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Bir Endüstriyel Tesis İçin Gerçek ve Simüle Edilen Fotovoltaik Sistemlerin Karşılaştırılması

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ÖZET

Bu çalışma, Türkiye'nin Konya ilinde yer alan bir endüstriyel tesise ait operasyonel ve simüle edilmiş fotovoltaik (PV) sistemleri, PVsyst yazılımı kullanılarak karşılaştırmaktadır. En yüksek ışınım şiddeti Temmuz ayında kaydedilirken, en düşük değer Aralık ayında gözlemlenmiştir. Yıllık küresel yatay ışınım 1761.1 kWh/m², yıllık etkili küresel ışınım ise 1661.1 kWh/m² olarak hesaplanmıştır. Etkili ışınım açısından en yüksek ve en düşük değerler sırasıyla Haziran ve Ekim aylarında elde edilmiş olup, yıllık bazda toplam fark %5.68 olarak bulunmuştur. Her iki sistem için en yüksek ve en düşük elektrik üretimi sırasıyla Temmuz ve Ocak aylarında gerçekleşmiştir. Yıllık ortalamaya göre, aylık ortalama elektrik üretimi operasyonel sistem için 210.2 MWh, simüle edilmiş sistem için ise 201.1 MWh olarak ölçülmüştür. Her iki durumda da, en yüksek performans oranı (PR) Şubat ayında elde edilmiş; bu değerler operasyonel sistem için 0.827, simüle sistem için ise 0.954'tür. En düşük PR değerleri Mayıs ayında gerçekleşmiş olup, sırasıyla 0.703 ve 0.656 olarak tespit edilmiştir. Operasyonel ve simüle sistemler için yıllık ortalama PR değerleri sırasıyla 0.797 ve 0.756 olarak belirlenmiştir. Elde edilen sonuçlar, simüle edilen sistem performansının gerçek sistem verileriyle güçlü bir uyum içinde olduğunu göstermekte olup, PVsyst yazılımının endüstriyel uygulamalarda fotovoltaik sistem davranışını değerlendirmede doğruluğunu ve güvenilirliğini ortaya koymaktadır.

Comparison of Actual and Simulated Photovoltaic Systems for an Industrial Facility

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ABSTRACT

The present study compares operational and simulated photovoltaic (PV) systems for an industrial facility located in Konya Province, Türkiye, using PVsyst software. The highest radiation intensity was recorded in July, while the lowest was in December. The global horizontal irradiance is 1761.1 kWh/m² per year, while the effective global irradiance is 1661.1 kWh/m² per year. The maximum and the minimum values were obtained in June and October, respectively, with an overall annual difference of 5.68%. The highest and the lowest electricity generation values have been observed for both systems in July and January, respectively. On annual basis, the monthly average electricity generation was 210.2 MWh for the operational system and 201.1 MWh for the simulated system. In both cases, the peak performance ratio (PR) was 0.827 for the actual system and 0.954 for the simulated one in February. The lowest values were obtained in May, with 0.703 for the operational system and 0.656 for the simulated system. The annual average PR values for the actual and the simulated systems were 0.797 and 0.756, respectively. The results demonstrate that the performance of the simulated system closely matches that of the actual system, confirming the accuracy and reliability of PVsyst simulations for evaluating real-world photovoltaic system behavior in industrial applications.

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INTRODUCTION

Energy is a fundamental component for sustaining life and plays a critical role in ensuring intergenerational welfare and global sustainability. It is utilized across a wide range of applications, from basic household appliances to advanced space technologies. As technological advancements progress, the size and functional complexity of machinery increase, leading to a parallel rise in global energy demand. Currently, a substantial portion of the energy production for the world relies on fossil fuels such as coal and petroleum [1]. However, the combustion of these resources poses significant environmental challenges, including greenhouse gas emissions, elevated carbon dioxide levels, global warming and long-term climate change. Furthermore, the uneven distribution of fossil fuel reserves worldwide creates a reliance on external energy sources, posing risks to national energy security and economic stability. To mitigate these environmental and economic drawbacks, the transition to renewable energy sources—such as solar, wind and hydropower—has become imperative [2]. Unlike fossil fuels, renewables offer a more secure and sustainable energy pathway, characterized by low operational costs beyond initial investment and minimal vulnerability to geopolitical fluctuations, economic crises or conflicts. Ultimately, increasing the share of renewables in the global energy mix is essential to establishing a resilient and sustainable energy infrastructure. This transition not only supports environmental preservation but also ensures a livable world for future generations [3-5].

