Feasibility study of rooftop solar photovoltaic system for 33/11 kV primary substation at Al Suwairah

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ABSTRACT

This article presents an overview of the technical and financial feasibility analysis of integrating a photovoltaic (PV) source with the conventional power system to supply the auxiliary load at the Al Suwairah 33/11 kV primary substation (PSS) in Suhar, Sultanate of Oman. This study estimates the required electrical energy for the primary substation's auxiliary load. A method is implemented to utilize the available area in the primary substation for determining the solar photovoltaic system's capacity. PVSyst software is employed to determine the ideal system capacity. The proposed solar PV system's payback period and overall annual savings have been evaluated using a series of simulated analyses. The proposed PV can inject 172.5 MWh/year with an average performance ratio of 0.826. The economic evaluation by the photovoltaic system (PVSyst) considering the present auxiliary load at the Al Suwarah PSS has suggested a total payback period of 8.9 years which is quite feasible. The cost of power generated by the proposed system is 49.2% less than the cost of power supplied from the utility service provider.

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1. INTRODUCTION

Photovoltaic (PV) systems play a significant role as a renewable energy source in creating a safe and secure environment. Technological advancement in PV systems is accelerating. The intermittent nature of the renewable source, high installation costs, and relatively poor energy conversion performance (from 12% to 29%) are drawbacks of the solar power plant [1]–[3]. Recently these costs have been reduced, since 2010, solar power expenses have decreased by 82%. According to data supplied by the International Renewable Energy Agency, the levelized cost of energy produced by large-scale solar plants is approximately $0.068/kWh, down from $0.378 ten years ago, and the price plummeted 13.1% between 2018 and last year alone [3]. In addition, solar PV has very low maintenance costs compared to other conventional sources.

Solar energy is a vital and sensible choice for generating electrical power in the Sultanate of Oman. It is enriched with enormous amounts of untapped territory and usable solar energy infrastructure. Oman has significant potential for the production and distribution of solar energy [3]. Solar energy is an optimal option for supplying electrical power demand in Oman, with a growing need for energy diversification. With total reliance on fossil fuels, growing population, and significant industrialization in towns like Duqm, Sohar, and Salalah, Oman's electricity infrastructure and hydrocarbon reserves threaten economic growth. Due to its strategic significance and geographic location, Oman can benefit from renewable energy technology on both small- and large-scale basis to boost its economy [3]. It contributes to reducing dependency on fossil fuels and to the development of a wholesome and affluent environment. Using PV and wind power has opened up opportunities in recent decades to use renewable energy sources in electricity generation. Services providers and distribution companies expect to have secure and stable networks [4]–[6]. However, the intermittent and unpredictable nature of PV systems integrating the grid makes it challenging. PV systems should be more continuously monitored and streamlined to minimize the detrimental consequences of this integration [7]–[9].

An intense analysis is required when many PV solar panels are installed on the distribution side. However, the saving can be quantified from installation and utilization of the PV system. Over the past three years, the number of installed small-scale PV projects has rapidly increased, contrastly the price of installing a PV system has decreased. Nowadays, in most countries, the authority of public service has eliminated electricity subsidies [10]–[12]. As a result, utility companies generating, transmitting and distributing their power, should still bear the huge expenses to provide power to the consumers. To overcome these issues, distributed generation helps in effective power generation and utilization [12], [13]. In this study, the design for utilizing the space in 33/11 kV Al Suwairah primary substation, Oman for installing the PV system and the economic analysis by evaluating the payback period is performed.

The method for redesigning an alternative primary distribution substation to have PV panels on its rooftop and supply the entire auxiliary load is presented in this paper [14]. PVSyst software presents the specific area's simulation-based results with real-time location data. The main objectives of this research are listed as:

- To predict the PV energy injected to the grid by utilising the space in 33/11 kV Al Suwairah primary substation, Oman.
- To provide power supply to the 33/11 kV Al Suwairah primary substation's 57.95 kW auxiliary load completely.
- To have economic and feasibility studies on roof-top PV system at Al Suwairah primary substation.

The paper is organized with a discussion on the site survey for the PV plant is presented in section 2. The modeling of the solar energy system using PVSyst is discussed in section 3. Section 4 comprises of proposed system result discussion. In the end, conclusions are presented in section 5.

