Sustainable Energy Technologies and Assessments 39 (2020) 100724

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Performance analysis of a grid-connected photovoltaic plant in eastern Turkey

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ARTICLE INFO

Keywords:
Photovoltaic power systems
Performance analysis
Performance ratio
Capacity factor
Final yield

ABSTRACT

Photovoltaic market is a globally growing market, and this also reflects the current trend in Turkey. In this study, a grid-connected photovoltaic (PV) power plant of 2130.7 kW_p rated power located in the eastern part of Turkey was analysed. The photovoltaic plant was assessed in terms of performance parameters such as reference yield, array yield, final yield, inverter efficiency, capture loss, system loss, system efficiency, capacity factor, performance ratio and annual final yield. In 2017, 3519.98 MWh of energy was generated by this PV plant. Mean final yield, mean performance ratio, system efficiency and capacity factor were found as 4.53 h/d, 81.15%, 13.18% and 18.86%, respectively. Besides the real-time analysis, a simulation of energy prediction and performance analysis were also done. A comparison with other PV plants located in different parts of the world lead to the conclusion that insolation and environmental conditions are the primary factors that affect PV plant performance.

Introduction

In its simplest form, the concept of 'development' can be described as an increase in per capita income with social development in a country. For the development of countries, industrial production needs to be increased and this process requires energy consumption. Therefore, it can be said that there is a relationship between energy consumption and development. It is observed that energy consumption rises with economic development and the increase in wealth level [1,2]. A great majority of world energy demand is met by fossil resources [3,4]. However, this situation causes some concern not only on the aspect of environmental pollution, but also in terms of natural reserves [5–7]. These resources, which cause significant damage to the environment, will soon be used up unless new reserves are found [8,9]. Consequently, more effective usage of alternative resources becomes an obligation. In this regard, solar energy, which has shown an upward trend in recent years, is one of the most important alternatives.

The sun is the most accessible energy resource. With developing technology and the increase in environmental awareness, installation of photovoltaic power capacity has displayed a huge increase on a global scale. While it was 40 GWp in 2000, it reached 402 GWp at the end of 2017 [10]. The global cumulative PV capacity has reached to 635.-GWp at the end of 2019.

With the optimum tilt angle, Turkey has an annual average solar energy potential of 1527 kWh/(m^2.y), and annual mean hours of sunshine is 2741 h, with an average of 7.5 h a day. Especially southern Turkey has high insolation. Turkey introduced a law in 2011, giving feed-in tariff of 0.133 $/kWh for the duration of 10 years. After the introduction of this law, the photovoltaic sector in Turkey made a great stride. In 2017, Turkey placed in the top five among countries making annual investment on PV capacity. Republic of Turkey Ministry of Energy and Natural Resources announced that the total installed PV plant capacity of Turkey at the end of 2019 reached to 6 GWp.

Performance analysis of a PV plant can be viewed as a means to determine the quality of the system. The results of the analysis would reveal whether the system is moderate. In this article, a 2130.7 kW_p grid-connected photovoltaic plant in eastern Turkey was simulated and also real-time analysed. The PV system was assessed in terms of energy output of the PV array, energy output of the inverter, array yield, system yield, reference yield, performance ratio (PR), capacity factor (CF), capture loss, system loss and system efficiency.

PV plant

The PV plant started electricity production in 2016. Modules are placed with a 25° tilt angle. Installation of the PV panels are arranged geometrically so that there are not any obstacles between two adjacent rows. Module row height is 3.92 m. The length of the unobstructed area

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https://doi.org/10.1016/j.seta.2020.100724
Received 5 December 2019; Received in revised form 21 March 2020; Accepted 6 May 2020

Fig. 1. A view of the PV plant.

between two rows and the shading angle are planned as 4.55 m and 20°, respectively. A view of the PV plant is shown in Fig. 1.

The system is composed of two subsystems which are Subsystem A and Subsystem B. Subsystem A consists of 3420xJKM315P-72 polycrystalline modules. In Subsystem A, 15 inverters are used. Each inverter has a set of 12 strings, and 19 modules are linked per string. Rated power of the first subsystem is 1077.3 kW_p. In Subsystem B, the same type of modules is used; however, the quantity of the modules is 3344. 16 inverters are used, each having a connection of 11 strings. Each string consists of 19 modules. Rated power of Subsystem B is 1053.4 kW_p. Both subsystems use a Sunny Tripower 60 inverter. Overall rated power is calculated by adding up of the two subsystems' values, which amounts to 2130.7kW_p (Fig. 2).

Specifications of PV module and inverter are shown in Tables 1 and 2.

Terrain specifications and geometrical structure of PV plant installation area are determinative factor on the PV performance. To obtain optimum performance of PV modules, it should be considered shadow effect generated by buildings, mountains, hills and other objects around the installation area. In addition to this, the tilt angle and orientation of the modules should be arranged to receive highest amount of solar radiation and avoid dust accumulation on PV modules [11]. The geographical specifications of the plant site shown on Table 3.

Performance parameters

In a PV plant, loss is inevitable. The loss can stem from environmental conditions like temperature, soiling, humidity etc. [12–14], or photovoltaic components and their connections like maximum peak point tracker failure, mismatch, inverter and ohmic loss [15,16]. It is necessary to evaluate performance parameters in accordance with international standards guide IEC 61,724 to observe PV plant performance and expose its miscellaneous loss [17].

Array yield

Array yield defines the ratio of energy generated by the array as direct current (E_A) to nominal rated power of the PV plant. It represents how many hours a day the array operates at maximum power to generate energy. It is calculated as:

$$Y_a = E_A/P_{rated} \quad (1)$$

where Y_a: Array yield [h/d], E_A: DC electricity generation of the array [kWh/d] and P_{rated}: Rated power of PV plant [kWp].

