Renewable Energy: Generation and Application - ICREGA'24 Materials Research Forum LLC
Materials Research Proceedings 43 (2024) 277-284 https://doi.org/10.21741/9781644903216-36

On the performance assessment of King Faisal University grid-connected solar PV facility

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Keywords: Energy Performance Index, Array Yield, Final Yield, Performance Ratio, Capacity Factor, System Efficiency, KSA 2030 Vision

Abstract. This paper evaluates the performance of the 9.8 kW grid-connected solar photovoltaic (PV) system mounted on the rooftop of the College of Engineering within the King Faisal University campus. The facility consists of four fields rated 2.45 kW each. Each field consists of ten 10 solar panels connected to a 3kW. The collected data include hourly and sub-hourly measurements of the radiation, ambient and module temperatures, AC and DC voltages, currents, and power outputs. Other measurements include cumulative produced energy and CO_2 savings. The assessed parameters of the PV facility include daily, and monthly energy, final yield, efficiency, and module performance ratio (PR). Aggregate performance analysis results show that the station operated as planned. The annual radiation measured in 2017 reached 2449 kWh/m^2 with a daily average of 6.710 kWh/m^2. The annual energy production reached 16.047 MWh with an average of 43.964 kWh/day. The system efficiency and capacity factor are 11.22% and 17.25%, respectively.

Introduction

Saudi Arabia's wealth in natural gas and oil has contributed to the country's rapid economic expansion over the last three decades. But the nation also produces the most carbon dioxide emissions, which suggests that it is becoming more and more dependent on gas and oil for electricity production. Saudi Arabia, having the biggest economy in the GCC, is heavily reliant on non-renewable energy sources, which makes the quest for alternate energy sources necessary. Saudi Arabia is viewed by experts as a potential hub for the production of photovoltaic solar energy. The European Commission Institute for Energy estimates that 0.3% of the light falling on the Middle East and Sahara deserts might supply Europe. Saudi Arabia, one of the largest developing countries, ranks eleventh in terms of electricity production globally. In particular, the oil and gas fuels dominate its electricity mix.

Meanwhile, evidence has shown that monitoring and performance analysis of both grid-connected and off-grid solar PV systems improve the performance of such systems. Several factors have a determinant impact on the performance of a PV system. Some of these factors have positive effects on performance while others have negative effects. Such factors and performance metrics are undertaken in this study.

The paper is organized as follows. Section 2 is devoted to Saudi Arabia's 2030 Vision and its renewable energy initiatives. The background, the motivation, and the objective of the present study are briefly introduced in this section. In Section 3, renewable energy prospects and operating large-scale facilities are discussed. In Section 4, solar PV performance metrics are discussed. Meanwhile, Section 5 and Section 6 are devoted to the analysis method and results discussion, respectively.

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Renewable Energy Initiatives in KSA

Substantial evidence indicates that the shift to sustainable sources of energy will address environmental issues such as greenhouse gas emissions, air pollution, and climate change to a certain extent. This shift is occurring at a considerable rate in developing countries [1]. As a result of recognizing the need to diversify its energy sources, reduce its carbon footprint, and create a more sustainable and resilient energy sector, Saudi Arabia has launched ambitious renewable energy programs based on eight pillars.

- The Saudi Vision 2030 is a plan that aims to reduce the country's dependence on oil transform its economy and increase the contribution of renewable energies.
- The second pillar is the National Renewable Energy Program (NREP), initiated in 2017 and aims to add significant renewable energy capacity to the Saudi grid. Such projects include the Sakaka solar power plant, one of the country's first major solar projects.
- The King Salman Renewable Energy Initiative. It aims to install 41 GW of solar PV by 2032.
- The Renewable Energy Project Development Office (REPDO) was established to supervise and manage the development of renewable energy projects in the country. REPDO plays a crucial role in the acquisition and execution of renewable energy projects.
- The focus on solar and wind energy is due to KSA's abundant natural resources in these areas. Solar projects include photovoltaic and concentrated solar power systems, while wind projects utilize the country's coastal and inland wind resources.
- The Energy Efficiency and Conservation initiative to increase renewable energy capacity by focusing on improving energy efficiency in the construction, transport, and industry sectors.
- Diversification of energy sources: The government has been working to diversify its energy resources by integrating renewable energy into its energy mix and developing infrastructure for electricity storage and grid integration.

