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Effect of Azimuth Angle on The Performance of a Small-Scale on-Grid PV System

Muharrem Hilmi AKSOY[1*], İsmail ÇİYLEZ[2], Murat İSPİR[1]

[1] Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, 42250, Konya, Türkiye
[2] Konya Technical University, Graduate Education Institute, Department of Mechanical Engineering, 42250, Konya, Türkiye
Muharrem Hilmi AKSOY ORCID No: 0000-0002-6509-8112
İsmail ÇİYLEZ ORCID No: 0000-0002-1113-5512
Murat İSPİR ORCID No: 0000-0001-5238-6011

**Corresponding author: mhaksoy@ktun.edu.tr*

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Abstract: In this study, the effective solar irradiation on the PV surface, electricity generation, and performance ratios were investigated for a 100 kW small-scale on-grid PV system in Konya, Turkey. Five different azimuth angles -30°, -15°, 0°, 15°, and 30° were investigated for no-shading simulations with a fixed optimum tilt angle of 33°. As a result, the highest effective solar radiation is obtained at an azimuth of 0° as 1966.4 kWh/m², which is 2.12%, 0.46%, 0.79%, and 2.66% greater than the other azimuth angles of -30°, -15°, 15°, and 30°, respectively. On the other hand, it is seen that the highest energy production is obtained from the system with an azimuth angle of 0° with annual energy of 174.33 MWh. This value is 1.91%, 0.37%, 0.89%, and 2.8% greater than the other azimuth angles of -30°, -15°, 15°, and 30°, respectively. In addition, to evaluate the shading effect on the performance of the PV panels, two different panel spacings as, 4 m and 8 m, were also considered. It was seen that the electricity generation with an 8 m span system was 8.88% better than the 4 m. Another finding is that the height of the panels is negligible according to electricity generation. Finally, the highest performance ratio is obtained from the azimuth angle of 0°, as 0.857.

Azimut Açısının Küçük Ölçekli Şebekeye Bağlı Bir PV Sisteminin Performansına Etkisi

Anahtar Kelimeler
Azimut açısı,
Performans oranı,
PV performansı,
Güneş enerjisi,

Öz: Bu çalışmada, Konya, Türkiye'de 100 kW'lık şebekeye bağlı küçük ölçekli bir PV sistemi için efektif güneş ışınımı, elektrik üretimi ve performans oranları PVsyst yazılımı ile incelenmiştir. Optimum 33° sabit eğim açısı ile gölgelemesiz simülasyonlar için -30°, -15°, 0°, 15° ve 30° olmak üzere beş farklı azimut açısı incelenmiştir. En fazla efektif ışınım, -30°, -15°,15° ve 30° azimut açılarından sırasıyla %2.12, %0.46, %0.79 ve %2.66 daha büyük olarak 1966,4 kWh/m² değeriyle 0° azimut açısında gerçekleşmiştir. En iyi sonuçların 0° azimut açısında yıllık toplam 174.33 MWh enerji üretilebileceği belirlenmiştir. Bu üretim değeri -30°, -15°, 15° ve 30° olan diğer azimut açılarından sırasıyla %1.91, %0.37, %0.89 ve %2.8 daha büyüktür. Ayrıca, PV panellerin performansı üzerindeki gölgeleme etkisini değerlendirmek için 4 m ve 8 m olmak üzere iki farklı panel aralığı da dikkate alınmıştır. 8 m aralık sisteminin 4 m aralık sistemine göre %8.88 daha iyi olduğu görüldü. Ancak 8 m aralıklı sistemin daha fazla kurulum alanına ihtiyaç duyduğu bilinmektedir. Diğer bir bulgu ise panellerin elektrik üretimindeki yüksekliğinin ihmal edilebilir düzeyde olmasıdır. Son olarak en yüksek performans oranı 0° azimut açısı konumunda 0.857 olarak elde edilmiştir.

1. INTRODUCTION

With the development of science and technology, the current energy crisis and carbon emissions goals have turned to renewables as more binding energy globally. Developed and developing countries cooperate to prevent harmful practices such as emissions and greenhouse gases. In December 2020, the European Union target to reduce greenhouse gas effects by at least 55% by 2030, which is an essential step toward reducing emissions [1]. While renewable energy sources are available in many countries, it also depends on the geographical location according to the type of renewable sources [2,3].