Final yield

Final yield is the ratio of generating energy from the PV plant as alternative current (E_{AC}) to rated power of the PV plant. It is considered as the time period during which the PV system is operated at rated power in a day. It is calculated as:

$$Y_f = E_{AC}/P_{rated} \quad (2)$$

where Y_f: Final yield [h/d], E_{AC}: AC electricity generation [kWh/d] and P_{rated}: Rated power of PV plant [kWp].

Reference yield

Reference yield is time required in terms of hours that is needed to be present at the reference irradiance level to obtain instantaneous irradiation. Reference yield is calculated theoretically as:

$$Y_r = H_I/G_{STC} \quad (3)$$

where Y_r: Reference yield [h/d], H_I is the solar irradiation on module plane [kWh/(m^2.d)] and G_{STC} is the irradiation corresponding to STC conditions (1000 W/m^2).

Inverter efficiency

Photovoltaic array generates DC power. However, if the energy produced is delivered to the grid or load that operates with AC power, it has to be converted by an inverter. During this transformation, some loss occurs, the amount of which depends on the efficiency of the inverter. Inverter efficiency displays a downward trend when the difference between rated power of the inverter and DC power of input rises [18]. The efficiency of the inverter is defined as the ratio of AC energy delivered to the grid to DC energy generated by the PV array, and is calculated as:

$$\eta_{inv} = E_{AC}/E_{DC} \quad (4)$$

where η_{inv}: Inverter efficiency [–], E_{AC}: AC electricity generation [kWh]

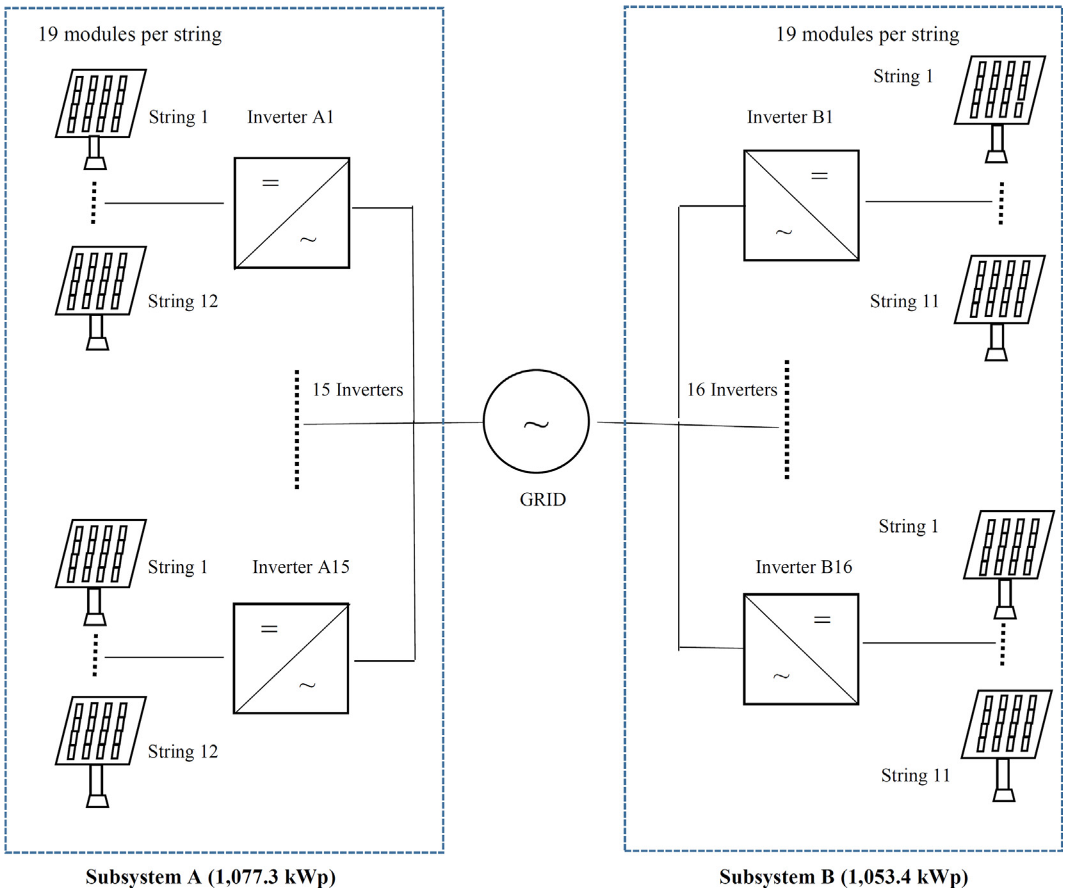

Fig. 2. Layout of the PV plant.

Table 1
Module specifications.

Module Type	Poly-crystalline silicon
Maximum Power (Pmax)	315 Wp
Maximum Power Voltage (Vmpp)	37.2 V
Maximum Power Current (Impp)	8.48 A
Open-circuit Voltage (Voc)	46.2 V
Short-circuit Current (Isc)	9.01 A
Module Efficiency STC	16.23%
Area (m^2)	1.94 m^2
Operating Temperature (°C)	from −40 to +85

Table 2
Inverter specifications.

Inverter Type	Sunny Tripower 60
Max. generator power	90,000 Wp
Rated Power (DC)	61,240 W
Max. input voltage	1000 V
Max. apparent AC power	60,000 VA
AC voltage range	360 V/530 V
Max. efficiency	98.8%
THD	≤1%

and E_{DC}: DC electricity generation [kWh].

Capture loss

In some instances, modules cannot ideally use insolation to generate energy. There are miscellaneous factors that reduce the PV array performance such as shading, soiling, mismatch effect and diode

Table 3
Geographical specifications of the plant site.

Site	Eastern Turkey
Coordinates	38°43′N 39°08′E
Site Type	Grounded
Tilt Angle	25 °C
Orientation	180 °C
Climate Type	Arid
Average Ambient Temperature	13–14 °C

performance [19]. Capture loss arises as a result of these adverse parameters. It represents loss in terms of hours in a day based on nominal rated power of the system, and it is calculated as the difference between reference yield and array yield, as follows:

$$L_c = Y_r - Y_a \tag{5}$$

where L_c: Capture loss [h/d], Y_r: Reference yield [h/d] and Y_a: Array yield [h/d].

