MANAS Journal of Engineering
ISSN 1694-7398 | e-ISSN 1694-7398

Volume 11, Issue 1, (2023) Pages 74-82
https://doi.org/10.51354/mjen.1223399

Analysis of the azimuth angles of a medium-scale PV system in non-ideal positions for roof application

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ABSTRACT

The installation of photovoltaic (PV) panels on building roofs has seen a significant increase in recent years due to the rising cost of conventional energy sources. This shift towards renewable energy sources has been driven by the urgent need to mitigate the effects of climate change. PV applications is one of the most sustainable and cleanest sources of renewable energy, producing no greenhouse gas emissions during operation. By reducing reliance on fossil fuels, the use of PV panels can help to reduce carbon emissions and lower the overall carbon footprint of buildings. In addition to the environmental benefits, the installation of PV panels can also provide economic benefits, such as reduced energy costs and increased property value. In the past, installations were mostly made in the direction of the south, but now the roofs of the buildings facing west, east, and even north are also considered for PV panel installations.

In this study, a grid-connected PV system with an installed power of 148 kWp at the Konya Technical University (KTUN) campus is modeled by PVsyst software. The PV systems' performance on building roofs oriented in different geographical directions (north, south, east, and west) with a 30° fixed tilt angle was investigated. In the modeling, the solar irradiation coming to the surfaces of the PV panels, electricity production values, performance ratios, and their economic feasibility were calculated. The highest effective irradiation value on the panel surface was obtained from the system facing south, found as 1964.4 kWh/m². It is 20.77%, 22.87%, and 73.48% higher than the solar irradiation obtained at -90°, +90°, and 180° azimuth angles, respectively. It is concluded that the electricity generation amounts of PV systems highly depend on the azimuth angle. Similarly, the highest annual electricity production was obtained from the system installed in the 0° azimuth angle found as 254.77 MWh. The annual total electricity generation is 19.66%, 22.55%, and 69.41% higher in systems modeled toward the east, west, and north, respectively. Performance ratio, defined as the ratio of radiation coming to the panel surface and the electricity produced, has relative values between 0.843 and 0.862 for four different azimuth angles. Furthermore, as an economic analysis, the Basic Payback Period (BPP) of the projects was found as 6.92 years, 4.08 years, 4.88 years, and 5.00 years for the systems modeled in the north, south, east, and west directions, respectively. It can be concluded that the most suitable orientation is south, and the other two directions, east, and west, can also be considered feasible.

ARTICLE INFO

Research article

Received: 25.12.2022
Accepted: 16.05.2023

Keywords:
azimuth angle,
economic analysis,
photovoltaic panel,
solar energy.

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1. Introduction

Renewable energy sources, such as solar and wind power, produce little to no greenhouse gas emissions, which can help to combat climate change. In addition, renewable energy can provide a reliable and stable source of electricity, particularly in remote or underserved areas. It can also help to create jobs and stimulate economic growth, particularly in rural communities where renewable energy projects are often located. Increasing the use of renewable energy can help reduce our dependence on foreign sources of fossil fuels, such as Turkey, which can have national security and economic benefits. It can also help reduce the impact of energy price fluctuations, as the cost of renewable energy sources is often more stable than fossil fuels [1]. Although renewable energy sources are found in every country, their technical and economic feasibility varies according to geographical locations. [2,3].