2. SITE SURVEY

Al Suwairah's primary substation is on the outskirts of Suhar City in the North Al Batina Region of the Sultanate of Oman. The longitude and the latitude of the Suhar region are 56° 35″ E and 24°.35″ N respectively. This primary substation (PSS) is 5 km from Suhar City and covers a total area of around 2500 m^2. It consists of 2x20 MVA transformers along with 8 feeders and a dedicated control room. The transformers are installed under the shed roof, as shown in Figure 1. This shed and rooftop of the PSS can be used to install the solar panels and feed all the LV load of the PSS in the daytime.

Figure 1. Al Suwairah PSS shed roof

Suhar is an ideal spot for tapping solar energy to develop the area into an ultimate metropolis. In addition to meeting the country's energy demand, the city's average yearly irradiation of roughly 6.3 kWh/m^2 per day will significantly be tapped for power generation. Figure 2 shows the monthly global horizontal irradiance (GHI) of the site Al Suwairah's primary substation. GHI parameter is more important to define the capacity of the PV system. This site had the highest GHI of 206.4 kWh/m^2 in May and the lowest GHI of 124.8 kWh/m^2 in December. To generate the power by effectively using the available area with feasible economic benefits, a thorough estimation of the anticipated solar PV power system structure has to be implemented in detail [7], [8], [14].

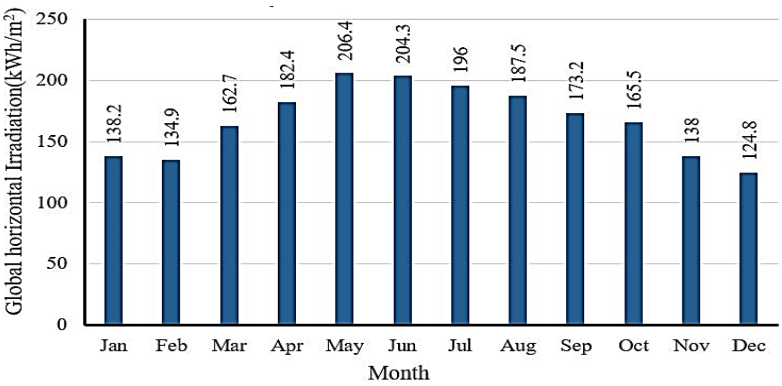


Figure 2. Monthly global horizontal irradiance

3. SYSTEM MODELLING IN PVSYST SOFTWARE

The literature research demonstrates that solar energy is used extensively worldwide and has much solar potential in the Sultanate of Oman. The project's research methodology is presented in this part. Initially, the Al Suwairah PSS site's load demand estimation and forecasting data are analyzed. As a second step, the mathematical interpretation of the operating parameters and mechanism of solar PV is illustrated. Thirdly, a thorough explanation of the solar PV system’s economic evaluation is provided, including the estimation approach used as input for PVSyst [2], [15]. Fourthly, the PV system's design and installation details are presented. Additionally, module assessment is discussed, which gives a brief overview of system sizing.

3.1. Load profile

The modeling of the rooftop solar photovoltaic plant in this paper is carried out for the Al Suwairah 33/11 kV primary substation auxiliary load. In addition to the regular load of 8 feeders, the substation also needs to cater the load for its auxiliary load within the station during the entire year. The considered auxiliary loads are 24 luminaries of 36 W each, 98 surface b-type luminaries of 36 W each, 10 waterproof type luminaries of 36 W each, 19 two-ton air conditioners of 2.5 kW each, 14 double socket points of 400 W each, and an exhaust fan of 100 W. The entire auxiliary load is operated almost throughout the day. The peak load demand occurs during the summer months (March–October) when all air conditioners are in use [4], [16]. If some air conditioners are turned off, it's reasonable to expect a slight decrease in load demand throughout the winter months (November–February). Based on PVSyst simulations, the site has a scaled yearly average energy demand of 24 kWh/day and a peak of 55 kW. The complete load profile of the PSS is calculated and presented in Table 1.

