

Research Paper

DESIGN AND SIMULATION ANALYSIS OF 1 MWP GRID-CONNECTED PHOTOVOLTAIC SYSTEM AT GAZIANTEP AIRPORT, TURKEY

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Abstract

The use of photovoltaic power plants is gradually increasing in order to reduce energy costs and greenhouse gas emissions at airports. Airports are suitable settlements for the installation of photovoltaic power plants as they have vast and free of shade areas that are not used in aviation activities. In this study, a 1 MWp photovoltaic power plant is proposed for Gaziantep Airport, Turkey. Performance, economic and environmental benefits of the proposed system were analyzed using the PVsyst simulation tool developed by the University of Geneva in Switzerland. The study demonstrates that Gaziantep Airport is suitable to installation of a grid-connected photovoltaic system and has a high solar energy resource. The proposed photovoltaic power plant at Gaziantep Airport is predicted to operate with an annual electricity generation of 1702.09 MWh, 78.6 % annual average performance ratio (PR), 19.43 % average capacity factor (CF) and 4.67 [h/d] annual average daily final yield.

Keywords: Photovoltaic, Gaziantep Airport, Performance, PVsyst.

1. Introduction

Airports have become settlements that consume huge amounts of energy due to the increase in the number of passengers and the comfort requirements of the terminal buildings [1–3]. Therefore, the contribution of the aviation industry to greenhouse gas emissions draws attention all over the world [4]. The most important energy resources used in airports are electricity and fuel. Electricity is usually supplied from the grid. Another possible energy source for airports is renewable energy sources [5–9]. There are many applicable renewable energy alternatives at airports including solar, wind, biomass, geothermal,

hydroelectric and fuel cells [9, 10]. Many technologies have been developed to benefit from solar energy. One of these technologies is photovoltaic (PV) systems. Airport buildings are typically large and horizontal, isolated and free of shading, and have a great potential for the integration of solar PV systems [11]. Today, PV systems tend to be the best technology for airports. Based on the available information, it can be said that PV systems have the best benefit/cost ratio of solar energy alternatives for an airport. Environmental benefits include clean air and less greenhouse gas generation that contributes to climate change [8, 12].

At airports, photovoltaic panels are typically mounted on the underutilized sections of the airfield, on the ground, on building roofs, or on the upper part of vehicle parking areas to cover surface [13]. If an airport is located in a rural or remote location, there is

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a relatively large area of land per unit load within the airport. In this case, the system design should be ground-mounted rather than roof-mounted PV or building integrated (BIPV) [14].

While the installing of PV power plants at airports offers advantages in terms of energy costs and emissions, it also brings some new and unpredictable safety concerns. Safety concerns that may be encountered in the use of PV power plant at airports are glare, radar interference and physical penetration of airspace [12, 15, 16]:

- (i) Glare: Sunlight reflected from solar panels may cause unwanted visual effects on air traffic control towers and aircraft pilots.
- (ii) Radar Interference: Radar interference occurs when photovoltaic panels are placed too close to the radar antenna, interfering with the transmission of signals between the radar antenna and the aircraft or control tower.
- (iii) Physical Penetration: Physical penetration occurs when solar panels penetrate imaginary surfaces that define navigable airspace.

Variety planning and analysis should be made by designers and engineers for all safety concerns before PV power plants are installed to avoid difficult safety issues.

Since the energy consumption at airports is high, it is of great importance to realize energy management with innovative operational strategies for energy saving [17]. Airports usually meet their electrical energy requirement from conventional energy resources that contribute to greenhouse gas emissions. However, the use of solar energy at airports around the world is gradually increasing. Until a decade ago, airports were settlements with solar power plants of several hundred kilowatts, today there are many airports with solar power plants of two, five or ten megawatts [18]. Turkey has a very large potential for PV applications [19]. However, the share of renewable energy in the total energy consumed at airports in Turkey is very low due to the solar energy potential have not been used effectively. Studies should be increased to utilize effectively renewable energy sources at airports which have a high renewable energy potential in Turkey. These studies should include technical issues such as the technical applicability, installation possibilities and performance parameters of the renewable energy system to be installed [8, 9].

Performance parameters of grid-connected PV power plants have been studied by many researchers in recent years. However, there is a limited number of studies in the literature on the performance evaluation

of existing or proposed grid-connected PV power plants at airports. M. Mpholo et al. [20] evaluated the performance of a 281 kWp grid-connected PV power plant installed at Moshoeshoe I International Airport, Lesotho. The results showed that the performance of the plant is satisfactory. It was also stated that the performance of the power plant could be improved with improved operational monitoring of the plant. S. Sukumaran and K. Sudhakar [4] performed the operational performance of the 12 MWp PV power plant at Cochin International Airport in India based on the first year's operating data. The performance of the system was also simulated using PVSyst and SolarGis. The results showed that the performance parameters obtained as a result of the simulation closely match with the measured performance parameters. Sukumaran and Sudhakar [21] proposed a 2 MWp PV power plant for Raja Bhoj International Airport in India. The performance of the proposed power plant was analyzed using the SISIFO simulation tool. It was found that the power plant has an annual electricity generation capacity of 2733.12 MWh and its performance ratio is 85.54 %. A. Azami et al. [17] were investigated the re-design of the Tabriz International Airport in Iran as building integrated photovoltaic (BIPV). As a result of the research, it was concluded that the proposed design might be altered to the existing airport in the future. B. Li [22] evaluated the performance of 8 kWp grid-connected PV systems with seven different PV module technologies in Nanjing, China. The results showed that the performance parameters are dependent on geographical location, PV module type, amount of solar radiation and ambient temperature. M. Banda et al. [23] presented the performance evaluation for the 830 kWp grid-connected PV power plant at Kamuzu International Airport in Malawi. The measured data and the data obtained from the simulation were compared. It was found that the annual average capacity factor was 17.7 % and the performance ratio was 79.5 % for the four-year period measured. P. Kalita et al. [24] carried out the installation feasibility of 2 MW PV solar power plant for eight states in India. The results showed that North-east India has immense potential for PV system installation. B. Prasad et al. [25] explained the design procedure of a 12.4 kWp grid-connected PV power plant using the PVSyst software. S. Sreenath et al. [26] analyzed the technical performance of the 20 MWp PV power plant proposed to be installed at Kuantan Airport in Malaysia, taking into account the glare occurrence using SolarGis software. It was predicted that the proposed system generates 26304

MWh of electricity annually, with a performance ratio of 76.88 % and a capacity factor of 15.22 %.

