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Statistical distribution of solar plant power with PV modules subject to failure

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Abstract

It is important to model the probability distribution of solar power to draw conclusions for installing a solar plant. The amount of solar power is depending on solar radiation. In this paper, we deal with the statistical distribution of the power generated by a system of PV modules subject to failure. We obtain some characteristics of the system considering the

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reliability of modules. We model the mean power and provide the optimum number of PV modules that need to be installed on the power plant. We present a real data analysis for a specific location in Izmir, Türkiye.

Subject Classification: *60E05, 90B25.*

Keywords: *Photovoltaic (PV) system, Solar power, Distribution function, Reliability, Optimization.*

1. Introduction

Renewable energy sources exist in nature and are constantly renewing themselves without any production process. They are eco-friendly, unlimited, and free with no or little environmental impact. One of the renewable energy sources is solar energy which is widely used around the world. Photovoltaic (PV) systems directly convert solar energy into electricity with no carbon dioxide emissions or any other air pollutants. The power generated by a PV system depends on the characteristics of solar irradiation and weather conditions. This stochastic nature of power systems has prompted researchers to use probabilistic and statistical techniques.

In a power system, modeling the theoretical distribution of the power enables one to obtain all the characteristics and it is significant in making decisions in the planning and installation procedures of the power plant. In the setting of the PV power modeling, [1] developed a model representing a relationship between the power output and the solar irradiation. [2] and [3] used this model for the reliability evaluation of a PV system and detailed how the distribution of solar irradiation is used in the reliability evaluation. For detailed information on the PV power, see the review study of [4]. There are some studies on the reliability of photovoltaics and wind energy sources. [5] provided a review study for the reliability evaluation methods and reliability indices for PV systems. [6] developed a power output model for a PV generation system using a probabilistic technique. Recently, [7] focused on the theoretical distribution of power by a wind plant considering the reliability of the wind turbine. [8] considered the dependence between turbine availability and the wind speed and derived the distribution of the wind farm power. [9] studied the theoretical distribution of hybrid solar/wind power systems considering the reliability of components in the system. [10] presented reliability models for solar energy systems in which PV modules have various levels of operational performance.

There are papers available in the literature where modeling the relationship between solar radiation and power output and how to evaluate reliability indices are the focus of attention. However, the amount of power generated by a PV system depends on both solar irradiation and reliability defined as the probability of PV modules performing their task in a certain period. Therefore, in modeling the power generation of the PV system, it is necessary to consider both solar irradiation, which is a source of randomness, and the working/failure state of the PV module. Contrary to the previous literature, which dealt with the problem using the model given by [1], we formulated the statistical distribution function of power in our study. To the best of our knowledge, there has been no study that derives the theoretical distribution function of the power generated by a solar plant with PV modules subject to failure. This approach will allow us to calculate probabilities about solar power capacity for the required production with a given level of reliability threshold and estimate various characteristics. Moreover, using the power distribution formulated in this study, the optimum number of PV modules that must be installed in a plant can be easily found depending on the reliability of the modules. Our aim is to make important inferences about the region before the solar plant is established.

The paper is organized as follows: In Section 2, we give some preliminaries for the PV power output model, which shows the relationship between solar irradiation and the power output. In Section 3, we obtain the statisticsl distribution of the solar plant power for a given reliability value of the PV module. In Section 4, we present a real data analysis using the data obtained from the PVGIS interactive tool for a specific location in Izmir, Türkiye. Finally, in section 5, we give the conclusion of the study.

Notation

The following notations will be used throughout the paper.

N: The number of PV modules.

G_{bi}: Global solar irradiation random variable (W/m^2).

G_s: Solar irradiation in a standard environment (W/m^2).

R_c: The certain irradiation point (W/m^2).

P_{sn}: Rated capacity of a PV module (W).

P_{PV}: The power generated by a PV module.

P_T: The total power random variable generated by a solar plant.

$F_{G_{bi}}$: Cumulative distribution function (cdf) of G_{bi}.

$f_{G_{bi}}$: Probability density function (pdf) of G_{bi}.

$W_N(p_t)$: The cdf of power generated by a solar plant.

$w_N(p_t)$: The pdf of power generated by a solar plant.