Solar energy systems developed significantly over the last two decades are one of the most popular renewable energy sources [4]. PV cells are divided into three groups: silicon-based, thin-film, and third-generation, currently under development and not commercially available [5]. Silicon-based PV cells constitute approximately 85-90% of the market share and are still widely used [6]. PV Cell efficiency is one of the most critical parameters that give information about the system. The efficiency of silicon-based cells has increased year by year. The experimental efficiencies of the monocrystalline cell, one of the silicon-based cells, is approximately 15% in the 1950s, 17% in the 1970s, and 28% today taken under laboratory conditions. [7]. Today, application efficiencies are around 15-20% for monocrystalline, 11-15% for polycrystalline, and 6-7% for amorphous. [8,9]. In addition to the PV system's efficiency, production cost plays a vital role. In experiments conducted in 1974, cells had an efficiency value only of 4-5%, and the price of these cells was $100/Wp [10]. In 2010, silicon-based cells' prices were between 3-3.5 USD/Wp [11]. In January 2018, the cost of installing a PV system varied between 1.73 USD/Wp and 1.23 USD/Wp depending on location [12]. In April 2020, the average price of PV cells was 0.177 USD/Wp for polycrystalline, 0.2 USD/Wp for monocrystalline, and 0.221 USD/Wp for thin film technologies [13]. As seen, the prices of PV cells have decreased, and their efficiency has increased over the years.

Turkey has a very advantageous position with an annual sunshine duration of 7.2 hours/day and annual total daily average irradiation of 3.6 kWh/m^2 [14,15]. Solar energy potential is relatively high in the Mediterranean Region and the South of the Central Anatolia Region, including Konya, as shown in Fig. 1 [16,17]. Turkey has reached a level of solar energy where it can compete with EU countries using the advantages of its geographical location. In 2019, PV systems were installed with a power of 3.9 GWp in Germany, 4.5 GWp in Spain, and 2.4 GWp in the Netherlands. Poland followed these countries with a new PV capacity of 800 MWp and Belgium, France, Hungary, and Italy with a PV capacity of 500 MWp [18]. The installed PV in Turkey was only 40 MW. This value has reached tremendous progress with a value of 7816 MW, with an increase of 19540% by 2021. While PV systems met 0.06% of electricity generation (E_G) in 2014, they accounted for 7.83% by 2021 [19,20]. The government's tax reductions in PV imports and incentives for plant establishment have a large share in this increase [21]. Also, in 2016, it made a tender for a 1000 MW PV plant in the renewable energy resource area (YEKA) in the Karapınar district of Konya [22]. Today, 756.05 MW of this facility has been completed, and, in this state, it meets the electricity needs of an average of 200000 people. The project is planned to be completed in August 2023. It is foreseen that the electricity needs of approximately 550.000 people will be met with an annual E_G of 2300 GWh upon the completion of the project [23]. This annual E_G is expected to meet 24% of Konya's and 0.6% of Turkey's electricity needs.

The tilt angle, which plays an important role in the performance of PV systems, is the ability to capture irradiation from the sun. This angle varies geographically. The optimum value of this angle is approximately equal to the latitude angle (φ) of the location. In addition, the optimum value of this angle changes seasonally. While this angle is 15° greater in latitude in summer season applications, it is 15° smaller in winter season applications. In addition to the tilt angle, the azimuth angle, representing the angle between the PV system and the south-north direction, greatly impacts the system's performance [25,26]. The tilt angle has a greater effect on the system performance than the azimuth angle [27]. However, while the tilt angles are adjustable, the azimuth angles can only be adjusted in field applications and cannot be adjusted much in roof applications.

Some studies investigate and examine the effects of tilt and azimuth angles on the performance of the systems. For example, the annual average E_G was calculated using ten different tilt angles including from 0° to 90° and five different azimuth angles including -90°, -45°, 0°, 45°, and 90° in Hong Kong, which has a latitude angle of 22°.

