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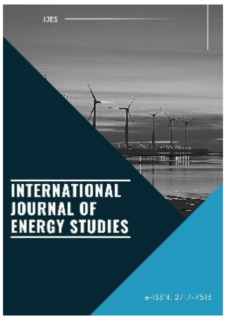


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# Investigation of the effects of installation parameters of bifacial PV systems on energy yield and determination of optimal tilt angle: A case study for Konya

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**Highlights**

- The effects of bifacial PV system installation parameters are investigated on energy yield.
- A comparative technical assessment of bifacial and monofacial systems is performed for Konya province.
- Optimal tilt angles of bifacial systems are determined under albedo coefficient, ground clearance height, and ground coverage ratio.
- Bifacial PV systems offer 5.23% more energy output compared to monofacial systems under widespread use PV installation conditions.
- Bifacial energy yield may reach up to 21.10% more energy by changing installation parameters.

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## ABSTRACT

The application areas of photovoltaic (PV) systems that allow scalable modular design are becoming increasingly widespread, ranging from residential installations to utility-scale power generation. In recent years, bifacial PV (bPV) systems have gained widespread attention due to their capability to harvest solar irradiance from both the front and rear surfaces, thereby increasing energy yield per unit area. The technical potential of PV systems is location-specific and varies according to numerous climatic and geographical factors. In this study, a comparative technical analysis of bifacial and monofacial PV systems is conducted for Konya, one of the regions with the highest solar energy installation potential in Türkiye, using the System Advisor Model (SAM). Moreover, sensitivity analyses are performed for parameters such as albedo, ground clearance height, and ground coverage ratio (GCR), which affect the energy output of bifacial systems. According to the results, bPV systems provide 5.23% higher energy output compared to monofacial systems under commonly used PV installation conditions. However, it is possible to achieve up to 21.10% higher energy yield by adjusting parameters such as the albedo coefficient, ground clearance height, and GCR that influence bPV performance. These findings demonstrate that bPV systems can provide substantial energy gains under suitable design and site conditions, enabling more efficient utilization of solar energy resources.

**Keywords:** Bifacial systems, Monofacial systems, Photovoltaic, Optimal tilt, Technical feasibility

# 1. INTRODUCTION

## 1.1. Motivation and Background

Photovoltaic (PV) systems have become a key component of the global energy transition due to their scalability and modular structure, enabling applications from residential rooftops to utility-scale power plants. In 2024, the cumulative solar installed capacity reached 2.25 TW in the world. However, achieving a total capacity of 1.18 TW took over 40 years as of 2022, yet only 2 years to multiply this twofold [1]. Moreover, solar PV panel prices were 5.39 USD/W in 2003, decreased to 0.81 USD/W in 2013, and reached 0.31 USD/W in 2023 [2,3]. Furthermore, with advancements in materials and manufacturing technologies, bifacial PV (bPV) systems have attracted increasing attention, as they are capable of harvesting solar irradiance from both front and rear surfaces, thereby enhancing energy yield per unit area compared to conventional monofacial systems [4].

Although bPV systems have demonstrated superior performance under appropriate conditions, their energy yield advantage is strongly influenced by installation-dependent parameters such as albedo, ground clearance height, and ground coverage ratio (GCR) [5]. For bPV systems, these predefined installation parameters significantly influence the amount of solar irradiance incident on the rear surface of the panels, thereby making pre-installation assessment essential, because optimal orientation toward the sun alone is insufficient. Therefore, evaluating the sensitivity of bPV performance to these parameters is essential for understanding their practical benefits and for guiding system design decisions in real-world applications such as carport, agrivoltaic, or utility-scale power plant applications [6].

Moreover, the technical performance of PV systems is highly dependent on location-specific climatic and geographical conditions, including solar irradiance levels, ground characteristics, and installation configurations, thus making region-specific analyses essential [7]. In this context, Konya, located in central Türkiye, represents one of the regions with the highest solar energy potential in the country and is characterized by wide flat lands suitable for utility-scale ground-mounted PV installations [8]. Beyond its high solar irradiance, the region offers representative ground conditions for bPV system deployment and plays a strategic role in Türkiye's solar energy expansion. Despite these advantages, Konya has received limited attention in detailed bPV performance analyses, making it a relevant and representative case study.

In this study, a comparative technical analysis of bifacial and monofacial PV systems is carried out for the province of Konya using the System Advisor Model (SAM). In addition, a sensitivity analysis is conducted to quantify the impact of key bifacial-specific parameters on energy production, such as albedo coefficient, ground clearance height, and GCR.

### 1.2. Literature Review

In the literature, numerous studies on the technical analysis of PV systems are applied to site- or region-specific locations. Since the energy output of PV systems is directly related to the climatic and geographical characteristics of the region. For this reason, determining the optimal tilt angles is important to collect the solar radiation falling on the PV panel. However, the majority of the studies in the literature are adapted to monofacial ground-mounted PV systems, and bifacial-related studies are more limited in number because they are just becoming widespread.

The studies related to fixed tilt PV systems generally focus on comparative analyses of the annual optimal tilt and tilt angle changes in certain periods, like monthly, seasonal, or semi-annual. Abdelaal and El-Fergany [9] determined the optimal tilt angle for PV panels to maximize solar radiation. Various scenarios are simulated from daily angle adjustments to fixed yearly angles. The results show that adjusting the tilt angle twice a year at 5° and 50° for Suez city yields nearly the same solar radiation as daily adjustments, with only a 1.56% difference, and performs 7.77% better than a fixed annual optimal angle of 28°. Jing et al. [10] established a high-resolution spatial analysis of global and diffuse solar radiation across China, and proposed a method to calculate the optimum tilt angle for PV panels based on latitude and altitude. The results show that using an optimum tilt angle between 14.5° and 49.1°, depending on the location, can increase annual PV power generation by an average of 10.41% compared to horizontal mounting. Mukisa and Zamora [11] investigated the optimal tilt angles for PV panels in low-latitude equatorial regions of Uganda. It is found that adjusting the tilt (0.0–5.1° annually) significantly improves solar irradiance. Moreover, they inferred that mounting the PV panels at the angle of the rooftop's slope reduces the efficiency dramatically and recommended modifying rooftop support structures (by 0.1–1.2 m) to optimize energy capture. Mansour et al. [12] evaluated the PV performance in five Saudi Arabian cities, considering the combined effect of tilt angle and ambient temperature. The anisotropic model provided 5% more energy than the isotropic one, and monthly tilt adjustments presented up to 4.2% more power than yearly adjustments. The estimated tilt angles changed from 20.1°-32.7° depending on the different cities. Gonzalez et al. [13] assessed the PV potential across the Iberian Peninsula by analyzing optimal tilt angle estimation methods, and the results indicated that a fixed tilt angle of 34° results in less than 1% annual energy loss compared to other tilt configurations. Ayodele et al. [14] investigated the potential of meeting Ibadan's electricity demand using rooftop solar PV systems and determined the optimal tilt angle as 11°. It is found that 7.54 km² of rooftop space is suitable for PV installations, corresponding to the 1.7 GWp capacity. Yunus Khan et al. [15] highlighted the importance of tilt angle to optimize the solar PV performance and examined various methods for determining the optimum tilt angle. The study reported that the optimal tilt angles varied with latitude, ranging from −2.5° to 2.5° at the equator to up to ±62° near the poles. Ullah et al. [16] modeled the optimal tilt angle for PV panels in Lahore and other major cities in Pakistan using solar radiation data. The model proposed a quarterly tilt adjustment schedule that increases annual production by about 6.6% compared to a fixed case, and is validated through experiments. Abdallah et al. [17] emphasized the importance of determining the optimum tilt angle for solar panels to enhance their performance. A mathematical model is used to calculate optimal tilt angles on various time scales (daily to annually) and estimate solar radiation on south-facing surfaces. The annual optimal tilt is found as 29° in Palestinian cities, which also results in about a 10% energy gain compared to horizontally mounted panels. Nicolas-Martin et al. [18] proposed global regression models to estimate the optimum annual tilt angle of PV panels based on latitude, diffuse fraction, and albedo. The models, suitable for areas lacking local meteorological data, showed that including diffuse fraction and albedo improves estimation accuracy. The results indicated that the tilt angle deviations of 10° and 40° caused energy losses of around 1% and up to 18%, respectively. Ali Morad et al. [19] determined the monthly and annual optimum tilt angles for PV panels in Baghdad, Diyala, and Tikrit provinces in Iraq, and the annual optimum tilt angle was found to be 31°. Bailek et al. [20] investigated the optimal fixed tilt angle for PV modules in Adrar, Algeria. The optimal tilt angle was determined as 27.8°, and semi-annual tilting (3.5° for warm and 49.2° for cold periods) was found to be the optimal case. Compared to horizontal placement, semi-annual and fixed tilt adjustments yielded 19.24% and 13.78% gains, respectively.

