Meteorological Parameters Effects on Solar Energy Power Generation

ŞAFAK SAĞLAM Technical Education Faculty, Department of Electrical Education Marmara University Göztepe Kampüsü, Kadıköy 34722 İstanbul TURKEY ssaglam@marmara.edu.tr

Abstract: - As Turkey lies near the sunny belt between 36 and 42°N latitudes, most of the locations in Turkey receive abundant solar energy. The yearly average solar radiation is 3.6 kWh/m² day, and the total yearly radiation period is approximately 2610 h. Meteorological data such as solar radiation, ambient temperature, relative humidity, wind speed, air pressure and sunshine duration are accepted as dependable and widely variable renewable energy resources. These data play a very important role in photovoltaic systems. In this study, permanent resistive load directly fed from photovoltaic panel which produce DC electrical energy. Experiments were done during 23 month period from 2008 to 2010. Permanent resistive load currents and voltages measured with power analyzer continuously during the day. At the same time meteorological parameters like outdoor temperature, air pressure, humidity, wind speed and solar radiation etc. measured and recorded with digital weather station. These measurement results compared with the graphics at the same time bases. Photovoltaic panel output power calculated with current and voltage measurements. A mathematical equation found with curve fitting method from power graphics to examine dependencies for meteorological parameters. Thus correlation between photovoltaic performance and meteorological conditions is examined for Istanbul-Goztepe.

Key-Words: - Meteorological Parameters, Electrical Energy, Photovoltaic System, D.C. Loads, Energy Consumption.

1 Introduction

The energy consumption optimization and the renewable energy generation are very important and actual problems due to oil, gas and carbon resources limitation. The CO_2 and other pollution gases emission of the conventional energy generation is another problem which makes these problems and their solutions more important. Particularly, the photoelectric (PV) energy is one of the most important renewable energy sources, because it's available almost everywhere and everyday [1].

As the conventional fossil fuel is depleting at a faster rate while the cost of electrical energy is increasing due to growing consumer demand, Photovoltaic (PV) energy becomes a promising renewable alternate source. The emerging renewable energy, Solar and wind are expected to play a major role in supplying at least 5-10% of total electrical energy demand worldwide. Over 2 billion people in the developing world have no access to electricity.

For these people, PV is probably the most economical and abundant power source today. It is anticipated that within the next 10 years, PV solar arrays will become cost competitive with traditional power sources in countries with extensive electrical infrastructure (like the U.S. and Europe). They have the advantages of requiring less maintenance and air pollution free, but their installation cost is relatively high and in most cases they need a power conditioner (DC/DC or DC/AC) for motorized loadinterface due to load non-linearity (V-I) relationship [2].

The photovoltaic (PV) effect is the electrical potential developed between two dissimilar materials when their common junction is illuminated with radiation of photons. The PV cell, thus, converts lights directly into electricity. A French physicist, Becquerel, discovered the PV effect in 1839. It was limited to the laboratory until 1954, when Bell Laboratories produced the first silicon cell. It soon found application in U.S. space programs for its high power-generating capacity per unit weight. Since then, it has been extensively used to convert sunlight into electricity for earth-orbiting satellites. Having matured in space applications PV technology is now spreading into terrestrial applications ranging from powering remote sites to feeding utility grids around the world. Equivalent circuit of PV shown in Fig. 1 [3].



Fig. 1 The Equivalent circuit of PV cell

The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic a street lighting, electric vehicles, military space applications) or grid connected and configurations (hybrid systems, power plants). PV generation systems have two major problems: the conversion efficiency of electric power generation is very low (9-17%) especially under low irradiation conditions, and the amount of electric power generated by solar array changes continuously with weather conditions [4].

The PV systems are, by nature, non-linear power sources that need accurate estimation of the maximum power generation and following the efficient operation among various distributed power sources. For the operation planning of power systems including PV systems, the accurate prediction of the maximum power from the PV systems is inevitable. The maximum power generation depends on the environmental factors, mainly the irradiation and the cell temperature. The measurement of the temperature is easy compared with that of the cell temperature.