System loss

System losses cover all the losses of energy, which occur during the conversion of the array generated DC energy into usable AC energy [20]. It is calculated as the difference between array yield and final yield, as shown below:

$$L_s = Y_a - Y_f \tag{6}$$

where L_s: System loss [h/d], Y_a: Array yield [h/d] and Y_f: Final yield [h/d].

Table 4
Predicted losses and efficiencies for the simulation of PV system.

Parameter:	Losses (%):	Efficiency (%):	Explanation:
Module efficiency	−83.77	16.23	The efficiency was taken from the technical specification supplied by the manufacturer (Table 1).
Shading	−1.6	98.4	Site location and the system's geometrical parameters result in varying shading losses for the simulation. These losses may be caused by shading of one row of modules by the row in front of it, or surrounding mountains, hills and nearby objects such as trees, buildings, building elements or electricity poles and pylons. To predict the shading losses rightly, the tilt and shading angles were measured on-site during the commissioning test of the plant. A Panorama Master was used to define the surrounding shading effect. The inclination angle of the modules is 25° and the shading angle between the rows are in the range of 15-20° and these values are acceptable.
Soiling	−1.0	99	For tilt angles greater than 15°, it is assumed that precipitation will effectively clean modules of dirt and that potential soiling will result in only marginal losses. During the commissioning test of the plant, a soiling analysis was also realized on-site. Consequently, it was observed that the PV plant has %1 soiling loss.
Deviations from STC	−9.2	90.8	The power specified in the data sheet for a solar module is determined under standard test conditions. Due to module reflection, spectral, irradiation and temperature-dependent losses, there will be some deviations.
Mismatch losses	−0.8	99.2	The connection of modules to form strings and the interconnection of several strings to a single inverter (with common MPP tracking) results in connection losses in comparison to the sum of the output power from individual modules (cabling losses not considered at this point).
DC cable losses	−1.0	99.0	Losses caused by cable length and cable connectors can be estimated from the cable lengths and cross-sections.
Inverter losses	−1.2	98.8	The efficiency was taken from the technical specification supplied by the manufacturer (Table 2).
Inverter power limitation	−0.7	99.3	The ratio of the rated module power at STC to the rated inverter power on the AC side effects the inverter efficiency and may cause power limitation by the inverter.
Additional consumption	−0.6	99.4	Additional consumption (e.g. for inverter operation, ventilation and lighting of the inverter room) needs to be taken into account.
AC cable losses	−0.5	99.5	Losses caused by cable length and cable connectors can be estimated from the cable lengths and cross-sections.
Losses due to transformers	−1	99.0	The efficiency curve for the transformer was derived from the technical specifications supplied by the manufacturer.
η_S (%)		**13.54**	**The overall system efficiency includes energy conversion losses of related all items of a PV system. Its value is calculated by multiplying the all efficiencies listed above.**

Table 5
Predicted monthly energy generation of the PV system.

	Monthly solar irradiation on module plane provided from GeoModel, $H_{I,m}$ [kWh/(m^2.m)]	Calculated monthly energy generation, E_{AC} [MWh/m]
January	92	163,5
February	105	186,6
March	152	270,1
April	164	291,5
May	198	351,9
June	224	398,1
July	245	435,4
August	233	414,1
September	205	364,3
October	154	273,7
November	117	207,9
December	84	149,3
Total	**1,973.-kWh/(m^2.y)**	**3506.4-MWh/y**

System efficiency

The overall efficiency of a photovoltaic system is the measurement of how much of the available solar energy is converted into usable AC electrical energy. It is defined as the ratio of AC energy delivered to the grid to the solar energy coming to the module plane, and is calculated as:

$$\eta_S = E_{AC}/E_{in} = E_{AC}/(H_I.\ A_{PV,a}) \tag{7}$$

where η_S: Total system efficiency [–], E_{AC}: AC electricity generation [kWh/y], E_{in}: Solar energy coming to the module plane [kWh/y], H_I is the solar irradiation on module plane [kWh/(m^2.y)] and $A_{PV,a}$ [m^2] is the total area of PV array.

Performance ratio

Performance Ratio (PR) indicates the quality of the PV system rather than the efficiency. It defines to what extent the PV system is affected by the overall loss. It is also considered a measurement of closeness to an ideal loss-free PV system. Furthermore, performance ratio is used to make comparisons to other PV plants that are located on other sites with different environmental conditions [21]. It is calculated as the ratio of final yield to reference yield, as follows:

$$PR = Y_f/Y_r \tag{8}$$

where PR: Performance Ratio [%], Y_f: Final yield [h/d] and Y_r: Reference yield [h/d].

Capacity factor

A PV plant cannot be operated 24/7 at nominal rated power because of the loss that occurs, and hours that lack insolation. Evaluation of capacity factor is based on the calculation of how much energy would be generated by the system if the system was operated full time at maximum capacity. Then this value is compared to the actual value of the energy produced by the PV plant. It is calculated as:

$$CF = E_{AC}/(P_{rated}.\ 24) \tag{9}$$

where CF: Capacity factor [%], E_{AC}: AC electricity generation [kWh/d] and P_{rated}: Rated power of PV plant [kWp].

Annual final yield

Annual final yield is the total energy given to the grid per rated power of the PV plant throughout the year. It is calculated as the ratio of AC energy delivered to the grid to the rated power of PV plant:

$$AFY = E_{AC}/(P_{rated}) \tag{10}$$

where AFY: Annual Final Yield [kWh/(kWp.y)], E_{AC}: AC electricity generation [kWh/y] and P_{rated}: Rated power of PV plant [kWp].