Bifacial system studies mostly focus on and examine the parameters that affect energy output. Asgharzadeh et al. [6] investigated how tilt angle, albedo, and installation height affect the bifacial gain and energy yield of PV systems. The results showed that while height and albedo directly improve performance, the optimum tilt angle varies seasonally and increases with system size and reflectivity. Sun et al. [7] presented a framework of bPV panels to show that elevating modules to 1 m and increasing ground albedo to 0.5 can enhance bifacial gain up to 30%. It also provides empirical design expressions for various regions, indicating that vertical east-west configurations outperform south-facing installations below 30° latitude. Ferry et al. [21] identified the most efficient fixed tilt angles for bPV systems at the European scale, and the results showed that optimal tilt mainly depends on latitude, while GCR significantly affects performance. Yakubu et al. [22] compared energy outputs of inclined bifacial, vertical bifacial, and monofacial PV systems using field data and simulations in West Africa. The inclined bifacial system provides more yield by 9–10% than the monofacials, while vertical bifacial panels yield less under low ground albedo. Berrian et al. [23] performed a comparison for bifacial solar PV systems in fixed and horizontal single-axis tracking systems using both simulations and measured data, utilizing the modeling of a bifacial distributed gain model, to predict rear-side solar irradiance. The results showed that tracking systems benefit more from ray tracing, and bifacial panels consistently outperform monofacial ones in energy yield. Radwan et al. [24] targeted to optimize the annual energy output of residential bifacial solar PV systems using Response Surface Methodology, and it is applied a design combined with PVsyst simulations to examine the effects of parameters like albedo, module spacing, tilt angle, and height affect energy yield. The result showed that optimal settings are determined as high albedo, 8.95 m spacing, 1.35 m height, and 35.7° tilt, which can provide a remarkable boost in production. Baghel et al evaluated and optimized the performance of grid-connected PV systems considering tilt angle and albedo using PVsyst simulations and Response Surface Methodology. Then, it is determined that a 25° tilt angle with a 0.54 albedo coefficient presents the highest energy output, and the system provides a 5.8-year payback period and 469.2% return on investment [25].

### 1.3. Contributions of the Study

In the literature, several studies have conducted technical analyses of bPV systems, and these are location-based because the energy output of PV systems is directly related to location characteristics. In addition to specific locations, bifacial-related studies also analyze the parameters that affect bifacial system output. This study provides the following contributions to the literature;

- A comparative technical assessment of bifacial and monofacial systems is conducted, and the optimal tilt angles of bifacial systems are determined for Konya province.
- Sensitivity analyses are being conducted for parameters such as albedo coefficient, ground clearance height, and GCR, which affect bifacial system output.
- The effects of the parameters affecting energy yield on the optimal tilt angle changes are evaluated.

- The changes in monthly and hourly energy output compared to monofacials are discussed.

## 2. METHODOLOGY

### 2.1. Monofacial and Bifacial PV Panels

There are two types of PV panels, which are classified as bifacial and monofacial due to their design, and they are differentiated by their energy generation capabilities. Monofacial PV panels are the traditional type of PV panels, and all solar cells are on the front side of the panel facing the sun. The backside of the panel is covered with an opaque layer, and there is no passing radiation through it [26]. Therefore, one-sided energy production is provided. In contrast, bPV panels have solar cells on both sides, allowing them to capture sunlight from both the front and rear surfaces. It increases the energy generation potential, especially in environments with high albedo surfaces (reflective surfaces), where the rear side can utilize reflected light. Their performance varies depending on installation height, tilt angle, and the surface reflectivity below the panel [27].

### 2.2. Solar Modeling

Solar radiation, a critical parameter in solar resource assessment, can be measured using instruments like pyranometers or estimated for a horizontal plane. However, while direct measurement is a negligible expense for large-scale investments, it is not cost-effective for small-scale investments. Therefore, solar radiation models are used. Solar radiation consists of three different radiation types, which are beam, diffuse, and reflected radiation (Figure 1), and diffuse radiation shows the highest variability due to atmospheric conditions.

Solar radiation models are categorized as isotropic or anisotropic, depending on the uniformity of diffuse radiation distribution. The widely used Perez model, an anisotropic approach, and the default solar model in the National Renewable Energy Laboratory (NREL) SAM is used in this study for its capability to account for non-uniform diffuse radiation distribution [28,29].

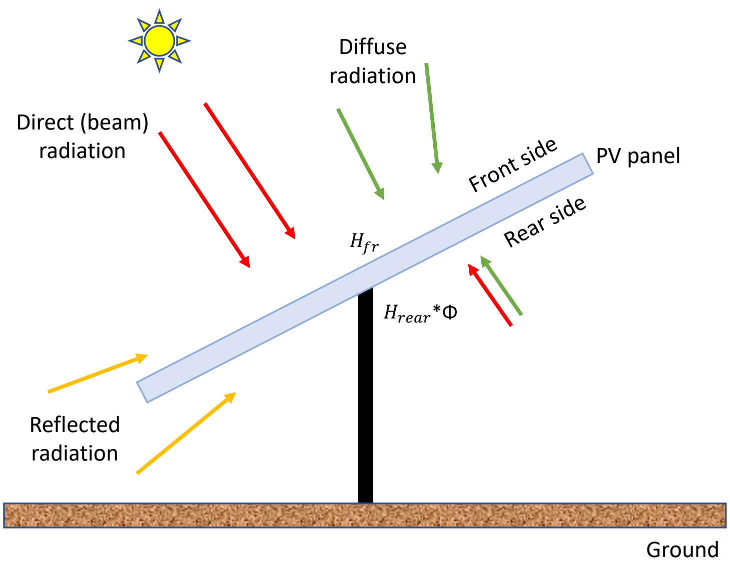



**Figure 1.** General representation of solar radiation types

The total radiation falling on the bPV panels is divided into two, which are from the front-side ($H_{fr}$ same as monofacial PV panels) and rear-side of the panel ($H_{rear}$) [30]. In Eq. (1), Ø represents the bifaciality factor, which is the efficiency ratio between front and rear surfaces.