In addition, the wind velocity is also easy to get. Therefore, the environmental factors such as the irradiation, the temperature, and the wind velocity are utilized for the prediction of the maximum power in the studies [5].

Efficiency is an important matter in the photovoltaic (PV) conversion of solar energy because the sun is a source of power whose density is not very low, so it gives some expectations on the feasibility of its generalized cost-effective use in electric power production. However, this density is not so high as to render this task easy. After a quarter of a century of attempting it, cost still does not allow a generalized use of this conversion technology.

Efficiency forecasts have been carried out from the very beginning of PV conversion to guide the research activity. In solar cells the efficiency is strongly related to the generation of electron-hole pairs caused by the light, and their recombination before being delivered to the external circuit at a certain voltage. This recombination is due to a large variety of mechanisms and cannot be easily linked to the material used to make the cell [6].

1.1 Characteristic and Efficiency of PV Cell

The instantaneous electric energy generated by a PV cell depends on several cell parameters and on variable environment conditions such as insulation and temperature. Its electric behavior may be simply modeled by a nonlinear current source connected in series with the intrinsic cell series resistance (R_s). In this model the current source can be represented by the following implicit expression.

$$i_{pv} = I_{ph} - I_{rs} (e^{q(v_{pv} + i_{pv}R_s)/AKT} - 1)$$
(1)

where I_{ph} is the generated current under a given insolation, I_{rs} is the cell reverse saturation current, i_{pv} and v_{pv} are, respectively the output current and voltage of the solar cell, q is the charge of an electron, K is Boltzmann's constant and T is the cell temperature. The factor A considers the cell deviation from ideal p-n junction characteristics, varying between 1 and 5. Besides, the reverse saturation current (I_{rs}) and the photocurrent (I_{ph}) depend on insolation and temperature according to the following expressions:

$$I_{rs} = I_{or} \left(\frac{T}{T_r}\right)^3 e^{q E_{go}(1/T_r - 1/T)/KT}$$
(2)

$$I_{ph} = (I_{SC} + K_1(T - T_r))\lambda/100$$
 (3)

Where I_{or} is the reverse saturation current at the reference temperature T_r , E_{go} is the band-gap energy of the semiconductor used in the cell, I_{SC} is the short circuit cell current at the reference temperature and insolation, K_1 is the short circuit current temperature coefficient and λ is the insolation in mW/cm^2 .

In Fig. 2 and Fig. 3 the corresponding electric power generated by the cell is depicted, and the dependency of the maximum power operation point (MPOP) on the atmosphere conditions can be observed [7].



Fig. 2 Typical power-voltage curves of PV cell

The design and the operation of an efficient solar cell have two basic goals:

- 1. Minimization of recombination rates throughout the device.
- 2. Maximization of the absorption of photons.





It is evident that, despite the apparent complexity of the expressions describing the operation of solar cells, the basic operating principles are easy to understand. Electron-hole pairs are created inside the solar cell as a result of absorption of the photons incident on the solar cell from the sun. The objective is to collect the minority carriers before they are lost to recombination [8].

1.2 Energy Consumption Optimization of PV Systems

The consumption optimization is mainly based on reducing the peak loads and equalization of the consumption time distribution. For a small home which has an 2-3 kW mean consumption, there are some cases of 7-8 kW peak consumption, if the residential equipments work simultaneously at a moment.

We can describe some ways to coordinate the residential equipments for optimizing the load curve for small residential electric power systems, in terms of peak load reduction. The residential electric heating, lighting and cooking, household and multimedia equipment, was taken into consideration.

The optimization method follows the aim of comfort maximizations with the minimum cost. For this purpose, it can be used a simple method, classifying the loads by their priority.