Performance and energy generation prediction of the PV system

To predict the performance and energy generation of the PV system the two input parameters should be mainly taken into consideration: the solar irradiation on module plane (H_I, kWh/m^2) and total system efficiency (η_S).

- For the solar radiation forecast, this article used the values from

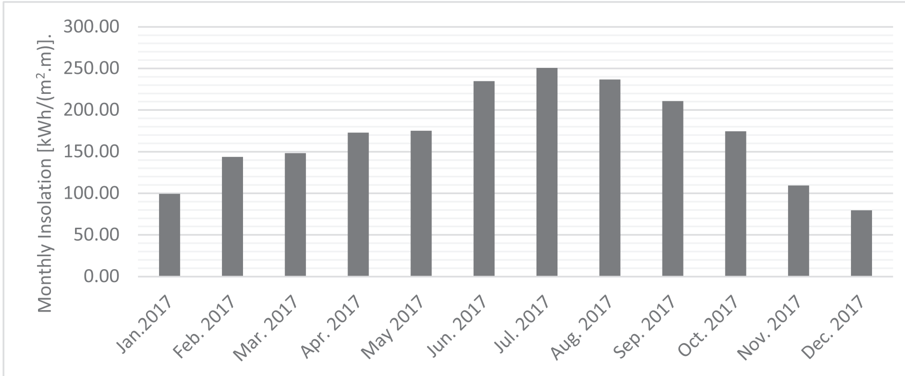

Fig. 3. Monthly variation of insolation on PV array plane.

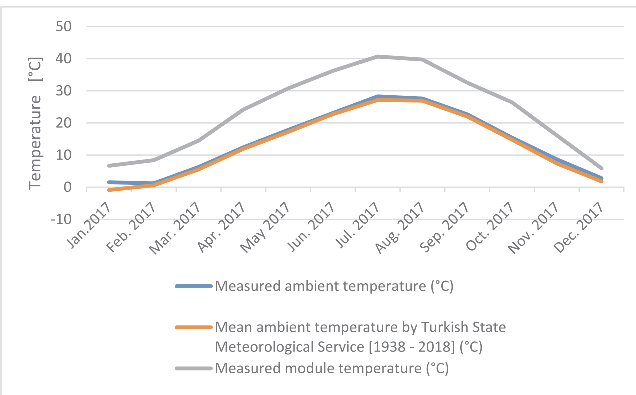

Fig. 4. Monthly variation of temperature values.

GeoModel data source which are informed as 1749 kWh/[m^2.y] on horizontal plane and 1973 kWh/[m^2.y] on module plane. The company GeoModel Solar s.r.o. provides solar radiation data which are determined from measurements taken from five differently positioned satellites. The solar radiation data is supplied with a resolution of 250 m × 250 m at 15 min time intervals.

- The total system efficiency was calculated as 13.54% as explained on Table 4.

Solar energy coming to the module plane (E_{in}), DC electricity generation of the array (E_A) and AC electricity generation to the grid (E_{AC}) are calculated by the following equations:

$$A_{PV,a} = (A_{PV,m}.\ N_m) = (1.94).\ (6764) = 13,\ 122.16[\mathrm{m}^2] \tag{11}$$

$$E_{in} = H_{I,y}.\ A_{PV,a} = (1973).\ (13,\ 122.16) = 25,\ 890[\mathrm{MWh/y}] \tag{12}$$

$$\eta_{Amean} = (0,\ 1623).\ (0,\ 984).\ (0.99).\ (0.908).\ (0.992).\ (0.99) = 0.141[-] \tag{13}$$

$$E_A = E_{in}.\ \eta_{Amean} = (25,\ 890).\ (0.141) = 3650.5[\mathrm{MWh/y}] \tag{14}$$

$$E_{AC} = E_{in}.\ \eta_S = (25,\ 890).\ (0.1354) = 3506.4[\mathrm{MWh/y}] \tag{15}$$

where $A_{PV,a}$ [m^2] is the total area of PV array, $A_{PV,m}$ [m^2] is the unit module area, N_m [–] is the number of modules used on the PV system, $H_{I,y}$ [kWh/(m^2.y)] is the annual solar irradiation on module plane, η_{Amean} is mean array efficiency [–] and η_S is the total system efficiency [–].

η_{Amean} covers the losses due to shading, soiling, deviations from STC, mismatch losses, DC cable losses and module efficiency (Table 4).

By using the equations explained on Section "Performance parameters" and the above calculated energy generations, the performance parameters of the PV system on annual basis were calculated as follows: Array yield, final yield, reference yield, capture loss, system loss, system efficiency, performance ratio, capacity factor and annual final yield were found as 4.69 h/d, 4.51 h/d, 5.41 h/d, 0.71 h/d, 0.18 h/d, 13.54%, 83.4%, 18.8% and 1,645.7 kWh/(kWp.y).

The monthly AC energy generation were also calculated by using the Eq. (16) as shown on Table 5.

$$E_{AC,m} = H_{I,m}.\ \eta_S.\ A_{PV,a}[\mathrm{kWh/m}] \tag{16}$$

where $E_{AC,m}$ [kWh/m] is the monthly AC energy generation, $H_{I,m}$ [kWh/(m^2.m)] is the monthly solar irradiation on module plane, η_S [–] is the total system efficiency and $A_{PV,a}$ [m^2] is the total area of PV array.