$$H_{total} = H_{fr} + H_{rear}\,\emptyset \quad (1)$$

To optimize solar energy utilization, PV panels are either fixed at specific tilt angles or aligned with tracking systems. The total radiation on inclined front surfaces ($H_{fr}$) is mathematically expressed, as shown in Eq. (2) [31].

$$H_{fr} = H_{B,t} + H_{D,t} + H_{R,t} \quad (2)$$

where $H_{B,t}$, $H_{D,t}$ and $H_{R,t}$ stand for the beam, diffuse and reflected radiation. They can be calculated by Eqs. (3-5) [32]. The three terms in Eq. (5) represent isotropic ($H_{sky}$), circumsolar ($H_{cir}$), and horizon brightening ($H_{hor}$) components, respectively.

$$H_{B,t} = H_B(\sin\theta_z \cos(\gamma - \gamma_s)\sin\beta + \cos\theta_z \cos\beta) \quad (3)$$

$$H_{R,t} = 0.5H_T\rho[1 - \cos(\beta)] \quad (4)$$

$$H_{D,t} = H_D\left(0.5(1 - P_1)(1 + \cos\beta) + P_1\left(\frac{x}{y}\right) + P_2 \sin\beta\right) \quad (5)$$

where the term multiply with $H_B$ represents the angle of incidence (AOI). $\theta_z$ is the zenith angle, $\gamma$ and $\gamma_s$ represent the solar and surface azimuth angle, respectively. $\rho$ is the Albedo constant, which depends on the installation surface reflectivity, and $\beta$ is the PV panel tilt angle with the horizontal surface [33]. The parameters $P_1$ and $P_2$ in Eq. (5) are the coefficients for the circumsolar and brightness parameters, and are defined in Eqs. (6-7). The other angular parameters ($x$ and $y$) are given in Eqs. (8-9) [28]. $P_{11}(\varepsilon) - P_{23}(\varepsilon)$ are the clearness related coefficients that are taken from in [28].

$$P_1 = \max\left(0, P_{11}(\varepsilon) + H_D/(1367(1 + 0.033\cos(360n/365))\cos\theta_z)P_{12}(\varepsilon) + \theta_z P_{13}(\varepsilon)\right) \tag{6}$$

$$P_2 = P_{21}(\varepsilon) + \Delta P_{22}(\varepsilon) + \theta_z P_{23}(\varepsilon) \tag{7}$$

$$x = \max(0, \cos AOI) \tag{8}$$

$$y = \max(0.087, \cos\theta_z) \tag{9}$$

The solar radiation reaching the back surface of the PV panel comes from many sources, such as the sun, diffuse sky, ground reflections, and radiation reflected from other panels, and is expressed by Eq. (10) [34].

$$H_{rear} = \mathrm{x}\ \mathrm{F}_b(H_B + H_{cir}) + \sum_{i=1}^{180} 0.5\ (\cos(\mathrm{i}-1) - \cos(\mathrm{i}))F_i H_i \tag{10}$$

The first term represents the direct and circumsolar radiation from the sun and is multiplied by the AOI correction factor and Sjerps-Koomen correction factor, respectively [35]. If the AOI is above 90°, the contribution is zero, while the Sjerps-Koomen factor considers the refractive properties of the surface. The other term represents the contribution of diffuse radiation components to the back surface. In bifacial applications, NREL SAM divides the field of view into 180° in 1-degree increments, and a cumulative sum of each degree of field of view is obtained. The term $0.5\ (\cos(\mathrm{i}-1) - \cos(\mathrm{i}))$ represents the field of view of a 1° slice at the back surface. $F_i$ represents the AOI correction factor, which corrects the angle at which each slice of angle reaches the panel and is practically determined by a look-up table [34,35]. $H_i$ represents the radiation sources in the respective angle increment portion, namely, the sky diffuse ($H_{sky} = H_D(1 - P_1)$), horizon brigtening ($H_{hor} = H_D P_2$), ground reflection ($H_{gr}^n$). If the segment *i* looks at the sky, then $H_i = H_{sky}$, if it looks at the horizon, then $H_i = H_{hor}$; and if it looks at the ground, then $H_i = H_{gr}^n$

given in Eq. (11). NREL SAM also takes into account the effects of two panels behind the existing panel in its view factor calculations, and considers the effects of shading by dividing the row-to-row distance into many small distances. Therefore, the $CF_{sky}$ is performed according to the following equation (Eq. (12)) [34,36].

$$H_{gr}^{n} = \rho\, y(H_B + H_{cir}) + CF_{sky}H_{sky} \tag{11}$$

$$CF_{sky} = 0.5\,((cos\beta_1 - cos\beta_2) + (cos\beta_3 - cos\beta_4) + (cos\beta_5 - cos\beta_6)) \tag{12}$$

$\beta_1$ is the maximum angle between the top and bottom edges of a panel 2 rows away. $\beta_2$ is the angle between the top and bottom edges of a panel 1 row away, that limits shading. $\beta_3$ is the maximum angle possible for a panel 1 row away. $\beta_4$ is the top edge of the panel in the same row (i.e., the top edge of the panel immediately in front of it). $\beta_5$ is the bottom edge of the panel in the same row. $\beta_6$ is the viewing angle behind the panel in the same row (i.e., the edge closest to the ground).

After calculating the solar radiation falling on the panel, the power output ($P_{pv}^{out}$) can be calculated as in Eq. (13). Since the cell temperature ($T_c$) directly affects panel efficiency, this parameter is also expressed as in Eq. (14) [31].s

$$P_{pv}^{out} = P_{stc}(H_{total}/H_{stc})d(1 + t_{pow}(T_c - T_{stc})) \tag{13}$$

$$T_c = \frac{T_a + (H_{total}/H_{stc})(T_{c,noct} - T_{a,noct})(1 - \frac{\eta_{max}(1-\alpha_p T_{c,stc})}{\alpha\tau})}{1 + (H_{total}/H_{stc})(T_{c,noct} - T_{a,noct})(\frac{\alpha_p \eta_{max}}{\alpha\tau})} \tag{14}$$

In Eqs. (13-14), the subscript '*stc*' represents the standard test conditions performance results of the panel under 1000 W/m$^2$ ($H_{stc}$), 25 °C ($T_{stc}$), and 1.5 air mass. $P_{stc}$ is the rated power capacity of the PV system. $t_{pow}$ and $d$ are the temperature power coefficient specified in panel datasheets, and the derating factor ($d$), which stands for losses, respectively. The other subscript '$noct$' stands for the nominal operating cell temperature, and these parameters are also given in product datasheets. $\alpha\tau$ is the multiplication of the absorbance and transmittance of the solar panel, respectively, and is assumed as 0.9 [31].

### 2.3. Solar energy in Türkiye and the case location

Turkey has high solar energy potential, and the average solar radiation amount and sunshine durations increase from north to south. According to Turkey's solar energy potential atlas (GEPA), shown in Figure 2, the amount of solar radiation varies between 1400 and 2000 kWh/m$^2$-year [37]. There has also been a significant increase in the installed solar energy capacity in recent years. The installed power, which was 248.8 MW in 2015, reached 6667.4 MW in 2020 and 22236.5 MW in April 2025 [38,39].

The selected location in this study is Konya, which has many PV power plants with its high solar potential and flat land structure suitable for installation. The installed solar power capacity in Konya was around 1400 MW in 2024 and corresponds to a remarkable portion of Turkey's solar capacity [8]. That's why this province is selected as a candidate region to compare the different PV systems, and the study aims to provide a repeatable representation that can be applied to other locations with comparative simulations of bifacial and monofacial PV systems.