The aim of this study is to analyze the performance, economic and environmental benefits of the 1 MWp grid-connected PV power plant which is proposed to be installed at Gaziantep Airport to reduce energy costs and CO₂ emission. For this purpose, system design, modelling and simulation of the proposed system was performed using the PVsyst v7.0 software, which has international validity and reliability. Meteorological data such as solar radiation and the ambient temperature of the geographic location where the system will be installed were obtained from Meteoronorm in the PVsyst program. This study helps to predict the technical feasibility of the proposed PV power plant and its economic and environmental benefits before it is physically installed. This article provides a comprehensive analysis of the prediction of competitive performance parameters such as power generation, performance ratio, capacity factor and final efficiency of a proposed PV power plant to be installed at the airport.

2. Materials and methods

2.1. Orientation of photovoltaic modules

Sun path diagram for the geographical location of Gaziantep Airport is shown in Figure 1. On June 22, the sun is in the highest position in the sky, whereas on December 22 the sun is in the lowest position in the sky. Figure 2 shows the tilt and orientation angles of the PV panels in order to maximize the global incident irradiation in the collector plane (GlobInc) and to minimize the loss with respect to the optimum. The loss with respect to optimum is 0 % when the tilt angle and sun azimuth angles are 32° and 0° respectively. Therefore, the simulation was carried out for these tilt and sun azimuth angle values.

2.2. PVsyst software

PVsyst is a package computer software developed by the University of Geneva in Switzerland to perform a technical and economic analysis of PV systems through simulation [19, 27]. The solar radiation data needed to perform the simulation is obtained by specifying the latitude and longitude of the place where the system will be installed [28]. While performing the simulation calculations, the program uses the database containing detailed solar radiation, regional soiling rate, surface reflection rate (Albedo) data, physical and technical characteristics of the

system tools such as the selected module and inverter [19]. PVsyst gives us the energy production, the Sankey diagram showing the array and system losses and simulation reports of the PV power plant to be installed [25].

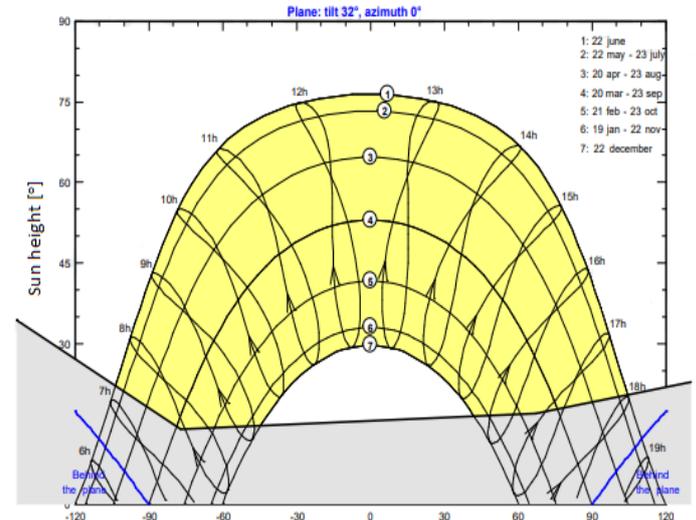


Fig. 1. Sun path diagram for Gaziantep Airport

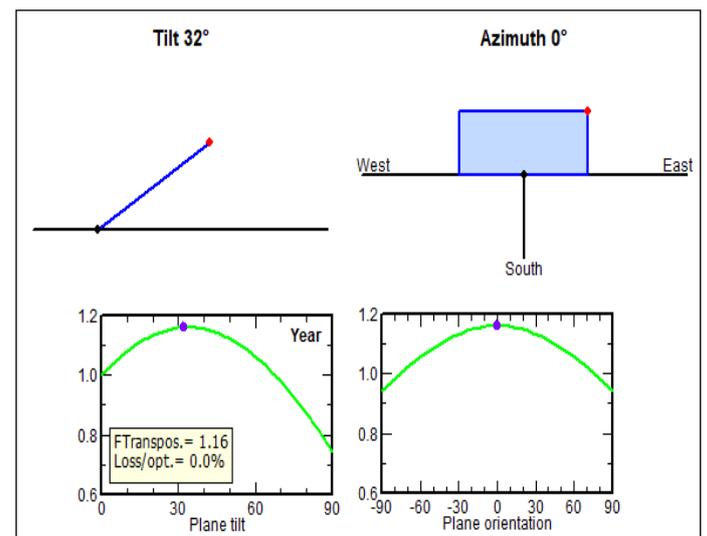


Fig. 2. Optimum tilt and azimuth angle of the proposed PV power plant for Gaziantep Airport

2.3. Gaziantep Airport

Gaziantep International Airport (36°56'52"N 37°28'44"E) is located within the boundaries of Oguzeli district and 20 km southeast of Gaziantep city. It was inaugurated in 1976. The passenger terminal covers an area of 5799 m² and has a parking lot for 400 cars. A new terminal building with 6 bellows is being built next to the existing terminal building of the airport, which will appeal to 5 million people annually [29]. The geographical location of the Gaziantep Airport receives an average of 8.25 h/day and 4.34 kWh/m²-day solar radiation [30]. The average annual

electricity consumption of the airport is predicted to be about 5300 MWh with the commissioning of the new terminal building. Figure 3 shows the view of the Gaziantep Airport from google earth.

The electrical requirement of an airport can be classified as airside energy demand (consisting of the airfield lighting and radio navigation systems, any auxiliary buildings) and landside energy demand (constitutes of the terminal building and other buildings) [4]. Natural gas has been using for heating and domestic hot water at Gaziantep Airport. Electricity has been using for cooling, lighting, room electricity, system pumps and fans in the terminal buildings.

