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OPTIMIZATION OF PHOTOVOLTAIC PANEL TILT ANGLES FOR MAXIMUM ENERGY YIELD: A CASE STUDY FOR EDIRNE, TÜRKIYE

Taşkın Tez[1], Dinçer Akal[2*], İlhan Umut[3]
[1]*Edirne Vocational College of Technical Sciences, Trakya University, Edirne, Turkey*
[2]*Department of Mechanical Engineering, Faculty of Engineering, Trakya University, Edirne, Turkey*
[3]*Department of Electronics and Automation, Corlu Vocational School, Tekirdag Namik Kemal University, Tekirdag, Turkey*

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ABSTRACT

*In this study, the optimal tilt angle of rooftop photovoltaic (PV) panels was investigated for a 5.3 kW grid-connected system located in Edirne, Turkey. The analyses were conducted using PV*SOL Premium 2024 software, evaluating different tilt angles ranging from 0° to 90°. Based on the simulation results, key performance indicators including annual energy yield, performance ratio (PR), CO_2 emission reduction, and payback period were assessed. The findings indicate that at a tilt angle of 30°, the system achieves an annual energy output of 7,763 kWh and a payback period of 4.2 years. This result aligns with the geographic and solar radiation characteristics of Edirne, suggesting that the optimal tilt angle is approximately 30°. Beyond 40°, both energy production and economic performance decline, with a significant drop in system efficiency observed at tilt angles of 70° and above. Furthermore, a strong linear relationship ($R^2 \approx 0.999$) was found between energy production and CO_2 emission reduction, emphasizing the direct environmental benefits of increased PV output. In conclusion, a tilt angle of 30° represents the most efficient configuration for maximizing energy production and minimizing payback time under the climatic conditions of Edirne.*

1. INTRODUCTION

The efficient utilization of solar energy potential plays a critical role in meeting the increasing global energy demand [1] and mitigating the adverse effects of climate change [2]. In this regard, ensuring sustainable development requires not only the installation of more photovoltaic (PV) panels but also the development of new solutions to enhance the energy production of existing PV systems [1]. One of the most critical parameters directly affecting the performance of panels used in solar energy systems is the amount of solar irradiance incident upon them. The impact of solar rays reaching the Earth's surface at varying angles throughout the year significantly alters the amount of radiation collected by the panel. This variability depends on factors such as the panel's tilt angle, orientation, time period, and geographical location [3]. To achieve maximum energy efficiency from solar panels, the angle between the panel and the horizontal plane must be optimized. Panels can be positioned at a fixed angle or adjusted with tilt angles that vary according to the month and seasons. In this context, the accurate determination of the panel's tilt angle is crucial both for the effective collection of solar irradiance and for improving system performance [4].

One of the foremost challenges in utilizing solar energy effectively stems from its inconsistent and intermittent availability. Since solar radiation reaching the Earth's surface is both irregular and spatially variable, harnessing this renewable energy source in a stable and efficient manner poses significant difficulties. As a result, enhancing the efficiency and optimizing the performance of solar energy systems have emerged as prominent areas of focus in recent energy research. Among various strategies proposed to improve solar energy utilization, adjusting the tilt angle of solar panels stands out as one of the most influential and practical methods for boosting performance [4]. To address this issue, several analytical and empirical models have been formulated that determine the optimum tilt angle for solar panels based on factors such as latitude, seasonal variations, and solar declination [5,6,7]. These models aim to calculate the ideal panel orientation for different geographical locations, thereby ensuring that panels are positioned to receive the maximum possible sunlight throughout the year. It is well-established that the most efficient tilt angle not only varies by location but also shifts with the seasons, which directly influences the amount of solar energy absorbed [8]. Accurate adjustment of this angle carries economic as well as technical implications. Improved energy capture through correct tilt optimization can lead to shorter payback periods for solar investments [9], enhance the accuracy of photovoltaic (PV) power output forecasts [10], and reduce energy losses caused by dust accumulation and soiling [11]. Several studies in the literature have focused on the influence of tilt angle on the performance of photovoltaic (PV) panels. One