$W_N(p_t;p)$: The cdf of power generated by a solar plant with N modules is subject to failure.

$w_N(p_t;p)$: The pdf of power generated by a solar plant with N modules subject to failure.

μ_0: The mean power generated by a single PV module.

μ_T: The mean power generated by a solar plant.

2. Preliminaries

In this section, we present the power output model that will be used in the derivation of the proposed model. The power of a PV module depends on solar irradiation, which is a random variable. Given the solar irradiation random variable G_{bi}, Eq. (1) represents the relationship between the solar irradiation and the power output of a PV module, P_{PV}, [2].

$$P_{PV} = H(g_{bi}) = \begin{cases} P_{sn}\frac{g_{bi}^2}{G_s R_c} & ,0 \leq g_{bi} < R_c \\ P_{sn}\frac{g_{bi}}{G_s} & ,R_c \leq g_{bi} < G_s \\ P_{sn} & ,g_{bi} \geq G_s. \end{cases} \quad (1)$$

In other words, when the solar irradiation is between zero and a certain irradiation point R_c, the module generates power and there is a quadratic relationship between the solar irradiation and the power. When the solar irradiation is between R_c and the solar irradiation in a standard environment, G_s, then the module generates power and there is a linear relationship between the solar irradiation and the power. As it is shown in Figure 1, if the solar irradiation is greater than G_s, the module generates power at a constant rate, P_{sn}.

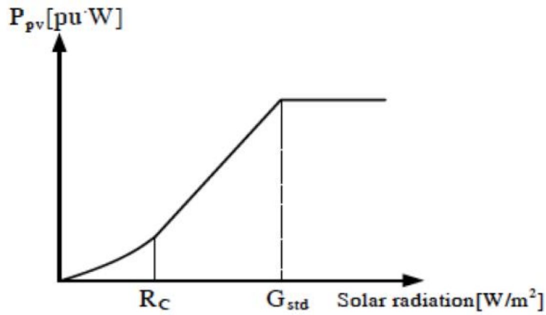

Figure 1
Power output model of a PV module [2]

3. Distribution function of the solar plant power

Let P_T be the total power generated by a plant and G_{bi} be the solar irradiation random variables with the cdf $W_N(p_t)$ and $F_{G_{bi}}(g_{bi})$, respectively. Given the relationship between the solar irradiation and the power output of a PV module in Eq. (1), the total power by the plant that consists of N independent and identical PV modules can be defined as follows:

$$P_T = NP_{PV} = NH(g_{bi}). \quad (2)$$

Then, using the Eq. (2), we have $P_{PV} = H(g_{bi}) = P_T/N$. To obtain the cdf of the solar plant power, Eq. (1) can be re-expressed by the inverse power function for the defined regions given below:

$$H^{-1}(p_t/N) = \begin{cases} H_1^{-1}(p_t/N) = \left(\frac{p_t G_s R_c}{NP_{sn}}\right)^{1/2} & ,0 < p_t < NP_{PV_1}, \\ H_2^{-1}(p_t/N) = \frac{p_t G_s}{NP_{sn}} & ,NP_{PV_1} \leq p_t < NP_{sn}, \end{cases} \quad (3)$$

where $P_{PV_1} = P_{sn}\frac{g_{bi}^2}{G_s R_c}$, i.e., P_{PV_1} is the first part in Eq. (1). Therefore, using (1) and (3), the corresponding cdf of the power generated by the solar plant, $W_N(p_t)$, can be defined as the following piecewise function:

$$W_N(p_t) = \begin{cases} F_{G_{bi}}\left(\left(\frac{p_t G_s R_c}{N P_{sn}}\right)^{1/2}\right) & , 0 < p_t < N P_{PV_1}, \\ F_{G_{bi}}\left(\frac{p_t G_s}{N P_{sn}}\right) - F_{G_{bi}}(R_c) & , N P_{PV_1} \le p_t < N P_{sn}, \\ 1 & , p_t = N P_{sn}. \end{cases} \tag{4}$$

