Effect of PV Orientation on Energy Generation and Economy: A Case Study for Istanbul-Turkey

[Ali Durusu, Ali Erduman. Mugdesem Tanrioven]

Abstract— This analysis consider the effect of azimuth angle of fixed photovoltaic (PV) system on energy generation of PV system. Detailed PV production model, including effect of solar radiation, temperature and wind speed, was used to calculate output of PV array for different azimuth angles of PV array. For determination of economic value of the PV produced power, daily electricity price variation of Turkey was also considered. A comparison between the produced power and economic value of produced power of different azimuth angle was performed. The results obtained from comparison are presented and discussed.

Keywords—economic value, effect of orientation, energy generation, PV array

I.   Introduction

Renewable energy sources utilization has been rapidly increasing for the last two decades because of reducing fossil based energy generation and environmental hazards [1]. Especially the photovoltaic (PV) systems have begun to be used frequently in order to meet the quickly increasing energy demand [2]. PV system, which can be stand-alone installed for providing electricity in some distant areas or be connected to grid for selling power, is the main technology to transform solar energy into electric power [3].

For optimal design of PV systems, it is important to define system performance at the location of application [4]. The amount of power produced by PV system contingent upon the solar radiation, tilt angle, azimuth angle and environmental effects. Alternative consideration for optimal location of PV system is economic-value of the electricity produced. Because PV system energy generation does not align with grid load [5]. So, the PV production based placement might not be optimal for economic value of the price of electricity produced. Electricity price might be shifted to the optimal positioning to further west of south. Economic value based investigation summarized in a national level by [6].

This analysis considers the effect of azimuth angle of fixed photovoltaic (PV) system on their total energy generation. Detailed PV production model, including effect of solar radiation, temperature and wind speed, was used to calculate output of PV array for different azimuth angles of PV array. For determination of economic value of the PV produced power, daily electricity price variation of Turkey was also considered. A comparison between the produced power and economic value of produced power of different azimuth angle was performed. The results obtained from comparison are presented and discussed.

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II.   Methods

This analysis uses solar radiation and electricity price data to (1) determine the available solar radiation on a given plane, (2) built a PV production model and (3) economic value of PV produced power. The region considered to determine the effect of orientation on PV energy generation is Istanbul (Lat:41.02, Long:29.02). Optimum tilt angle is taken as 27° and azimuth angles are chosen as; east:-90°, south-east:-45°, south:0°, south-west:45° and west:90°.

A.   *Available Solar Radiation on a Plane*

The measured solar radiation on the earth's surface (global radiation) is lower than extraterrestrial radiation due to the various effects of the atmosphere. The main effect is that 30% of incoming solar radiation is reflected back into space by the atmosphere [7]. Total radiation reached to the earth`s surface is sum of direct (I_b) and diffused radiation (I_d) as given in (1).

$$I = I_b + I_d \tag{1}$$

Separation of global radiation into direct and diffused components can be calculated by empirical formulas which are developed as a function of clearness index (k_T) as given in (2). Clearness index (3) is described as function of the global radiation and extraterrestrial radiation.

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09k_T & k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T{}^2 - 16.638k_T{}^3 + 12.336k_T{}^4 & 0.22 \le k_T \le 0.80 \\ 0.165 & k_T > 0.80 \end{cases} \tag{2}$$

$$k_T = \frac{I_o}{I} \tag{3}$$

Total radiation on a tilted plane is sum of the direct, diffused and reflected radiation as given in (4) [8].

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + I\rho \left(\frac{1 - \cos \beta}{2} \right) \tag{4}$$

where β is the plane tilt angle, ρ is ground albedo (0.2) and R_b is the direct radiation ratio coefficient. R_b is given in (5) [9].

$$R_b = \frac{\cos \theta}{\cos \theta_Z} \tag{5}$$

where θ is radiation incident angle and θ_Z is zenith angle.