As a result of the framework of the National Renewable Energy Program, the number of renewable energy projects reached 13 projects with a total capacity of 4,470 MW of PV and 40 MW of wind. The expected annual energy produced amounts to 15,109 GWh with an estimated CO_2 emission reduction of 9,828,156 Ton/year by 2024. Table 1 lists some of the grid-connected PV systems in the country. With the increasing role of solar energy in meeting the kingdom's need for energy and the installation of many solar PV projects in the kingdom, it is necessary to assess the performance of existing and future off-grid and grid-connected solar PV systems in the kingdom. The proposed method has been applied in many countries and the study results will be compared to current studies in the field of solar PV system performance assessment.

Methodology

Research has been conducted recently to examine the effectiveness of grid-connected solar PV power systems in various settings. Reference yield, array yield, final array yield, capture losses, system losses, and performance ratio were among the performance metrics that were computed. Furthermore, it has been demonstrated that doing a performance analysis of the actual efficiency of photovoltaic installations is a difficult undertaking since it necessitates processing data from solar PV system operation monitoring. Procedures were therefore developed to assess solar power plant performance using data from actual system monitoring. Monitored data include radiation, ambient and module temperatures, AC voltage/current, DC voltage/current, and DC/AC power. Assessed parameters include daily, and monthly energy, final yield, efficiency, and module performance ratio (PR).

Table 1: Major solar PV projects in KSA [2]

Plant Name	Location	Size (MW)	Starting Year
Sakaka Solar PV Park	Al Jouf	405	2020
Haradh Solar PV Park	E. Province	30	2021
King Abdulaziz International Airport Solar PV Park	E. Province	10.5	2013
King Abdullah Petroleum Studies and Research Center Solar Park	E. Province	3	2013
King Abdullah Univ. of Science and Tech.-Solar Park	Jeddah	2	2010
Saudi Aramco Park Project	Khobar	10.5	2012
Al Fanar Jinko Solar PV Plant	Makkah	5.4	2018
Al Kharj Solar PV Park	Riyadh	15	2019
Matco Solar PV Plant	Riyadh	3.5	2019

Performance Assessment of PV Power Plant Performance Using Metric Indicators

IEC61724 standard mandates that the final yield (Y_f), array yield (Y_a), reference yield (Y_r), energy efficiency (η), and the total energy generated by the PV system E_{AC}, are used to evaluate the performance of a grid-connected PV installation.

Array yield.

The array yield (Ya) is the ratio of the DC energy output delivered by the PV modules over a defined period divided by the PV-rated power and is given as [4]:

$$Y_a = \frac{E_{DC}\,(kWh)}{PV_{Rated}(kWp)} \quad (1)$$

The daily array yield ($Y_{a,d}$) and the monthly average array yield ($Y_{a,m}$) are given as [4]:

$$Y_{a,d} = \frac{E_{DC}\,(kWh/day)}{PV_{Rated}(kWp)} \quad (2)$$

$$Y_{a,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{a,d} \quad (3)$$

E_{DC} is the DC energy output delivered by the PV modules (kWh) and N is the number of days in the month.

Final yield

The final yield is the total AC energy during a specific period divided by the rated power of the PV system. This metric is used to compare a given PV system with other existing PV systems.
The daily array yield ($Y_{f,d}$) and the monthly average array yield ($Y_{f,m}$) are given as: [5]

$$Y_{f,d} = \frac{E_{AC}\,(kWh/day)}{PV_{Rated}(kWp)} \quad (4)$$

$$Y_{f,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{f,d} \quad (5)$$

E_{AC} is the AC energy output delivered by the PV modules to the grid (kWh) *and* N is the number of days in the month.

$$E_{AC,m} = \frac{1}{N}\sum_{d=1}^{N} E_{AC,d} \quad (6)$$

With $E_{AC,m}$ being the monthly AC energy output and N the number of days in a month.

Reference yield

The reference yield is the ratio of the global solar radiation H_t (kWh/m^2) and the PV's reference irradiance. The reference yield is given as [6]:

$$Y_r = \frac{H_t\,(kWh/m^2)}{H_g} \quad (7)$$

In this case, H_g=1 kW/m^2

Performance ratio

The performance ratio (PR) depends on the total losses by the PV system components (modules, inverters, trackers, and cables) and losses due to weather conditions such as ambient temperature, rain, shade, etc. The performance ratio (PR) is defined as the final yield divided by the reference yield and is expressed as:

$$PR = \frac{Y_f}{Y_r} \quad (8)$$

Array capture losses.

The array capture losses (L_C) are due to the PV array losses and are expressed as:

$$L_C = Y_r - Y_a \quad (9)$$

System losses

The system losses (L_S) are caused by inverter losses.

$$L_S = Y_a - Y_f \quad (10)$$

Capacity factor

The annual capacity factor (CF) is:

$$CF = \frac{E_{AC}}{8760 * P_{PV,rated}} \quad (11)$$

Where E_{AC} is the annual energy produced by the system and $P_{PV,\,rated}$ is the PV rated capacity.

