

Article

Comparative Modeling and Validation of Stationary and Tracking Photovoltaic Installations Using Real-World Systems

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Abstract

This paper proposes a manner of modeling properties of stationary and tracking photovoltaic installations. A SPICE-based model of such photovoltaic installations is proposed. With the use of this model, the properties of two photovoltaic installations located adjacent to each other are compared. The first is stationary, while the second is equipped with a solar-tracking system. The design of both installations is described. The results of measurements and computations for both installations are presented and compared. These results illustrate the daily changes in the generated power. These measurements and computations were conducted for selected days across four seasons. The energy produced by each installation in each month was also determined. The obtained results are discussed. It was demonstrated that the use of a solar tracker can significantly increase annual energy production, especially during months with a high solar trajectory. The presented research results demonstrate that the developed model provides accurate predictions of the performance of both photovoltaic installations and that their efficiency is strongly influenced by seasonal meteorological conditions.

Keywords: photovoltaics; solar tracker; fixed-tilted; PV installation productivity; seasonal analysis; daily analysis; PV micro-installation; renewable energy; measurements; modelling; SPICE; pvlib

1. Introduction

Photovoltaics is currently one of the most important technologies for generating electricity from renewable sources [1]. A systematic increase in the number of prosumer micro-installations is observed worldwide, including Poland [2]. As they become more popular, optimizing the energy efficiency of photovoltaic installations is becoming increasingly important. This is important from both a technical and economic perspective [3,4].

A classic photovoltaic installation consists of PV modules, which convert solar radiation energy into electricity, inverters, and control systems. The modules in a PV installation are connected in strings, containing several to a dozen or so modules connected in series. Each module contains several dozen PV cells. The MPPT system ensures the panels' proper operating point, maximizing the module's output power. An inverter or a set of inverters converts the DC power obtained from photovoltaic conversion into AC power, which is then transferred to the power grid [1,5].

Over the past 50 years of photovoltaic system development, the durability of photovoltaic cells and the efficiency of converting solar energy into electricity have significantly increased. In the early 1970s, this efficiency reached 15%, and it currently exceeds even



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40% [6]. Of course, achieving high power conversion efficiency requires that solar rays strike perpendicularly onto the surface of photovoltaic cells [7]. Unfortunately, both the altitude of the Sun above the horizon and the direction from which the solar rays fall are subject to diurnal and seasonal changes. For example, in Poland, the altitude of the Sun at noon varies throughout the year from about 15° to about 60° , and the duration of daylight in northern Poland varies from about 7 h in December to 17 h in June [8,9]. These fluctuations in daylight duration and maximum solar altitude cause the electricity produced per day in December to be up to six times lower than the value recorded in June [7]. Therefore, it seems advisable to use photovoltaic systems in which PV panels will be placed on a moving platform following the apparent daily movement of the Sun in the sky. A possible solution to meet this requirement is the use of solar-tracking systems that adjust the position of PV modules relative to the Sun.

These systems are divided into single-axis and dual-axis systems [10,11]. Studies described in [10,11] indicate that tracker systems can increase annual energy production by several to even several dozen percentage points. The benefits of using tracker systems depend on the geographic location of the installation, the extent of its shading, local atmospheric conditions, and the design of the tracker system [10]. On the other hand, building systems that track the position of the Sun is associated with higher investment and operating costs. There is also a risk of mechanical component failure [12]. Furthermore, these systems require additional energy consumption for propulsion. For this reason, the validity of tracker use, especially in small installations, remains a matter of debate.

Most previous studies of tracking systems are characterized in [11]. The authors of [13–15] describe large commercial PV installations. A single-axis solar tracker is presented in [13]. In turn, the authors of [14] describe a PV installation with a dual-axis solar tracker. An economic analysis of such a kind of PV installation is given in [15]. The authors of [16] propose a fuzzy-logic-based PID control strategy integrated into a photovoltaic-system-powered electric-vehicle-charging system to address uncertainties such as fluctuating solar irradiance, grid instability, and dynamic load demands. A problem of modeling photovoltaic installations is considered in [17,18]. Both the electrical and the mechanical properties of the tracking system are taken into account in the model presented in [18]. Relatively little attention has been paid to prosumer tracking systems. They operate under non-standard conditions and may be subject to different technical, economic, and operational constraints.