The geographical coordinates of the case location are latitude: 37.87° and longitude: 32.51°. Weather data is obtained from the National Solar Radiation Database (NSRDB) [40]. Average global horizontal radiation is 4.89 kWh/m2/day, and annual average temperature and wind speed are 12.7°C and 2.3 m/s, respectively.

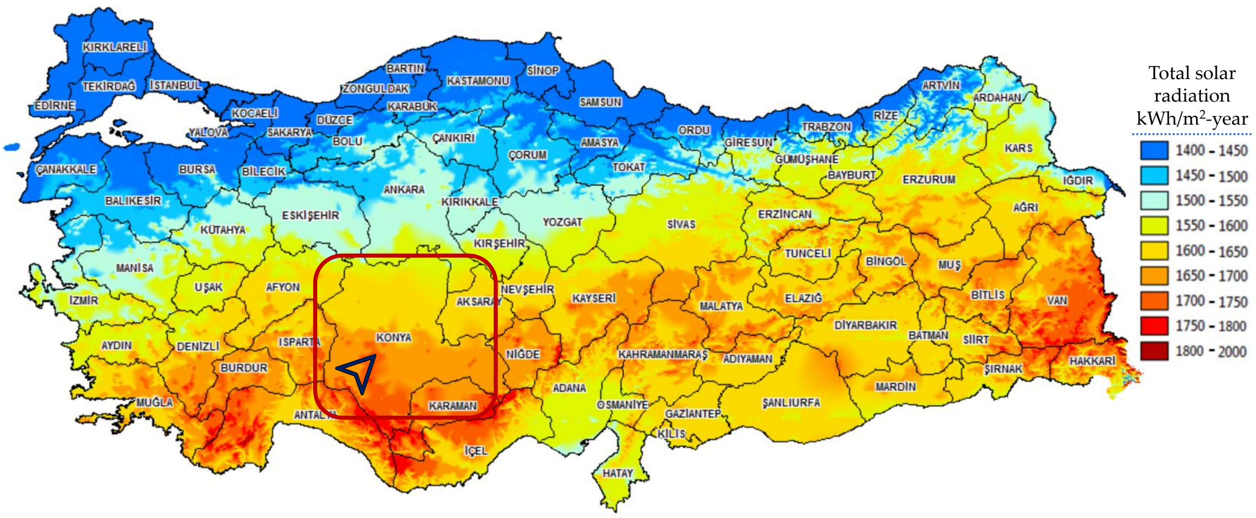



**Figure 2.** Turkey's solar energy potential atlas and the case location

## 3. SIMULATION RESULTS

### 3.1. System Configuration

The simulated PV system in the study represents a typical residential PV installation. The system has a power of 4.8 kW and can meet the basic needs of an average consumer group. Technical specifications of the system equipment are given in Table 1. In order to compare monocrystalline and bPV systems, all specs except bifaciality are considered the same. PV panels are simulated with different albedo coefficients, ground clearance heights, and GCR to observe the effects of parameter changes affecting the system output.

**Table 1.** Technical specifications of the system [29].

| **Parameters** | |
|---|---|
| System DC sizing | 4801 W |
| AC to DC ratio | 1.14 |
| Ground clearance height | [0.5, 1, 1.5] |
| Ground coverage ratio | [0.2, 0.3, 0.4, 0.5] |
| Albedo coefficient | [0.2, 0.4, 0.6] |
| **PV panel specifications (Trina Solar TSM-400DEG15HC from SAM database)** | |
| Nominal efficiency | 19.0% |
| Maximum power | 400.081 W |
| Open circuit voltage | 49.9 V |
| Short circuit current | 10.4 A |
| Temperature coefficients | -0.355 %/C |
| Bifaciality | 0.7 |
| **Inverter (ABB: PVI-4.2-OUTD-S-US-Z-M-A from SAM database)** | |
| Efficiency | 96.049% |
| Maximum DC power | 4369.96 W |
| Maximum DC voltage | 480 V |
| Nominal DC voltage | 340 V |

### 3.2 Optimal Tilt Angles of Bifacial and Monofacial Systems

Simulations are carried out to determine the optimal inclination angles of bifacial and monofacial PV systems for the selected location and to comparatively analyze the energy yields. Table 2 provides the optimal angle values under different albedo (different reflective surfaces) and heights.

**Table 2.** Optimal tilt angles (°) of bifacial and monofacial PV systems for Konya (GCR=0.3).

| **Albedo** | **Monofacial** | **h=0.5** | **h=1** | **h=1.5** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| 0.2 | 32 | 35 | 32 | 32 |
| 0.4 | 35 | 38 | 36 | 34 |
| 0.6 | 39 | 43 | 38 | 37 |

According to the simulation results, the optimal tilt angle for Konya is determined as 32° when the albedo coefficient is 0.2. The optimal tilt angle for bifacial systems for the same surface is determined as 35° when the ground clearance is 0.5 m. The reason for this is that the tilt angle is increased in the system close to the ground, and more diffusive and reflected radiation is used. In the case of installation on different surfaces, the optimal angle value for monofacial systems also increases. The reason for this is the increase in the amount of diffusive and reflected radiation. When the albedo coefficient is 0.4 and 0.6, the optimal tilt angles for monofacial systems are 35° and 39°, respectively. An increase occurs in the optimal tilt angles (38°-43°) for bifacial systems at different ground clearance values and increasing albedo coefficients. However, the optimal tilt angles of bifacial systems higher than the ground vary less compared to those closer to the ground. The reason for this is that the panel can receive sufficient diffuse and reflected radiation when positioned high. The higher the angle of inclination close to the ground due to geometry, the more diffuse radiation can be used.

Since different GCR, albedo coefficients, or ground clearance height values are effective parameters in maximizing the solar radiation benefited by bifacial panels, the optimal tilt angles under the change of these parameters are given in Table 3. As the albedo coefficient increases, the optimal tilt angles also increase for all cases, and an increase of 4° to 10° is required according to the lowest albedo coefficient case of 0.2. In installations close to the ground (h=0.5), the optimal tilt angle change in albedo changes is higher, which is due to the increase in the use of diffuse and reflected radiation. In installations higher than the ground, the optimal angle change is less. The changes in GCR affect the optimal tilt angles less compared to the changes in the albedo coefficient. However, the optimal tilt angles generally tend to decrease with the increase in GCR.