[*] Corresponding author. E-mail: dincerakal@trakya.edu.tr

study, conducted across various cities in Saudi Arabia, determined that adjusting the tilt angle six times annually can achieve up to 99.5% of the solar radiation that would otherwise be captured through daily adjustments [12]. Another study, carried out in Abu Dhabi, United Arab Emirates, identified the optimal tilt angles for PV panels and recommended at least two adjustments per year to enhance system efficiency [13]. In a recent experimental investigation, researchers sought to identify the optimal azimuth and tilt angles specifically for photovoltaic panels used in solar electricity production. For this purpose, a dedicated measurement setup was constructed to collect data on solar radiation, ambient and panel temperature, and electrical output. Simultaneous measurements of generated power, open-circuit voltage, and short-circuit current were carried out. The collected data facilitated a comparative evaluation of PV panel performance under various azimuth and tilt angle configurations. Results clearly revealed that both azimuth and tilt angles significantly affect output power, current characteristics, and fill factor. From both theoretical calculations and experimental observations, it was concluded that for the Konya region of Turkey, the most efficient tilt angle relative to the horizontal plane is 32.08°, with an ideal azimuth angle of 0° [14]. Another noteworthy study focused on next-generation bifacial photovoltaic panels, aiming to determine optimal tilt configurations to maximize system efficiency across diverse European climates. This research utilized Typical Meteorological Year (TMY) datasets to compute the cumulative sky brightness for multiple European locations on a consistent basis. By accounting for various forms of solar irradiance namely direct, diffuse, and ground-reflected radiation the study analyzed how annual energy yield on both front and rear surfaces of bifacial panels can be improved. Parameters such as ground albedo and row spacing between panel arrays were also assessed for their impact on system performance. Findings revealed that latitude is the dominant factor influencing the ideal tilt angle, with optimal values ranging from 26° in Greece to 36° in Finland. The results also showed that while Ground Coverage Ratio (GCR) plays a substantial role in system design, the effect of albedo was comparatively minor [15].

In this study, differing from the existing literature, the optimum panel tilt angle for a 5.3 kW photovoltaic system to be installed on the roof of a villa located in the Serakent area of central Edirne was determined using PV*SOL Premium 2024 software. Simulations were performed for tilt angles ranging from 0° to 90°, and the resulting data were compared based on criteria such as annual energy production, performance ratio (PR), carbon reduction, and levelized cost of electricity (LCOE). The findings indicate that a tilt angle of 30° offers the most favorable outcome in terms of energy generation for the Edirne region.

2. MATERIALS AND METHODS

This study aims to determine the optimum panel tilt angle for a 5,3 kW rooftop photovoltaic (PV) system located in central Edirne (41.68°N, 26.56°E). Simulations were carried out using PV*SOL Premium 2024 (R3) software. The system consists of 10 monocrystalline half-cell PV panels (CW Enerji CWT530-144PMB10-V) and a Huawei SUN2000-4.6KTL-1 inverter. The PV panels were installed with a south-facing orientation (180° azimuth).

Figure 1 illustrates the basic structure of the grid-connected photovoltaic (PV) system. The direct current (DC) electricity generated by the PV panel modules is converted into alternating current (AC) through the inverter, and the produced energy is transferred to the utility grid via a bidirectional meter.

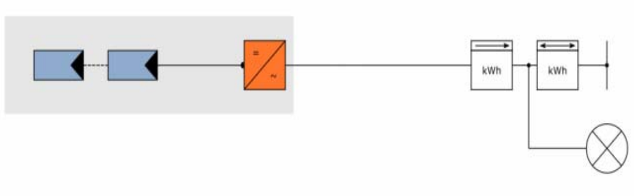

Fig. 1. Schematic Diagram of the Grid-Connected Photovoltaic (PV) System [16]

Simulations were conducted at 10° intervals between 0° and 90°, with additional analyses performed at 1° increments within the 30°-40° range for higher precision and validation. Climatic data were based on Meteonorm 8.2 (2001–2020), utilizing long-term averages for the Edirne region. In the financial analysis, the investment cost was assumed to be $800/kW, the electricity unit price was $0.1637/kWh, the annual inflation rate was 33%, and the interest rate was 1%.

As a result of the simulations, the following parameters were calculated: specific yield (kWh/kW), annual energy production (kWh), CO_2 emission reduction (kg/year), performance ratio (PR, %), levelized cost of electricity (LCOE, $/kWh), and payback period (years).