Table 1. Auxiliary load details of the Suwairah PSS

SN	Load	Watt (W)	Quantity	Total watts	Usage hours	Total energy (Wh)	Back up (Hrs)	Back up energy (Wh)
1.	Louver Luminaries	36	24	864	24	20,736	11	9504
2.	Surface b type	36	98	3,528	24	84,672	11	38,808
3.	Waterproof	36	10	360	24	8,640	11	3960
4.	AC (2 ton)	2,500	19	47,500	24	1,140,000	11	522,500
5.	Double socket	400	14	5,600	24	134,400	11	61,600
6.	Exhaust fan	100	1	100	24	2,400	11	1,100
	Total			57,952		1,390,848		636,372

3.2. System component summary

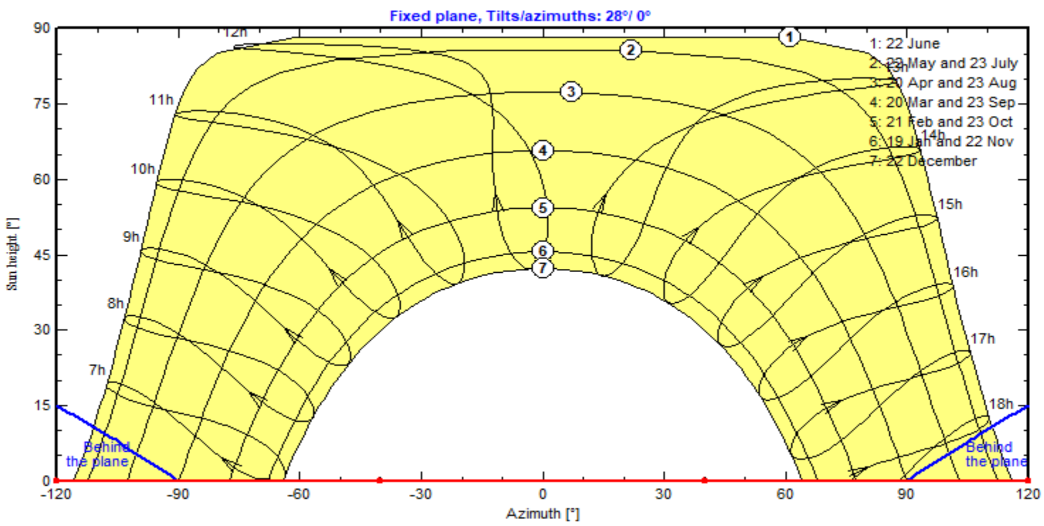
Solar power system depends on many factors, such as types of PV modules, inverter quality, latitude and longitude coordinates, inclination and orientation of PV panels [17]–[19]. Parameters like monthly global horizontal irradiation (MGH), monthly horizontal diffuse irradiation (MHDI), monthly ambient Temperature (MAT), global incident (GI), effective global (EG), effective energy at the PV array's output (EEA), adding energy to the grid (EG), performance ratio (PR) at the PSS site are presented in Table 2.

3.3. Effect of orientation and inclination of PV panel

The orientation of the PV system with the sun's path is one of two factors that must be optimized for maximum performance [20]–[22]. Figure 3 shows the sun’s path and corresponding PV panel tilt required to have mimimum loss factor through the year as suggested by the PVSyst software. Figure 3(a) shows the angular position of the sun at solar noon in a given location (1: 22 June and 2: 22 May). Both orientation and inclination help to maximize solar energy production. The optimal tilt of the PV panel to be maintained as per PVSyst is 28° of inclination, and 0° of azimuth. Tilt of PV panel and Azimuth position is shown in Figure 3(b).

Table 2. Measured data of Sohar city

Month	MGH kWh/m^2	MHDI kWh/m^2	MAT °C	GI kWh/m^2	EG kWh/m^2	EEA MWh	EG MWh	PR ratio
January	138.2	35.2	18.61	192.1	183.9	15.45	15.28	0.837
February	134.9	55.3	20.01	166.2	158.1	13.50	13.35	0.845
March	162.7	78.8	23.84	177.8	168.3	14.30	14.14	0.837
April	182.4	88.1	28.42	182.0	171.9	14.41	14.25	0.824
May	206.4	97.4	33.60	190.1	178.9	14.77	14.60	0.808
June	204.3	101.9	34.58	182.2	171.2	14.14	13.98	0.807
July	196.0	106.1	34.17	177.9	167.1	13.88	13.72	0.811
August	187.5	103.9	32.48	180.7	170.3	14.21	14.05	0.818
September	173.2	81.5	30.38	183.5	173.7	14.49	14.33	0.822
October	165.5	59.8	28.58	198.1	189.2	15.61	15.44	0.820
November	138.0	40.2	24.14	187.2	178.7	14.97	14.81	0.832
December	124.8	39.6	20.40	178.4	169.6	14.56	14.41	0.850
Yearly	2013.7	887.8	27.48	2196.1	2081.0	174.27	172.35	0.826