System efficiencies

The system efficiencies consist of 3 components-namely the PV module efficiency, the inverter efficiency and the system efficiency. The PV module efficiency is expressed:

$$\eta_{PV} = \frac{100 * E_{AC}}{S * H_t}\ (\%) \quad (12)$$

The monthly PV module efficiency ($\eta_{PV,m}$) expression is:

$$\eta_{PV,m} = \frac{\sum_{i=1}^{n} E_{DC}}{S * \sum_{i=1}^{N} H_t}\ (\%) \quad (13)$$

Where E_{DC} is the total energy produced by solar PV modules, N is the number of days in a month and, and S is the total PV module surface (m^2).

The inverter efficiency is given as

$$\eta_{PV} = \frac{100 * E_{AC}}{E_{DC}}\ (\%) \quad (14)$$

The temperature loss coefficient (η_{tem}) is

$$\eta_{tem} = 1 + \alpha_P\,(T_C - T_{C,STC}) \quad (15)$$

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{C,STC}}\right) \left[1 - \alpha_P (T_C - T_{C,STC})\right] \quad (16)$$

Where α_P indicates the power temperature coefficient (%/°C), T_C is the PV cell temperature (°C), and $T_{C,STC}$ is PV cell temperature at STC (°C).

$$T_c = T_a + \frac{P}{800}(T_{NOCT} - 20) \quad (17)$$

Where P is the power density at a specific time and T_{NOCT} is the normal operating cell temperature.

Description of KFU 9.8kW PV Facility

The 9.80 kW grid-connected PV facility has been operating since 2014. The facility consists of four arrays rated 2.45 kW each. Each array is made of ten 245Wp panels with two different solar cell specifications: efficiency and robustness in harsh weather conditions. Each field is connected to a 3-kW inverter with an efficiency of 97%. The characteristics of the solar panel technologies are listed in Table 2 . The detailed performance analysis was done for Array 1.

Table 2. Characteristics of the Solar Modules

Parameter	SM-D245PC2 (Arrays 1@2)	SM-245PC8 (arrays 3&4)
Rated power (Pmax)	245W	245W
Voltage at Pmax (Vmp)	30.4V	30.4V
Current at Pmax (Imp)	8.06A	8.08A
Warranted minimum Pmax	245W	245 W
Short-circuit current (Isc)	8.39A	8.63A
Open-circuit voltage (Voc)	37.8V	37.4V
Module efficiency	14.91%	14.72%
Operating module temperature	-40°C to + 85°C	-40°C to + 85°C
Isc Temperature coefficient	0.061%/ºC	0.052%/ºC
Voc Temperature Coef.	-0.345%/ºC	-0.312%/ºC
Power Temperature Coef.	-0.458%/ºC	-0.429%/ºC
Inverter Efficiency	97%	97%

Performance Analysis

As discussed earlier, the solar PV facility consists of four arrays. Each array consists of 10 solar panels connected in series yielding a peak power of 2.45 kW. The first part of the performance analysis focuses on Array 1. Therefore, a detailed performance analysis is carried out. The second part of the analysis includes the system aggregate efficiency and capacity factor for all four arrays. Figure 2 displays (a) the daily AC energy produced in May 2017, (b) the weather statistics for June 13, 2017 and (c) that the cumulative energy produced by Array 2 reached 17.5 MWh in June.

(a) (b) (c)

Figure 1: Array 2 Performance and Monitoring statistics (a) Daily AC energy (kWh) statistics May 2017.(b) Weather statistics, June 13, 2017. (c) Monitoring statistics, June 1, 2017.

Array 1 Performance Analysis

The nameplate efficiency of Array 1 is 14.91%. Tables 3 and 4 display the 2017 performance analysis results for Array 1. Based on these tables, the following observations are worth mentioning:

- The average plane of array radiation is 181 kWh/m^2. This is equivalent to 5.94 kWh/m^2/day.
- Maximum power output ranges from 1.60 kW to 2.40 kW in March 2017.
- The highest monthly AC energy output of 400 kWh was produced in March and July.

- The annual AC energy output is 3.8 MWh. This is equivalent to an average of 10.42 kWh/day.
- The average efficiency exceeded 100%. This was because data are measured within one decimal point, which resulted in roundup and round-down errors. This has impacted the overall system efficiency and rendered higher than the solar conversion itself. In this case, the overall efficiency varied from 9.36% to 14.25%.
- The average performance varied from 55.8% to 84.9% with an overall average of 74.2%. The average monthly capacity factor varied from 13.97% to 21.59%.
- As seen in Tables 3 and 4 the obtained results of the capacity factors are aligned with the geographical location of the PV system and the harsh weather conditions. The system efficiency and capacity factors are compared with PV GIS based simulation results.
- The comparison results are shown in the last two rows of Table 4. The measured and simulated efficiency/capacity factor are slightly different with moderate deviation. However, they vary from one month to another.