Real-time performance analysis of the PV system

In this study, the performance of a 2130.7 kW$_p$ grid connected photovoltaic system was monitored for a one-year period in 2017. It

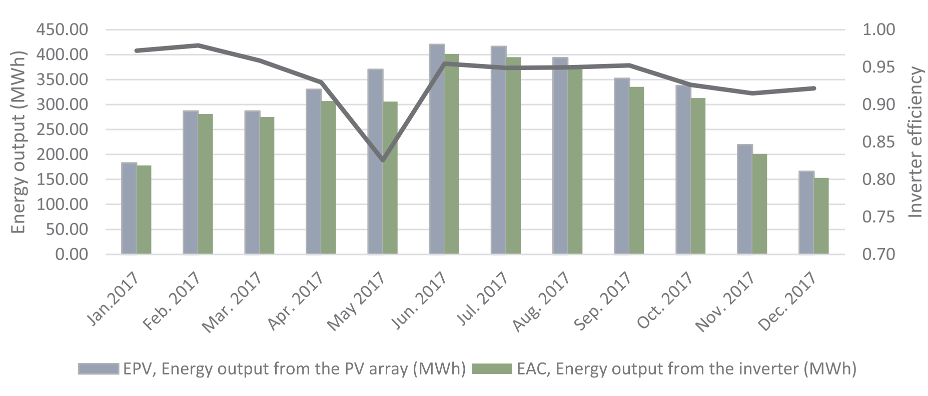

Fig. 5. Monthly energy output and inverter efficiency.

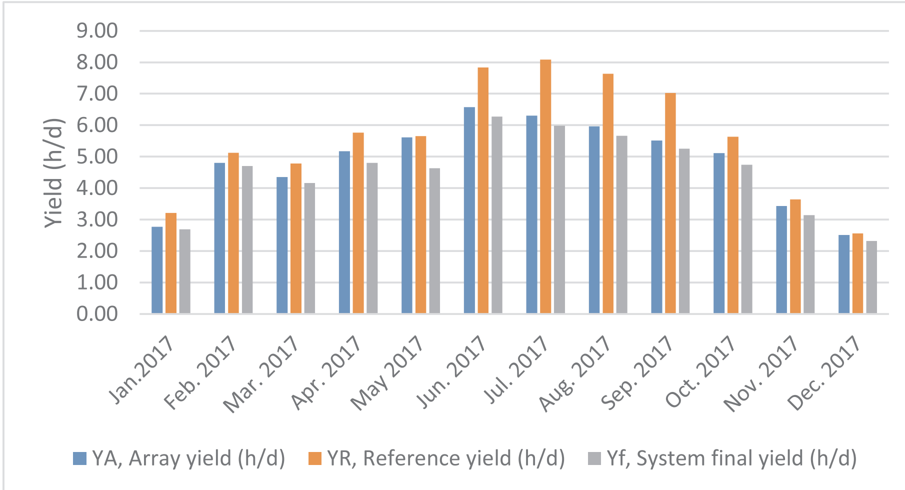

Fig. 6. Monthly reference yield, array yield and final yield.

Table 6
Seasonal reference, array and final yield.

Seasons	Reference Yield (h/d)	Array Yield (h/d)	Final Yield (h/d)
Winter	3.63	3.36	3.24
Spring	5.4	5.04	4.54
Summer	7.85	6.28	5.97
Autumn	5.44	4.69	4.38

Table 7
Seasonal system and capture loss.

Seasons	System Losses (h/d)	Capture Losses (h/d)
Winter	0.13	0.27
Spring	0.51	0.35
Summer	0.31	1.57
Autumn	0.31	0.75

was studied with the aim of conducting a performance analysis of the PV plant.

Meteorological data

Meteorological data for the project location was real-time, gathered throughout the one-year period starting from January and ending in December. Monthly mean insolation on the module plane for the period from January to December 2017 was determined. The highest monthly insolation was observed in July, as 250.74 kWh/(m^2.m), and the lowest insolation in December, as 79.50 kWh/(m^2.m). Mean insolation for each season was also analysed seasonally (winter, spring summer and autumn). The highest insolation was detected in summer (240.79 kWh/(m^2.m)) and the lowest was observed during winter (107.51 kWh/(m^2.m)). In spring and autumn, the amount of insolation was almost the same, at 163.36 kWh/(m^2.m) and 164.43 kWh/(m^2.m), respectively. Monthly insolation on the PV module is shown in Fig. 3. The annual solar insolation is measured as 2,035.77 kWh/(m^2.y) which is a little higher than the predicted data by GeoModel [1973 kWh/(m^2.y)].

Monthly average of the measured ambient and module temperature values is shown on Fig. 4. As seen, the monthly variation of mean ambient temperature values is quite close to the data provided by Turkish State Meteorological Service (DMI). Yearly average of the measured ambient temperature and data provided by DMI are 13.95 °C and 13.08 °C, respectively.

Results of performance analysis

Insolation is the determinant factor of energy generation of the PV system performance. Energy generation is directly associated with this factor. When insolation increases, it is possible to generate more energy.

Energy that is generated by the array is in DC form. However, it needs to be converted into AC to deliver to grid. In this study, the 2130.7 kW_p grid connected PV system generated 3764.47 MWh DC energy in the array throughout the year 2017. However, generated energy was carried to the grid as 3519.98 MWh because of inverter loss. In the monitoring period, electricity generation varied from 153.05

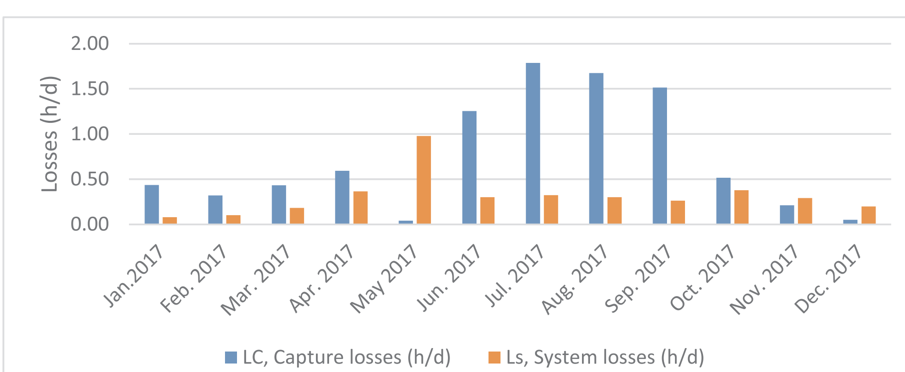

Fig. 7. Monthly average system loss and capture loss.