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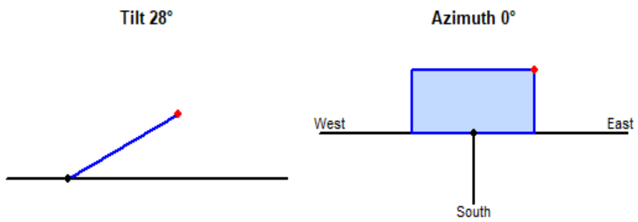


(b)

Figure 3. Sun's path and corresponding PV panel tilt, Azimuth (a) sun's path diagram for Suhar City, North Al Batina, Oman and (b) fixed tilt panel inclination

3.4. PV system description

Details about the grid-connected PV panel system's construction used in this analysis are tabulated in Table 3. Table 3 presents the operating characteristics of the implemented PV system. Table 4 presents the proposed inverter details for converting the DC to AC. The proposed layout uses 198 silicon-monocrystalline modules to produce 70 kW of power. The area covered by the PV panels is 473 m². To ensure grid compatibility, a 70 kW inverter was installed at the Suhar location of the Al Suwairah primary substation.

Figure 4 shows the perspective of the PV field describing the direction and orientation of the PV panels placed. It can be observed that PV panels are facing the south direction with an inclination of 28°.

Table 3. Operating characteristics PV system

Parameter	Type/value
Type of PV	Standard
PV module tech	Si-Mono
Power nominal	70 kWp
Load profile	Grid-Connected
No. of PV modules	198
Area of modules	473 m^2
Rating of PV module	480 Wp, 50.8 V
Vmpp (60 °C)	36.7 V
Voc (-10 °C)	55.9 V

Table 4. Operating characteristics of inverter

Parameter	Value
Number of inverters	1
Inverter rating	70 kW, 200-500, 50-60 Hz
Vmpp (60 °C)	661 V
Vmpp (20 °C)	772 V
Voc (-100 °C)	1100 V
Irradiance at the plane	1000 W/m^2
Impp (at STC)	103 A
Isc (at STC)	108 A
Operating max power	70.7 kW

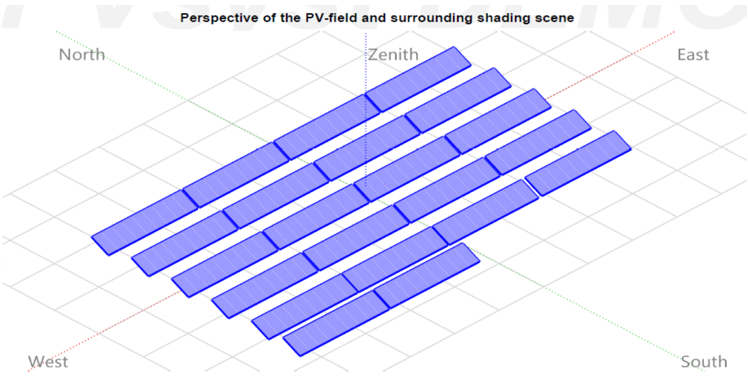


Figure 4. Perspective of the PV field

3.5. Efficiency of PV system

The efficiency (η_{System}) of the PV system is measured in terms of the ratio between the amount of actual energy injected into the grid (E_{Actual}) and the amount of irradiation present at the collector plane (G_{Total}). Using (1), it is possible to determine the efficiency of the PV system [23]–[25]. The PV panels used in the installation are Si-Mono TSM-DE18M-(II)-480 Trina solar, and the peak power output is 480 W. Increasing incident irradiation, and cell temperature is associated with an increase in voltage. These variations can be observed by comparing various curves of incidence irradiation and cell temperature.