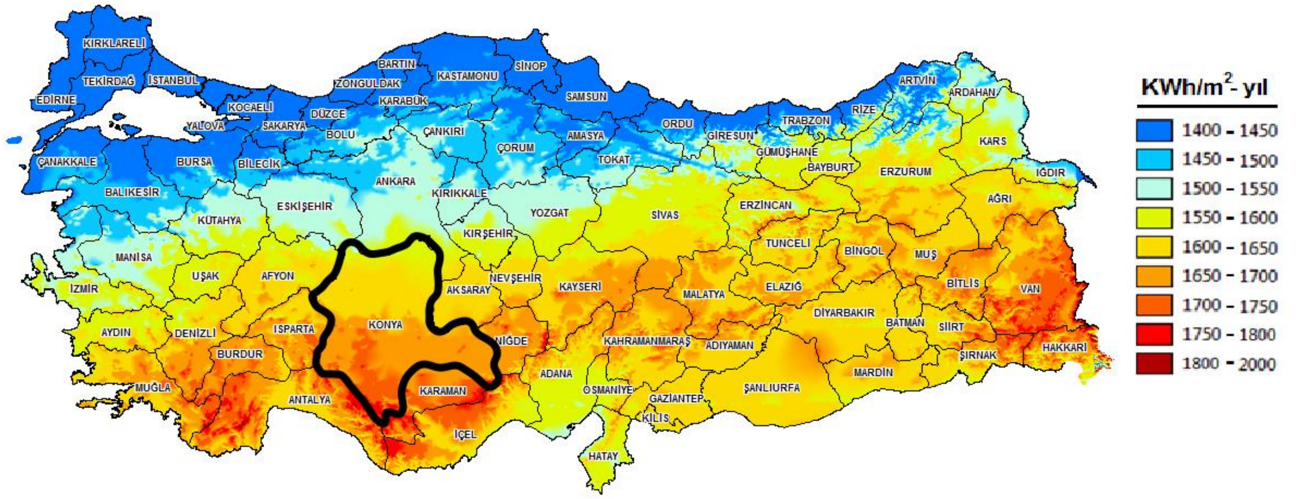

Figure 1. *The Solar Irradiation Potential of Turkey and Konya* [4,5]

Solar energy is a clean and abundant source of energy that can be harnessed in various ways, including PV cells. In addition, the cost of solar energy is decreasing, making it a more affordable option for residential and commercial users [6,7].
Solar energy systems can be used in various installation cases, including grid-connected, stand-alone, and a combination. In addition, these systems have wide application areas such as irrigation, cooling, and water pumping [8].

PV panels are devices that convert sunlight into electricity. As of 2021, the total installed capacity of PV panels worldwide is approximately 600 GW [9]. This installation represents a significant increase from previous years, as the global PV market has been growing rapidly in recent years due to falling costs and increasing demand for clean and renewable energy. Most PV panels are installed in Asia, particularly in China, which has the world's largest installed capacity at over 200 GW [10,11]. Other major PV markets include the European Union, the United States, and Japan. Due to Turkey's geographical conditions, it is in an advantageous position compared to many European countries with its 7.2 hours/day sunshine duration and 3.6 kWh/m² daily average solar radiation value [12]. The efficiency that can be achieved in Turkey also varies according to the location. As seen in Figure 1, the annual amount of radiation is higher in the southern and Mediterranean regions of Central Anatolia, including Konya, compared to other regions.

As of 2021, Turkey's total installed capacity of PV panels is approximately 7.8 GW [13]. This instillation represents a significant increase from previous years, as the Turkish government has been implementing policies to support the country's PV market growth [14]. A combination of favorable solar resources and government policies has driven the growth of the PV market in Turkey. As the country continues to transition away from fossil fuels and towards clean and renewable energy, the use of PV panels is expected to continue to grow and play an important role in meeting Turkey's energy needs. Installed power and the ratios of total installed power of PV systems between 2014 and June 2022 are given in Figures 2 and 3, respectively [15]. The figures show that the tendency to obtain electrical energy from solar energy has increased considerably in recent years in Turkey. Also, bank financings and incentives are given by the government to establish facilities play an important role in this increase [16]. In addition, a tender was made for the facility with an installed capacity of 1000 MW in the Renewable Energy Resources Area (YEKA) in Konya's Karapınar district in 2016 [17]. When the project is completed, it is expected to meet 24% of the electricity consumption of Konya and 0.6% of Turkey, with an electricity production of 2300 GWh.