In this approach, three load categories described (Fig. 4):

- CL (Continuous Loads). This category includes those equipments which require continuous access to the AC power line (ex. lighting, air conditioning etc.)

- HPL (High Priority Loads). This category includes those equipments which require urgent, frequent and short time access to the AC power line (ex. heating, air conditioning, household equipment etc.)

- LPL (Low Priority Loads). This category includes those equipments which require rare, not urgent and long time access to the AC power line (ex. boiling water, some heating equipments, water pumping etc.)



Fig. 4 The Electric energy structure

These load categories are supplied in specific conditions, due to the system settings, available power, on-grid, or off-grid supply, day/night etc.

The FPGA Controller contains the logic blocks which control all the system functions, including the load switching control.

The Automatic Power Switch contains power electronics which switch loads on/off and from renewable to grid (in this exists) and back [1],[6].

Meteorological data such as solar radiation, ambient temperature, relative humidity, wind speed, clearness index and sunshine duration, are accepted as dependable and widely variable renewable energy sources. It is therefore required to be able to formulate forecasting and estimation models of these meteorological data. These data play a very important role in PV systems. However, in many cases these data are not available owing to the high cost and complexity of the instrumentation needed to record them.

The conventional methods (empiric, analytic, numeric simulation and statistic approaches such as AR, ARMA, ARIMA, Markov chain (MC), etc.) for estimation and modeling of the meteorological data are reviewed in several studies in this area [9].

Despite the significance of solar radiation measurements, they are not yet available everywhere in the world. Due to the cost and maintenance and calibration requirements, this information is not readily available in many developing countries. Therefore, it has been of great importance to propose an efficient alternative to be used as a solar radiation estimator based on other more readily available meteorological data.

Several empirical models for calculating solar radiation have been suggested in literature. Some of these models use variables like sun hours, air temperature, relative humidity, and cloudiness. The most widely used parameter to estimate solar radiation is sunshine duration, which can be easily and reliably measured.

Angstrom regression model is the most commonly used method, which is a linear correlation between the average daily global radiation to the corresponding value on a completely clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration. Prescott suggested replacing the clear sky global radiation with the extraterrestrial radiation, producing a more convenient form of Angstrom equation called Angstrom – Prescott regression model [10].

2.1 Averaged Data Sets for Solar Radiation

Fundamentals and terminology of solar engineering should be known for studying with utilization of solar energy converted from the global radiation. Global (or: total) solar radiation is the sole energy carrier for the whole nature. Fossil fuels are in fact chemically stored primeval solar radiation. Yet more - thermal stresses and fatigue due to changing insolation involve the destruction of the lithosphere and they also participate in the development of (desert) landscape. Variability of the insolation has to be considered in the solar engineering too and it is analyzed with different approaches. Utilization of the solar energy is mostly supported and limited with its storing, which has to be based on the consideration of the dynamical behavior of solar radiation. Fatigue effects mentioned above assess the life-time of materials used and should be considered in solar engineering [11], [12].

Declination caused by the slope of the Earth's axis with regard to the elliptic path about the Sun and rotation of the Earth involves additional periodical changes of solar radiation. These processes assess the yearly periodical component. Diurnal periodical component is assessed by rotation of the Earth.

The state of the atmosphere involves both stochastic and periodical changes. The turbidity of the atmosphere and cloud cover has mainly stochastic origin, but not only. Periodical monsoon seasons in tropical areas are well known. Less attention has been paid to the trajectories of Atlantic and Arctic cyclones over Northern Europe (Scotland, Scandinavia, the Baltic states and North-West Russia), which have also seasonally periodical behavior [13].

2.1.1 Annual Sums of Global Radiation

Annual sums of global radiation are suitable for long-term process analysis and mainstream trend development. Fig. 5 shows the set of annual global irradiance Tartu-Toravere Meteorological Station (TOR) of the Estonian Meteorological and Hydrological Institute.