Solar energy is one of the most important renewable sources for heating, cooling, drying, distillation and electricity generation. The most important of these energy generation methods is photovoltaic (PV) cell technology, which generates electricity by converting sunlight into electricity. Because by using electricity, work can be done in many application areas. Many parameters affect the generation of electricity from PV cells. The main reason is that the intensity of irradiation and the duration of sunshine cannot be equal everywhere. In addition, many PV cell types, such as monocrystalline, polycrystalline, amorphous silicon, cadmium telluride and organic PV cells, also affect electricity generation efficiency. Aksoy and Ispir [6] compared the electricity generation and economic analysis of three PV cells consisting of monocrystalline, polycrystalline and amorphous silicon using PVsyst software. Their study concluded that the monocrystalline PV system produced 1.91% and 3.07% more electricity than polycrystalline and amorphous silicon.

Regardless of these reasons, there are also issues to consider during the panel installation phase, such as the azimuth and tilt angles, which constitute the panel geometry [7]. Aksoy, Ispir [8] investigated the electricity generation performance of four different azimuth angles (-90°, 180°, 90° and 0°) at a fixed tilt angle using PVsyst software. In this study, it was concluded that the system with an azimuth angle of 0° generated 19.65%, 22.55% and 63.49% more electricity than the systems with azimuth angles of -90°, 90° and 180°, respectively. Gunerhan and Hepbasli [9] conducted a study to determine the optimal tilt angle for PV systems in Izmir under three conditions: summer, winter and annual. They found the optimum summer, winter and annual tilt angles to be 23.46°, 38.46° and 53°, respectively. Tang and Wu [10] analyzed monthly and annual radiation intensities in 30 cities in China and determined the optimal tilt angles for each city. When the results were analyzed, they concluded that the tilt angle is location-dependent and important. Jafarkazemi and Saadabadi [11] aimed to find the optimum angle values using twenty-three different tilt angles between -20° and 90° and ten different azimuth angles between 0° and 90° in Abu Dhabi. In the study, the optimum tilt angle was found to be 22° and the azimuth angle was found to be 0°. They also concluded that radiation intensities decrease significantly as they move away from these angles. Benghanem [12] conducted a study to find the seasonally optimum tilt angle in Madinah. The optimum tilt angles for winter, spring, summer and fall are 37°, 17°, 12° and 28°, respectively. There is an 8% energy loss if the optimum tilt angle is used annually. Many studies, such as [8-12], emphasize the importance of the tilt and azimuth angles.

With an annual average daily irradiance density of 3.6 kWh/(m²day) and a sunshine duration of 7.2 h/day, Türkiye is well-positioned compared to many countries worldwide [3]. However, as shown in the irradiation intensity map of Türkiye given in Fig. 1, irradiation intensity and sunshine duration do not reach the same amount everywhere. It can be seen that a PV system to be installed around Konya, which has approximately 4.42 kWh/(m²day) of irradiance and 7.95 h/day of sunshine hours in Türkiye, would be more efficient [13]. As Konya is one of major industrial cities in Türkiye, it is crucial to regularly monitor the power generation and efficiency of solar power plants used in industrial applications to ensure resource sustainability and energy efficiency [14]. Bakirci [15] studied the radiation intensities in eight cities: Adana, Ankara, Diyarbakir, Erzurum, Istanbul, Izmir, Samsun and Trabzon. The highest radiation intensity has been observed in Diyarbakir, with a value of 7052.27 MJ/(m²year) and the lowest in Trabzon with a value of 4623.18 MJ/(m²year).