3. RESULTS

Figure 2 presents the annual energy production values of the photovoltaic panel system under different tilt angles. As seen in the graph, energy production exhibits an increasing trend between 0° and 30°. Notably, at a tilt angle of 30°, the system achieves its highest annual energy output of 7,763 kWh. This result confirms that the optimal tilt angle aligns with Edirne's geographic latitude (approximately 41.6°), where an optimal tilt occurs around 30°. At tilt angles of 40° and above, annual energy production begins to decline, with the decrease becoming more pronounced beyond 60°. At tilt angles of 70° and higher, energy losses increase due to reduced solar irradiance incident on the panel surface. In the vertical position (90°), annual energy production drops to as low as 4,907 kWh. These findings indicate that a 30° tilt angle provides maximum energy efficiency under the climatic conditions of Edirne, representing the most suitable panel inclination for system design.

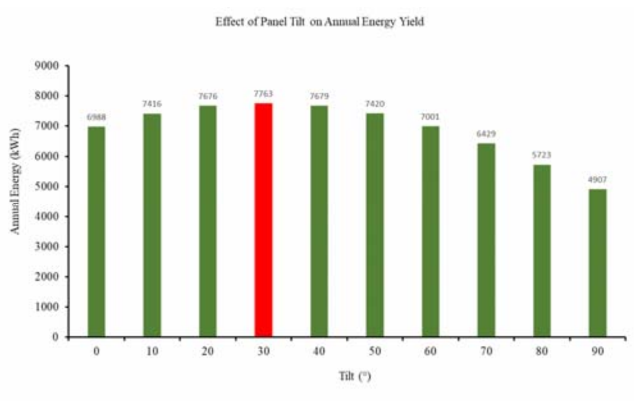

Fig. 2. Variation of Annual Energy Production with Tilt Angle for the PV System in Edirne, Türkiye[16]

Figure 3 shows the payback period values of the photovoltaic panel system for different panel tilt angles. The graph reveals an inverse relationship between tilt angle and payback period. Between 0° and 30°, the system's economic return improves, with the payback period decreasing accordingly. At a tilt angle of 30°, the payback period reaches its minimum value of 4.2 years, which is directly related to the maximum energy production achieved at this angle. For tilt angles of 40° and above, as system efficiency declines, the payback period gradually increases. Beyond 70°, the economic attractiveness of the investment significantly decreases with further increases in tilt angle. At the vertical position (90°), the payback period extends to 6.64 years, indicating a reduction in the economic efficiency of the system.

In conclusion, under Edirne's climatic conditions, a 30° tilt angle represents the optimal point not only in terms of energy efficiency but also with respect to economic return on investment.

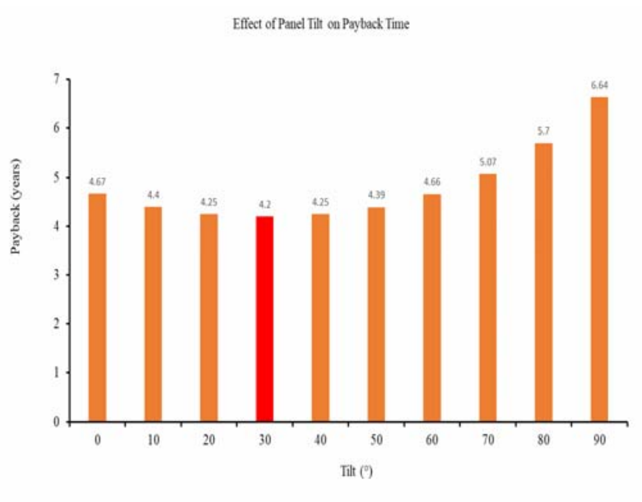

Fig. 3. Variation of Payback Period with Tilt Angle for the PV System in Edirne, Türkiye [16]

Figure 4 presents the annual carbon dioxide (CO_2) emission reduction values achieved by the photovoltaic panel system at different tilt angles. The graph clearly demonstrates the impact of tilt angle on the system's environmental contribution. Between 0° and 30°, the amount of CO_2 reduction increases steadily with increasing tilt angle. The highest reduction is observed at a 30° tilt angle, calculated as 3,643 kg/year. This outcome is directly linked to the maximum energy production achieved at this angle.

For tilt angles of 40° and above, CO_2 reduction gradually declines due to decreased energy output caused by irradiation losses. Notably, between 70° and 90°, the reduction in carbon savings becomes more pronounced as the tilt angle increases. At the vertical position (90°), annual CO_2 reduction drops to 2,301 kg. In conclusion, under the conditions of Edirne, a 30° tilt angle is identified as the most optimal not only in terms of energy efficiency but also in terms of environmental sustainability.