For the derivation of the pdf of P_T using (4), we will need to use the Dirac delta function $\delta(\cdot)$ to address the probabilities of solar power being exactly equal to NP_{sn} (see, for example, [7]). For other values of P_T, the traditional change of variable method will be used. The corresponding pdf of P_T when $0 \le p_t \le NP_{sn}$ is defined as follows:

$$\begin{aligned} w_N(p_t) = {} & f_{G_{bi}}(H_1^{-1}(p_t/N))\frac{dH_1^{-1}(p_t/N)}{dp_t} + f_{G_{bi}}(H_2^{-1}(p_t/N))\frac{dH_2^{-1}(p_t/N)}{dp_t} \\ & + (1 - F_{G_{bi}}(G_s))\delta(p_t - NP_{sn}), \end{aligned} \tag{5}$$

where $f_{G_{bi}}(.)$ is the pdf of the solar irradiation evaluated at $H_j^{-1}(p_t/N)$, $j = 1,2$.

3.1 *Statistical distribution of solar plant power with PV modules subject to failure*

The main purpose of this section is to derive the distribution of the power generated by a solar plant considering the reliability of PV modules. The total power of the solar plant is defined as $P_T = H(g_{bi}, \mathbf{X})$, where G_{bi} is the solar irradiation random variable and $\mathbf{X} = (X_1, X_2, \dots, X_N)$ is a vector, which defines the state of PV modules, failure, or working. Suppose that during a fixed period, ith PV module works with probability p, that is $P\{X_i = 1\} = p$, $i = 1, \dots, N$. Thus, the parameter p indicates the reliability of the PV module. Let us consider a solar plant that consists of N independent and identical PV modules installed. Then, the cdf of the power generated by the solar plant can be calculated by the following:

$$W_N(p_t; p) = P\{P_T \le p_t\} = \sum_{i=0}^{N} \binom{N}{i} p^i (1-p)^{(N-i)} W_i(p_t), \tag{6}$$

where

$$W_i(p_t) = \begin{cases} 0 & , p_t < 0 \\ K_{1,i}(p_t) = F_{G_{bi}}\left(\left(\frac{p_t G_s R_c}{i P_{sn}}\right)^{1/2}\right) & , 0 \le p_t < i P_{PV_1} \\ K_{2,i}(p_t) = F_{G_{bi}}\left(\frac{p_t G_s}{i P_{sn}}\right) - F_{G_{bi}}(R_c) & , i P_{PV_1} \le p_t < i P_{sn} \\ 1 & , p_t \ge i P_{sn}. \end{cases} \tag{7}$$

Note that the functions $K_{1,i}(p_t)$ and $K_{2,i}(p_t)$ are defined using Eq. (4). It is obvious that $W_0(p_t) = 0$ if $p_t < 0$ and $W_0(p_t) = 1$ if $p_t \ge 0$.

For simplicity, the cdf of the power output by a single PV module can be written as follows:

$$W_1(p_t;p) = \begin{cases} 0 & ,p_t < 0 \\ (1-p) + pK_{1,1}(p_t) & ,0 \le p_t < P_{PV_1} \\ (1-p) + pK_{2,1}(p_t) & ,P_{PV_1} \le p_t < P_{sn} \\ 1 & ,p_t \ge P_{sn}. \end{cases} \tag{8}$$

Then, the corresponding pdf which is obtained using (8) is given below:

$$w_1(p_t;p) = pk_{1,1}(p_t) + pk_{2,1}(p_t) + w_1(0;p)\delta(p_t) + w_1(P_{sn};p)\delta(p_t - P_{sn}), \tag{9}$$

where $\delta(\cdot)$ is the Dirac delta function. In Eq. (9), $w_1(0;p)$ defines the probability that no power is generated by the module. This case arises only when modules do not work. So, $w_1(0;p) = 1 - p$. Thus, (9) becomes

$$w_1(p_t;p) = pk_{1,1}(p_t) + pk_{2,1}(p_t) + (1-p)\delta(p_t) + p[1 - F_{G_{bi}}(G_s)]\delta(p_t - P_{sn}). \tag{10}$$

Based on (10), the mean power generated by a single PV module is found as the following:

$$\mu_0 = p\left[\int_0^{P_{PV_1}} p_t k_{1,1}(p_t)dp_t + \int_{P_{PV_1}}^{P_{sn}} p_t k_{2,1}(p_t)dp_t + P_{sn}(1 - F_{G_{bi}}(G_s))\right]. \tag{11}$$

Thus, the mean power generated by the solar plant that consists of N identical PV modules is computed by $\mu_T = N\mu_0$.