**Table 3.** Optimal tilt angles (°) of bifacial and monofacial PV systems under different GCR, ground clearance height, and albedo coefficients for Konya.

| GCR | Albedo | h=0.5 | h=1 | h=1.5 |
|---|---|---|---|---|
| | 0.2 | 34 | 33 | 33 |
| 0.2 | 0.4 | 40 | 36 | 34 |
| | 0.6 | 45 | 42 | 37 |
| 0.4 | 0.2 | 34 | 32 | 32 |

| | | | | |
|---|---|---|---|---|
| | 0.4 | 38 | 35 | 34 |
| | 0.6 | 40 | 40 | 37 |
| 0.5 | 0.2 | 32 | 32 | 32 |
| | 0.4 | 37 | 34 | 34 |
| | 0.6 | 42 | 39 | 39 |

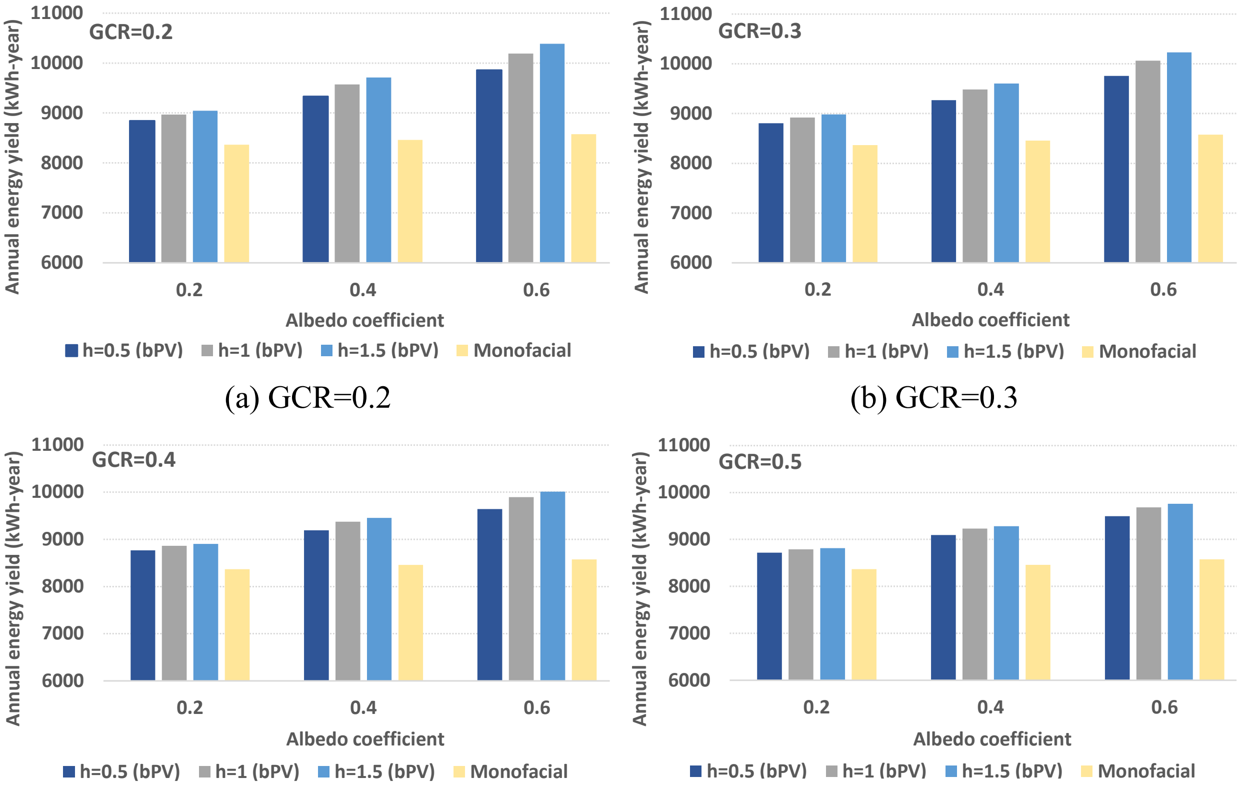
### 3.3. Energy Yields from the PV Systems

Since bPV systems can also produce energy from the back surface of the panel, they can provide more energy than monofacial systems. In this section, the amount of energy that a PV system can provide to meet the basic energy needs of a small-scale residential unit can provide with monofacial and bPV modules is compared. Table 4 shows the annual energy production of monofacial and bPV systems and how much more energy bifacial systems can produce compared to monofacials. It is determined that monofacial systems can produce 8366.6 to 8576.5 kWh/year of energy on surfaces with different reflection coefficients. Bifacial systems offer a significant increase in energy yield compared to monofacials. On surfaces with low reflection coefficients, 5.23-7.36% more energy can be produced compared to monofacials. On surfaces where reflectivity is increased even more, 9.57-13.55% more energy is produced with an albedo coefficient of 0.4, and 13.76-19.31% more energy is produced for an albedo coefficient of 0.6. These increases are significant and are equal to the energy yields obtained with solar tracking systems in many regions. An increase in energy yield can be achieved with surface coatings or synthetic dyes to be applied to the ground on the back surfaces of bifacial modules.

**Table 4.** The energy yield and the increase (%) compared to monofacial systems.

| **Albedo** | **Monofacial (kWh-year)** | **Bifacial** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **h=0.5** | | **h=1** | | **h=1.5** | |
| | | **Energy yield (kWh-year)** | **Increase (%)** | **Energy yield (kWh-year)** | **Increase (%)** | **Energy yield (kWh-year)** | **Increase (%)** |
| 0.2 | 8366.6 | 8804.6 | 5.23 | 8919.8 | 6.61 | 8982.6 | 7.36 |
| 0.4 | 8459.1 | 9268.9 | 9.57 | 9486.6 | 12.15 | 9605.4 | 13.55 |
| 0.6 | 8576.5 | 9757.0 | 13.76 | 10061.7 | 17.32 | 10232.4 | 19.31 |

Another parameter affecting the energy yield of bPV systems is the GCR value. Figure 3 shows the annual energy yields according to the variable parameters (GCR, albedo, ground clearance height). GCR basically represents the area covered by the bifacial panel on the ground surface. As GCR increases, there is a decrease in energy yield. The reason for this is that bifacial panels cannot receive enough diffuse and reflected radiation from the back surfaces. In different cases, bifacial systems provide 4.18-21.10% more energy yield compared to monofacials. High albedo coefficient (0.6) and low GCR (0.2) provide 14.95-21.10% more energy yield in different ground clearance situations. Under the same GCR but with low albedo, energy yield is 5.71-8.08%. While the increase in ground clearance and reflective surface coefficient provides a positive contribution to energy yield, the increase in GCR has a negative effect. In systems where space constraints are not high, more energy can be obtained by keeping the GCR ratio low. In cases where land constraints exist, energy production can be increased by increasing the panel back surface coefficients.




(a) GCR=0.2 (b) GCR=0.3

(c) GCR=0.4 (d) GCR=0.5

**Figure 3.** Annual energy yields (kWh-year) of the PV systems under different GCR values.

When the energy production of the PV system is evaluated monthly in Figure 4, bifacial systems can produce more energy compared to monofacial systems, especially in the summer months. The change or increase in the winter months is more limited. In addition, the production in the summer months increases even more with the increasing albedo coefficient. In the case of an albedo coefficient of 0.2, the changes in terms of the increase rate are more balanced for the summer and winter months. For example, while the energy produced for the monofacial system in January is 368.24 kWh, in the case of a ground clearance of 0.5, it is 393.29 kWh, and the increase rate is

6.8%. A similar situation is in July for monofacial and bifacial systems, 942.24 kWh and 986.49 kWh, respectively, and the increase rate is 4.7%. In the case of an increase in the albedo coefficient (0.6), the change in the summer months is more noticeable. In the case of 0.6 albedo, the production of the monofacial system is 391.01 and 935.08 kWh for January and July. In bifacial systems, for 1.5 m above the ground, the energy produced is 448.69 kWh in January and 1173.35 kWh in July. The changes here are 14.75% and 25.48%, respectively. Moreover, the change in energy production under different ground clearance heights occurs significantly in the summer months, while the change is more limited in the winter months. For example, when the albedo coefficient is 0.2, the change in production at different height values compared to monofacial systems is 6.24-6.80% in January, while the change in July is 4.70-8.73%. Similarly, when the albedo is 0.6, the increase in production compared to monofacial systems under varying heights is 13.98-14.75% in January, while the change in July is 16.08-25.48%.