Solar-tracking systems can substantially enhance photovoltaic energy yield, although their performance depends on local irradiation and system configuration [19]. Comparative studies in temperate climates indicate that residential PV systems equipped with trackers can outperform fixed installations, with efficiency gains varying according to latitude and weather patterns [20]. Similarly, recent analyses of fixed and dual-axis tracking panels have shown that trackers can significantly increase annual energy production, particularly in regions with variable solar irradiation. These findings emphasize that the benefits of tracking systems depend not only on the technology itself but also on local climatic conditions and careful system design [21]. Simulation-based analyses using PVsyst software further confirm that both large-scale and residential systems achieve higher annual energy yields when equipped with trackers [22]. However, high investment costs remain a barrier [20], highlighting the importance of developing strategies to reduce the construction costs of tracker-based installations, thereby making this technology more accessible without compromising its energy advantages. While solar trackers improve energy yield, they may also inadvertently accelerate degradation mechanisms associated with prolonged light exposure and thermal stress. Consequently, the long-term performance of tracker-based photovoltaic

systems strongly relies on the intrinsic stability of the active materials, an issue highlighted in recent reviews [23].

Computer programs such as PLECS [24] or SPICE [25] are often used in the design and analysis of electronic systems. They require models of all components present in these systems. The literature presents models of individual components of photovoltaic installations such as solar cells [5] or PV modules [26] and entire installations [7,27]. Both papers [7,27] consider properties of photovoltaic systems situated in Poland and analyze an influence of seasons on the produced power. These models contain numerous simplifications; for example, they require the time history of irradiance [26], ignore the shading of some photovoltaic modules [5], do not consider the effect of temperature changes on the properties of the PV installation, ignore the properties of the MPPT system, or limit the minimum value of the inverter input voltage.

The literature contains many models describing irradiation on the surface of photovoltaic installations depending on their location, date, and time. These irradiation models are described, among others, in [28,29]. The authors of [30] compare the results of time-dependent irradiation patterns obtained using the models described in [28,29,31]. However, these results only apply to stationary photovoltaic installations. The cited papers provide information on three components of irradiation: direct, diffuse, and reflected from the substrate. This is particularly important for the analyzed installations equipped with bifacial photovoltaic modules.

The literature lacks a model of a tracking photovoltaic installation and a comparison of its properties with a stationary installation operating under identical conditions. Additionally, an important issue is finding solar radiation data for a given day and specific geographic coordinates of the photovoltaic installation. Often, to obtain reliable modeling results, solar radiation measurements in the vicinity of the modeled installation are required.

The aim of this paper is to formulate a model of photovoltaic stationary and tracking installations containing bifacial PV modules and compare the performance of such photovoltaic micro-installations located at a single prosumer. The first is a stationary installation with a rated power of 6.46 kWp. The second is a tracking installation with a rated power of 3.52 kWp, built by one of the authors. The form of the proposed model is described. The designs of both installations are described and their measured and computed characteristics are compared. The accuracy of the proposed model is analyzed and the range of the usefulness of the proposed model is discussed. The needed data to estimate the waveforms of daily irradiances was obtained using a model described in [28]. The analysis is based on annual measurement data obtained from independent inverter systems connected to the PV installations under consideration. Both daily and seasonal variations in energy production are considered. Normalized daily and monthly power values from both installations are compared, as well as their seasonal efficiency.

Section 2 presents the used model of PV installations. Section 3 describes both PV installations studied and provides information on the data collection method. Section 4 describes the irradiance model used. Section 5 presents the used methodology of evaluation the tested installations. Section 6 presents and discusses the obtained results of measurements and computations. Section 7 contains an economic analysis. Section 8 discusses the obtained results.

2. Model Form

The presented model is dedicated to the SPICE program. It takes the form of a substitute circuit diagram, as shown in Figure 1.