B.   *PV Production Model*

PV production model was built to estimate PV production from solar radiation considering cell temperature

and wind speed. General model of PV production is given in (6) [10].

$$P_{pv} = \eta_{pv} x \eta_{other} x I_T \tag{6}$$

where P_{pv} is PV production for per square meter (W/m²), η_{pv} is PV array efficiency and η_{other} is other derate factor (mismatch, connection, etc., taken as 0.93). PV array efficiency is given in (7) [5].

$$\eta_{pv} = \eta_{ref}\left[1 - \beta_{ref}\left[T_a - T_{ref} + T_c - T_N\left(\frac{I_T}{I_N}\right)\right]\right] \tag{7}$$

where η_{ref} is reference efficiency (12%), β_{ref} is temperature coefficient (0.0045) of PV array [11], T_a is ambient temperature, T_{ref} is reference temperature (25°C), T_c PV cell temperature, T_N is nominal operating condition temperature (20°C) and I_N is incident radiation (800 W/m²) at nominal operating condition [10]. PV cell temperature is given in (8) [12].

$$T_c = 1.14\left(T_a - T_{ref}\right) + 0.0175\left(I_T - 300\right) - k_r\omega_s + 30 \tag{8}$$

where k_r is wind speed coefficient (taken as 1.509) and ω_s is wind speed (m/s). Fig. 1 shows global radiation, ambient temperature and wind speed variation during the year for Istanbul-Turkey [5].
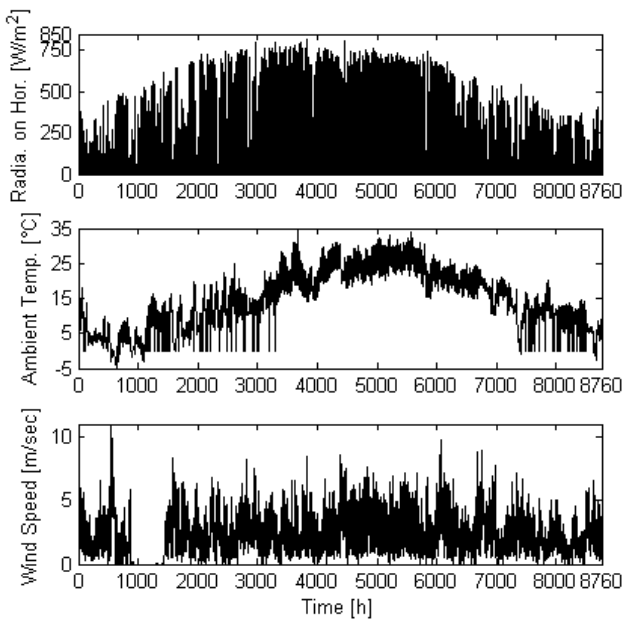

Figure 1.   Global solar radiationon horizontal plane, ambient temperature and wind speed variation during the year

C. *Economic Value Model*

Economic value of PV produced power is determined considering daily electricity price variation of Turkey including all taxes as given in (9) [5].

$$p(t) = \begin{cases} p_p, t \in T_p, T_p = [17,22) \\ p_o, t \in T_o, \ T_o = [22,6) \\ p_s, t \in T_s, \ T_s = [6,17) \end{cases} \tag{9}$$

where $p_p = 0.21538$ \$/kWh is the electricity price for the peak load period, $p_o = 0.07692$ \$/kWh is the electricity price for the off-peak period and $p_s = 0.14231$ \$/kWh is the electricity price for the standard period. Total income of selling electricity is calculated as given in (10).

$$M = \sum_{d=1}^{365}\sum_{t=1}^{24} p(t) x P_{pv}(t) \tag{10}$$

where d is day number of a year (1-365).