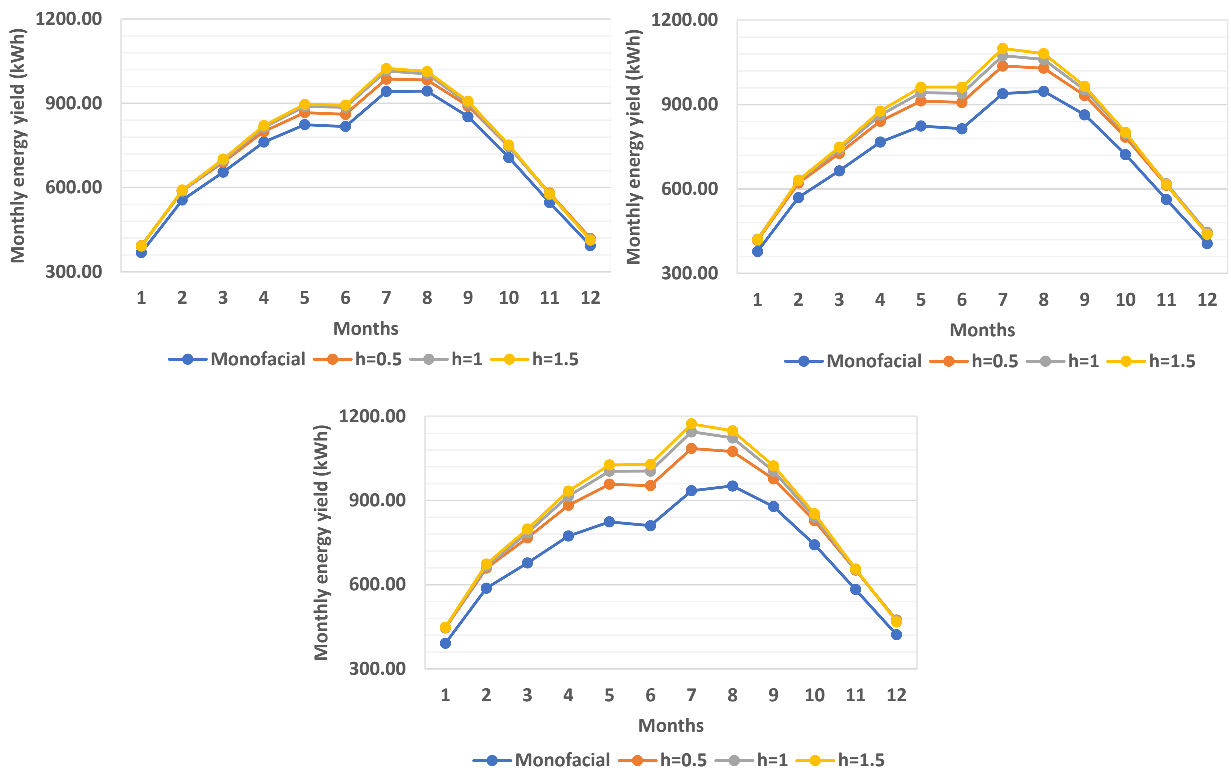
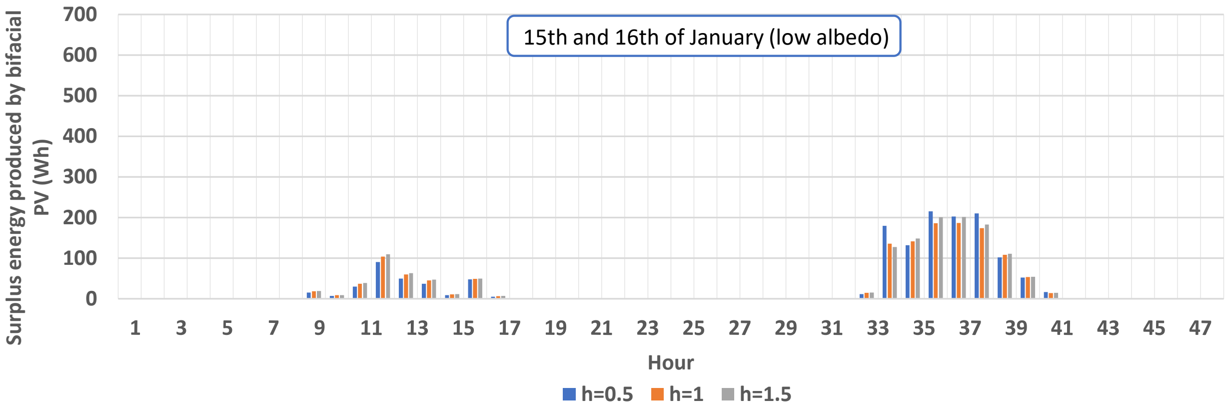
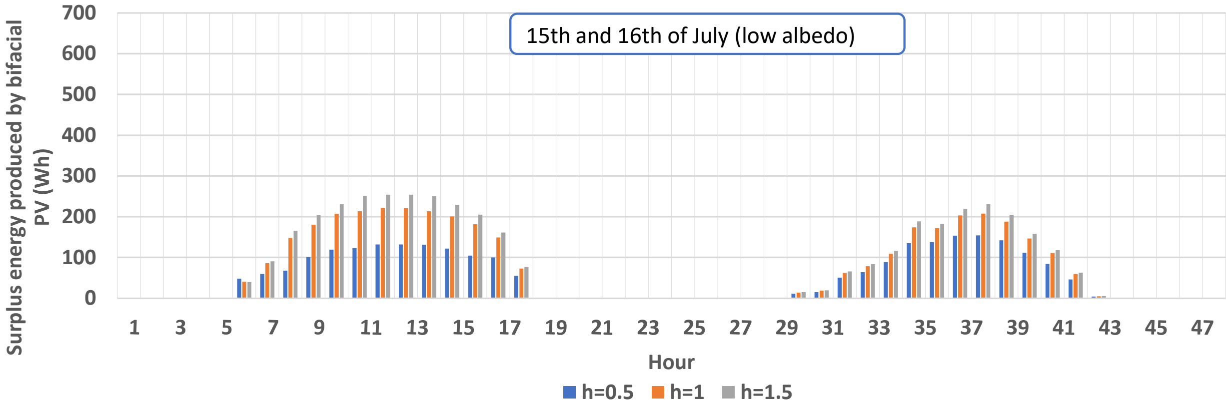
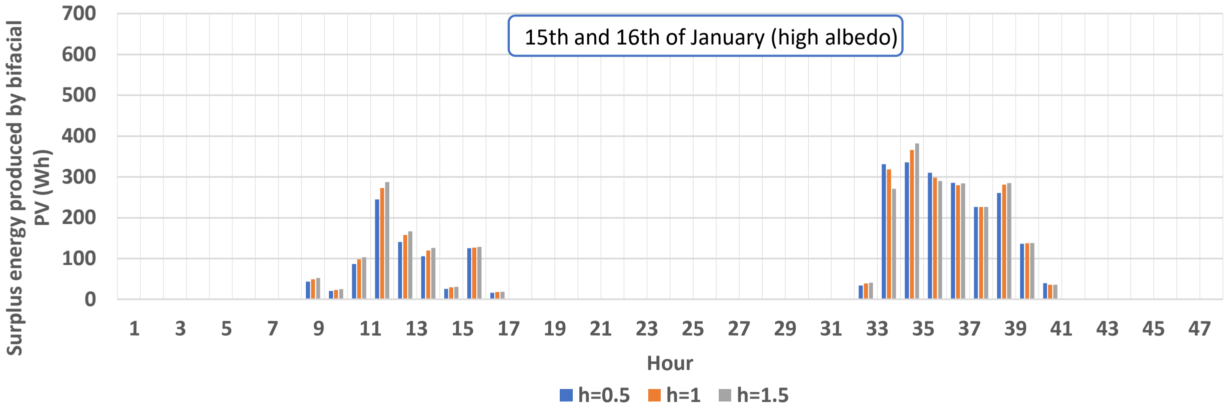