2.4. Description of the proposed PV power plant

Airports usually operate on a 24 hours basis throughout the year, with variable schedules and occupancy rates [31]. However, since solar energy is intermittent, solar power plants at airports must be grid-connected. The 1 MWp PV power plant, which is proposed to be installed to meet some of the electrical

energy requirement of Gaziantep Airport, is designed as grid-connected. There are no energy storage devices in grid-connected PV power plants. Therefore, system losses and system maintenance are less. Grid-connected PV power plants are gaining in popularity day by day since they are both reliable and environmentally friendly systems [25]. Figure 4 shows the schematic diagram of the grid-connected PV power plant.

In addition, the proposed system is designed as ground-mounted near the airport's lodging buildings. The PV power plant is planned to be installed on an area of approximately 17.100 m². The location where the system is planned to be installed receives an annual average of 1587.22 kWh/m²/y global horizontal irradiation throughout the year [30]. The plant consists of 3330 units Si-mono PV modules with 300 kWp power and 21 units with 50 kW (200–850 V) inverters (Figure 5). Modules are placed with an azimuth angle of 0° and a tilt angle of 32°. Technical specifications of the module and inverter are summarized in Table 1 and Table 2, respectively.



Fig. 3. Google earth view of the Gaziantep Airport

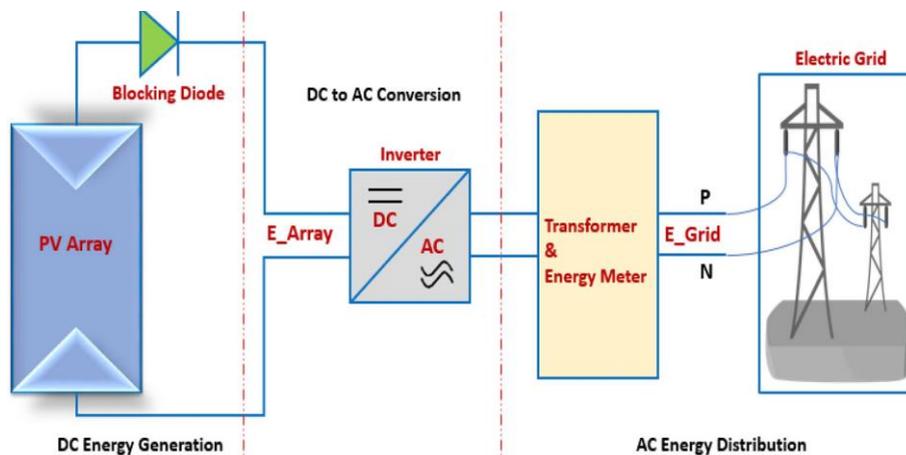


Fig. 4. Schematic diagram of the solar PV system [32]

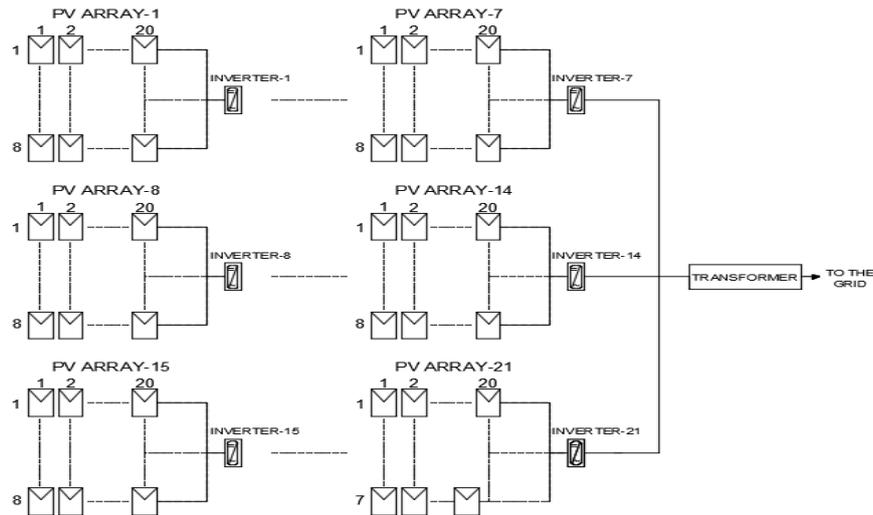


Fig. 5. Schematic diagram of the proposed 1 MWp PV power plant to be installed at Gaziantep Airport

Table 1. Technical specifications of selected PV module

Parameter	Value
Manufacturer	CW Enerji
Model	CWT300-60PM-V
Nominal Power (at STC)	300 Wp
Power Tolarence	±3 %
Short-Circuit Current (I _{SC})	9.79 A
Open Circuit Voltage (V _{OC})	39.9 V
V max power point (V _{mpp})	32.69 V
I max power point (I _{mp})	9.18 A
Sizes	1648×995×35mm, 18 kg
Efficiency (at STC)	18.3 %

Table 2. Technical specifications of selected inverter

Parameter	Value
Manufacturer	Goodwe
Model	GW50K-MT
Nominal PV Power	51.5 kW
Maximum PV Power	60 kW
Maximum PV Current	125 A
Maximum Efficiency	98.89 %
Operating Voltage	200–850 V
Nominal AC Power	50 kVA
Nominal AC Current	80 A
Maximum AC Current	80 A

2.5. The simulation

In order to simulate a grid-connected photovoltaic system using the PVsyst software, the geographical location and meteorological data of the location where the system will be installed must be inserted. Then, the data such as PV panel type, tilt and orientation angles of the PV panels, system design, system power, inverter type, shadings etc. must be entered into the program. The meteorological data used in the simulation were obtained from the Meteonorm software which provides monthly meteorological data for

any place in the world and is embedded in the PVsyst database. PVsyst also allows manual insertion of data if not available in the database. Simulation results were obtained for the whole month. In addition, daily and hourly simulation results were obtained by using synthetically generated meteorological data. Synthetic data generation provides a mean of constructing hourly meteorological data from only monthly known values. As a result of the simulation, array and system losses, as well as meteorological data and energy generation, were obtained. Array and system losses that cause efficiency loss in the PV system are modelled with a number of assumptions in the «Project design>Array and system losses» tab (Table 3). For example, the efficiency loss due to temperature (PV loss due to temperature) is taken into account in PVsyst's calculation algorithm, depending on the ambient temperature, the array temperature and the PV module temperature behaviour.