Table 3: Array 1 Monthly Energy ambient and module temperatures

Month	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
POA (kWh/m^2)	160.6	130.8	162.3	204.7	209.4	188	209.9	211	211.4	214.1	169.8	188.8	181[γ]
Pac_max (kW)	2.1	2.3	2.4	2.1	2.2	1.7	1.6	1.6	1.6	1.6	2	2.1	2.4[*]
POA_max (kWh/m^2)	1.000	1.041	1.041	1.041	1.041	1.008	1.004	1.041	1.041	1.041	1.041	1.041	1.041[*]
T_mod_max (°C)	47.7	53.4	60.4	69.1	67.5	66.1	70.1	71.5	70.4	63.8	55.9	52.2	71.5[*]
T_amb_max (°C)	31	30	37.8	48.1	48.8	50.1	53.3	53.2	50.8	44.3	37.6	33.8	53.23[*]
DC Energy (kWh)	302	275	322	381	351	352	336	331	312	293	246	350	321[γ]
AC Energy (kWh)	300	200	400	300	400	300	400	300	300	300	300	300	317[γ]

[*]Maximum value [γ]average value

Table 4: Array 1 efficiencies, performance ratio and capacity factor for 2017.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Eff_PV (%)	12.68	14.17	13.54	12.68	11.37	12.71	10.85	10.67	10.02	9.27	9.84	12.62	12.65
Eff_Inv (%)	100.3	100.6	100.3	100.5	100.9	100.9	101.0	100.8	100.9	100.9	101.0	100.7	99.5
Eff_sys (%)	12.72	14.25	13.59	12.75	11.47	12.82	10.96	10.76	10.12	9.36	9.94	12.71	12.44
$Y_{a,m}$ (kWh)	121.2	109.4	127.3	152.0	139	142.4	133.1	131.4	123.5	114.2	95.7	136.6	127.2
$Y_{f,m}$ (kWh)	122.1	111.1	131.4	155.5	143.1	143.7	137.1	135.3	127.4	119.4	100.6	143.0	129.0
Y_ref	160.6	130.8	162.3	204.7	209.4	188.0	209.9	211.0	211.4	214.1	169.8	188.8	181.0
P.R.(%)	76.1	84.9	81.0	76.0	68.3	76.4	65.3	64.1	60.3	55.8	59.2	75.7	74.2
C.F. (%)	16.42	16.53	17.66	21.59	19.23	19.95	18.43	18.18	17.7	16.05	13.97	19.22	18.61
Simulated Eff_PV (%)	13.6	13.2	12.7	12.4	11.9	11.6	11.6	11.8	12.0	12.4	13.1	13.5	12.4
Simulated C.F. (%)	18.6	18.2	20.5	18.7	19.8	19.7	20.1	20.9	21.2	21.5	18.2	19.0	19.7

Aggregate Performance Analysis

An aggregate performance analysis of the entire PV facility was conducted considering all four fields. The results are shown in Tables 5 and 6.

- Table 5 displays the monthly efficiency and the capacity factor for each of the four arrays. Array 4 has the highest annual values of 12.26% and 18.85%, respectively. Meanwhile, Array 2 has the lowest annual values of 9.67% and 14.87%, respectively.
- According to Table 6, the highest efficiency and the highest capacity factor were obtained in February and April, respectively. The annual efficiency and capacity factor were 11.22%

and 17.25%, respectively. Compared to reported capacity factors around the world shown in Figure 2, the recorded capacity factor at KFU is slightly below KSA figures and other countries.

Table 5. Aggregate Performance of the Entire Grid Connected PV Facility.