$$\eta_{System} = \frac{E_{Actual}}{G_{Total}} \quad (1)$$

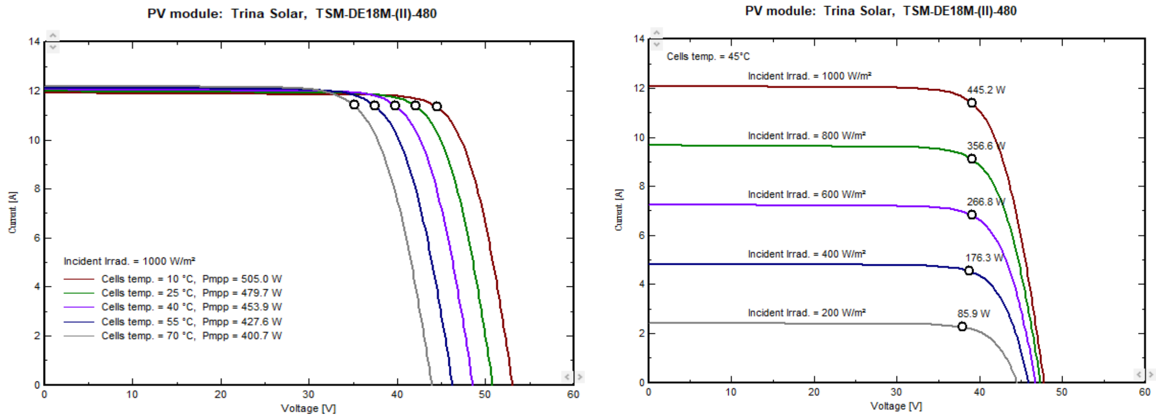
This relationship of V-I for different temperatures and irradiation is presented in Figure 5. Figure 5(a) shows the V-I characteristics of the proposed PV panel Trina Solar, TSM-DE18M-(II)-480 under constant 1000 W/m^2 with different cell temperatures. Figure 5(b) presents the V-I characteristics of the PV panel under a constant cell temperature of 45 °C with different incident radiations [18], [26].

3.6. Efficiency of inverter

The efficiency of an inverter is defined as the ratio of the inverter's AC power output (P_{AC}) to the DC input power (P_{DC}) (2) [20]:

$$\eta_{Inverter} = \frac{P_{AC}}{P_{DC}} \quad (2)$$

The inverter utilized to convert DC to AC at the PSS is the power gate AE from Huawei company; the nominal power rating is 70 kW_{ac}. The input voltage rating is 200-1000 V with a maximum efficiency of 99.0%. The efficiency characteristics of the inverter for the given output (P_{AC}) and input power (P_{DC}) are presented in Figure 6. The inverter efficiency corresponding to AC power output is presented in Figure 6(a). Relatively the inverter efficiency corresponding to DC power input is shown in Figure 6(b).

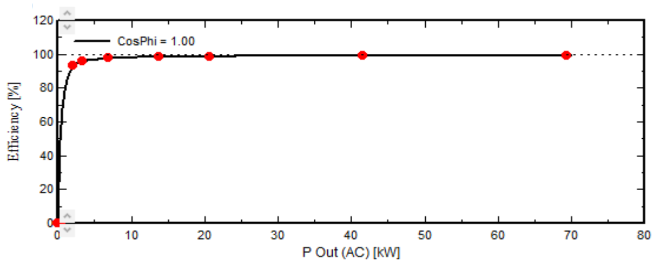


(a) (b)

Figure 5. V-I characteristics at different (a) cell temperatures with constant incident radiation of 1,000 W/m^2 and (b) irradiations with constant cell temperature of 45 °C on module TSM-DE18M-(II)-480

3.7. Cost and financial analysis

The total installation cost, financial analysis, and payback period of the grid-connected PV system for PSS at Al Suwairah are summarized by the reports generated from PVSyst software. These report of cost analysis by the PV Syst software is presented in Figure 7 and the financial analysis is presented in Figure 8. The study is carried out by considering the sunshine for 6 hours of supply to feed the entire auxiliary load from the rooftop photovoltaic plant, and the remaining period is supplied from the grid. The complete cost of the system including installation cost, operating cost and energy produced through year is presented in Figure 7. Total installation cost of PV system is 90301.55 USD, operating cost is 1213.2 USD/year and the total energy produced is predicted to be 172 MWh/year. Evaluated cost of produced energy is 0.033 USD/kWh which is much low as compared to the conventional utility power supply. This cost is 49.2% less when compared to the tariff rate. The project lifetime is assumed to be 20 years starting from the year 2023, with the inflation rate of the Sultanate of Oman at 3% per year and the feed-in tariff rate as 0.065 USD/kWh. The payback period evaluated from PVSyst is 8.9 years with return of investment (ROI) is 121.3%. Detailed economic and financial report by PV Syst is presented in Figure 8.