Table 3. Assumptions for simulation model

Parameter	Assumption
Constant loss factor U _c	20 W/m ² K
Ohmic loss fraction at STC	1.5 %
Module efficiency loss	0.8 %
Power loss at MPP	2 %
Soiling loss factor	0 %

Actual meteorological data (solar irradiation, ambient temperature etc.) for any year in which energy generation occurs with PV systems may be incompatible with the meteorological data used in the simulation. PVsyst explains this situation with the P50–P90 evaluations. The P50–P90 evaluation is a probabilistic approach for the interpretation of the simulation results over several years. P50–P90 represent

different yield levels, for which the probability that the production of a particular year is over this value is 50–90 %. The uncertainty and variability of meteorological data provide the main contribution to the creation of possibilities.

2.6. Cost analysis and payback period

The payback period is an indicator used to evaluate the economic benefit of the proposed system. The payback period is the ratio of the initial investment cost to the annual financial gain. While calculating the initial investment cost of the system, unit prices were obtained from the unit price book of the Ministry of Environment and Urbanization (Table 4). Also, electricity tariff for Gaziantep is approximately 0.09 \$/kWh, including taxes.

Table 4. Unit prices used in calculating the initial investment cost of the proposed PV system

Component	Unit Price (\$/Wp)
PV module	0.370
Inverter	0.078
Structure	0.113
Electrical items	0.062
Design, project and engineering	0.003
Preliminary and pre-operative expenses	0.026
Land	Free
Total	0.652

3. Performance parameters of a PV power plant

Before a PV power plant is physically installed, making a general design assessment and performance analysis using simulation software is very important in terms of economic and technical planning of the plant to be installed. Performance parameters suggested by the International Energy Agency (IEA) and evaluated in this study are energy generation, capacity factor, array, reference and final yield, array capture and system losses, performance ratio, PV module, system and inverter efficiency. In addition, CO₂ balance was evaluated to analyze the environmental benefits of the proposed system.

3.1. Energy generation

Energy generation (E_{AC}) is defined as the amount of energy injected into the grid. Energy generation can be expressed as daily, monthly or yearly. Yearly energy generation is calculated using equation 1 [4, 26].

$$E_{(AC,y)} = \sum_{m=1}^{12} E_{(AC,m)} \cdot \tag{1}$$

3.2. Capacity factor

The capacity factor (CF) is defined as the ratio of the annual AC energy generated by the PV array to the maximum annual energy that the PV array can theoretically generate at full rated power for 24 hours [20, 33, 34].

$$CF = \frac{E_{AC} [kWh]}{P_o [kW] \times 8760 [h]} \times 100. \tag{2}$$

3.3. Array, reference and final yield

The yields of a grid-connected PV system are array yield, reference yield and final yield. Yields can be calculated on a daily, monthly or annual basis. The first of these yields is the array yield (Y_A) and it defines the ratio of DC energy (E_{DC}) generated by the PV array to the total nominal power (P_0) in a certain time period (day, month, year). In this study, equations give monthly average daily yield values. Y_A indicates the time taken by the PV array to generate the DC energy at nominal power (P_0) of PV array [20, 33, 34].

$$Y_A = \frac{E_{DC} [kWh / day]}{P_o [kW]} \tag{3}$$

The second of the yield definitions is the reference yield. The reference yield (Y_R) defines the number of hours that the reference irradiation occurs. It is the ratio of the total amount of irradiation (G_{POA}) on the plane of the array to the amount of irradiation at standard test conditions (STC) (at 25 °C, $G_0 = 1000 \text{ W / m}^2$, A.M. = 1.5).

$$Y_R = \frac{G_{POA} \left[\frac{kWh}{m^2} / day \right]}{G_0 [kW / m^2]} \tag{4}$$

Another yield definition is the final yield. Final yield (Y_F) is obtained by dividing the AC energy (E_{AC}) injected into the grid by the PV system by the nominal power (P_0) of the system.

$$Y_F = \frac{E_{AC} [kWh / day]}{P_o [kW]} \tag{5}$$

3.4. Array capture and system losses

While energy generation takes place in PV systems, many losses occur. These losses are divided into two groups – system losses (L_S) and capture losses (L_C). Capture losses are reduction in radiation level, temperature increase, ohmic wiring loss. System losses are the ones caused by the switching losses in the inverter [20, 33, 34].

$$L_C = Y_R - Y_A, \quad (6)$$

$$L_S = Y_A - Y_F. \quad (7)$$

3.5. Performance ratio

The performance ratio is a parameter that shows the effect of all losses (array and system losses) on the energy injected into the grid. Therefore, the performance ratio is not only an indication of how closely actual performance of solar PV system approaches the ideal performance, but also a parameter that facilitates the comparison of PV systems with each other regardless of geographical location, orientation, tilt angle and nominal power [35]. The performance ratio is formulated as the ratio of final yield to reference yield [20, 33, 34].

$$PR = \frac{Y_F}{Y_R} \times 100. \quad (8)$$

3.6. PV module, system and inverter efficiency

The photovoltaic module efficiency is defined as the ratio of the DC energy generated by the PV array to the global plane of array (G_{POA}) irradiance (kW/m²) on the total PV module surface area [20, 33, 34].

$$\eta_{PV} = \frac{E_{DC} [kWh]}{G_{POA} [kWh/m^2] \times A [m^2]}. \quad (9)$$

System efficiency is defined as the ratio of the AC energy injected into the grid to the global plane of array (G_{POA}) irradiance (kW/m²) on the total PV module surface area [20, 33, 34].

$$\eta_{sys} = \frac{E_{AC} [kWh]}{G_{POA} [kWh/m^2] \times A [m^2]}. \quad (10)$$

Inverter efficiency is defined as the ratio of the effective energy at the output of the array to the energy injected into the grid [20, 33, 34].