Fig. 5 A Sample graphic for annual sum of the global irradiance

Linear trend line "I" shows decreasing solar radiation in 1955–1990. Since 1990 the trend line "II" has been increasing. Such a behavior of global radiation is possibly the result of the changing circulation of the atmosphere particularly in Northern Europe [14].

2.1.2 Monthly Sums of Global Radiation

Monthly sums of global radiation are widely used for several purposes. It is a good tool to calculate seasonal storages or analyze (seasonal, annual) efficiency of solar installations. Fig. 6 shows the time diagram of monthly sums of global radiation at Tartu-Toravere Meteorological Station (TOR) of the Estonian Meteorological and Hydrological Institute for 2003–2005, which has no trend for the selected interval [11], [14].



Fig. 6 A Sample graphic for monthly sum of the global irradiance

2.1.3 Daily Sums of Global Radiation

Daily sums of radiation are the most frequently used average values. Variance of this variable has to be considered in short-time storage design used in PV systems. Fig. 7 shows the diagram of the daily sums of global irradiance in Tartu-Toravere Meteorological Station (TOR) of the Estonian Meteorological and Hydrological Institute for 2005.



Fig. 7 A Sample graphic for daily sum of the global irradiance

Some specific intervals may be highlighted in the diagram in Fig. 7 most stable days (with minimum

of variability) occur in the interval 12–28 April and 18–27 May. Most variable days occur between 8–7 May and 28–14 June. After 8 November, for the rest of the year, it is also very stable without any beam radiation [11], [15].

2.1.4 Hourly Sums of Global Radiation

Diurnal periodicity can be shown perfectly well at the one-hour averaging interval. Figure 10.10 presents the time diagram of global radiation between 15 and 25 May 2005 in Tartu-Toravere Meteorological Station (TOR) of the Estonian Meteorological and Hydrological Institute. In the example, successive days correlate well and this example can be classified as solar radiation "stable in general".



Fig. 8 A Sample graphic for hourly sum of the global irradiance

The trend line shown in Fig. 8 supports such conditions in Fig. 7. Hourly averages are widely used for analysis and solar equipment design [11], [14].

2.2 Regression Models for Predicting Global Solar Irradiance

Several types of regression models have been proposed in the literature for predicting global solar irradiance on horizontal from the daily sunshine hours and extraterrestrial solar radiation. Table 1 shows some of these regression models. The regression models in table 1 are given in terms of the clearness index, $K_T = G / G_o$ is the ratio of the monthly average daily global radiation on horizontal and its corresponding extraterrestrial radiation, the other variable is the sunshine duration ratio (R_s), which is the ratio between measured daily sun hours (S) and theoretical maximum daily solar hours (S_o).

 Table 1 Regression Model Samples

Model (Source)	Regression Model
Linear (Angstrom – Prescott)	$K_T = a + bR_S$
Quadratic (Akinoglu & Ecevit)	$K_{T} = a + bR_{S} + cR_{S}^{2}$
Third order (Samuel)	$K_{\rm T} = a + bRS + cR_{\rm S}^{2+} dR_{\rm S}^{3}$
Logarithmic (Ampratwum & Dorvlo)	$K_T = a + blog(R_S)$
Linear – Logarithmic (Newland)	$K_{\rm T} = a + bR_{\rm S} + clog(R_{\rm S})$
Exponential (Elagib & Monsell)	$K_{\rm T} = ae^{(bRS)}$
Power (Coppolino)	$K_T = e^a R_S^b$

The daily extraterrestrial solar radiation on Horizontal can be calculated as shown in Eq.1.

$$G_o = \frac{24}{\pi} G_{sc} (1 + 0.33 \cos(2\pi d_n / 365))$$

$$* (\cos\phi\cos\delta\sin\omega_s + \omega_s\sin\phi\sin\delta)$$
(1)