III. **Results and Discussion**

The amount of PV power generated by the PV array is affected by solar radiation, temperature and wind speed. Based on (1-5), the total solar radiation falling on PV array, which is oriented at different azimuth angle, is determined. The monthly solar radiation (for per square-meter surface) for the inclined surface at the optimal angle (tilt:27°), and the five vertical surfaces facing east, south-east, south-west and west were determined and presented in Figure 7.
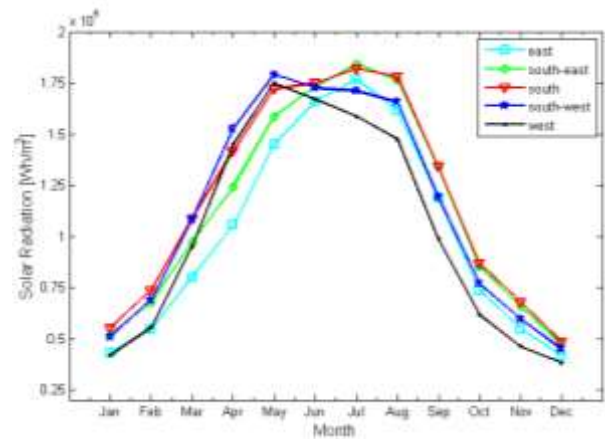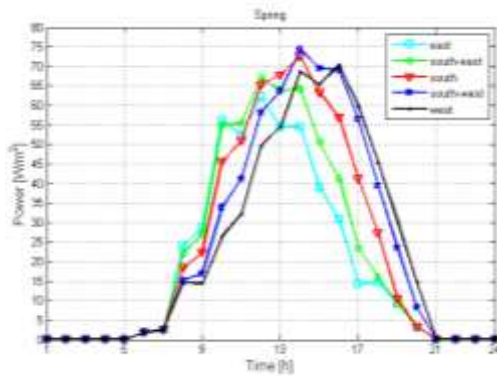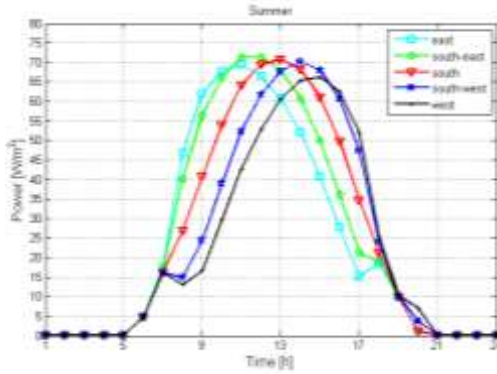

Figure 2.   Mothly total radiation for different orientation (tilt:27° and azimuth: east=-90°, south-east=-45°, south=0°, south-west=45°, west=90°)

Monthly profile of solar radiation is for different orientation is similar. South-west and west oriented surface receive largest solar radiation on April. East, south-east and south oriented surfaces are received the largest solar radiation on June. The low solar radiation for all surfaces obtained from December to January.
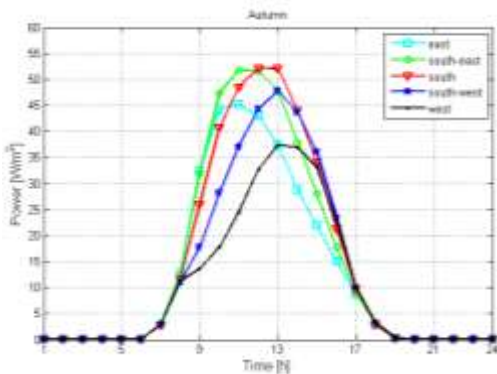
Based on (6-8), PV array (one square-meter) productions for 5 different azimuth angles are determined. Fig. 3 displays the daily average PV array production for seasons.
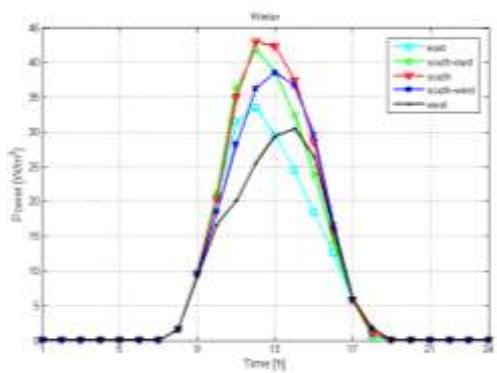
a

b

c

d

Figure 3.   Daily average PV production for different season (tilt:27° and azimuth: east=-90°, south-east=-45°, south=0°, south-west=45°, west=90°)

It is clear from the Fig. 3 that when PV azimuth angle is deviated from south to east, PV production increases during the morning hours. However, when PV azimuth angle deviate from south to west, PV production increases during the afternoon hours. Total PV productions for different orientation during the year are given in Table I. South orientated PV array production has highest value for all season and east orientated PV array production in spring and west orientated PV array in the other seasons has lowest value. It is also clear from Table I that, when south orientated PV production is chosen as base, energy differences value is lowest at east orientation in spring and west orientation in the other seasons. Energy differences value is highest at west orientation in spring, south-west orientation in summer and south-east orientation in autumn and winter.