**Figure 4.** Monthly energy yield of the PV system under different albedo coefficients (0.2 for top left, 0.4 for top right, 0.6 for bottom figure)

In addition, two consecutive days are considered to examine the system's hourly energy output for summer and winter months, and the 15th and 16th days of January and July are selected as representative consecutive days. In Figure 5, the excess energy productions of the two representative days are shown for both low and high albedo coefficients. Accordingly, the energy produced by bifacial systems for representative winter days is more fluctuating and intermittent compared to summer days, and less energy is produced. For summer days, more energy is produced compared to monofacial. In addition, the long duration of sunshine in the summer months also contributes to the production. When the high albedo situation is considered, a remarkable difference is seen in summer days. In addition, the fact that cooling loads will increase due to the hot summer months of the region, and also the agricultural irrigation needs of PV systems in the summer months, emphasizes the importance of this increase.



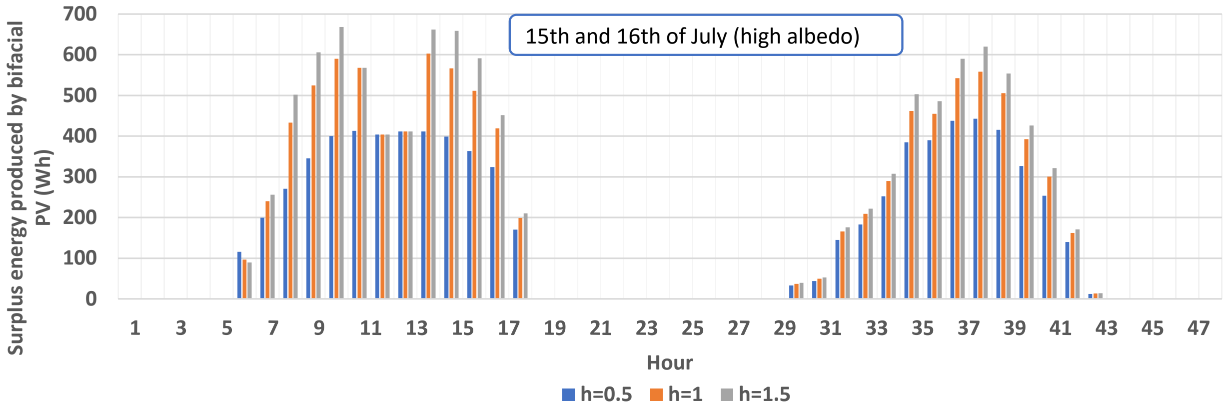
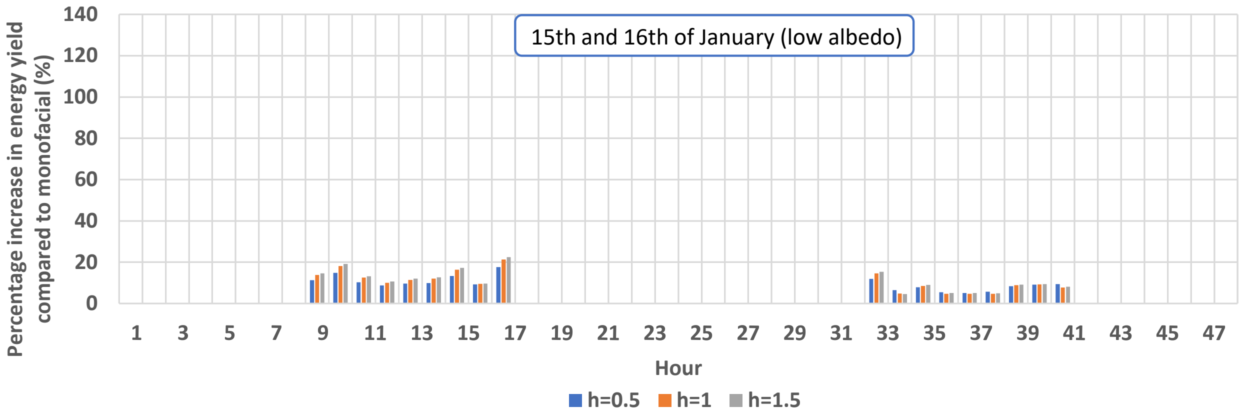



**Figure 5.** Surplus energy production of bifacial systems under low and high albedo for representative January and July days

When the contribution rates (%) of surplus energy gains shown in Figure 6, compared to monofacial systems, are examined, the contribution offered in the middle of the day, when the sun's angles are steep, is less than in other hours of the day. The reason for this is that the scattering of solar radiation in the middle of the day is less compared to other hours of the day. This also increases production. In case the reflection coefficient of the surface increases, the morning and afternoon contributions appear more pronounced. In addition, the dramatic increases in some morning hours are because energy production is very low in the relevant time period. The increase in energy production between sunrise and noon peak and from noon peak to sunset is similar to that in solar tracking systems, extending the classical bell-shaped solar energy production even further, and this allows for more balanced production.