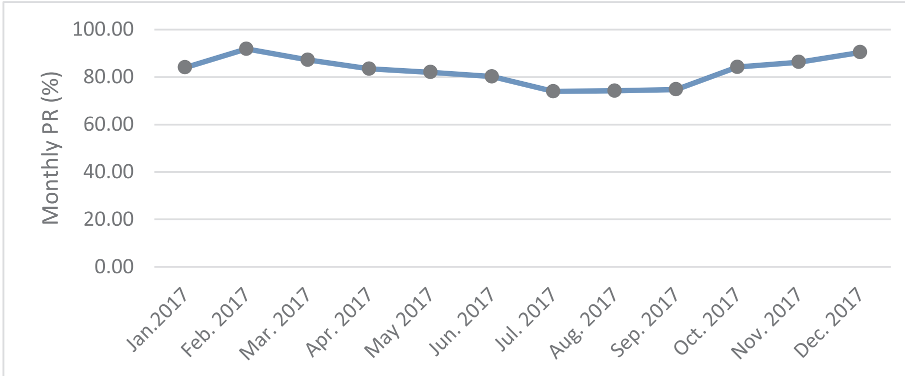

Fig. 8. Monthly performance ratio.

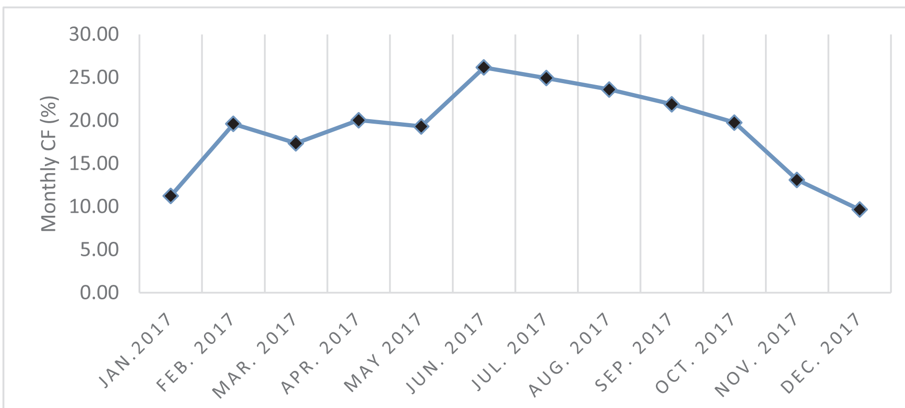

Fig. 9. Monthly capacity factor.

Table 8
Seasonal performance ratio and capacity factor data.

Seasons	Capacity Factor (%)	Performance Ratio (%)
Winter	16.57	88.71
Spring	18.9	84.21
Summer	24.89	76.08
Autumn	18.24	81.69
Annual Average	18.86	81.15

MWh in December to 401.32 MWh in June. Monthly energy generation and inverter efficiency data is shown in Fig. 5. As displayed in Fig. 5, there is an unexpected efficiency loss in May 2017. In May, some of the energy produced by the PV array could not be converted to AC form due to the power limitation. The limitation is required due to the regulations of local distribution companies.

Yield of the PV system over the one-year period was monitored and monthly reference yield, array yield and final yield are displayed in Fig. 6. Reference yield, array yield and final yield were assessed in that regard. In addition, annual final yield was calculated. Reference yield experiences an increasing trend with rising insolation. In the year of 2017, reference yield ranged from 8.09 h/d (July) to 2.56 h/d (December) in accordance with insolation. Annual mean value of reference yield was 5.58 h/d. For array yield and system yield, loss factors were included. Unlike reference yield, maximum array yield and final yield were observed in June, as 6.58 h/d and 6.28 h/d, respectively. While the minimum value of array yield was 2.51 h/d, final yield dropped to 2.32 h/d in December. Annual final yield was calculated as 1652.06 kWh/(kW$_p$.y).

The yield data were also assessed seasonally. While the highest values for yield were achieved in the summer season, the lowest were in the winter season. Table 6 displays seasonal mean values of reference, final and system yield.

Fig. 7 shows monthly average system loss and capture loss data that were gathered over the monitoring period. System loss varied from 0.98 h/d in May to 0.08 h/d in January. Average value of system loss

Table 9
Comparison of Performance Parameters for different PV systems.

Site	Rated Power	Module Type	PR (%), min/mean/max	Y_f (h/d), min/mean/max	Y_a (h/d), min/mean/max	Y_r (h/d), min/mean/max
Mauritania [24]	15 MWp	a-si, µ-si	63.59/67.96/73.56	2.95/4.27/4.94	3.05/4.39/5.07	4.6/6.45/7.15
Crete [23]	171.36 kWp	pc-si	58/67.36/73	1.96/3.66/5.07	2.25/*/6.6	–/5.44/–
Present study	2,130.7 kWp	pc-si	73.92/81.15/91.78	2.32/4.53/6.28	2.51/4.84/6.58	2.56/5.58/8.09
Singapore [25]	142.5 kWp	pc-si	/81/	2.52/3.12/3.75	–/3.86/–	–
Algeria [26]	2.5 kWp	mc-si	66.66/73.82/85.93	3.98/4.88/5.74	–/5.25/–	5.79/6.4/7.68
India [27]	190 kWp	pc-si	55/74/83	1.45/2.23/2.84	–	2.29/–/3.53
Malawi [28]	830 kWp	HIT	75/79.5/83	3.50/4.25/5.02	3.70/4.46/5.27	4.23/5.35/6.12
Oman [29]	1.4 kWp	–	52/65/72	3.15/4.1/4.79	3.47/4.56/5.28	4.65/6.36/7.25

a-si: amorphous silicon, µa-si: micromorph silicon, pc-si: Poly-crystalline silicon, mc-si: mono-crystalline silicon, HIT: heterojunction with intrinsic thin layer.

for the entire period was 0.31 h/d. The total system efficiency is calculated as 13.18%. Contrary to system loss, capture loss exhibited minimum value (0.04 h/d) in May. The highest value and mean value of capture loss were 1.67 h/d in August and 0.74 h/d, respectively.