3.7. Carbon balance

The carbon balance obtained using PVsyst software allows predicting the amount of CO₂ that will be saved as a result PV system installation. When calculating the amount of CO₂ emission to be saved, not only the CO₂ savings achieved as a result of electricity generated by the PV installation, but also the life cycle emissions (LCE) values that include the production, operation, maintenance and disposal of the PV system components (modules, inverters and supports) installation are taken into account [36].

$$\begin{aligned} \text{Carbon Balance} = & E_{AC} \left[\frac{kWh}{yr} \right] \times \text{Lifetime} [yr] \times \\ & \times \text{Grid LCE} \left[\frac{gCO_2}{kWh} \right] - \text{System LCE} [gCO_2]. \end{aligned} \quad (11)$$

4. Results

Accurately predicting the performance of a PV power plant prior to installation plays an important role in decision-making for the economic investment of the system. Researchers, designers, engineers, and investors need highly accurate predictive modelling and simulation tools to evaluate the performance of the PV systems. In this study, the modelling and simulation of the 1 MWp grid-connected PV system, which is proposed to be installed at Gaziantep Airport was performed using the PVsyst v7.0 software. Simulation results were analyzed and evaluated in terms of performance, economic and environmental benefits. Meteorological data such as GlobHor, DiffHor, wind speed and ambient temperature, were obtained from the Meteonorm file in the PVsyst database and used for this analysis.

Balances and main results of the PV power plant are shown in Table 5. Balances and main results include monthly average values of the horizontal global irradiation (GlobHor), horizontal diffuse irradiation (DiffHor), global incident irradiation in the collector plane (GlobInc), ambient temperature (T_{amb}), effective global irradiation after all optical losses (shadings, IAM, soiling) (GlobEff), effective energy at the output of the array (E_{Array}) and energy injected into the grid (E_{Grid}). Irradiances such as GlobHor, DiffHor, GlobInc, GlobEff are presented in Table 5 because they are the primary variables used in the calculation of energy so-called "Effective incident energy" that the irradiance is effectively reaching the PV cell surface after optical corrections [36]. As can

be seen from Table 5, the annual AC electricity generation of the proposed system is 1702087 kWh. Considering that the annual electricity consumption of the airport will be approximately 5300 MWh with the

commissioning of the new terminal building, the proposed PV power plant can meet approximately 32 % of the total electricity requirement of the airport.

Table 5. Balances and main results

Month	GlobHor [kWh/m ²]	DiffHor [kWh/m ²]	T _{amb} [C°]	GlobInc [kWh/m ²]	GlobEff [kWh/m ²]	E_Array [kWh]	E_Grid [kWh]	PR
January	72.7	31.81	3.29	113.5	96.5	90853	89376	0.788
February	82.4	34.11	4.96	115.1	102.5	95656	94074	0.818
March	141.5	58.02	9.93	172.6	158.5	145418	143041	0.830
April	177.5	67.93	14.17	192.3	177.9	159879	157255	0.819
May	211.7	73.04	20.04	203.8	188.6	165284	162556	0.798
June	243.2	57.10	26.37	222.8	208.7	177484	174489	0.784
July	250.1	52.67	30.93	233.3	218.6	181301	178248	0.765
August	224.3	50.57	30.19	232.0	217.0	180359	177358	0.765
September	182.0	39.42	24.31	218.0	202.3	170847	168000	0.771
October	135.2	38.11	18.41	188.7	171.7	150665	148170	0.786
November	91.3	27.65	10.00	148.0	128.2	116974	115037	0.778
December	72.7	25.35	4.94	126.8	103.2	96074	94481	0.746
Year	1884.5	555.80	16.53	2166.9	1973.7	1730794	1702087	0.786

Figure 6 shows the daily input/output diagram of the proposed PV power plant. There is a direct proportion between the energy injected into the grid and global incident in the collector plane. As we can see from the diagram, the dots are concentrated above 6000 kWh/day. This situation shows that the energy injected into the grid by the system for most of the year will be 6000 kWh/day or more.

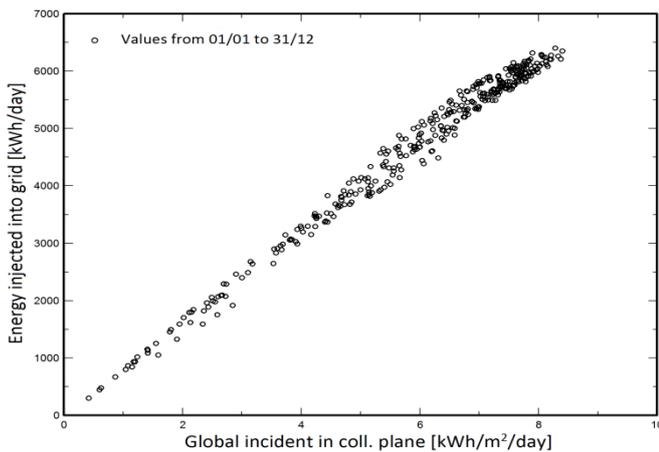


Fig. 6. Daily input/output diagram

The monthly average normalized energy productions of the proposed PV power plant are shown in Figure 7. Normalized energy production in summer months is higher than it is in winter months. Annual average daily produced useful energy, system loss and collection loss are 4.67 kWh/kWp/day,

0.08 kWh/kWp/day, 1.19 kWh/kWp/day respectively. Collection losses are approximately fifteen times higher than the system losses.

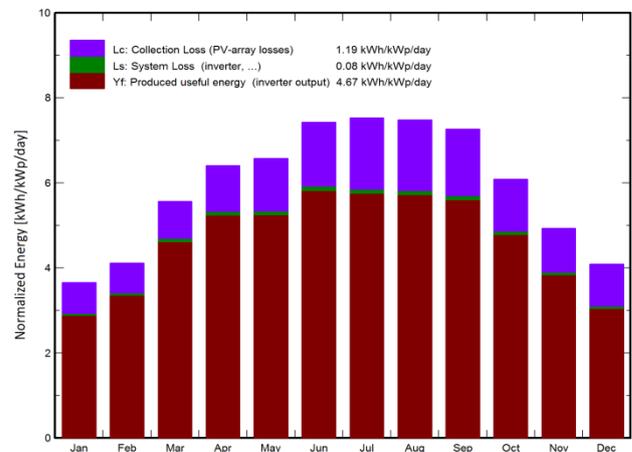


Fig. 7. Normalized energy productions per installed kWp

Figure 8 shows the monthly change in performance ratio (PR) and capacity factor (CF). The performance ratio of the system varies from 74.6 to 83 %, while the capacity factor varies from 12.01 to 24.23 % throughout the year. The performance ratio is high in February, March and April, while it is relatively low in July, August and December. The annual average performance ratio of the proposed 1 MWp Si-mono photovoltaic system is 78.6 %. The high-performance ratio indicates that the plant will operate

efficiently. The plant operates with an average capacity factor of 19.43 %.