Where G_{sc} is the solar constant and it is approximately 1367 W/m², d_n is number of the day in the year, Φ is the sun azimuth angle, δ is the solar declination angle and is calculated using Eq.2, ω_s is the daily sun rise hour and is calculated using Eq.3. While So can be calculated using Eq.4.

$$\delta = \pi \frac{23.45}{180} \sin(2\pi \frac{284 + n}{365}) \tag{2}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{3}$$

$$S_o = \frac{2}{15}\omega_s \tag{4}$$

As shown in

Table 1, the objective of the prediction models is to determine the regression coefficients of the seven regression models, which are "a", "b", "c", and "d". Each one of these coefficients gives an indication about the solar radiation characteristics for the location under investigation [10], [16].

2.3 Irradiance Forecast Methods for Photovoltaic's (A Sample Study)

There are many different methods used to forecast irradiance values for photovoltaic panels to predict power generation. In this section a study which is done in Germany is given as a sample study to explain structure of forecast methods. For very short-term forecast these steps should be followed with using weather data.

a) Spatial Averaging and Temporal Interpolation: Different spatial interpolation techniques have been investigated to optimize the forecast for a given site. The use of the arithmetic average of surrounding pixels is proposed, as the use of distance dependent weights does not improve the results. An analysis of the forecast accuracy in dependence on the number of grid points used for averaging revealed that with average values of 4x4 grid points best results are achieved.

The of a forecast is improved by scaling the amplitude of the prediction in accordance with the correlation of predicted and measured time series, which is one effect of the averaging procedure.

For the temporal interpolation, it can be considered two different approaches. A very simple approach to derive hourly resolved forecasts is the linear interpolation of the three-hourly mean values that are provided by the ECMWF.

As a second approach, it is combined the forecast data with a clear sky model to better account for the typical diurnal course of irradiance. For the calculation of the clear sky irradiance it is applied the model proposed by the model. This model uses the Linke turbidity factor as a measure of the optical thickness of the atmosphere [9], [17].

b) Improved Clear Sky Forecasts:

The quality of the irradiance forecast for correctly predicted clear sky situations is strongly dependent on the atmospheric input to the model. The ECMWF model considers aerosols using a worldwide climatology of the annual cycle of different aerosol types.

In order to investigate the potential for a better modeling of clear sky irradiances, it is compared the interpolated ECWMF irradiance forecasts with the clear sky model in these situations. The forecast error when assuming as forecast value is plotted over the forecast of the total cloud cover comparison to the ECMWF based forecasts [9], [17].

c) Post Processing with Ground Data:

In a last step to derive an optimized forecast of hourly values of the global irradiance, it is investigate the application of a post processing procedure to correct for systematic deviations. For that purpose, results analyzed the forecast in dependence on the cloud situation and the solar zenith angle.

Fig. 9, where the of the forecast is displayed over the predicted clear sky index and the cosine of the solar zenith angle, shows that there is a considerable overestimation of the irradiance for cloudy situations with clear sky index values between $kt^*=0.3$ and $kt^*=0.8$.

Also, it has observed this overestimation of the irradiance for cloudy situations and relates it to the "handling of the amount of condensed water in clouds, with too small optical thickness."





For situations predicted as overcast the actual measured irradiance is underestimated. In order to avoid these systematic deviations, it is introduced a situation specific bias correction. To allow for independent testing of this adaptation to ground data, the data were divided into training and test data. The first 15 days of each month were chosen as training set, the remaining data form the test set. [9], [17].

3 System Description

In this study, resistive load is directly fed by PV panel. PV is polycrystalline panel which characteristic's is described in Table 2.

Fable 2 Polycrystalline P	V Characteristic
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Voc	20.8 V
lsc	3.3 A

Vp	17.0 V
lp	3.0 A
Рр	51 W

Rating at $1000W/m^2$ irradiance, temperature $25^{\circ}C$ (Direct Current Values)

In experiment system current and voltage values measured with power analyzer. Power analyzer is connected PC via RS232 serial port. All measurements are recorded at PC with software. Against the power outage PC and power analyzer fed by UPS. For this purpose experiment set was setup as shown in Fig. 10.