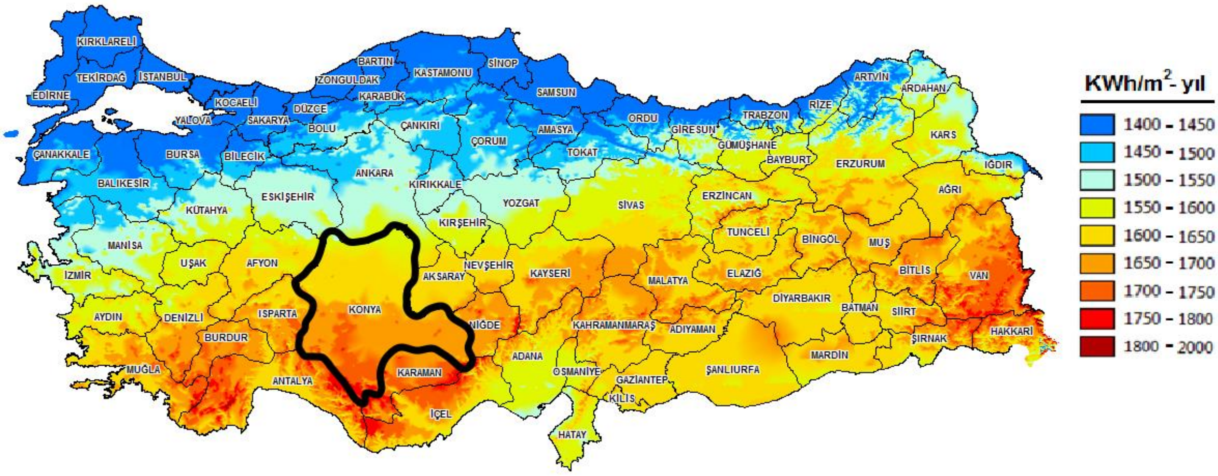

Figure 1. The solar energy potential map of Turkey and Konya [24]

In the study, when the tilt angle is constant, it has been observed that the most E_G is obtained with an azimuth angle of 0°. Furthermore, when the azimuth angle is constant, it has been observed that most E_G is obtained with a tilt angle of about 20° degrees [28].

In addition to tilt and azimuth angles, the shading area is one of the parameters affecting system performance [29,30]. According to an indoor experimental study, the model area is shaded with eight different percentage areas from 10% to 80%. It was concluded that the system efficiency and the output power decreased with the increase in the shading percentage [31]. A shading experiment with monocrystalline and polycrystalline cells was performed for five shading areas, 0%, 25%, 50%, 75%, and 100%. It was observed that the current produced decreased as the shading increased. In addition, it was concluded that if the system is shaded by 50%, E_G decreases by approximately 30% [32].

There are six mainly used software for modeling and analysis of PV systems, including PVsyst, RETScreen, HOMER, TRNSYS, INSEL, and PV F-Chart [33]. Developed by the University of Geneva, Switzerland, PVsyst software is a simulation and analysis program whose results can be obtained by performing on-grid or off-grid PV system design modeling. Compared to other software, this one has advantages such as containing more parameters and giving more detailed results. [34,35]. A study was conducted to compare E_G of Berlin and Kathmandu with the same PV cells with 60 kWp power using PVsyst software. While the tilt angle is 40^0 in Berlin, it is 30^0 in Kathmandu. According to the study, since Kathmandu receives more solar irradiation, the electricity produced is 70% more than in Berlin [36]. A power analysis was conducted at 1 MW with 3924 polycrystalline modules using PVsyst in Morocco. A study was conducted with tilt angles varying according to the seasons, 15° in summer and 48° in winter. In addition, analyses were made using a fixed tilt angle of 32° throughout the year. The fixed tilt angle system, with a performance ratio of 77.3%, was better than the seasonally different tilt angle system, with a performance ratio of 76.9% [37]. A study was carried out with bifacial PV cells on different surface grounds, including white, sand, and asphalt, using PVsyst Software in Konya. The bifacial system with white, sand and asphalt grounds has 8.86%, 4.55%, and 2.68% higher PR than the monofacial system. [38] Other findings from PVsyst in Algeria with a performance ratio of 83.9% [39], Poland with a performance ratio of about 88% [40], India with a performance ratio ranging from 74.9% to 52.57% [41], laboratory with a performance ratio 81% [42], simulation with a performance ratio 72.4% [43], and more.

This study investigates the effects of panel height and spacing on system performance and efficiency using a fixed tilt angle of 33° and different azimuth angles. In this way, it will be possible to comment on the amount of energy obtained from a system installed on the roofs of houses facing different directions.