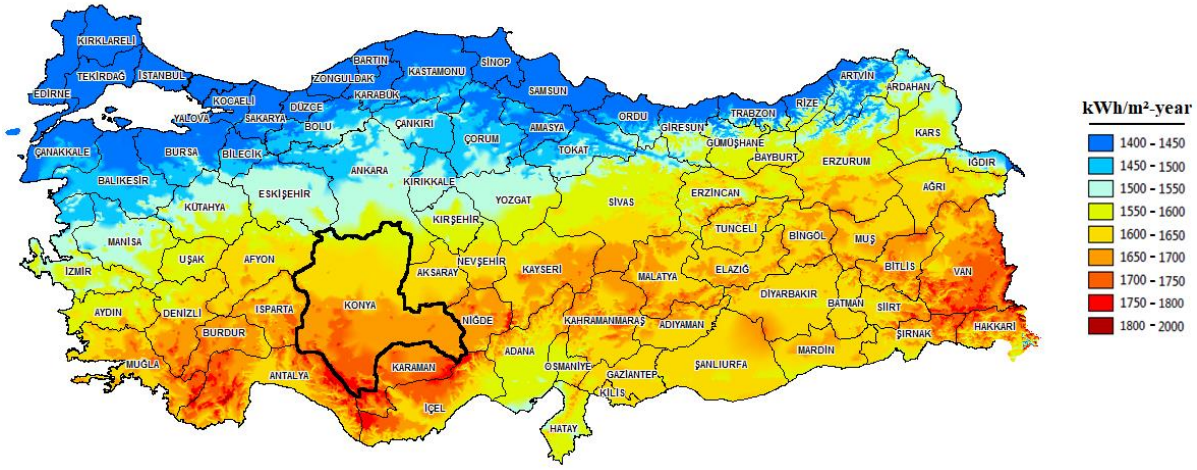

Figure 1
A map for average annual solar radiation intensity in Türkiye [8,16].

Although Türkiye has realized this potential late, it has rapidly increased the number of solar power plants and has moved ahead of many countries. While Turkey had an installed capacity of 40 MW in 2014, it increased by 39033.5% in 2023 and reached 15613.4 MW [17].

In recent years, software science has evolved considerably. The development of this technology has brought many advantages, such as reduced experiment costs and time savings. In solar energy technologies, many software such as PVsyst, RETScreen and HOMER have become a branch of this field and have facilitated the modelling of solar energy systems [18]. The precision of these software applications is essential for assessing the performance of PV systems and energy efficiency. To evaluate the accuracy of various software packages, de Souza Silva et al. [19] compared experimental data with PVsyst, HOMER and PVSOL. The results, with power generation variances of 1.02% and a performance ratio (PR) of 84.1% showed that PVsyst was the most accurate software. On the other hand, PVSOL had a variance of 2.04% and a PR of 87.91%, while HOMER software had a variance of -10.38% and a PR of 90%. These results highlight the importance of selecting a precise software application for PV system modeling to achieve accurate, reliable results. Moreover, the PR values have also been presented for different locations, angles, cell types and power values, as shown in Table 1.

METHODS

The photovoltaic system has been active since mid-2021 at an industrial facility in Konya, Türkiye. This system consists of 5383 monocrystalline cells with dimensions of 1669 mm × 1002 mm,

each with a nominal power of 330 Wp. It has an installed power of 1776.39 kWp and operates between -40 °C and 85 °C. Due to the location and roof structure of the relevant factory, all panels have a tilt

Table 1
The PR values using PVsyst software.

Studies	Location	Tilt – Azimuth Angles [°]	Cell Type	Power [kWp]	PR
[20]	Afghanistan	30° – 0°	Si-Mono, Si-Poly	10.23	0.822 0.818
[21]	Afghanistan	34° – 0°	Si-Poly	700	0.797
[22]	India	19° – 0°	Si-Poly	500	0.790
[23]	India	20° – 0°	Si-Poly	50	0.732
[24]	Egypt	30° – 0°	Si-Mono	400	0.838
[25]	Nigeria	5° – NaN	Si-Poly	787	0.832
[26]	Morocco	32° – 0°	Si-Poly	1000	0.781
Present Study	Türkiye	32° – 37° 32° – -53° 32° – 127°	Si-Mono	1776.39	0.756

angle of 8°. To use the roof more efficiently, three different azimuth angles of 37°, -53° and 127° have been used and 820, 3234 and 1340 modules have been used for these azimuth angles, respectively. The top view and schematic structure of the roof of this industrial facility are given in Figure 2.

