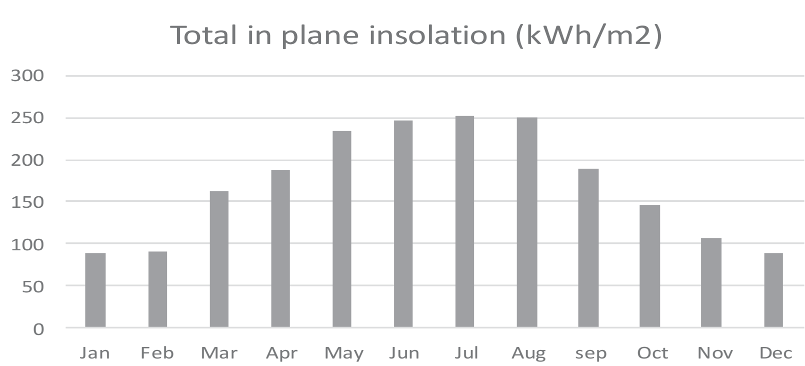

Figure 5. Monthly average solar insulations over the year 2016.

3.3. System efficiencies for PV systems

The efficiency of a PV system is cascading of PV array efficiency, system installation efficiency and inverter efficiency, the PV array efficiency is the DC energy generated by the PV array system according to the available irradiation on the total PV module surface (Padmavathi & Daniel, 2013). The array efficiency ηPV is given as in Equation (6):

$$\eta_{pv} = \frac{100 \times E_{DC}}{H_T \times A_M}(\%) \tag{6}$$

where Am is the PV module total area (m^2).

η pv = 100*74,552/2046.507*245.6.

η pv = 14.8% (as an average per year)

The system installation efficiency reflects the performance of all system arrays and calculated as in Equation (7):

$$\eta_{SYS} = \frac{100 \times E_{AC}}{H_T \times A_M}(\%) \tag{7}$$

η sys = 100*68,990.3/2046*245.6

η sys = 13.7% (as an average per year)

The inverter efficiency can be calculated as in Equation (8):

$$\eta_{INV} = \frac{100 \times E_{AC}}{E_{DC}}(\%) \tag{8}$$

η inverter = 100*68,990.3/74,552

η inverter = 92.5% (as an average per year)

The temperature losses coefficient (η tem) is given as in Equation (9):

$$\eta_{tem} = 1 + \beta(T_C - 25) \tag{9}$$

where (Tc) is the PV cell temperature which is calculated as in Equation (10), (Ta) is the air temperature and β is the temperature factor of the PV module.

$$T_C = T_a + \frac{P}{800}(T_{noct} - 20) \tag{10}$$

where P is the power density at a specific time and Tnoct is the normal operating cell temperature.

3.4. Performance ratio

The Performance Ratio (PR) describes the quality of a PV solar system that is independent of capacity and location of system, it can be calculated as percent and describes the relationship between the real and estimated energy outputs of the PV system (Ayompe, Duffy, McCormack, & Conlon, 2011). Performance ratio is calculated as the ratio of the final energy yield of the PV system YF to the reference yield YR as in Equation (11), the monthly PR results shown in Figure 6.

$$P_R = 100 \times \frac{Y_F}{Y_R}(\%) \tag{11}$$

Average yearly PR for year 2016 = 0.88, for year 2017 = 0.81, and for year 2018 = 0.83

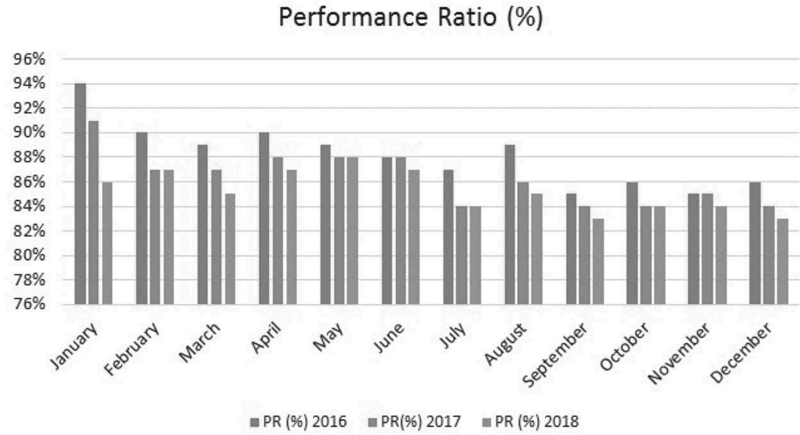

Figure 6. Average performance ratio.