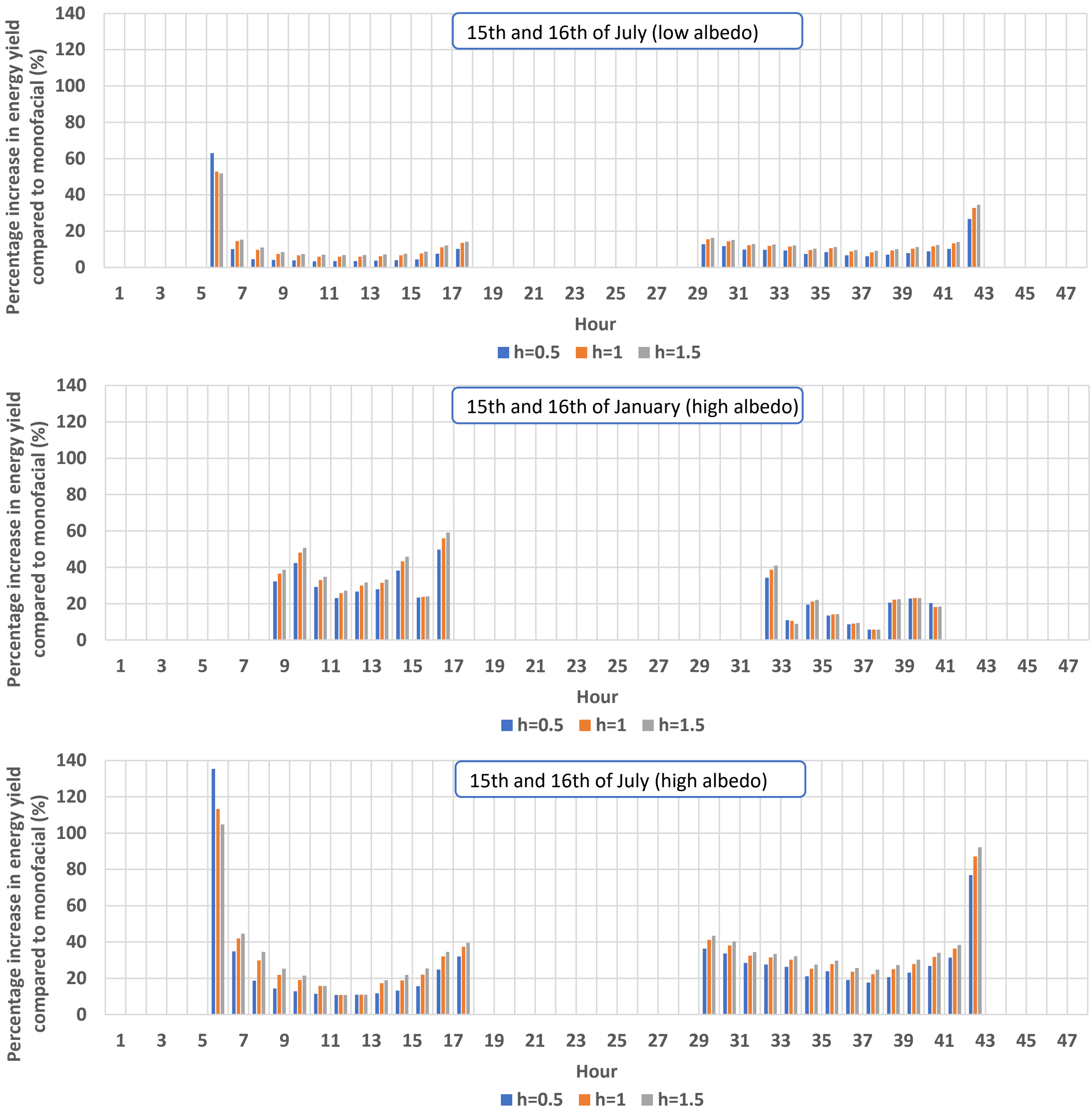



**Figure 6.** Increase rates of surplus energy production of bifacial systems under low and high albedo for representative January and July days

## 4. DISCUSSION

Bifacial PV systems offer a significant increase in energy production compared to monofacial fixed systems. Because they can generate energy from solar radiation received from the rear surface of the panel, diffuse and reflected radiation are more important for these types of PV panels. It is necessary and significantly important to determine the optimal tilt angle to maximize solar radiation falling on the panel. Moreover, the reflective surface of the ground and the panel's height above the ground, which allows it to collect more radiation, are also important parameters for bifacial systems, and these criteria should be taken into account.

Simulation studies conducted for Konya province indicate that bPV systems can generate 21.10% more energy than monofacial systems under favorable conditions (high albedo and height above the ground). When the albedo coefficient is low, energy yield decreases significantly, and the reflective surface effect is a more significant parameter than the ground clearance height. For example, when the reflective ground surface is held constant, and the ground clearance height of bPV panels is increased, the energy yield is less than when the height above ground is held constant, and the albedo is increased (Table 4). When the albedo coefficient is 0.2, the increase in annual energy yield compared to monofacial systems varies between 5.23% and 7.36% at different ground clearance heights. When the albedo coefficient is 0.6, the annual change ranges from 13.76% to 19.31%. However, when the height above ground is held constant, the increase for h=0.5 varies between 5.23% and 13.76% at different albedo coefficients, while for h=1.5, it varies between 7.36% and 19.31%. A related bifacial study conducted for Konya in the literature [41], which examined the effects of different ground types, stated that white ground could provide 15.9% more energy yield, and it correlates with the results of this study. In the literature, the albedo coefficient of white ground is taken by over 0.5 [42,43], and looking at the energy yield obtained at an albedo coefficient of 0.6 in this study, it is seen that even at low ground height (0.5m), where the lowest energy yields are obtained, energy yields under different GCR cases are varied between 13.5% and 17.8%. Moreover, the study on bifacial systems for other locations at similar latitudes to Konya, such as Madrid, Spain, indicates that bifacial systems provide around an 8% extra yield when the albedo is 0.3 [44]. These results are consistent with the results obtained for Konya using albedo coefficients of 0.2 and 0.4.

The significant energy yield increase obtained in this study indicates that bifacial systems can offer competitive performance results comparable to single-axis tracking systems, while providing the additional advantage of lower operation and maintenance risks associated with electromechanical components [45]. Furthermore, the increased energy production profile, especially during the summer months with high albedo, aligns well with peak demand periods such as cooling loads and agricultural irrigation in the Konya region. Although this study focused on the technical analysis, the results suggest that bifacial technology also holds substantial potential for improving storage sizing efficiency in future applications.

## 5. CONCLUSIONS

PV systems are widely used due to their modularity and scalability from residential to large-scale power plants. Recently, bPV systems have gained an increasing trend as they present a higher energy yield per unit area. While the optimal tilt angle in fixed monofacial systems significantly depends on latitude, it is further influenced by factors such as surface reflectivity, ground clearance height, and GCR for bifacial systems. In this study, a comparative technical analysis of bifacial and monofacial PV systems was carried out for Konya province, one of the most suitable regions in Türkiye in terms of both geographical installation feasibility and technical solar potential. Unlike standard yield assessments, this study specifically focused on the sensitivity of energy production to installation parameters such as albedo, ground clearance height, and GCR. The key findings obtained from the analysis are as follows:

- The optimal tilt angles for monofacial systems in Konya province vary between 32° and 39° (at different albedo values).
- The change in optimal tilt angle for bPV systems is greater to increase the amount of solar radiation received from behind the panel. If the bifacial system is 0.5 m above ground level, the optimal tilt angle is between 32° and 45° (under different albedo and GCR values).
- The change in optimal tilt decreases slightly with increasing panel height. For h=1.5 m, the optimal tilt angle change is between 32° and 39°. This is because the panels' higher ground clearance allows them to receive sufficient solar radiation.
- Assuming that the effect of PV panel height is minimum (0.5 m) for bifacials and the albedo effect is 0.2 for monofacials, bifacial systems provide 5.23% more energy than monofacials.
- By changing the ground clearance height and increasing the ground reflectivity, energy yield increases by 19.31% compared to monofacials. Considering the effect of the GCR, energy yield increases by 21.10%.
- When only the ground reflectivity is variable, and other conditions are kept constant and provide optimal energy yield, the change in energy yield is affected by up to 15%. On the other hand, when albedo and GCR are kept constant and at their highest, the change in the ground clearance height parameter affects the yield by over 5%. When albedo and ground clearance height provide optimal results, the GCR change presents an average change of about 2% for each GCR change.
- Monthly, energy yield increases proportionally by 25% in winter months and by around 16% in summer months under high ground reflectivity.

This study contributes to the literature by demonstrating that optimizing tilt angle alone is insufficient for bifacial systems; the variations in albedo, ground clearance height, and GCR are critical for the energy output. Based on these results, since the albedo variation offers a higher yield, it may be recommended that researchers focus on high-albedo material development strategies, or investors also prioritize cost-effective albedo materials for installations. Additionally, policymakers might consider incorporating targeted incentives for bPV technologies in future tenders to better exploit the solar potential. As a result, bifacial systems can provide significant energy yields compared to monofacial systems. Evaluating the technical potential of bifacial solar systems across different regions can allow for more efficient utilization of solar systems and may be crucial in applications with land constraints.

## DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing that is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

## CONTRIBUTION OF THE AUTHORS

**Ömer Gönül:** Conceptualization, Investigation, Methodology, Simulation and Software, Visualization, Writing - Original Draft, Writing - Review and Editing.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

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