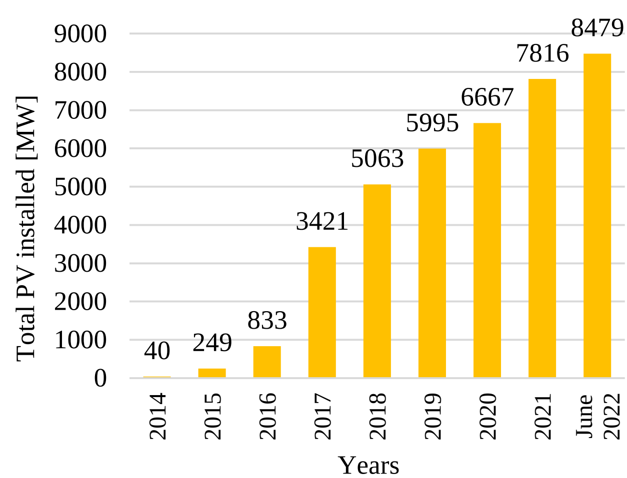

Figure 2. *Turkey's total PV installed capacity by years* [15]

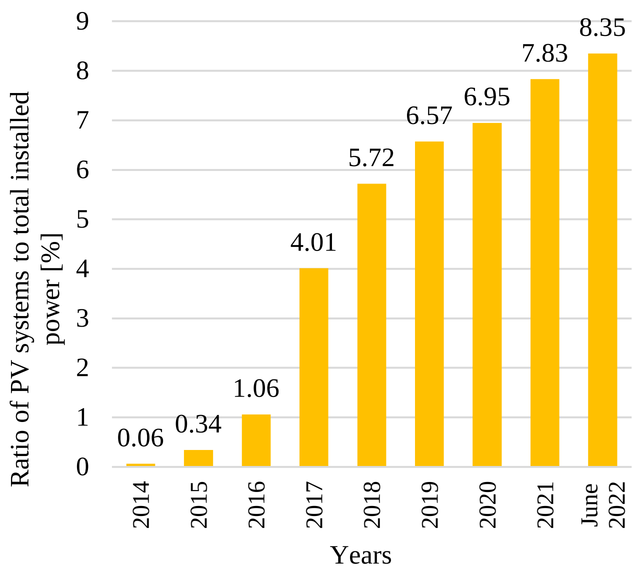

Figure 3. *The ratio of Turkey's PV systems to installed power by years* [15]

The tilt angle, known as the angle of the PV panel surface with the ground, has a very important place in the PV performance. The annual optimum value of this angle is approximately equal to the latitude angle of the place where the system will be installed. In addition, this angle changes seasonally. Since the angle of incidence of the radiation changes, the optimum tilt angle is approximately 15° smaller than the latitude angle in summer and approximately 15° greater in winter. In addition to the tilt angle, the azimuth angle, which is the angle that the panel makes in the north-south direction, also plays an important role in the PV performance [18]. The azimuth angle of the system located in the northern hemisphere and established towards the south is 0°. While this value is positive towards the west, it is negative towards the east. When these two angles are compared, the tilt angle is more important than the azimuth [19]. However, the tilt angle can be adjusted in both field and roof applications, while the azimuth angle can be adjusted in field applications but not generally in roof applications. Some studies examine the performance of the tilt and azimuth angle on the system. For example, roof models were made using four different azimuth angles as -87°, -32°, +2°, and +17° and electricity generation of the systems was examined in Huddersfield, England. The highest electricity production was obtained from the system with an azimuth angle of +2°, while the lowest was obtained with an azimuth angle of -87° [20]. Another study found that the orientation of PV panels can significantly affect their electricity-generating potential. The study found that south-facing PV panels in the northern hemisphere could generate more electricity than east- or west-facing panels and that the difference in output increased as the latitude of the panels increased [21]. Kiviluoma et al. [22] found that the angle at which PV panels are tilted can also affect their performance. The study found that tilting PV panels at an angle equal to their latitude maximized the amount of sunlight they could capture and convert into electricity and that this angle varied depending on the location of the panels. Pal et al. [23] examined the combined effect of orientation and tilt angle on the performance of PV panels. The study found that the optimal orientation and tilt for PV panels varied depending on the system's location and the time of year, but that, in general, south-facing panels tilted at an angle equal to their latitude were able to generate the most electricity. Barbón et al. [19] investigated the effects of tilt and azimuth angles on the system. Within the scope of the study, ten different cities were considered. They calculated the energy losses at different tilt angles using an azimuth angle of 0°. They calculated that 5% energy loss occurs at tilt angles between 21 and 23°, 10% at tilt angles between 31 and 33°, 15% at tilt angles between 37 and 40°, and 20% at tilt angles between 43 and 47°. They also concluded that azimuth and tilt angles have less effect in cities with low latitudes. Sun et al. [24] modeled the electricity generation obtained from the PV system at various shading percentages in Hong Kong using five different azimuth angles as -90°, -45°, 0°, 45°, and 90°, and seven different tilt angles as between 20 and 80. They obtained the most electricity production from the system with an azimuth angle of 0° and without shading. In addition, they observed that the amount of electricity decreased with the increase in the tilt angle in Hong Kong, which has a latitude of 22.57°. Aksoy et al. [25] investigated the effect of five different azimuth angles -30°, -15°, 0°, 15°, and 30° on system performance using PVsyst. In addition, they also examined the effect of shading losses on the system, which will occur from two different panel heights of 0.1 m, and 1 m and two different panel spacings of 4 m, and 8 m, and compared with no-shading systems. They obtained the highest annual electricity generation (E_G) from no-shading systems with 0° azimuth angle as 174.33 MWh and found this value to be 12.86% and 3.68% higher than for systems with 4 m and 8 m panel spacing, respectively. They also concluded that the panel heights do not affect the system performance.