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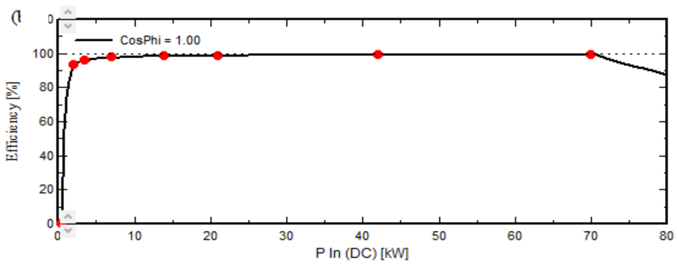

(b)

Figure 6. Inverter efficiency (a) inverter efficiency corresponding to output alternating current (AC) power and (b) inverter efficiency corresponding to input direct current (DC) power

Project: 70kW_SS_AuX_PV Plant_Sohar
Variant: 86.5kWDC PV_SS_AUX_70 kw ac

PVsyst V7.2.21
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Cost of the system

Installation costs

Item	Quantity units	Cost USD	Total USD
PV modules			
TSM-DE18M-(II)-480	198	195.00	38610.00
Inverters			
SUN2000-70KTL-INMO	1	9620.00	9620.00
Other components			
Solar DC Cables	737	1.30	958.10
Taxes			
VAT	1	0.00	4300.05
DC Earthing Cable	330	0.78	257.40
Remote Monitering			1560.00
MC4 Connectors	30	5.20	156.00
Ac Cable	50	15.60	780.00
Earthing Kit	2	195.00	390.00
Interface Protection Panel			3120.00
Interface panel			650.00
Civil Cost			9100.00
Installation costs	70	260.00	18200.00
MZEC solar			1300.00
Cleaning system			1300.00
Total			90301.55
Depreciable asset			48230.00

Operating costs

Item	Total USD/year
Maintenance	
Salaries	903.00
Total (OPEX)	903.00
Including inflation (3.00%)	1213.20

System summary

Total installation cost	90301.55 USD
Operating costs (incl. inflation 3.00%/year)	1213.20 USD/year
Produced Energy	172 MWh/year
Cost of produced energy (LCOE)	0.033 USD/kWh

Figure 7. Installation and operating cost of the PV system report by PVSyst software

Project: 70kW_SS_AuX_PV Plant_Sohar
Variant: 86.5kWDC PV_SS_AUX_70 kw ac

PVsyst V7.2.21
VC2, Simulation date:
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with v7.2.21

Financial analysis

Simulation period
Project lifetime 20 years Start year 2023

Income variation over time

Inflation	3.00 %/year
Production variation (aging)	0.00 %/year
Discount rate	0.00 %/year

Income dependent expenses

Income tax rate	0.00 %/year
Other income tax	0.00 %/year
Dividends	0.00 %/year

Financing
Own funds 90301.55 USD

Electricity sale

Feed-in tariff	0.0650 USD/kWh
Duration of tariff warranty	20 years
Annual connection tax	0.00 USD/kWh
Annual tariff variation	0.0 %/year
Feed-in tariff decrease after warranty	0.00 %

Return on investment

Payback period	8.9 years
Net present value (NPV)	109519.36 USD
Return on investment (ROI)	121.3 %

Detailed economic results (USD)

	Electricity sale	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amortl.
2023	11204	903	0	10301	0	10301	-80000	11.4%
2024	11204	930	0	10274	0	10274	-69726	22.8%
2025	11204	958	0	10246	0	10246	-59480	34.1%
2026	11204	987	0	10218	0	10218	-49262	45.4%
2027	11204	1016	0	10188	0	10188	-39074	56.7%
2028	11204	1047	0	10157	0	10157	-28917	68.0%
2029	11204	1078	0	10126	0	10126	-18791	79.2%
2030	11204	1111	0	10094	0	10094	-8697	90.4%
2031	11204	1144	0	10060	0	10060	1363	101.5%
2032	11204	1178	0	10026	0	10026	11389	112.6%
2033	11204	1214	0	9991	0	9991	21380	123.7%
2034	11204	1250	0	9954	0	9954	31334	134.7%
2035	11204	1287	0	9917	0	9917	41251	145.7%
2036	11204	1326	0	9878	0	9878	51129	156.6%
2037	11204	1366	0	9838	0	9838	60967	167.5%
2038	11204	1407	0	9797	0	9797	70765	178.4%
2039	11204	1449	0	9755	0	9755	80520	189.2%
2040	11204	1493	0	9712	0	9712	90232	199.9%
2041	11204	1537	0	9667	0	9667	99899	210.6%
2042	11204	1583	0	9621	0	9621	109519	221.3%
Total	224085	24264	0	199821	0	199821	109519	221.3%