4. Real data study

In order to apply the theoretical findings, data was obtained from the PVGIS interactive tool (https://ec.europa.eu/jrc/en/pvgis) for the location of Izmir, Türkiye (38.367° Latitude, 27.202° Longitude). Typical meteorological year (TMY) data of solar radiation for specific months are used in the analysis for the given location, covering the period (2007-2016). The PVGIS interactive tool provides data from high-quality measurement sensors and has been publicly available for a long period of time. In this tool, global horizontal solar irradiation data (W/m^2) are measured during daylight hours. Therefore, the solar radiation data obtained is divided by the day length (i.e., daily solar radiation =(solar radiation)/day length).

Since the beta distribution is widely used for the statistical modeling of the solar irradiation data ([11, 12, 13] and [14]), we used the beta distribution with the parameters $\alpha, \beta \ge 0$. Maximum likelihood estimates of the α and β parameters, Anderson-Darling (AD) goodness-of-fit test results and estimated mean solar irradiance are presented in Table 1. As shown in Table 1, the solar irradiation data for each month fits the beta distribution. The mean solar irradiation values are estimated by the formula $\frac{\hat{\alpha}}{\hat{\alpha}+\hat{\beta}}$, where $\hat{\alpha}$ and $\hat{\beta}$ are parameter estimates.

Table 1
Estimates of parameters of the solar irradiation distribution and the p-values of AD test

Month	$\hat{\alpha}$	$\hat{\beta}$	Mean solar irradiation (kW/m^2)	p-value
January	4.20460	15.08123	0.218015	0.4269478
February	4.75891	10.16528	0.318872	0.5377671
March	2.93630	4.95088	0.372288	0.4880588
April	6.31650	7.49185	0.457441	0.5404154
May	9.31303	9.24445	0.501848	0.0545316
June	41.28674	36.67319	0.529589	0.7901044
July	286.60568	200.63740	0.588219	0.2779499
August	92.71945	76.53802	0.547801	0.2227270
September	150.33816	148.14115	0.503680	0.2008657
October	7.69043	12.56987	0.379581	0.1584497
November	101.04814	186.60547	0.351284	0.9247952
December	4.74844	18.63601	0.203060	0.5894238

For this application study, the rated capacity of the PV module is assumed to be $P_{sn} = 280\ W$, the solar irradiation in a standard environment is $G_s = 1000\ W/m^2$, and the certain irradiation point is $R_c = 150\ W/m^2$. Then, from [7], the cdf of the power generated by a single PV module can be written as the following:

$$W_1(p_t;p) = \begin{cases} 0 & , p_t < 0 \\ (1-p) + pK_{1,1}(p_t) & , 0 \le p_t < 42 \\ (1-p) + pK_{2,1}(p_t) & , 42 \le p_t < 280 \\ 1 & , p_t \ge 280. \end{cases} \tag{12}$$

In Table 2, we compute the reliability values for each month of the year when $p = 0.95$ using (6). Recall that the reliability is defined as $P\{P_T > p_t\} = 1 - P\{P_T \le p_t\} = 1 - W_N(p_t;p)$, which is the probability that N PV modules produce power (W) greater than the desired level p_t. It is seen that the probability of producing power more than $150\ W$ is 0.49587 in the plant that consists of two PV modules for any day of January while the probability of the same event is 0.73553 for any day of March. Since the cdf value for $450\ W$ with two modules is equal to 1 for any day of July, then, the reliability value is obtained at zero and the plant is producing power at full capacity. As expected, the reliability values decrease for the same number of PV modules when the level of producing power is increasing. Also, the reliability values are increasing at the same level of producing power for each monthwhen the number of PV modules has been increasing.

As an illustration, we give the cdf graph in Figure 2 that gives the probabilities of achieving the desired power levels when $N = 5$ for the solar plant power for June with different working probability values of PV modules. It can be observed that when the working probability p is 0.95, the system is more reliable.