The widespread adoption of PV roof applications in recent years can be attributed to several factors, including the rising cost of electricity, government incentives and regulations, advances in technology and manufacturing processes, the need for energy independence, and growing concerns about climate change. Additionally, the improved aesthetics and design options of PV panels have made them more appealing to consumers, further contributing to their widespread adoption. The roofs of houses and factories may not be positioned toward the south, and the electricity generation values of the systems installed in directions other than the south should be evaluated [26]. Therefore, in this study, PV system modeling and comparisons of different oriented systems were made using the PVsyst software with a fixed tilt angle of 30° and four different azimuth angles, -180°, 0°, -90° and 90° to the north, south, east, and west directions, respectively.

2. Material and method

PVsyst is a software program used to design and simulate PV systems. It is a commonly used tool among PV professionals and researchers, as it offers a range of features and tools for analyzing and optimizing the performance of PV systems. PVsyst allows users to create detailed models of the systems, considering factors such as the location and orientation of the panels, the type of PV cells and inverters used, and the environmental conditions at the site. The program then simulates the performance of the PV system under different conditions, allowing users to evaluate its performance and identify potential issues or areas for improvement. In addition, PVsyst also offers a range of tools for analyzing and optimizing the performance of PV systems. These tools include sizing PV systems, calculating energy yield, and estimating the financial return on investment. In the literature, studies from Turkey [27-32] and around the world [33-37] analyzed PV systems using PVsyst. For example, Aksoy et al. [38] performed performance analysis of three different cells, monocrystalline, polycrystalline, and amorphous silicon, with a fixed installed power of 300 kWp using PVsyst in Konya, Turkey. They used a tilt angle of 35° and an azimuth angle of 0° in this study. the highest electricity production was obtained from monocrystalline cells with an annual value of 513.91 MWh. This value is 1.91% and 3.07% higher than the electricity produced by polycrystalline and amorphous silicon. In addition, in the economic analysis, it was found that monocrystalline and polycrystalline systems pay for themselves in about 6 years, while amorphous silicon pays off in 9 years.

A PV system with a power of 148 kWp was modeled on the roof of any building in the KTUN campus with a latitude of 38.03 °N and longitude of 32.51 °E, which was determined by using the METEO 8.0 program, which is a part of the PVsyst software. The view of KTUN from space is given in Figure 4. Totally 528 modules, with 22 horizontal and 24 vertical, were used in all modeled systems. While the total area covered by the modeled system is 866 m², the panel surface area is 779 m². Polycrystalline cells with model number CWT280 – 60P produced by Generic were selected as PV panels.