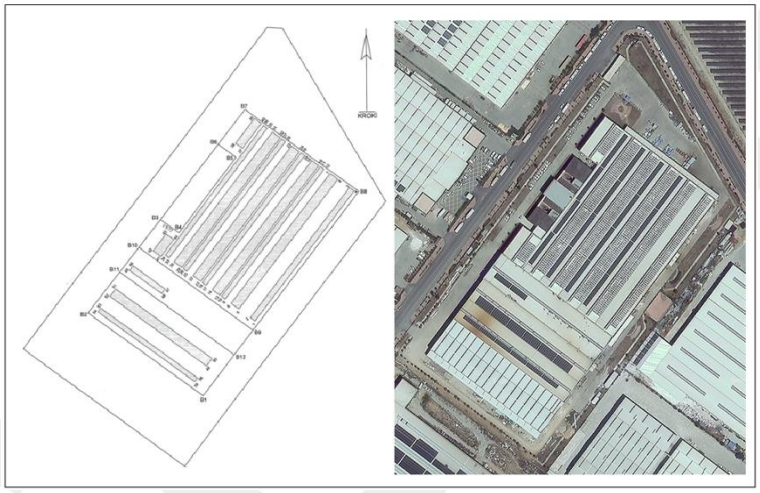

Figure 2
The top view and schematic structure of the roof of the factory.

PVsyst software was used to compare data from the rooftop application and an accuracy study was conducted. As in the actual roof application, a model has been created with three different azimuth angles (37°, -53° and 127°) and a fixed tilt angle of 8°. Meteonorm has been used as a database to obtain solar irradiance values at coordinates within the modelling scope. Monocrystalline PV modules with model number End-2H-60C-330W-G1 from Endustriyel Solar, each with a nominal power value of 300 Wp, have been utilized. For the azimuth angles of 37°, -53° and 127° of the modelled system, 820 modules (20 series × 41 strings), 3234 modules (21 series × 154 strings) and 1340 modules (20 series × 41 strings) have been used, respectively. The inventor of the device that converted direct current to alternating current was the inventor of the model number SUN2000-100KTL-M1-400Vac from Huawei Technologies. As in the PV system model, 140 inventors have been added to the system, 21, 86 and 33 for azimuth angles of 37°, -53° and 127°, respectively.

A good way to analyze system performance in PVsyst is by evaluating the PR value. As in Eq. 1, this value could be calculated as the ratio of electricity generated per unit of power to the global horizontal irradiance [8].

$$PR = \frac{E_G}{G_I \times P_{PV}} \quad (1)$$

Where E_G is the monthly average electricity generation, G_I is the monthly average global horizontal irradiance density and P_{PV} is the installed capacity of the PV system. The PR value can also be computed based on daily electricity output and incident solar radiation. This requires the prior calculation of daily radiation intensity, as formulated in Equation (2). [8].

$$H_0 = \frac{24 \times 3600 G_{SC}}{\pi}\left[1 + 0.033cos\left(\frac{360n}{365}\right)\right] \times cos\varphi cos\delta cos\omega_s + \frac{2\pi\omega_s}{360} sin\varphi sin\delta \quad (2)$$

Where n is the number of days per year, φ is the latitude angle, δ is the declination angle calculated using Eq. 3 [8] and ω_s is the sunset angle for the average month day calculated using Eq. 4 [8].

$$\omega = 15(ST - 12) \quad (3)$$

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

RESULTS AND DISCUSSION

This study aims to compare electricity generation data from a real-world PV system with simulated results from PVsyst software to assess the accuracy and reliability of the simulation model. One of the most important factors in electricity generation is the location where the system is installed, because the radiation intensity reaching this location is directly proportional to the electricity generation. Not all the incoming irradiation at the current location can be used to generate electricity and some of it is lost. These losses can be caused by shadowing due to panel spacing, the albedo of PV cell, photon refraction due to air pollution and reflected irradiance due to the surface material on which the PV cells are installed. The irradiance that reaches the surface and is used in electricity generation is called effective global irradiance. As on-site irradiance measurements for the operational system are unavailable, the corresponding irradiance values were obtained solely from PVsyst simulations. Fig. 3 shows the total monthly average global horizontal irradiance at the location and the effective global irradiances used in electricity generation.