Figure 5 illustrates the linear relationship between the annual energy production of the PV panel system and the corresponding carbon dioxide (CO_2) emission reduction. The graph shows a strong correlation between the increase in annual energy production and the reduction in CO_2 emissions, depending on the tilt angle. The data reveals a highly robust linear relationship ($R^2 \approx 0.999$) across all tilt angles between 0° and 90°. This indicates that the amount of electricity generated by the PV panel system translates directly into environmental benefit that is, every increase in energy production contributes proportionally to carbon reduction. The fact that both energy output and CO_2 reduction reach their maximum at a 30° tilt angle confirms this value as the optimal tilt under Edirne's climatic conditions. Moreover, this relationship demonstrates that photovoltaic panel systems provide not only economic advantages but also significant contributions to environmental sustainability. In conclusion, the strong linear correlation between energy production and carbon reduction highlights the strategic role of solar energy systems in achieving regional carbon neutrality goals.

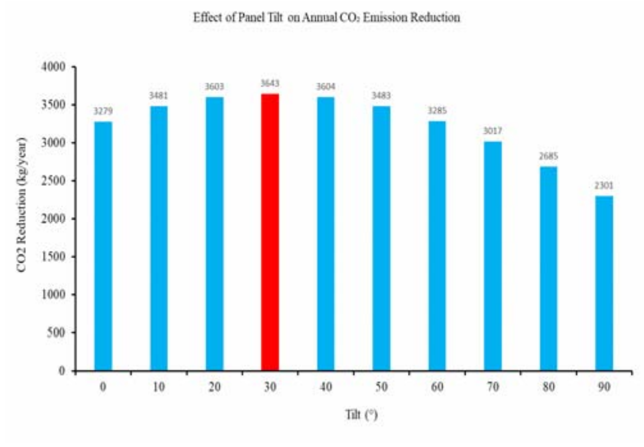

Fig. 4. Variation of CO_2 Reduction with Tilt Angle for the PV System in Edirne, Türkiye [16]

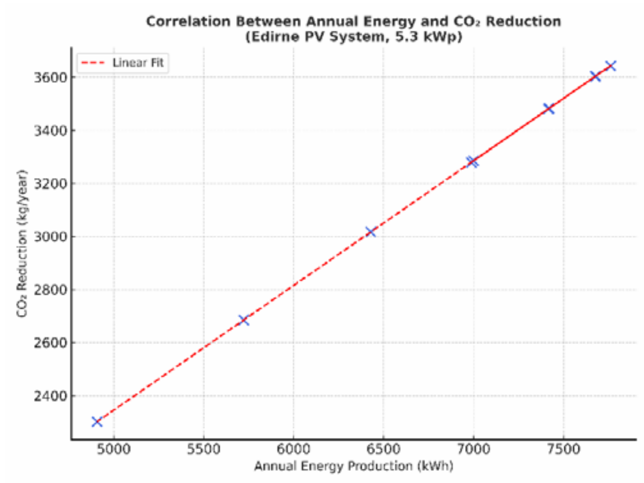

Fig. 5. Correlation Between Annual Energy and CO_2 Reduction (Scatter Plot) [16]

4. CONCLUSION

In this study, the optimum panel tilt angle for a 5.3 kW rooftop photovoltaic (PV) system located in Edirne, Turkey, was determined using PV*SOL Premium 2024 software. Various tilt angles ranging from 0° to 90° were evaluated, and system performance was analyzed in terms of energy production, environmental impact, and economic efficiency. The findings indicate that a tilt angle of 30° maximizes annual energy output (7,763 kWh/year) under Edirne's climatic conditions, while also minimizing the payback period (4,2 years). The analysis revealed that as the tilt angle increases beyond 30°, the amount of solar irradiance received by the PV panels decreases, directly affecting energy production, CO_2 emission reduction, and overall system efficiency. After 40°, energy yield declines, and beyond 70°, the economic performance of the system drops significantly. According to the CO_2 reduction analysis, the system achieves a maximum annual emission reduction of 3,643 kg/year at a 30° tilt angle. Furthermore, an almost perfect linear relationship ($R^2 \approx 0.999$) was observed between energy production and CO_2 emission reduction, emphasizing that photovoltaic systems contribute not only to energy supply security but also to carbon neutrality targets.

In conclusion, for the Edirne region, a tilt angle of approximately 30° is identified as the optimal configuration, aligning with local solar radiation conditions and offering the highest return on investment.

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