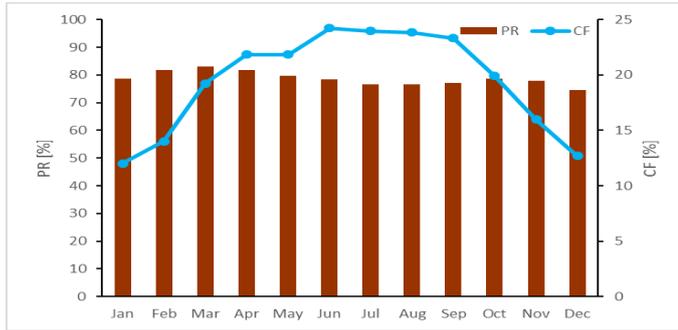


Fig. 8. Monthly change of performance ratio and capacity factor

Figure 9 shows the effect of cell temperature and incident global irradiation on the proposed PV cell efficiency. As the irradiation increases, cell efficiency grows up to a certain extent and then remains almost constant. The effect of the cell temperature on efficiency is different from the irradiation. The PV cell efficiency decreases as the cell temperature increases at the same irradiance value. The PV cell efficiency is 18.3 % on STC.

Inverter efficiency used in photovoltaic systems varies according to the DC power at the inverter input. The technical specifications of the selected inverter are given in the Table 2 and the inverter efficiency curve is shown in Figure 10. The efficiency of the inverter is 98.32 % at 50 kW DC power, and it reaches maximum inverter efficiency at 25 kW DC power (98.69 %). Inverter efficiency is maximum in almost over the entire operating ranges. This situation shows that the selected inverter size is optimal. The inverter efficiency starts to drop dramatically at values below 2.5 kW DC power. Variations in inverter efficiency have a significant influence on the energy performance of the system.

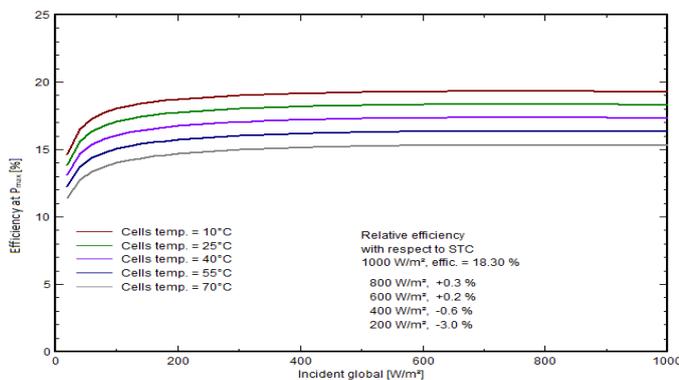


Fig. 9. The effect of cell temperature and incident global irradiation on PV cell efficiency

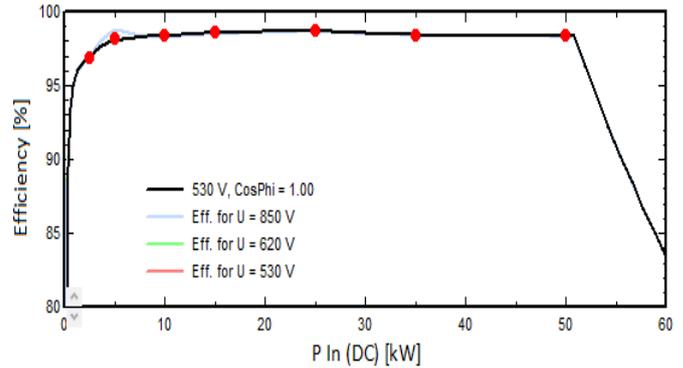


Fig. 10. The effect of DC power at inverter input on inverter efficiency

Loss diagram of the proposed 1 MWp grid-connected PV power plant for Gaziantep Airport is shown in Figure 11. The highest loss in the plant comes from PV loss due to temperature. Total energy generation after losses due to shadings (far and near shadings) and IAM is 1972 MWh. Effective energy at the output of the array is achieved as 1738 MWh after the PV losses due to temperature and irradiance level, mismatch loss, ohmic wiring loss. The losses so far are called collection losses. Then energy injected into the grid is achieved as 1702 MWh due to inverter losses.

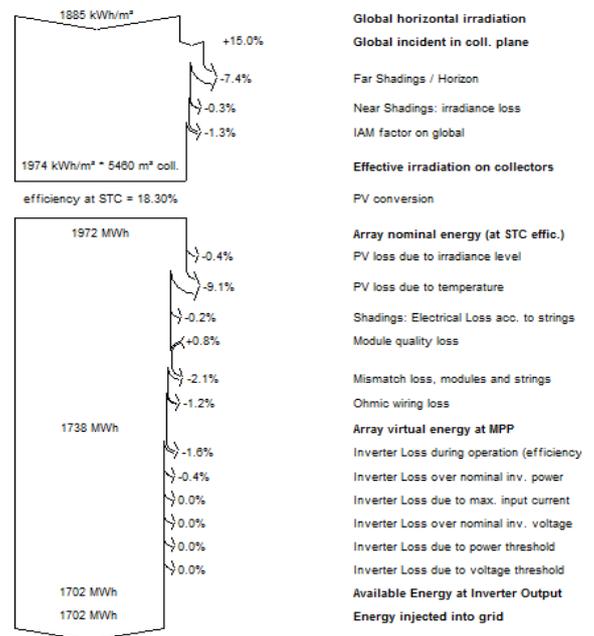


Fig. 11. Loss diagram of the proposed system over the year

Figure 12 shows the yearly CO₂ emission savings of the proposed PV power plant for Gaziantep Airport. According to the simulation results, if 1702 MWh/yr energy, which is predicted to be generated by the PV power plant, is generated by PV system instead of conventional energy sources, the total CO₂ emission saving for 30 years is 19838.9 tons. Since the CO₂

generated as a result of the production of PV system components (modules, inverters and supports) is taken into account, the saved CO₂ emission starts with a negative value and then increases linearly for 30 years.