2. MATERIAL AND METHOD

In this study, an installed capacity of 99 kW PV system is considered in Konya province with a latitude of 38.3°. The optimum tilt angle was determined as 33°, close to the latitude angle, using the METEO 8.0 program, which includes meteorological data and is included in PVsyst. A monocrystal panel with a 300 Wp capacity and a Solectria brand inverter with 50 kW 300-850 V 60 Hz were selected for the system. The system capacity has reached 330 cells, 22 on the horizontal axis and 15 on the vertical axis. Because it affects the output power, overload loss varies according to the array. For example, the 22 x 15 array has a 0.5% overload loss, which is acceptable. This array obtained a surface area of 537 m^2 as an on-grid system, where no batteries are needed.

Horizontal irradiation is independent of panels and angles. The amount of irradiation coming to the panel surface increases according to the coating material of the panel surfaces. However, contrary to irradiation reaching the horizontal plane, the irradiation incident on the panel surface depends on the angles and affects the system efficiency [44]. The amount of irradiation to the panel decreases significantly with a factor called the Incidence Angle Modifier (IAM). When the irradiation passing through the glass reaches the cell, it is reflected and reaches the glass surface again. IAM, dependent on b_0, surface glass quality, glass number, and albedo, is calculated as follows [45,46].

$$F_{IAM} = 1 - b_o\left(\frac{1}{\cos i} - 1\right) \tag{1}$$

Where, i is the panel tilt angle. One of the essential pieces of information about the system is the Performance Ratio (PR). The PR is the ratio of the energy effectively produced with respect to the energy produced if the system continuously worked at its nominal STC efficiency. The PR is defined in the norm IEC EN 61724 [47].

$$PR = \frac{E_G}{G_I \times P_{PV}} \tag{2}$$

Where, E_G, is the amount of electricity supplied to the grid in kWh, G_I is the amount of irradiation coming into the panel in kWh m² and P_{PV} is the power of the system in kWp.

The sun is known to move from east to west. Therefore, hourly, the sun's radiation reaches the earth at a certain angle. This angle is called the hour angle (ω), defined as the hourly angle of the sun's irradiance with the location's meridian due to the earth's rotation of 15° per hour around its axis and the sun's movement from east to west. It is calculated as follows.

$$\omega = 15(ST - 12) \tag{3}$$

Where, ST is local time and equals 12 at midday. In addition, the sun's rays come daily at a certain angle to the equatorial plane. This angle is called the declination angle (δ), which is the angle between the sun irradiation coming to the earth and the earth's equator. This angle varies between -23.45° and 23.45° and is calculated as follows.

$$\delta = 23.45\, sin \left(360 \frac{284 + n}{365}\right) \tag{4}$$

Where, n is the number of days as of January 1. Also, the altitude angle (α) is the angle between the sun irradiation and the horizontal plane and is calculated as follows.

$$sin(\alpha) = sin(\varphi) sin(\delta) + cos(\varphi)\, cos(\delta) cos(HA) \tag{5}$$

The optimum azimuth angle of a location is calculated using Eqs. 3, 4 and 5 as follows.

$$sin(\gamma) = \frac{cos(\delta)\, sin(\omega)}{\cos(\alpha)} \tag{6}$$

3. RESULTS AND DISCUSSION

It is known that the amount of irradiation dramatically affects the performance of PV cells. The monthly average horizontal diffuse irradiation (G_{DH}) and global horizontal irradiation (G_H) from the sun to the horizontal plane in Konya using PVsyst are shown in Table 1.

Table 1. Monthly average total irradiation variations in Konya

Month	**G_H [kWh/m^2]**	**G_{DH} [kWh/m^2]**	**Ambient Temperature [°C]**
January	68.4	27.38	-1.43
February	86.6	32.85	0.55
March	129.8	50.26	5.55
April	165.9	65.31	9.72
May	209.7	67.94	14.87
June	222.8	63.59	19.63
July	229.6	70.10	23.86
August	207.5	57.67	23.58
September	169.0	42.77	18.16
October	118.8	39.98	12.14
November	78.4	31.1	5.28
December	62.1	22.9	0.27
Year	1748.7	571.83	11.08

The observance of highest ambient temperature is 23.86 °C, and the highest irradiation G_{DH} is 70.1 kWh/m^2 and G_H is 229.6 kWh/m^2 in July. So, an increase in irradiation values and ambient temperature towards summer in Table 1, while these values decrease towards winter, can be seen.