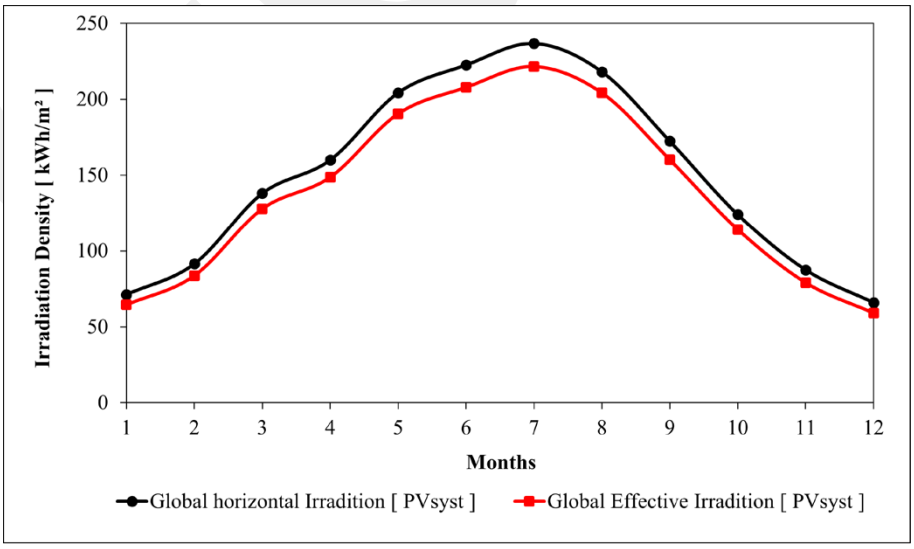

Figure 3
The monthly average global horizontal irradiance and effective global irradiance obtained from PVsyst.

Since the installed system is in the Northern Hemisphere, irradiation intensity is higher in summer than in winter. In global horizontal irradiation and effective global irradiation, the highest intensities are observed in July, with 234.4 kWh/m² and 221.6 kWh/m², respectively, while the lowest are observed in December, with 62.4 kWh/m² and 59.1 kWh/m², respectively. When the radiation intensities are analyzed, it is seen that the radiation losses are at lower levels. Table 2 shows the values of monthly radiation losses. On an annual basis, the global horizontal irradiance is 1761.1 kWh/m² while the effective global irradiance is 1661.1 kWh/m².

Table 2
Monthly differences between global horizontal irradiance and effective global irradiance.

Months	1	2	3	4	5	6	7	8	9	10	11	12
Difference [%]	4.87	5.00	5.12	6.06	6.43	6.69	6.26	5.51	4.98	4.60	4.70	5.29

Since irradiation intensities are higher in the summer months, the difference between them is observed then. The largest difference was observed in June, with a value of 6.69%, while the smallest was observed in October, with a value of 4.60%. When the irradiation intensities are analyzed annually, it is observed that the difference is 5.68%.

The monthly average electricity generation obtained from the actual PV system and PVsyst software is given in Fig. 4.

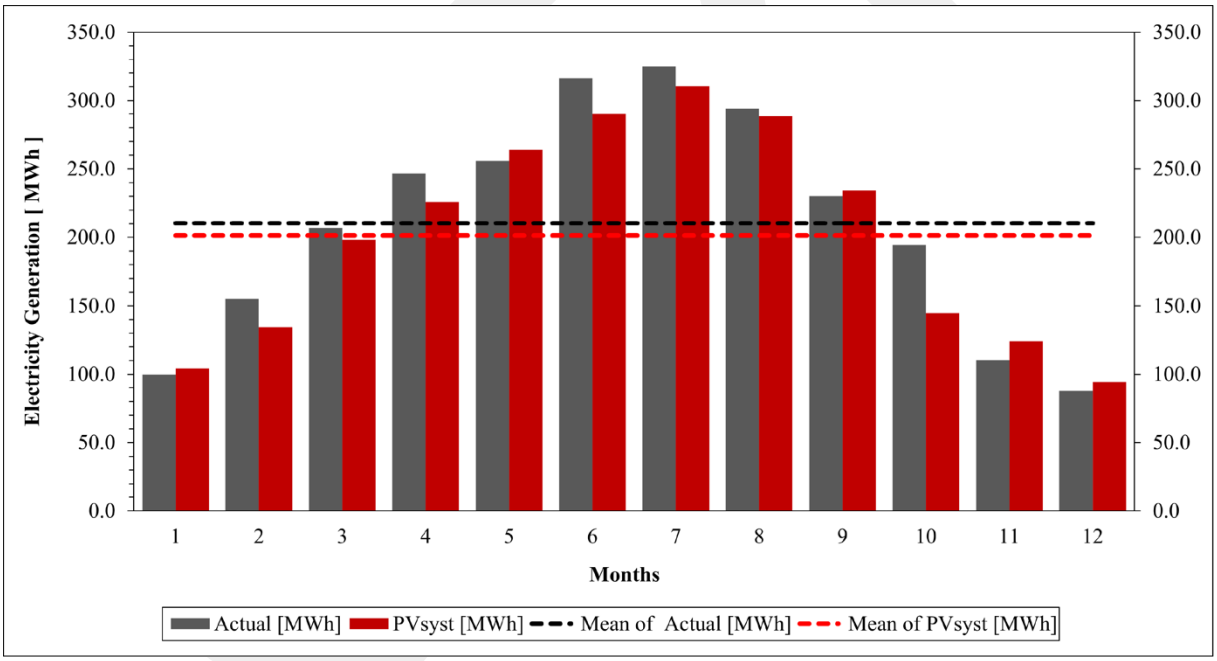

Figure 4
Monthly average electricity generation values and actual averages in 2024 and PVsyst.