	Array 1		Array 2		Array 3		Array 4	
Month	Eff_sys (%)	C.F. (%)	Eff_sys (%)	C.F. (%)	Eff_sys (%)	C.F. (%)	Eff_sys (%)	C.F. (%)
Jan.	12.84	16.51	10.49	13.50	12.20	15.69	16.12	20.74
Feb.	14.40	16.70	11.99	13.91	13.82	16.03	17.91	20.77
Mar.	13.76	17.88	11.52	14.98	13.17	17.12	15.99	20.79
April	12.78	21.66	10.64	18.03	12.31	20.86	12.71	21.54
May	11.58	19.42	9.45	15.85	11.12	18.65	11.55	19.37
June	12.82	19.95	10.49	16.33	9.44	14.68	12.64	19.67
July	11.03	18.54	9.04	15.20	13.05	21.94	9.53	16.02
Aug.	10.84	18.32	8.80	14.87	10.39	17.56	6.69	11.30
Sept.	10.21	17.86	8.49	14.80	9.72	17.01	11.31	19.78
Oct.	9.44	16.18	7.68	13.17	8.93	15.31	13.47	23.10
Nov.	10.08	14.17	8.15	11.45	9.48	13.32	9.96	14.00
Dec.	12.81	19.37	10.74	16.24	12.26	18.54	12.75	19.27
Annual	11.74	18.06	9.67	14.87	11.21	17.24	12.26	18.85

Table 6. Aggregate Performance Analysis of the PV Facility.

Month	POA (kWh/m^2)	Monthly Energy (kWh)	Daily Energy (kWh)	System efficiency η_{sys} (%)	Capacity Factor (%)
Jan.	160.6	1211.0	39.06	10.49	13.50
Feb.	130.8	1110.0	39.64	11.99	13.91
Mar.	162.3	1290.0	41.61	11.52	14.98
April	204.7	1448.0	48.27	10.64	18.03
May	209.4	1336.0	43.10	9.45	15.85
June	188.0	1246.0	41.53	10.49	16.33
July	209.9	1307.0	42.16	9.04	15.20
Aug.	211.0	1131.0	36.48	8.80	14.87
Sept.	211.4	1226.0	40.83	8.49	14.80
Oct.	214.1	1235.0	39.84	7.68	13.17
Nov.	169.8	934.0	31.13	8.15	11.45
Dec.	188.8	1338.3	43.17	10.74	16.24
Annual	188.4	1234.4	40.57	11.22	17.25

Summary

In this paper, a 9.8 kW grid-connected PV system in the College of Engineering Building at King Faisal University has been monitored since its commission. In particular, the 2017 performance was assessed on a daily, monthly, and annual basis. Array 1 performance analysis results show that this array's annual efficiency and capacity factor are 12.44% and 19.22%. respectively. The aggregate performance analysis results show that the station operated as planned. The overall efficiency and capacity factors are 11.22% and 17.25%. This is because Array 1 performed less than the other three arrays. The annual radiation measured in 2017 reached 2.449 kWh/m^2 with a daily average of 6.710 kWh/m^2. The annual energy production reached 16.047 MWh with a daily average of 43.964 kWh/day. Overall, the KFU facility capacity factor is slightly below KSA reported capacity factors. Further studies deem necessary to investigate the deviation of the capacity factor from KSA reported results.

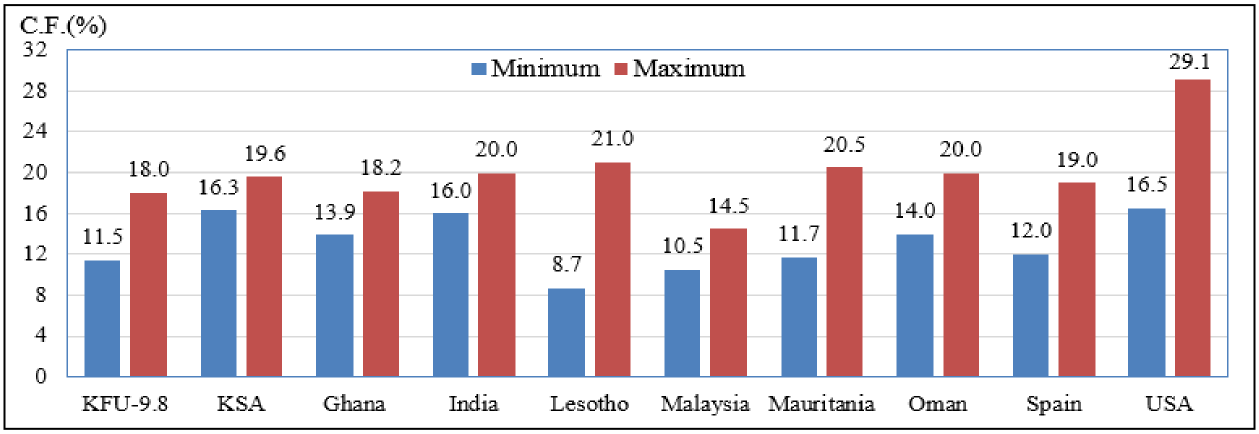

Figure 2: Capacity Factor for Selected Grid Connected PV Systems around the world [8-11].

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