In this study, five different azimuth angles -30°, -15°, 0°, 15°, and 30°, were investigated for the effects on the system using PVsyst software. The monthly average irradiation amount coming to the panel surface is defined as G_I and varies according to the azimuth angles calculated using PVsyst and given in Table 2.

Table 2. Monthly average total G_I values with different azimuth angles

Month	**Monthly average annual G_I [kWh/m^2]**				
	-30°	**-15°**	**0°**	**15°**	**30°**
January	104.2	110.1	112.7	111.8	107.4
February	117.7	122.6	124.3	122.9	118.3
March	154.7	159.2	160.9	159.6	155.7
April	177.9	178.1	177.1	174.5	171.2
May	205.2	203.3	201.7	200.5	199.0
June	204.8	202.9	202.8	203.6	206.1
July	219.7	216.7	215.6	214.7	215.3
August	213.5	214.9	216.0	215.3	213.8
September	198.4	202.2	202.9	200.1	195.2
October	156.9	162.5	164.3	162.1	156.3
November	114.4	120.3	122.8	121.8	117.2
December	99.9	105.3	107.3	105.8	100.8
Year	1967.4	1998	2008.5	1992.7	1956.2

Among considered cases, the highest monthly G_I was obtained in July as 219.7 kWh/m^2 from the system with an azimuth angle of -30°, while the lowest monthly G_I was received in December as 99.9 kWh/m^2 from the system with an azimuth angle of -30°. However, the highest annual G_I obtained as 2008.5 kWh/m^2 for the 0° azimuth case, while the lowest one, 1956.2 kWh/m^2, was received for the 30° azimuth case, which is more meaningful for comparison

The G_I reaching the earth is affected by losses like shading and IAM. The obtained irradiation after these effects is called Effective Global Irradiation (G_E) and given in Table 3.

Table 3. Monthly total average G_E values with different azimuth angles

Month	**Monthly average G_E [kWh/m^2]**				
	-30°	**-15°**	**0°**	**15°**	**30°**
January	102.0	108.4	111.2	110.2	105.4
February	115.3	120.4	122.3	120.7	116.0
March	151.7	156.4	158.2	156.9	152.7
April	174.3	174.4	172.8	170.3	167.3
May	200.5	198.4	196.7	195.6	194.7
June	199.7	197.7	197.4	198.3	201.1
July	214.4	211.4	210.0	209.2	210.2
August	209.1	210.5	210.9	210.6	209.6
September	194.6	198.2	198.6	195.9	191.4
October	154.2	159.8	161.7	159.4	153.4
November	112.0	118.3	121.0	119.8	114.9
December	97.8	103.6	105.8	104.1	98.8
Year	1925.5	1957.4	1966.4	1951	1915.4

Like G_I, the highest monthly G_E was received in July as 214.4 kWh/m^2 with an azimuth angle of -30°. However, the highest annual G_E as 1966.4 kWh/m^2 was received with an azimuth angle of 0°. Since the irradiation intensity is higher in the summer, the value difference is enormous in summer than in winter. With a decrease of 2.66%, the most significant difference occurred in June, while the lowest was in January as 1.33%.

The monthly average annual E_G with a fixed tilt angle of 33° and various azimuth angles is given in Table 4.

Table 4. Monthly average electricity generations with different azimuth angles in Konya

Month	-30°	-15°	0°	15°	30°
January	0.930	0.931	0.932	0.933	0.935
February	0.918	0.916	0.915	0.914	0.916
March	0.890	0.889	0.888	0.887	0.887
April	0.871	0.871	0.868	0.868	0.870
May	0.848	0.847	0.846	0.845	0.846
June	0.827	0.826	0.824	0.823	0.822
July	0.811	0.810	0.808	0.807	0.807
August	0.811	0.810	0.806	0.806	0.807
September	0.828	0.825	0.823	0.822	0.823
October	0.867	0.864	0.864	0.864	0.863
November	0.903	0.904	0.903	0.901	0.899
December	0.924	0.925	0.924	0.923	0.921
Year	0.858	0.858	0.857	0.856	0.855

The highest annual E_G was obtained at an azimuth angle of 0° as 174.33 MWh, which is %2.8 higher than the azimuth angle of the 30° case. However, the highest monthly E_G was obtained from an azimuth of -30° as 18.09 MWh in July. In other words, in all cases, while the highest E_G is observed in the summer months, especially in July and August, and the lowest is observed in the winter months, especially in December and January.