Table 2
Reliability values for the solar plant power when p=0.95

Month	$p_t\ (W)$	$N=2$	$N=3$	$N=5$
January	50	0.87279773	0.92324444	0.96629137
	150	0.49587177	0.82566194	0.82773494
	280	0.22907338	0.34656114	0.73388012
	350	0.22515840	0.27121867	0.53995857
	450	0.22505981	0.24907878	0.36253593
	550	0.22505980	0.24759656	0.28379956
February	50	0.97129164	0.98707621	0.99559376
	150	0.64424454	0.91049890	0.96232469
	280	0.12108303	0.43701995	0.86328652
	350	0.06275846	0.23621126	0.70708014
	450	0.05575708	0.09739165	0.47035251
	550	0.05573480	0.06464965	0.27799325
March	50	0.95697446	0.97355519	0.98676550
	150	0.73553015	0.93111334	0.94538303
	280	0.27171928	0.59046444	0.89732560
	350	0.13643081	0.41172340	0.79018023
	450	0.07431179	0.22348795	0.62197153
	550	0.07040449	0.12199851	0.45957904
April	50	0.99605601	0.99943995	0.99991146
	150	0.86845085	0.98045227	0.99793181
	280	0.33944666	0.75898485	0.97497138
	350	0.09821872	0.54307249	0.92610750
	450	0.00583100	0.24311000	0.79742204
	550	0.00361867	0.06277706	0.61124620
May	50	0.99741199	0.99986243	0.99999884
	150	0.92379620	0.99261178	0.99987423
	280	0.45731652	0.86609277	0.99428587
	350	0.12997272	0.67748134	0.97624138
	450	0.00207525	0.33213196	0.90265555
	550	0.00020411	0.07853838	0.75050012
June	50	0.99750000	0.99987500	0.99999969
	150	0.94608101	0.99601854	0.99998362
	280	0.63208767	0.95202323	0.99962785
	350	0.03963173	0.84397541	0.99840004
	450	0.00000003	0.39332311	0.98483311
	550	0.00000000	0.01014775	0.92152045
July	50	0.99750000	0.99987500	0.99999969
	150	0.99657451	0.99980559	0.99999940
	280	0.90245804	0.99274371	0.99996995
	350	0.04366631	0.86392495	0.99889646
	450	0.00000000	0.84902249	0.99863306
	550	0.00000000	0.00100809	0.97743097
August	50	0.99750000	0.99987500	0.99999969
	150	0.96192262	0.99720670	0.99998857
	280	0.80678944	0.97839341	0.99985036
	350	0.01851752	0.85989335	0.99885854

Contd...

	450	0.00000000	0.53628913	0.99080151
	550	0.00000000	0.00180955	0.96328590
September	50	0.99750000	0.99987500	0.99999969
	150	0.91524029	0.99370552	0.99997398
	280	0.49697651	0.93192148	0.99946310
	350	0.00000934	0.85631032	0.99881523
	450	0.00000000	0.11498115	0.98024309
	550	0.00000000	0.00000004	0.90985208
October	50	0.99506270	0.99927499	0.99990925
	150	0.78309823	0.96373211	0.99659021
	280	0.12631100	0.58516816	0.94875004
	350	0.01760336	0.31269268	0.85177244
	450	0.00635896	0.07251857	0.62864308
	550	0.00634429	0.01193143	0.37612146
November	50	0.99750000	0.99987500	0.99999969
	150	0.90159879	0.99261482	0.99996887
	280	0.00000016	0.63079048	0.99316280
	350	0.00000000	0.00968963	0.96086911
	450	0.00000000	0.00000000	0.67017221
	550	0.00000000	0.00000000	0.05532729
December	50	0.86022821	0.91847330	0.96654433
	150	0.46698223	0.80560171	0.80784432
	280	0.25558707	0.33977245	0.70367092
	350	0.25450371	0.29002290	0.50691622
	450	0.25449276	0.28027137	0.35230169
	550	0.25449276	0.27994465	0.29815173