Since electricity generation is directly proportional to radiation intensity, energy generation decreases in winter and increases in summer. The highest electricity generation was 324.9 MWh in July, while the electricity generated with PVsyst was 310.3 MWh in July. In January, the lowest electricity generation in both systems is 99.9 MWh in the actual system and 104.1 MWh in the PVsyst software. It is also observed that the actual value is higher in some months, while the value obtained from the software is higher in others. On an annual basis, the actual system generates 2522.2 MWh of electricity, whereas PVsyst software shows 2413.1 MWh. When the annual average monthly electricity generation is considered, the actual value is 210.2 MWh, whereas 201.1 MWh is generated with PVsyst. The

monthly differences between these values are given in Table 3.

Table 3
Monthly differences between actual and PVsyst-derived electricity generation.

Months	1	2	3	4	5	6	7	8	9	10	11	12
Difference [%]	-4.24	13.24	4.11	8.46	-3.14	8.31	4.49	1.91	-1.81	25.48	-12.32	-7.70

Negative values in the table mean that the electricity generation from the software is higher, while positive values mean the opposite. The largest difference is in October, with a value of 25.48% and the smallest difference is in September, with a value of 1.81%. When the total annual electricity generation difference is considered, it is concluded that PVsyst gives quite acceptable results with a difference of 4.32%.

The monthly average PR values, which determine the performance of PV systems and the monthly average electricity generation and global horizontal irradiation intensities used to obtain the PR value are given in Fig. 5.

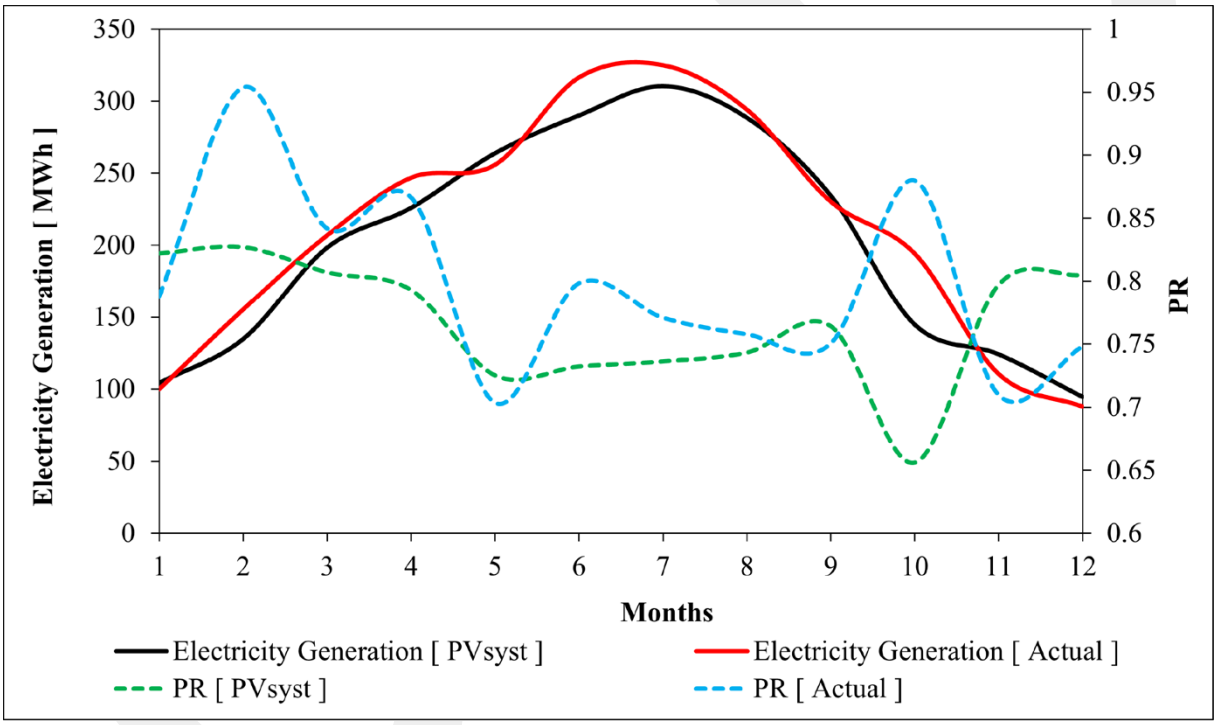

Figure 5
Monthly average Performance Ratio values and averages obtained with actual and PVsyst.