The performance ratio gives information about the system. The monthly average annual performance ratios of the systems calculated with various azimuth angles are given in Table 5 using the PVsyst software.

Table 5. Monthly average annual PRs with different azimuth angles

Month	-30°	-15°	0°	15°	30°
January	0.930	0.931	0.932	0.933	0.935
February	0.918	0.916	0.915	0.914	0.916
March	0.890	0.889	0.888	0.887	0.887
April	0.871	0.871	0.868	0.868	0.870
May	0.848	0.847	0.846	0.845	0.846
June	0.827	0.826	0.824	0.823	0.822
July	0.811	0.810	0.808	0.807	0.807
August	0.811	0.810	0.806	0.806	0.807
September	0.828	0.825	0.823	0.822	0.823
October	0.867	0.864	0.864	0.864	0.863
November	0.903	0.904	0.903	0.901	0.899
December	0.924	0.925	0.924	0.923	0.921
Year	0.858	0.858	0.857	0.856	0.855

The highest PR was found as 0.935 at an azimuth of 30° in January, while the lowest one was obtained in August as 0.806 at an azimuth of 0° and 15°. Namely, the PR values are seen at low levels in the summer and at high levels in the winter months. When viewed annually, there is no significant change in the PRs with various azimuth angles. In addition, annual performance rates are at satisfactory levels.

In addition, by keeping the 33° tilt and 0° azimuth angles constant, four different systems were created for shading analysis by using two different PV panel distances, 4 m, and 8 m, and two different panel heights as 0.1 m and 1 m to evaluate their effect on the efficiency. In comparison, it was understood that the height of the panels had no significant effect on the system. In contrast, it was concluded that panel spacing significantly affects the system's performance. These two shading systems are compared with the no-shading system at 0° azimuth angle. The tilt angle is 33° for both shading and no-shading systems. Since the positions of both shading and no-shading systems are the same, G_I values do not change. However, the changes occur in G_E value, mainly due to some losses especially shading losses. The monthly average G_E values of shading and no-shading systems at 0° azimuth and 33° tilt angles are given in Fig. 2.

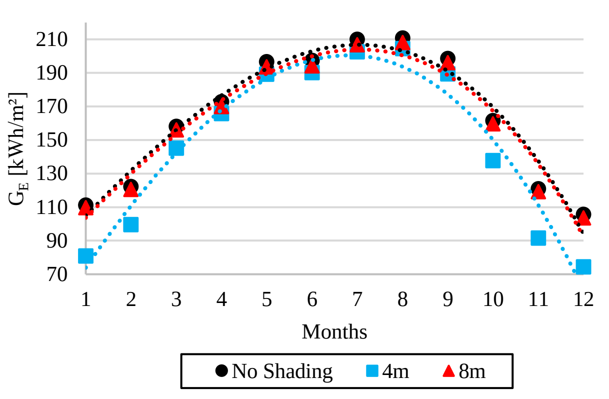

Figure 2. Monthly average of the G_E for no-shading case, 4 m and 8 m panel spans

As expected, the G_E of the no-shading system is higher than the other cases. In addition, since the losses will decrease with the increase of the panel spacing, the G_E value of the system with 8 m spacing is higher than that of the system with 4 m spacing. While there is not much G_E change in the 4 m panel spacing system in the summer months and considerable changes in the winter months, especially in December and January. The system with an 8 m panel span shows little change between the summer and winter. Because G_E comes to the panel surface more horizontally than in summer months in the 4 m panel space system, and the shorter panel spacing causes shadows. The monthly variations of the average E_G of the systems with 0° azimuth angle without shading and the shading systems with 4 m and 8 m panel distances are given in Fig. 3.

Because of the G_E coming to the panel surface in the summer months, as shown in Figure 2, is higher than in the winter months; more electricity is produced in the summer. As expected, E_G at the no-shading system is higher than in other cases. Because the G_E changes according to the months and shadows, the difference in E_G is huge in the winter, especially in December and January at the 4 m panel space case. The PRs of shading systems with 4 m and 8 m panel spacing are given in Fig. 4.