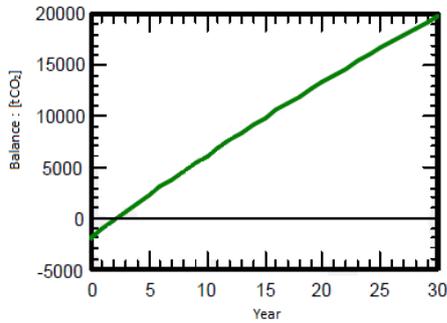


Fig. 12. Yearly saved CO₂ emission from the proposed system

The monthly change of the array yield, reference yield, final yield, ambient temperature and plane of array irradiance are presented in Figure 13. All values increase in the summer months and decrease in the winter months. Both the ambient temperature and the plane of array irradiance reach their highest value in July. The annual average daily final yield, array yield and reference yield are 4.67, 4.75 and 5.94 [h/d] respectively.

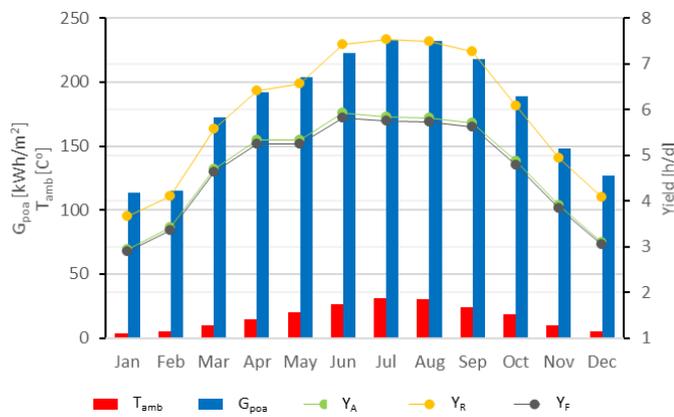


Fig. 13. Monthly change of ambient temperature, a plane of array irradiance and yields

Figure 14 shows a monthly change of the effective energy at the output of the array (E_{DC}), energy injected into the grid (E_{AC}) and the plane of array irradiance. The lowest energy generation occurs in January while the highest energy generation occurs in July when the plane of array irradiance is at its highest value. The annual total E_{DC} is 317 kWh/m² while the E_{AC} is 311.74 kWh/m² due to inverter losses.

Figure 15 shows the monthly change of PV module and system efficiency. The highest PV module and system efficiencies are 15.42 and 15.16 % in

March while the annual average values are 14.62 and 14.37 %, respectively. Energy efficiency values are also affected by seasonal weather changes such as performance ratio. As expected, PV module efficiency is higher than system efficiency throughout the year.

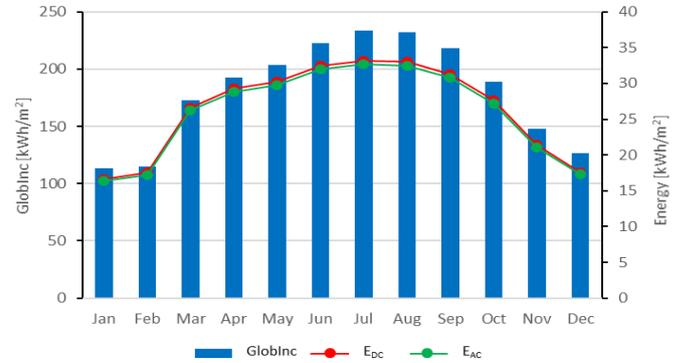


Fig. 14. Monthly change of the energy generation and plane of array irradiance

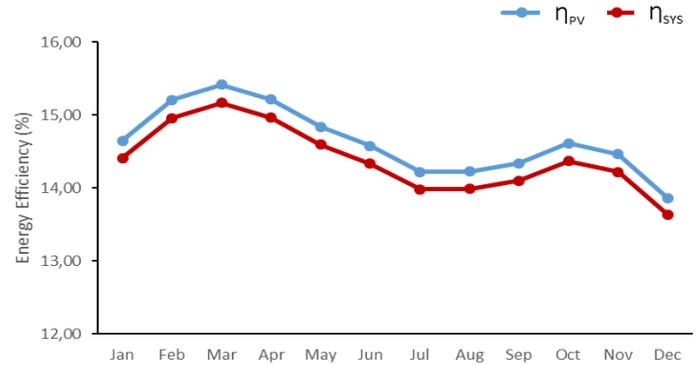


Fig. 15. Monthly change of PV module and system efficiency

Figure 16 shows the variation of the capture and system losses with ambient temperature. The losses increase linearly with growth in ambient temperature. Linear correlation coefficient values show that there is a close relationship between variables. This proves that high ambient temperatures have an effect on the capture and system losses in PV systems. Capture losses range from 0.69 to 1.67 h/day while system losses range from 0.05 to 0.1 h/day. Annual average daily values of capture and system losses are 1.19 and 0.08 h/day, respectively.

Table 6 shows the comparison of the performance parameters predicted for Gaziantep Airport with the performance parameters of other airports in the literature. While making the comparison, both the airports with the proposed system installation and the airports with the installed system are taken into consideration. The results show that the performance parameter values obtained for Gaziantep Airport are sufficiently well. Additionally, results are consistent with the other studies in the literature.