3.5. Capacity utilization factor

The capacity utilization factor (CUF) is calculated as the ratio of real annual energy output by the PV system (Ea) to the amount of energy the PV system would generate if it is operated at full rated power for full day for a year. (Elhadj Sidi et al., 2016), and is given as in Equation (12), the results are illustrated in Table 5.

$$C_F = \frac{E_{AC}}{P_{PVrated} \times 8760} \quad (12)$$

3.6. Penetration factor

The penetration factor of three installed PV systems analyzed each month and the results illustrated in Table 6 and calculated as in Equation (13).

$$PV_{penetration} = \frac{Energy \text{ produced from PV system}}{\text{Energy Consumption}} \quad (13)$$

The penetration factor for the 3 years is illustrated in Table 6.

4. Results and discussion

In Table 7. Illustrated the performance indicators including measured solar radiations, energy output, system efficiency, and performance ratio and capacity factor over 1 year of the monitored period.

Table 5. PV system capacity utilization factor

Years	CUF
2016	18.9 %
2017	18.4 %
2018	18.3 %

Table 6. Yearly penetration factor for installed PV systems

Item	2016	2017	2018
Yearly Energy Produced	67,820.76	56,668.68	55,396.41
Yearly Energy Consumption	320,795	321,684	326,996
Penetration Factor	0.21	0.17	0.17

Table 7. Performance indicators in 2016

Months	Solar radiation (kWh/m2)	Energy output (kWh)	System efficiency ηsys (%)	Performance Ratio (%)	Capacity Factor (%)
January	89.1	3943.15	16.2	94%	13.7
February	103.8	5048.36	16.4	90%	14.2
March	153.5	5595.38	15.6	89%	17.9
April	184.6	6541.71	14.9	90%	18.9
May	227.9	6611.95	14.7	89%	20.6
June	239.4	6753.96	14.4	88%	20.3
July	243.4	6960.99	14.2	87%	20.9
August	224.6	6824.33	14.2	89%	21.1
September	182.4	6072.58	14.5	85%	19.7
October	144.2	5714.16	14.7	86%	18.2
November	102.2	4457.88	16.2	85%	15.1
December	83.9	3296.24	16.4	86%	13.3

Table 8. Comparison of final yields in several MENA countries

Country	Average solar radiation (kWh/m2.day)	Final energy yield (kWh/kWp. year)
Morocco (Almarshoud, 2017)	5.3	1624
Iraq (Adaramola & Vagnes, 2015)	5.2	1496
Egypt (KamalAttari & Elyaakoubi, 2016)	5.6	1569
Tunisia (Photovoltaic system performance monitoring- Guidelines for measurement, data exchange and analysis, 2010)	5.9	1861
Oman (Ayadi et al., 2018)	6.18	1872
Kuwait (Hassan & Elbaset, 2015)	5.7	1642
Jordan (Shahhoseini et al., 2018)	5.5	1715
Algeria (Kazem et al., 2017)	5.21	1788
Saudi Arabia (Ahmadi et al., 2017)	6	1927
Present Study (Palestine)	5.4	1680

The monthly performance ratio varies from 85% in November to 94% in January.

The performance of a grid-connected PV system is usually examined using the above-selected set of performance indicators, the most important of these indicators are final energy output, final energy yield and performance ratio. The overall performance of any grid-tied PV system can be evaluated and compared with other systems.