Figure 8. Financial analysis of the PV system report by PVSyst software

4. RESULTS AND DISCUSSION

The experimental findings utilizing metrological data in the PVSyst software are achieved by considering the features of the proposed model (weather patterns and regional climate) into account from January 2021 to December 2021. The simulated parameters with fixed tilt position of PV panel by the PVSyst software as shown in Table 5. The performance ratio is between the final PV system yield (Y_f) and the reference yield (Y_r). It represents the total energy lost during the transformation from DC to AC. The performance ratio of the complete system considering the system components (transformer, inverter, and internal network) can be determined using (3) [27].

$$PR = \frac{Y_f}{Y_r} \tag{3}$$

The performance ratio of the complete system in the coming 20 years will be close to 82.6%. The energy production with fixed-tilt solar panels on the rooftop of PSS at Al Suwairah for a year is presented in Figure 9. The effective irradiation on the solar collector plates is 2086 kWh/m^2. The global incident radiation on the collector panel is 9.1%. The solar plates cover an area of 473 m^2. It can be observed that the main source of losses is from the PV panels, which account for 11.4%. The inverter losses during operation are around 1.1%. The available energy, or the energy injected into the grid, is 172.5 MWh in a year.

Table 5. Simulated parameters with fixed tilt position

Parameters	Value
Global horizontal irradiation (kWh/m²)	2014
Global Incident irradiation (kWh/m²)	2196
Ambient temperature (°C)	27.5
Effective global, corr. for IAM and shadings (kWh/m²)	2196.1
Energy injected into the grid (MWh)	172.5
The energy at the output of the array (MWh)	174.3
Performance ratio (PR)	0.826

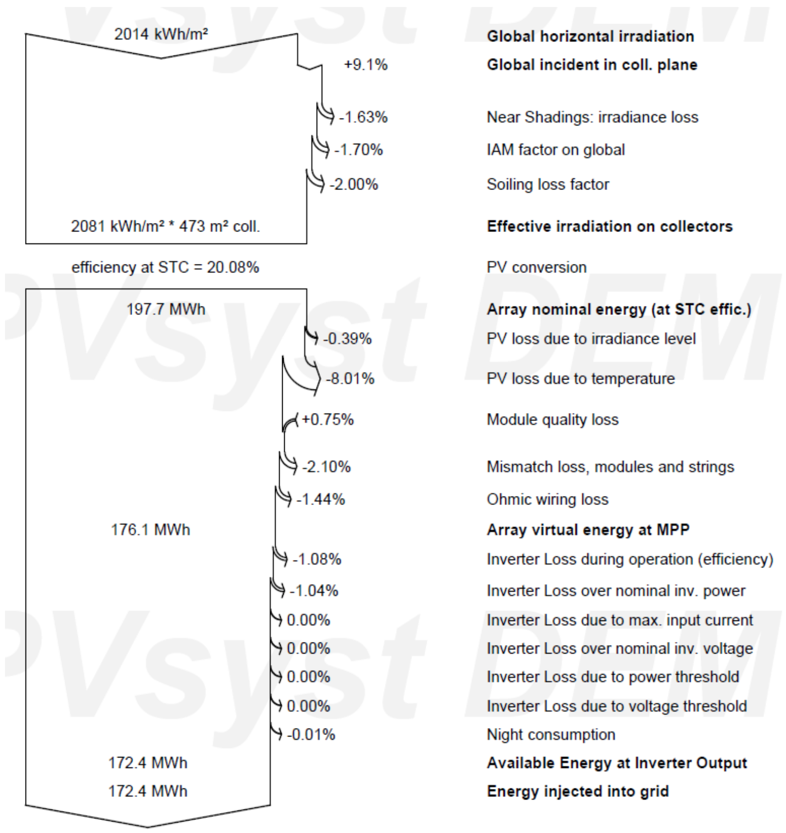
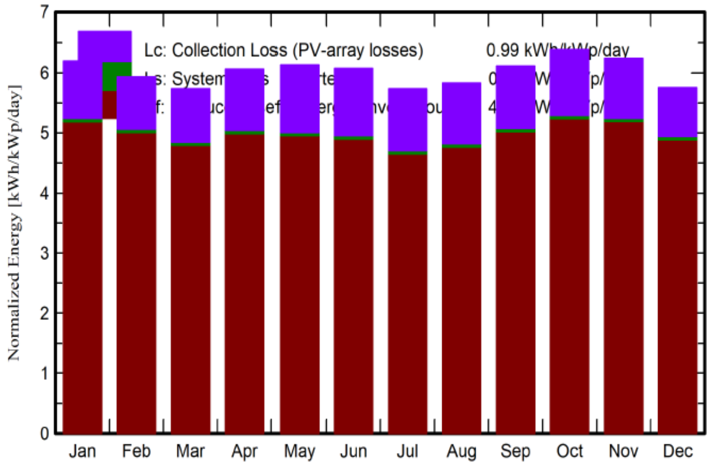