Electricity generation and irradiation intensities increase in summer and the PR value is the ratio of the two. However, the value increase in the summer also means that losses will be higher. Therefore, PR values are expected to decrease in the summer. PR values obtained with PVsyst software indicate that this situation occurs except in October. There is a difference in October due to lower electricity generation. When actual values are considered, it seems suitable for most months. The reason is the lack of irradiation intensities of the actual values. In both cases, the highest PR values were obtained in February, with 0.827 for the actual values and 0.954 for the values obtained from PVsyst. The smallest PR values were obtained, with 0.703 in May for actual values and 0.656 with PVsyst. The annual average PR values of 0.797 have been obtained from actual values and 0.756 from PVsyst. The monthly average difference between the actual and PVsyst-derived PR values is given in Table 4.

Table 4

Monthly differences between actual and PVsyst-derived PR values.

Months	1	2	3	4	5	6	7	8	9	10	11	12
Difference [%]	-4.32	13.28	4.14	8.48	-3.08	8.30	4.51	1.93	-1.83	25.43	-12.31	-7.62

The variations in PR values presented in Table 3 closely align with the differences in electricity generation outlined in Table 2, as both rely on the same solar radiation data for their calculations. Consistent with this, the maximum monthly discrepancy was observed in October at 25.43%, while the minimum difference occurred in September at 1.83%. When assessed annually, the overall PR deviation was 5.18%, which is within an acceptable margin of error.

CONCLUSIONS

Actual and simulated photovoltaic (PV) systems have been compared for Konya in Türkiye. PVsyst software has been used to evaluate the solar energy potential. The peak radiation intensity occurred in July, while the lowest occurred in December. The global horizontal irradiance is 1761.1 kWh/m² per year, while the effective global irradiance is 1661.1 kWh/m² per year. The value difference has been observed, with higher irradiation intensities in the summer months. The maximum and minimum values occur in June and October, respectively. The annual difference is 5.68%. The highest and lowest values of electricity generation are in July and January for the actual and simulated systems, respectively. For the actual one, the annual monthly average electricity generation is 210.2 MWh. The simulated one is 201.1 MWh. The peak PR values were attained in February, with 0.827 for the actual and 0.954 for the simulated. In May, the lowest values were 0.703 for the actual and 0.656 for the simulated. The annual average PR values are 0.797 and 0.756 for the actual and the simulated systems, respectively. The results indicate that the simulated values agree with those of the actual system. The significance of advancing potential energy technologies has been stated as a result.

Future work should validate the results with multi-year field data and cross-check PVsyst outputs using alternative simulation tools; additionally, a dedicated physics-based mathematical model can be developed to represent site-specific losses and improve prediction accuracy.

Author Contributions

Research Design (CRediT 1) M.D. (%30)- M.I. (%20)- M.H.A. (%30)- I.G. (%20)
Data Collection (CRediT 2) M.D. (%40)- M.I. (%30)- M.H.A. (%20)- I.G. (%20)
Research - Data Analysis – Validation (CRediT 3-4-6-11) M.D. (%30)- M.I. (%30)- M.H.A. (%20)- I.G. (%20)
Writing the Article (CRediT 12-13) M.D. (%30)- M.I. (%30)- M.H.A. (%20)- I.G. (%20)
Revision and Improvement of the Text (CRediT 14) M.D. (%10)- M.I. (%30)- M.H.A. (%30)- I.G. (%30)

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Conflict of Interest

There is no conflict of interest declared by the authors.

Sustainable Development Goals (SDG)

Sustainable Development Goals: 7 Affordable and Clean Energy
Sustainable Development Goals: 9 Industry, Innovation and Infrastructure
Sustainable Development Goals: 11 Sustainable Cities and Communities
Sustainable Development Goals: 12 Responsible Consumption and Production
Sustainable Development Goals: 13 Climate Action

GCRIS

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