Seasonal assessment revealed that while the lowest system and capture loss values were recorded in winter, the highest values were observed in spring and summer, respectively. Table 7 shows seasonal system and capture loss data.

Performance ratio and capacity factor were assessed monthly (Figs. 8 and 9, respectively). Performance ratio varied from 91.78% in February to 73.92% in July. Whole year average performance ratio was 81.15%. Capacity factor was directly related to energy production. While maximum value of capacity factor was recorded in June as 26.16%, minimum capacity factor was observed in December as 9.65%.

Both capacity factor and performance ratio were also calculated for each season. These parameters showed significant differences seasonally. The highest and lowest value of capacity factor were in summer and winter, respectively, whereas it was the opposite for performance ratio. Table 8 indicates seasonal changes in performance ratio and capacity factor.

One of the most significant factor affecting PV performance is temperature. The calculated and actually achievable PR is higher in winter because the modules are significantly cooler in winter. Rising of module temperature causes power loss of the PV module. That is the reason why performance ratio reaches the peak value in the winter season when there is not any snow obstacle on the PV modules and takes the minimum value in the summer season [22].

Comparison of photovoltaic systems

A comparison was made as part of this study of photovoltaic power plants which are located on different sites around the world (Mauritania, Crete, Singapore, Algeria, Malawi, Oman and India). Each power plant studied in the literature has been used to make the comparison. In this comparison, rated power, module type, performance ratio, final yield, array yield, and reference yield parameters were used. The reason why the comparison was based on these parameters is that they are the most determinative factors in describing a PV plant performance. Data belonging to the used parameters for the PV plants in eight countries is shown in Table 9.

PV plants that are located in Oman, Mauritania and Crete Island displayed the lowest performance ratio. Their performance ratios were around 65–68% even though Oman, Crete and Mauritania have abundant insolation. Despite the corresponding performance ratio parameters between them, a significant difference can be observed in terms of local environmental characteristics and rated power. Similar to the observation in Oman, Crete and Mauritania, performance ratios of Algeria and India are almost the same, as 73.82% and 74%, respectively, although there are significant inconsistencies in their climates. Present study of the PV plant exhibited the highest performance ratio among the eight countries, with 81.15%. Similar result can also be observed in Malawi, Singapore and present study. In spite of relatively lower PV performance in Algeria and Mauritania, the highest yield data was collected in these two countries due to their high levels of insolation. The lowest final, array, and reference yield values were observed in India. It can be deduced that environmental conditions can be effective factors on the performance of PV plants.

Conclusion

In this article, performance analysis of a 2130.7 kW_p grid connected photovoltaic power plant located in the east part of Turkey was conducted. Besides a simulation study, the large-scale power plant was monitored and real-time data were collected from January to December in 2017. Performance of the PV plant was analysed monthly, seasonally and yearly for the duration. Furthermore, the results of this analysis were compared to seven other grid connected power plants in different locations that have different environmental factors. In light of the data obtained, performance of the PV system was assessed. The conclusions of the analysis of the PV system can be summed up as follows:

- The simulated performance parameters and energy generation values were quite close to the real-time measured ones. For instance, the AC energy delivered to the grid, system efficiency, performance ratio and annual final yield were predicted as 3506.4 MWh/y, 13.54%, 83.4% and 1,645.7 kWh/(kW_p.y), respectively. These values were measured and calculated during the real operation in 2017 as 3519.98 MWh/y, 13.18%, 81.15% and 1,652.06 kWh/(kW_p.y), respectively. Since the measured insolation on the module plane [2035.77 kWh/(m^2.y)] was a little higher than the GeoModel's forecast [1973 kWh/(m^2.y)], the energy generation increased on real operation. On the other hand, the realized performance ratio and system efficiency was a littler lower than estimated.
- Maximum energy generation was detected in summer, where the monthly average was 390.06 MWh, and minimum energy generation was in winter (monthly average: 203.93 MWh).
- Final yield varied from 2.32 h/d to 6.28 h/d and capture loss ranged from 0.04 h/d to 1.79 h/d.
- Energy generation and performance of the PV plant showed significant differences among seasons. While the loss and energy generation displayed peak values in summer, the opposite was observed in the winter season.
- Performance ratio varied from 73.92% to 91.78%, and annual average PR was 81.15%. The figures for the PR took the lowest value in summer and the highest value in winter.

A comparison with seven other countries around the world was also carried out. Each of the grid connected PV plants had specific local environmental characteristics. The comparison revealed that the performance of a PV plant was not only dependent on the intensity of insolation, but that environmental factors also played a significant role on PV plant performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors of this study would like to express their sincere gratitude to the owner of the reviewed PV system for their cooperation, permission and assistance throughout the monitoring period.

References

[1] Arto I, Capellán-Pérez I, Lago R, Bueno G, Bermejo R. The energy requirements of a developed world. Energy Sustainable Develop 2016;33:1–13. https://doi.org/10.1016/j.esd.2016.04.001.
[2] Asafu-Adjaye J. The relationship between energy consumption, energy prices and economic growth: time series from Asian developing countries. Energy Econ 2000;22:615–25. https://doi.org/10.1016/S0140-9883(00)00050-5.
[3] Banda MH, Nyeinga K, Okello D. Performance evaluation of 830 kWp grid-connected photovoltaic power plant at Kamuzu International Airport-Malawi. Energy Sustainable Develop 2019;51:50–5. https://doi.org/10.1016/j.esd.2019.05.005.
[4] Kaygusuz K. Energy for sustainable development: a case of developing countries. Renew Sustain Energy Rev 2012;16:1116–26. https://doi.org/10.1016/j.rser.2011.11.013.
[5] Adaramola MS, Vågnes EET. Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. Energy Convers Manage 2015;90:458–65. https://doi.org/10.1016/j.enconman.2014.11.028.
[6] Nguyen V, Nguyen K, Nguyen D, Nguyen H, Le T. Experimental study on improving performance and emission characteristics of used motorcycle fueled with ethanol by exhaust gas heating transfer system. Energy Sustainable Develop 2019;51:56–62. https://doi.org/10.1016/j.esd.2019.05.006.