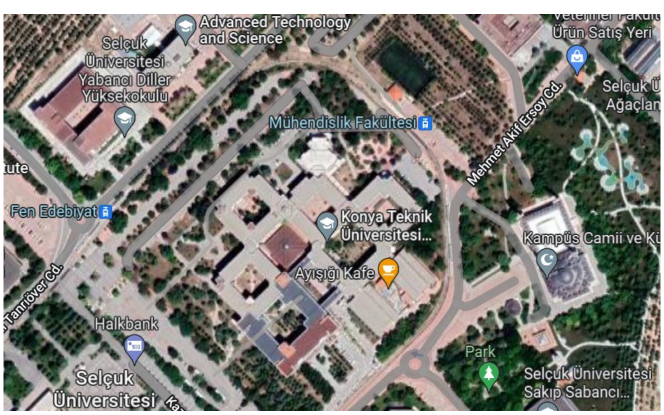

Figure 4. *The satellite view of KTUN*

Another parameter of a PV system is the performance ratio (P_R) which is calculated as the ratio of E_G to the global horizontal radiation (I_{GH}) incident on the panel surface in a system with a unit installed power [39].

$$P_R = \frac{E_G}{I_{GH} \times P_{PV}} \tag{1}$$

Where P_{PV} is the rated power of the PV system

The amount of radiation was calculated mathematically on a daily or monthly basis depending on the location. The daily radiation amount was calculated as follows [40].

$$I_{GH} = \frac{24\times3600 G_{SC}}{\pi}\left[1 + 0.033 cos\left(\frac{360n}{365}\right)\right] \times cos\varphi\, cos\delta\, cos\omega_s + \frac{2\pi\omega_s}{360} sin\varphi sin\delta \tag{2}$$

Here n is the number of day, φ, δ and ω_s are the latitude angle, declination angle, and sunset time angle for the mean day of the month, respectively, and are calculated as follows.

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

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

Where ST is local time and equals 12 at midday. Current PVsyst software uses the Perez model as the transposition method. In this model, the aim is to calculate the amount of radiation incident to the inclined plane from the horizontal radiation data. When compared with these real data, the error rate of PVsyst is less than 2% [41].

For the projects to be implemented, primarily economic analysis is required. The basic step of economic analysis is BPP is calculated as follows.

$$BPP = \frac{Initial\ investment}{Annual\ net\ cash\ inflow} \tag{5}$$

3. Result and discussion

Global solar radiation on a surface refers to the amount of solar radiation received by a surface over a period. Global solar radiation is typically measured in power units per unit area, as watts per square meter (W/m^2). The amount of global solar radiation that a surface receives depends on various factors, including the location of the surface, the time of year, and the angle at which the sun's rays strike the surface. In general, surfaces closer to the equator and receive direct sunlight for a longer period each day will receive more global solar radiation than surfaces located at higher latitudes and with less direct sunlight. The amount of irradiation coming to the panel surface affects the performance of PV systems directly. I_{GH} is the monthly average global horizontal irradiation for the location of KTUN in Konya, Turkey, given in Figure 5. These irradiation values were analyzed with different mathematical models according to the tilt angle of the panels using PVsyst. The highest solar irradiation of all orientations occurred in July as 199.3 kWh/m², 219.8 kWh/m², 212.5 kWh/m², and 218.5 kWh/m² for north, east, west, and south, respectively. As seen in the summer months, the difference in radiation values is not so much, but in winter, the difference seems more visible. Yearly total solar radiation is obtained as 2007.4 kWh/m² from the south-oriented system. This value is annually 20.13%, 22.05%, and 66.4% higher than east, west, and north, respectively. The electricity generation values are also calculated on the inclined surface of the panels.