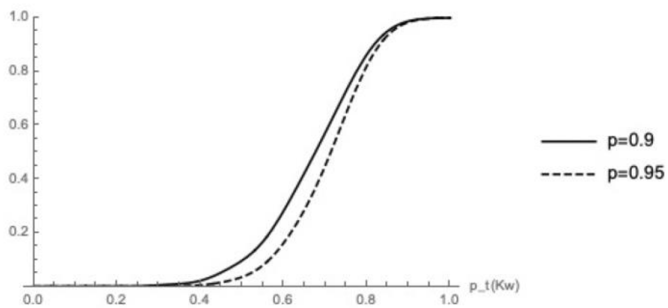

Figure 2
The cumulative distribution function of the solar plant power in June when N= 5

4.1 *Estimation of the mean power*

The estimated mean power generated by a single PV module for each month is given using Eq.(11) in Table 3. Suppose that we are interested in the estimation of power generation for July, which is the hottest month in Izmir, Türkiye. As seen from the table, the mean power generated by a single PV module is $164.701\ W$ on any day of July when a PV module is fully reliable i.e. $p = 1$. When the reliability of a module is $p = 0.90$, the mean power generated by a single PV module is $148.231\ W$ and, hence, it will be $\mu_T = N\mu_0 = 1482.31\ W$ with identical $N = 10$ modules for any day of July.

Table 3
The estimated mean power generated by a single PV module (kW)

Month	$\mu_0(p=1)$	$\mu_0(p=0.90)$
January	0.0593843	0.0534459
February	0.088923	0.0800307
March	0.103718	0.0933463
April	0.128064	0.115258
May	0.140517	0.126465
June	0.148285	0.133456
July	0.164701	0.148231
August	0.153384	0.138046
September	0.14103	0.126927
October	0.106252	0.0956264
November	0.0983595	0.0885236
December	0.0550035	0.0495032

4.2 *Determination of the number of PV modules*

Next, we consider the problem of the optimal number of PV modules for a solar plant subject to failure. We assume that the probability distribution is known for solar irradiation, hence we can answer the question about the minimum number of PV modules that must be installed in a plant to generate the desired production p_{t_0} with a given threshold reliability value r_0. Now, it is enough to compute $W_N(p_{t_0}; p)$ to get the optimal number of modules, N, considering the following inequality

$$P\{P_T > p_{t_0}\} = 1 - W_N(p_{t_0}; p) \geq r_0. \tag{13}$$

As shown previously in Table 2, for any day of June, the minimum number of PV modules to be installed in the plant is found $N = 5$ when the desired power level is $p_{t_0} = 450W$ with a given reliability value $r_0 = 0.95$.

5. Conclusion

In this study, we have investigated the theoretical distribution of power generated by a solar plant with N modules subject to failure, assuming that all PV modules experience the same solar irradiation and have the same power curve. Additionally, we have conducted a real data study using the developed model and obtained results under the assumption that the solar radiation distribution is beta with parameters α and β. In optimal power generation planning, the mean power of the solar plant has been considered under the known PV module characteristics and the solar irradiation distribution of the region. Also, the minimum number of PV modules that must be installed in a plant has been discussed for obtaining the required production level under the given threshold reliability value. Determining the number of PV modules will improve the performance of systems as it significantly increases the reliability of their power generation and prevents downtime. Having prior knowledge of the power the solar plant will provide can be very beneficial for the continuity of power generation.

As opposed to previous literature that handles the problem using the relationship between solar irradiation and power output, we use the statistical distribution function of the power in our analysis. This approach allows for the effect of the reliability of PV modules and solar irradiation distribution on the probability of power generation in the system.

For the installation of a solar power plant, planning should be done considering the amount of solar radiation in the planned area. The applicability of the developed model to real-life problems will largely depend on the estimation of the problem parameters such as solar radiation distribution, reliability of the PV module, and other properties. With the accurate estimation of such parameters, the model can be adapted to any environment where modules are subject to failure. Since solar irradiation is a random variable, the probability distribution of solar irradiation data and some of its properties must be determined. Then, using the theoretical distribution of solar plant power considering the characteristics of PV modules subjected to failure will provide us with more accurate results. We can also calculate the mean power produced by the solar plant and determine the minimum number of PV modules that should be installed with the probability of providing the least desired power level.

Disclosure statement

The authors declare no potential conflict of interests.

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