[7] Stamford L, Azapagic A. Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy Sustainable Develop 2014;23:194–211. https://doi.org/10.1016/j.esd.2014.09.008.
[8] Höök M, Tang X. Depletion of fossil fuels and anthropogenic climate change – a review. Energy Policy 2013;52:797–809. https://doi.org/10.1016/j.enpol.2012.10.046.
[9] Shafiee S, Topal E. When will fossil fuel reserves be diminished? Energy Policy 2009;37:181–9. https://doi.org/10.1016/j.enpol.2008.08.016.
[10] REN21, 2018. Renewables 2018 Global Status Report. REN21 Secretariat, Paris, France.
[11] Mavsar P, Sredenšek K, Štumberger B, Hadžiselimović M, Seme S. Simplified method for analyzing the availability of rooftop photovoltaic potential. Energies 2019;12(22):1–17. https://doi.org/10.3390/en12224233.
[12] Díez-Mediavilla M, Alonso-Tristán C, Rodríguez-Amigo MC, García-Calderón T, Dieste-Velasco MI. Performance analysis of PV plants: optimization for improving profitability. Energy Convers Manage 2012;54:17–23. https://doi.org/10.1016/j.enconman.2011.09.013.
[13] AlBusairi HA, Möller HJ. Performance evaluation of CdTe PV modules under natural outdoor conditions in Kuwait, 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion (2010) 3468–70.
[14] Tian W, Wang Y, Ren J, Zhu L. Effect of urban climate on building integrated photovoltaics performance. Energy Convers Manage 2007;48:1–8. https://doi.org/10.1016/j.enconman.2006.05.015.
[15] Maghami MR, Hizam H, Gomes C, Radzi MA, Rezadad MI, Hajighorbani S. Power loss due to soiling on solar panel: a review. Renew Sustain Energy Rev 2016;59:1307–16. https://doi.org/10.1016/j.rser.2016.01.044.
[16] Silvestre S, Chouder A, Karatepe E. Automatic fault detection in grid connected PV systems. Sol Energy 2013;94:119–27. https://doi.org/10.1016/j.solener.2013.05.001.
[17] IEC Photovoltaic system performance monitoring—guidelines formeasurement, data exchange and analysis. IEC standard 61724 1998 Geneva, Switzerland.
[18] Mondol JD, Yohanis Y, Smyth M, Norton B. Long term performance analysis of a grid connected photovoltaic system in Northern Ireland. Energy Convers Manage 2006;47:2925–47. https://doi.org/10.1016/j.enconman.2006.03.026.
[19] Sundaram S, Babu JSC. Performance evaluation and validation of 5 MW_p grid connected solar photovoltaic plant in South India. Energy Convers Manage 2015;100:429–39. https://doi.org/10.1016/j.enconman.2015.04.069.
[20] Yadav SK, Bajpai U. Performance evaluation of a rooftop solar photovoltaic power plant in Northern India. Energy Sustainable Develop 2018;43:130–8. https://doi.org/10.1016/j.esd.2018.01.006.
[21] de Lima LC, de Araújo Ferreira L, de Lima Morais FHB. Performance analysis of a grid connected photovoltaic system in northeastern Brazil. Energy Sustainable Develop 2017;37:79–85. https://doi.org/10.1016/j.esd.2017.01.004.
[22] Seme S, Sredenšek K, Štumberger B, Hadžiselimović M. Analysis of the performance of photovoltaic systems in Slovenia. Sol Energy 2019;180:550–8. https://doi.org/10.1016/j.solener.2019.01.062.
[23] Kymakis E, Kalykakis S, Papazoglou TM. Performance analysis of a grid connected photovoltaic park on the island of Crete. Energy Convers Manage 2009;50:433–8. https://doi.org/10.1016/j.enconman.2008.12.009.
[24] Elhadj Sidi CEB, Ndiaye ML, El Bah M, Mbodji A, Ndiaye A, Ndiaye PA. Performance analysis of the first large-scale (15 MWp) grid-connected photovoltaic plant in Mauritania. Energy Convers Manage 2016;119:411–21. https://doi.org/10.1016/j.enconman.2016.04.070.
[25] Wittkopf S, Valliappan S, Liu L, Ang KS, Cheng SCJ. Analytical performance monitoring of a 142.5kW p grid-connected rooftop BIPV system in Singapore. Renewable Energy 47 2012:9–20. https://doi.org/10.1016/j.renene.2012.03.034.
[26] Cherfa F, Hadj Arab A, Oussaid R, Abdeladim K, Bouchakour S. Performance analysis of the mini-grid connected photovoltaic system at Algiers. Energy Procedia 2015;83:226–36. https://doi.org/10.1016/j.egypro.2015.12.177.
[27] Sharma V, Chandel SS. Performance analysis of a 190kWp grid interactive solar photovoltaic power plant in India. Energy 2013;55:476–85. https://doi.org/10.1016/j.energy.2013.03.075.
[28] Banda MH, Nyeinga K, Okello D. Energy for sustainable development performance evaluation of 830 kWp grid-connected photovoltaic power plant at Kamuzu International Airport-Malawi. Energy Sustainable Develop 2019;51:50–5. https://doi.org/10.1016/j.esd.2019.05.005.
[29] Al-Badi AH. Measured performance evaluation of a 1.4 kW grid connected desert type PV in Oman. Energy Sustainable Develop 2018;47:107–13. https://doi.org/10.1016/j.esd.2018.09.007.