TABLE I
TOTAL ENERGY AND TOTAL INCOME

Season	Orientation	Energy [kWh/m^2]	Energy Differences [%]	Total Income [$]	Income Differences [%]
Spring	-90°	37.161	-21.996	5.552	-24.028
	-45°	42.841	-10.072	6.427	-12.044
	0°	47.639	0	7.308	0
	45°	46.695	-1.982	7.881	7.847
	90°	46.753	-1.860	7.585	3.802
Summer	-90°	51.592	-5.559	7.642	-7.088
	-45°	54.594	-0.064	8.115	-1.345
	0°	54.629	0	8.225	0
	45°	51.990	-4.831	7.971	-3.095
	90°	48.255	-11.668	7.503	-8.777
Autumn	-90°	26.843	-14.637	3.898	-14.522
	-45°	31.065	-1.212	4.500	-1.316
	0°	31.446	0	4.560	0
	45°	27.803	-11.587	4.047	-11.263
	90°	22.395	-28.785	3.280	-28.074
Winter	-90°	16.785	-21.647	2.429	-21.453
	-45°	20.150	-5.943	2.908	-5.969
	0°	21.423	0	3.093	0
	45°	19.836	-7.409	2.871	-7.172
	90°	16.324	-23.799	2.371	-23.325

Economic value of PV produced power considering (9-10) are given in Table I. Total income is highest at south-west orientated PV array in spring and south orientated PV array in the other season. Total income value is lowest at east orientated PV array in spring and west orientated PV array in the other seasons. Total income difference values have same order with total income value.

Because of the electricity selling price is not constant during the day, energy differences and income differences are not same. In east and south-east orientation, income differences are increased comparing to the energy differences because of the large part PV production is generally in morning hours (standard period). However in south-west and west orientation, income differences are decreased comparing to the energy differences because of the large part of PV production is generally in afternoon hours (standard and peak period). Fig. 4 displays the daily average PV array production for one year.
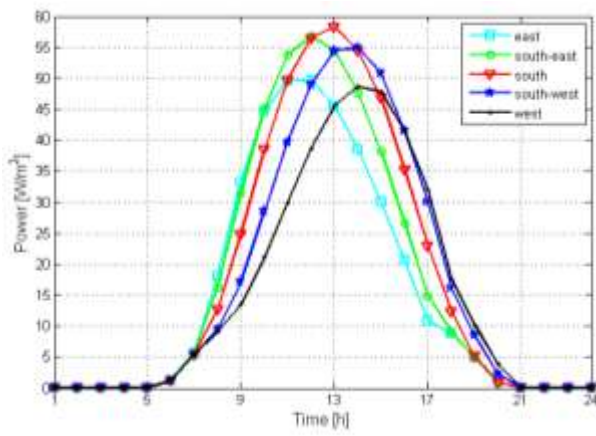
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Figure 4.   Daily average PV production for one year (tilt:27° and azimuth: east=-90°, south-east=-45°, south=0°, south-west=45°, west=90°)

Generally, the energy output values of PV array decreases with increasing or decreasing the azimuth angles. For a given tilt angle (27°), PV panels oriented to south always generate the largest energy outputs except from south-west and west orientation in spring.

IV. Conclusion

The effect of PV orientation on energy output and unit energy cost of PV system are analyzed. The whole year 1 hour recorded horizontal solar radiation, temperature and wind speed data is used for analysis. The incident solar radiations on various orientated surface are calculated. The surface tilt angle is taken as 27°. The monthly solar radiation results demonstrated that the amount of solar radiation received by surface mounted on different orientations are similar. However the radiation is reached to highest and lowest value at different month in a year. Daily average PV production results show that when PV azimuth angle is deviated from south to east, PV production increases during the morning hours. However, when PV azimuth angle deviate from south to west, PV production increases during the afternoon hours. PV production results show that optimum orientation for all season is south. However the total income values show that the optimum orientation in spring and the other season are south-west and south respectively.

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