A comparison of final energy yields for the above system with other MENA countries is presented in Table 8, mentioned also the average solar radiation in each country.

The final energy yields in Palestine 1680 kWh/year, it can be considered as a moderate value comparing with other MENA countries.

Table 9. NPV for medicine faculty at different years			
Item	**2016**	**2017**	**2018**
NPV ($)	67,859.94	56,668.68	55,396.41

5. Economic analysis of on-grid PV system

For the purpose of evaluating cost-effectiveness of using on-grid photovoltaic systems in Palestine, in order to obtain the cost of purchasing electricity and also a secure investment, the following economic analysis will be investigated.

5.1. Net present value

Net present value (NPV) or present worth can be calculated as a difference between the present worth of cash inflows and the present worth of cash outflows over a period of time. The function simply requires cash flow input (NCF) from all years of operation of the solar system, and cash flow output including capital investment, maintenance and replacement cost as a negative amount. The discount rate (i) it can be 8% for solar system project in Palestine.

For above case study, the net present value will be calculated as in Equation (14):

Investment cost of PV system = $ 52,000

Saving/year = $ 12,208, $ 11,938, 11,802 for the three years 2016–2018, respectively.

Selvage cost = $ 6500, at the end of life cycle

Replacement cost of inverter (10th year) = $ 2850

Interest i = 8%, life cycle n = 20 years

$$N_{PV} = \text{Income cash flow} - \text{Outcome cash flow} \quad (14)$$

The results for 3 yearsthree years areis shown in Table 9.

The net present value is positive, it means the project is feasible, managers and investors should invest in PV on-grid projects.

5.2. Simple payback period

Simple Payback Period (SPBP) is another technique can be used to analyze the project feasibility and it can be defined as the length of time required to recover the capital cost or the (LCC) of an investment. If the SPBP was lower than the project lifetime this mean the project is feasible otherwise is not. The SPBP can be estimated using Equation (15).

$$\text{S.P.B.P} = \text{Investment}/\text{saving cost per year} \quad (15)$$

Investment = $ 52,000

Saving/year = $ 12,208, $ 11,938, 11,802 for the three years 2016–2018, respectively.

Using Equation (15), the SPBP can be calculated and the results shown in Table 10.

Table 10. PV system yearly SPBP			
Item	**2016**	**2017**	**2018**
Yearly Energy produced	67,820.76	66,325.17	65,568.74
Saving ($)	12,208	11,938	11,802
SPBP	4.25	4.35	4.40

This SPBP which as average equals to 4.33 years, means that all project cost will be recovered by the first 5 years of the lifetime and the other 15 years it will profit which mean also the project is feasible.

6. Conclusion

This paper assessed the long-term operation of a rooftop solar PV system installed at one of An-Najah National University buildings. The 3 years of energy fed to grid showed that system performance was steady and quite similar yearly output during the 3 years. As a conclusion the following results are obtained:

- The total annual electricity delivered to the grid was found to be 66,571.5 kWh.
- The annual average final yield was compared with other systems installed in different locations worldwide, the value in Palestine was found 1684 kWh/kWp and the average annual performance ratio of the installation was found 84%.
- From Figure (6) we can note the decrease of the average performance ratio over the years of 2016, 2017 and 2018, and the yearly produced energy. This due to weather conditions, especially in sunny days, and it has to do with some dust that may be accumulating in the PV panels. Although the panels are subjected to cleaning, verification of voltages and output currents as maintenance type.
- The average annual capacity factor for PV installations in Palestine was found 18.5%.
- The annual average module, system and inverter efficiency were: 14.8%, 13.7% and 92.5%, respectively. Compared to other results from other publications, the PV system in Palestine has higher average daily final yield.
- Solar electricity delivered to the grid was verified with PVsys package results, and high consistency in energy fed to the grid between the actual and the simulated system was reported.

These results will be useful in identifying solar PV technologies that are appropriate for Palestine and provided important information to policy-makers and individuals about the performance and feasibility of installing grid-tied PV systems on the roof-top of buildings in Palestine.

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