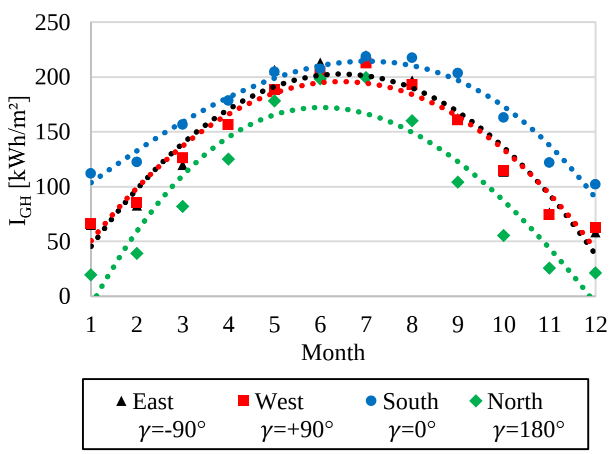

Figure 5. *Average monthly I_{GH} at various azimuth angles*

The solar irradiation is affected by losses such as shading and IAM and loses some of its energy levels. The irradiation after these loses is called Effective Global Radiation (I_{EG}). The monthly average I_{EG} reaching panel surfaces of different azimuth angles obtained with PVsyst is given in Figure 6.

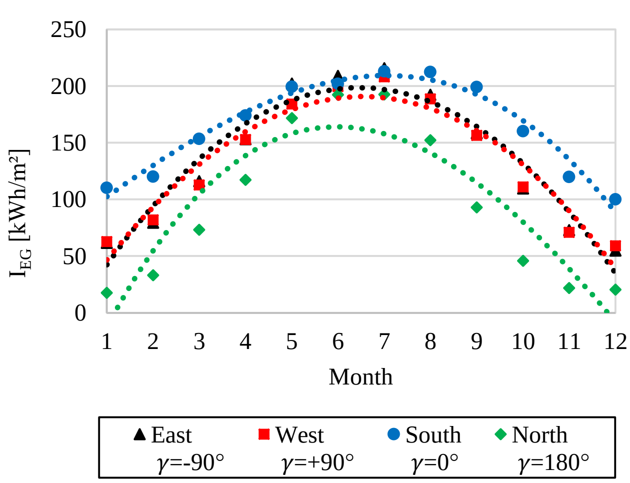

Figure 6. *Monthly average I_{EG} amounts coming into the system at various azimuth angles*

Like I_{GH}, the amount of I_{EG} is highest in the south direction and the lowest in the north direction surfaces. Systems modeled toward north, south, east, and west directions suffered radiation losses of 6.14%, 2.14%, 2.79%, and 2.66%, respectively. The lowest loss was found in the system modeled toward the south direction. Because according to KTUN, which is located in the northern hemisphere, the sun rises and sets in the southern direction. Therefore, the least loss occurs in systems modeled towards the south.

The monthly total E_G values obtained from PV systems with various azimuth angles using I_{EG} are given in Figure 7.

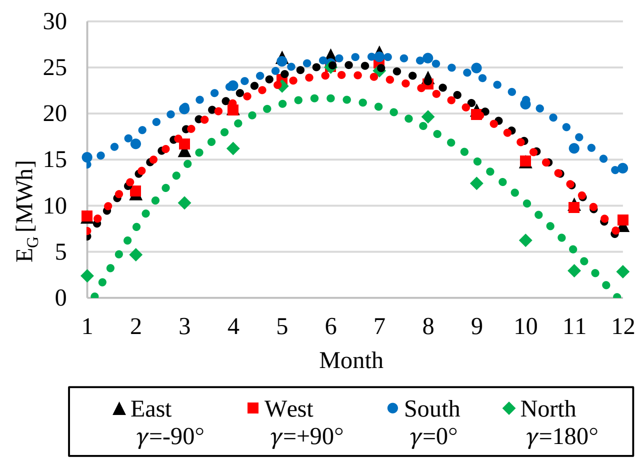

Figure 7. *Monthly average I_{EG} amounts of systems at various azimuth angles*

Since I_{EG} coming to the panel surface is higher in summer, E_G is also higher too. In addition, since I_{EG} It has the highest radiation value in the south direction, producing the highest electricity with a yearly total of 254.76 MWh. This value is 69.43%, 19.65 and 22.55% higher than the E_G by systems modeled toward north, east, and west directions, respectively. Using the values in Figures 5 and 6 and Eq. (1), P_R can be calculated. The P_R of a PV system refers to the ratio of the actual power output of the system to its theoretical maximum power output under specific operating conditions. The performance ratio can be affected by various factors, including the efficiency of the PV panels, the amount of sunlight available, and the panels' temperature. The monthly P_R values of the systems modeled in four different directions are shown in Table 1.