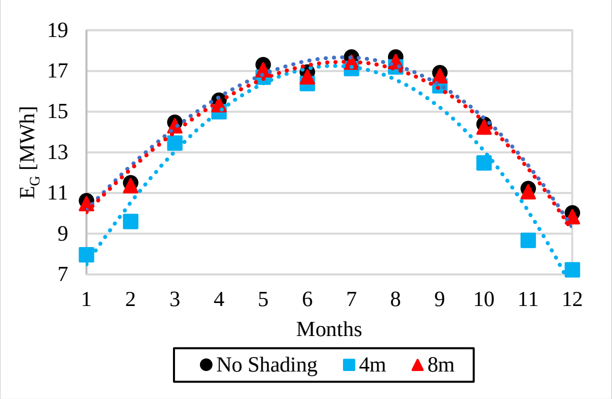

Figure 3. Monthly average variation of E_G of shading and no-shading cases

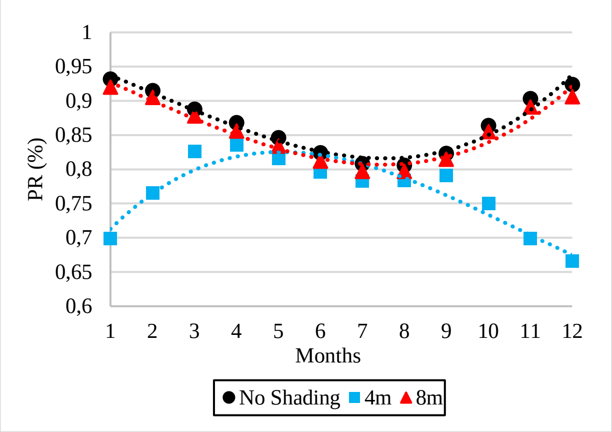

Figure 4. PRs of systems with 4 m and 8 m panel spacing and no shading cases

The PR of the system with 8 m panel spacing is higher in winter and lower in summer. Contrary to this system, the PR of the 4 m panel spacing system is lower in winter and higher in summer. When both systems are compared, the PR of the system with 8 m panel spacing is higher than that of the system with 4 m panel spacing in all months. However, the performance rates of these two systems in the summer months are very close. The PR of the system with panel spacing of 4 m decreased to 27.92% compared to the system without shading. The PR of the system with 8 m panel spacing shows a decrease between 0.97% and 1.95% throughout the year.

4. CONCLUSION

In this study, the effects of no-shading systems with a fixed tilt angle of 33° and five different azimuth angles, -30°, -15°, 0°, 15°, and 30°, were investigated for an on-grid PV system using PVsyst software.

- It was observed that the highest G_E, as 1966.4 kWh/m² occurred at an azimuth angle of 0°, while the lowest one as 1915.4 kWh/m² at an azimuth angle of 30°.
- Similarly, the annual highest E_G was obtained from the system with an azimuth angle of 0° as 174.33 MWh. The lowest E_G was obtained as 169.57 MWh with an azimuth angle of 30°, which is 2.74% lower than the 0° case.
- The highest PR, 0.858, was obtained from the systems with an azimuth angle of -30^0 and -15°. Similarly, for the system with an azimuth angle of 0°, PR was obtained as 0.857, which is approximately the same.

As a result, it is seen that the most proper system is the azimuth angle of 0° for PV applications in Konya.

Furthermore, by keeping a constant tilt angle of 33° and azimuth angle of 0°, the shading systems' effects consist of two different panel heights of 0.1 m, 1 m, and two different panel spacings 4 m, and 8 m, were examined. The obtained results are listed below.

- Although there should be some cooling differences in PV surface temperatures, for these simulations, it is seen that the panel height does not affect the system's performance.
- It is seen that the annual G_E at 4 m panel spacing case was decreased by 11%, while the reduction for the system with 8 m panel spacing was 1.45% compared to no shading case.
- The annual E_G with 4 m and 8 m, panel spacing cases were 154.47 MWh and 168.14 MWh, respectively, 12.85% and 3.68% lower than a no-shading system.
- Similarly, the PR of the systems with 4 m and 8 m panel spacing cases was calculated as 0.777 and 0.846, which are also lower than the no shading case.

It is seen that the results obtained from the system with 8 m panel spacing are better than the one with 4 m panel spacing. However, it should be considered that more land is needed for the system with the 8 m panel spacing case.

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