Atmospheric Weather parameters measurements recorded with electronic weather station which is installed at the roof of the building. These parameters and PV output current, voltage and power values are merged in database file. These database files examined and several graphics plotted to understand correlation between these values for different weather conditions. Solar irradiance is depending meteorological conditions so PV output current and voltage is strictly related with it.



Fig. 10 Experimental setup for measurements

Resistive load is set of 18 parallel connected resistors. Each resistor 100 Ω and 5 W wire wound resistor. Ohmmeter measurements show that set resistance value is 5.5 Ω including with contact resistance. Wire wound resistor used at load because long period load current exist in circuit which fed from PV [18].

4 Experimental Results

Experiments were done in Istanbul, Goztepe from 4 July 2008 to 01 June 2010. During twenty three months period load voltage (V) and load current (A) measured with 2 minutes intervals. Weather station recorded parameters like outdoor temperature, air pressure, humidity, wind speed and solar radiation etc. with 5 minutes intervals and these measurements were recorded during the day (24 hour)[19],[20], [21].



Fig. 11 Comparison of PV peak output power with solar radiance

In Fig. 11 comparison of PV peak output power with solar radiation is shown. Solar radiance directly effects PV system output power. But this direct effect is slightly changed especially in December, January, February and March. Because the cloud cover is so thick to effect direct solar radiation on PV cells surfaces.



Fig. 12 Comparison of PV peak output power with produced electrical energy

Fig. 12 shows that differences between PV peak output and produced electrical energy for seasonal weather conditions.

During the experiments in sunny winter and spring day's peak output power reached the high values but produced daily electrical energy values couldn't reach the high values.



Fig. 13 Curve fitting graphic of PV peak power

Experimental results are recorded approximately 23 months period that begins on 4 July 2008 and ends on 01 June 2010. This period is covered two year long term. These recorded values can be used to compare the two different year's photovoltaic panel electrical measurements. On Fig. 13 shows PV peak power and curve fittings graphic. If the seasonal part of these curves is compared for the two year it can be seen that these curves are different. The meteorological conditions are main factors of these differences. The curve fitting results 6th order equation. PV Cells converted direct solar radiation to electrical energy depending on several environmental effects.

5 Conclusions

In this study electrical energy which is produced with stand alone PV performance is measured experimentally for Istanbul. Stand alone PV system is loaded with resistive load and output power is observed continuously. Experiment results have recorded during the 23 months periods covers the different seasonal weather and atmospheric conditions. According to experiment results Climate effects on PV system putt forward briefly. PV peak electrical energy production is reached which is highest value in August and lowest value in February. Seasonal climate chancing is effected PV efficiency approximately % 50 percent.

In yearly base, PV electrical energy production is 39,107 watt-hour in first year and 37,520 watt-hour in second year. These results show that a PV panel which is located same position during the experiments can be produced different electrical energy within two year. Meteorological conditions differences observed the digital meteorological stations recorded values for the same time period.

Besides that PV efficiency is decreasing because of humidity, corrosion and equipment breakdown with time. For advanced studies to determining PV performance changing's depending on time, system will be followed and efficiency will be compared for same periods in several years.

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Şafak Sağlam, was born on September 11, 1976 in Samsun, Turkey. He graduated from Marmara University, Technical Education Faculty, Istanbul, in 1997, and received MS and PhD degrees from Marmara University, Institute of Pure and Applied Sciences, in Istanbul, Turkey, in 2000 and 2006 respectively.

He has been employed as a research assistant in Technical Education Faculty between 1997 to 2009. Presently Dr. Sağlam is an Associate Professor of Technical Education Faculty Electrical Education Department in Marmara University. His special fields of interest include renewable energy sources, illumination and power systems.