Table 1. *The monthly average P_R values of different oriented systems*

Months	East ($-90°$)	West ($+90°$)	South ($-0°$)	North ($\pm180°$)
1	0.916	0.910	0.921	0.838
2	0.926	0.919	0.923	0.815
3	0.904	0.895	0.884	0.854
4	0.885	0.880	0.872	0.878
5	0.856	0.850	0.848	0.872
6	0.837	0.830	0.829	0.854
7	0.820	0.811	0.809	0.837
8	0.822	0.813	0.809	0.831
9	0.848	0.836	0.828	0.807
10	0.881	0.874	0.871	0.765
11	0.902	0.891	0.900	0.789
12	0.916	0.913	0.933	0.901
Average	0.862	0.855	0.858	0.843

It is seen that the highest P_R's are seen in the winter months. While the P_R values of the systems modeled towards the east, west, and south directions decrease towards the summer and increase towards the winter. However, since KTUN is in the northern hemisphere and is opposite to solar radiation, the situation is the opposite in the system modeled towards the north. The monthly highest P_R value of 0.933 was observed in the system modeled towards the South direction in December, while the lowest one was observed in the system modeled towards the north with a value of 0.765 in October.

The economic feasibility of a PV system depends on several factors, including the system's initial cost, the local climate and weather conditions, the amount of sunlight the system will receive, and the current and projected cost of electricity from the grid. Other factors that may affect the economic feasibility of a PV system include any available incentives or subsidies, the expected lifespan of the system, and the maintenance and repair costs over time [42-46]. The Basic Payback Period (BPB) is the time it takes for the savings generated by an investment to equal the initial cost of the investment. In the case of a PV system, also known as a solar panel system, the payback period is the length of time it takes for the savings on electricity bills to equal the initial cost of the PV system. BPP was calculated by using Eq. (5) in this study. The values listed below were used in the calculation.

- The unit investment cost of the panels is taken as 1.2 $/Wp [47].
- The operation and maintenance costs of the systems have been accepted as 2.5% of the investment cost [47].
- The electricity sales price has been determined as 0.175 $/kWh

Using the above items, the BPP values of the systems installed toward the north, south, east, and west directions were calculated as 6.92 years, 4.08 years, 4.88 years, and 5.00 years, respectively.

4. Conclusion

In conclusion, the installation of photovoltaic (PV) panels on building roofs has become increasingly common in recent years due to the urgent need to mitigate the effects of climate change and the economic benefits it offers. This study provides valuable insights into the performance and economic feasibility of PV systems on building roofs oriented in different geographical directions. The results indicate that the electricity generation amounts of PV systems are highly dependent on the azimuth angle, with south-facing systems producing the highest effective irradiation values and annual electricity production. The obtained results are given below.

- The maximum I_{GH} and I_{EG} coming on the panel surface were obtained from the model towards the south direction (azimuth angle of 0°) with values of 2007.4 kWh/m² and 1964.4 kWh/m², respectively.
- Since I_{GH} and I_{EG} on PV panels are highest, the highest annual E_G was also obtained from the system modeled toward the south with a total value of 254.76 MWh. The annual total electricity generation from the systems towards the north, east, and west directions were found to be 150.38 MWh, 212.9 MWh, and 207.88 MWh, respectively.
- It was determined that the P_Rs of the systems modeled towards the east, west, and south directions decreased towards the summer and higher in winter due to low loss due to ambient temperature.
- On the other hand, it has also been observed that the P_R values between the modeled systems are very close to each other and at a negligible level.
- The lowest BPP was obtained from the system modeled towards the south with 4.08 years. This value is 40.98%, 16.42% and 18.40% lower at the north, east and west directions, respectively.

This research underscores the importance of considering geographical orientation in the planning and implementation of PV systems to maximize their energy production and economic viability. It is recommended to make the economic analysis with Internal rate of return and Net present value methods for systems installed in different directions.

Acknowledgment

This study was orally presented at the 6th International Conference on Engineering Technologies (ICENTE'22).

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