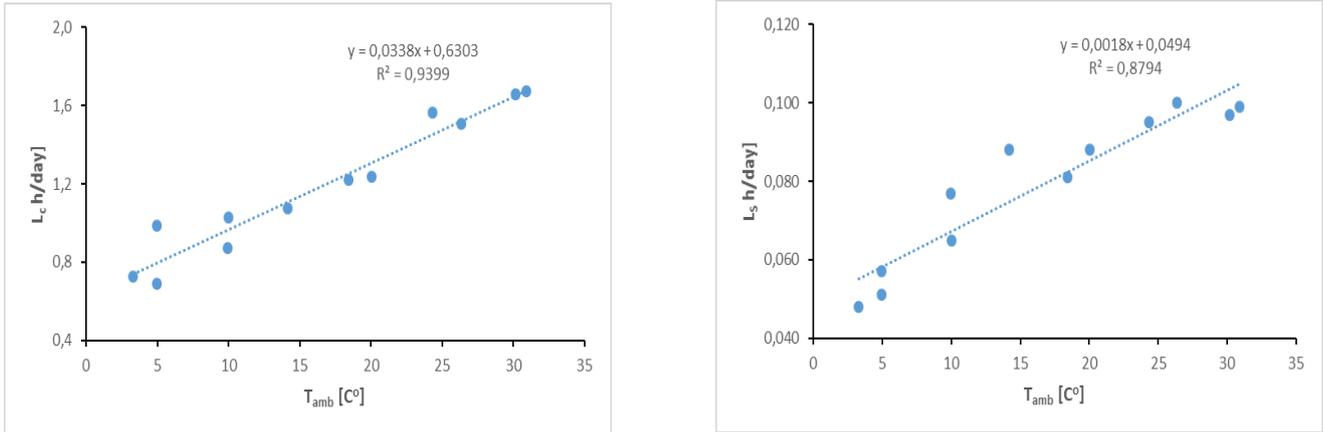


Fig. 16. Variation of the capture and system losses with an ambient temperature

Table 6. Comparison of performance parameters

Airport	Capacity (kWp)	Installed Proposed	PR [%]	CF [%]	Y _F [h/day]	Reference
Cochin International Airport, India	12.000	Installed	86.5 6	20.12	5.44	[4]
Kamuzu International Airport, Malawi	830	Installed	79.5	17.7	4.25	[23]
Moshoeshoe I International Airport, Lesotho	281	Installed	70	17.2	4.11	[20]
Raja Bhoj International Airport, India	2.000	Proposed	85.5 4	15.82	3.74	[21]
Kuantan Airport, Malaysia	20.000	Proposed	76.8 8	15.22	3.6	[26]
Gaziantep Airport, Turkey	1.000	Proposed	78.6	19.43	4.67	Present study

In this study, besides the technical and environmental evaluation of the 1 MWp PV power plant proposed to be installed at Gaziantep Airport, the economic evaluation was made. For this purpose, the initial investment cost and the payback period of the system were calculated. The annual energy generation of the proposed system is 1702087 kWh. Considering the initial investment cost, the proposed system payback period is found to be 4.26 years.

5. Conclusions

In this study, the performance analysis, economic and environmental benefits of the proposed for installation 1 MWp grid-connected PV power plant to reduce the energy costs and CO₂ emissions of Gaziantep Airport are evaluated. The main results obtained are given below:

- (1) Gaziantep Airport has a great potential for PV system installation, as it has vast, discrete and free of shade areas and high solar radiation potential. In addition, these areas are not the ones where system installation is inconvenient in terms of flight safety.
- (2) The proposed PV power plant can meet 32 % of the annual electricity requirement of the airport.

- (3) PV modules should be placed with 32° tilt angle and 0° azimuth to receive maximum solar radiation.
- (4) According to the simulation results, it is predicted that 1702.09 MWh/yr energy will be generated in case of the proposed PV power plant installation at Gaziantep Airport. This will provide with great economic savings to the airport in the long run.
- (5) It is observed that the energy generated on many days of the year will be over 6000 kWh/day.
- (6) A total of 19838.9 tons of CO₂ emission is saved in 30 years compared to conventional energy sources.
- (7) The proposed PV power plant operates with an average performance ratio of 78.6 % and capacity factor of 19.43 %.
- (8) The efficiency of the selected PV cell is 18.3 % in standard test conditions (STC). This efficiency value decreases with increasing temperature whereas it increases rapidly up to 200 W/m² radiation value at all temperature and then remains almost constant.
- (9) The efficiency of the selected inverter is 98.32 % at 50 kW DC power and 98.69 % at 25 kW DC power. Inverter efficiency is maximum in almost

- over the entire operating ranges. This shows that the proposed inverter size is optimal.
- (10) The loss diagram demonstrates that 16.5 % of the global incident in the collector plane is converted to energy injected into the grid.
 - (11) The annual average daily final yield of the proposed system is 4.67 [h/d], the array yield is 4.75 [h/d], and the reference yield is 5.94 [h/d].
 - (12) The effective energy at the output of the array and the energy injected into the grid increase with the plane of array irradiance. The highest and lowest energy generation occurs in July and January, respectively.
 - (13) There is a close relationship between ambient temperature and losses (capture and system).
 - (14) The annual average module efficiency is 14.62 %, and the system efficiency is 14.37 %.
 - (15) Considering the annual energy generation and initial investment cost of the proposed system, payback period is found as 4.26 years.
 - (16) The performance parameters predicted for Gaziantep Airport are sufficiently well and coincide with the other studies in the literature.
 - (17) Simulations can be reproduced by modelling different PV modules, inverters, tilt and azimuth angle etc. In this way, the optimum system design can be made.
 - (18) Safety concerns and economic feasibility aspects should be analyzed and evaluated in detail before installing a PV power plant at Gaziantep Airport.

Nomenclature

A	Total PV module surface area
AC	Alternating current
CF	Capacity factor
DC	Direct current
E_{AC}	Energy injected into the grid
E_{DC}	Effective energy at the output of the array
G_{POA}	Solar irradiance on the plane of array
G_0	Reference irradiance
L_C	Array capture loss

L_s	System loss
P_0	Nominal power
PR	Performance ratio
STC	Standard test condition
T_{amb}	Ambient temperature
Y_A	Array yield
Y_F	Final yield
Y_R	Reference yield
η_{pv}	PV module efficiency
η_{sys}	System efficiency

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