Figure 9. Energy output throughout the year (kWh/kWp/day) by PVSyst

Figure 10 presents performance evaluation of PV system at Al Suwairah substation with parameters of normalized energy output for each month throughout the year, performance ration and monthly energy injection capacity of the PV power plant. Figure 10(a) normalized energy output for every month for a year. It is observed that the total collection loss or the PV-array loss (L_c) is around 0.99 (kWh/kWp/day), system loss (L_s) is 0.12 (kWh/kWp/day), and the produced energy is 4.6 (kWh/kWp/day). Figure 10(b) present the performance ratio of the proposed PV system at Al Suwairah substation is 0.826. Figure 10(c) shows the monthly energy injection by the PV plant in to the grid for a year. The lowest injected power is 13.35 MWh in the month of February and highest is recorded during October with 15.44 MWh.



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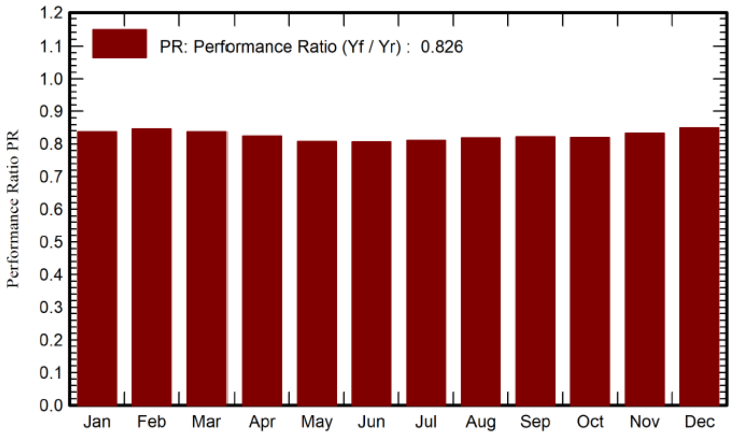

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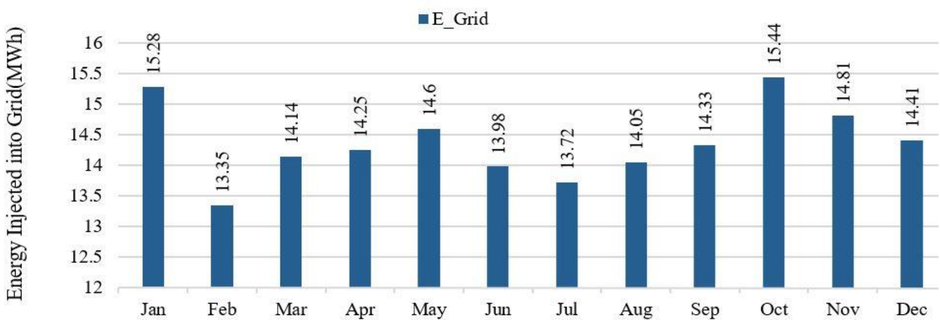

(c)

Figure 10. Performance evaluation of PV system using PVSyst (a) loss diagram of Al Suwairah 33/11 kV PSS-yearly, (b) performance ratio of PV system, and (c) monthly energy injection from PV system into the grid

5. CONCLUSION

An attempt has been made to identify the feasibility of the photovoltaic panel installation at Al Suwairah 33/11 kV primary substation, Suhar. The PVSyst software was employed effectively to have the economic analysis for the rooftop PV plant at the Al Suwairah 33/11 kV PSS. The existing geographical conditions suggested an optimal angle of 28° for fixed tilt. As a result, the performance ratio obtained is 82.6%. The total energy injected into the grid is 172.5 MWh/year. The economic evaluation by the PVSyst considering the present auxiliary load at the Al Suwarah PSS has suggested a total payback period of 8.9 years which is quite feasible. The cost of power generated by the proposed system is 49.2% less than the cost of power supplied from the utility service provider. The results demonstrate that the proposed solar power plant at Al Suwirah PSS can be economic and feasible for implementation.

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