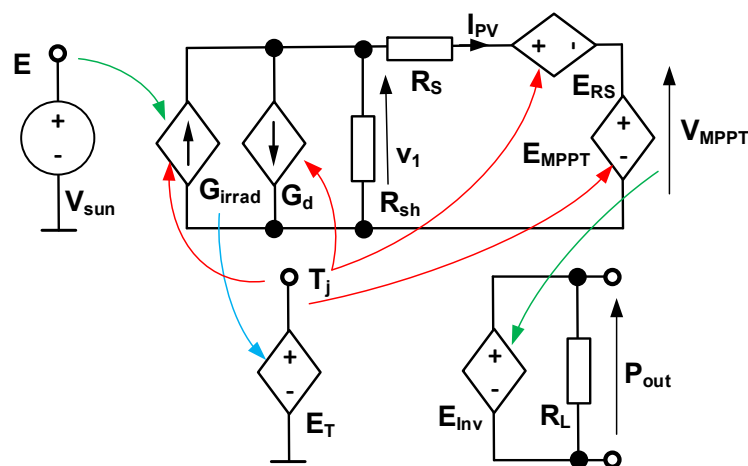


Figure 1. Network form of the model of PV installation.

This model contains five blocks. The first is a voltage source, V_{sun} , representing the irradiance on the surface of the PV modules. The second block describes the properties of the PV modules connected in a string. This block contains controlled current sources, G_{irrad} and G_d , a controlled voltage source, E_{RS} , and resistors, R_{sh} and R_s . The load for these modules is an MPPT system, represented by a controlled voltage source, E_{MPPT} , ensuring their operation at maximum power. The fourth component of the model is an inverter, represented by a controlled voltage source, E_{Inv} , loaded with resistor R_L . The voltage across this resistor corresponds to the power generated by the considered installation. The efficiency of individual voltage sources depends on the internal temperature of the installation components, particularly the temperature T_j of the photovoltaic modules. This temperature is determined by the controlled voltage source E_T , which calculates the temperature T_j taking into account the ambient temperature and self-heating.

In Figure 1, the interactions between the individual components of the model are indicated by arrows. Green indicates electrical interactions, blue indicates power interactions, and red indicates thermal interactions.

The presented model is designed for use in transient analysis in SPICE. It allows for the determination of temporal waveforms of power generated by modeled photovoltaic installations, taking into account their geographic location and date. A correct description of irradiance at the surface of photovoltaic modules is crucial for modeling accuracy.

Using available solar radiation models [28], daily solar radiation patterns can be determined on the surface of the tested photovoltaic modules for selected geographic coordinates of the installation, their angle of inclination relative to the Earth's surface, and the date. These models can also take into account the albedo of the surface surrounding the considered installation, atmospheric transparency, and the type of photovoltaic panels under consideration. Based on the obtained data, a description of the temporal course of irradiance is determined in the form of a linear function with segments. This allows a simple description of the voltage efficiency of the PWL-type V_{sun} source to be generated. Individual pairs of coordinates of points on the considered characteristic represent time and irradiance, respectively. In the calculations, it was assumed that the points on the modeled characteristic are separated by 20 min.

In turn, in the description of photovoltaic modules, the G_{irrad} controlled current source represents the photocurrent, I_{ph} , generated in the modules. It is described by the following formula:

$$I_{ph} = E \cdot m \cdot S \cdot \eta \cdot (1 + \alpha_T \cdot (T_j - T_0)) \quad (1)$$

where E is the irradiation on the surface of the modules, m is the number of PV cells connected in series, S is the active surface of a single photovoltaic cell, η is photovoltaic conversion efficiency, α_T is temperature coefficient of photocurrent, and T_0 is the reference temperature for which the efficiency value η was given.

In turn, the controlled current source G_d describes the current-voltage characteristic of series-connected photovoltaic cells. The current of this source is given by the following formula:

$$I_d = J_0 \cdot m \cdot S \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{V_{go}}{n \cdot \frac{k_B}{q} \cdot T_j}\right) \cdot \left(\exp\left(-\frac{V_1}{m \cdot n \cdot \frac{k_B}{q} \cdot T_j}\right) - 1\right) + J_{0R} \cdot m \cdot S \cdot \left(\frac{T_j}{T_0}\right) \cdot \exp\left(-\frac{V_{go}}{n_R \cdot \frac{k_B}{q} \cdot T_j}\right) \cdot \left(\exp\left(-\frac{V_1}{m \cdot n_R \cdot \frac{k_B}{q} \cdot T_j}\right) - 1\right) \quad (2)$$

where J_0 is the saturation current density, n is the emission coefficient, k_B is the Boltzmann constant, q is the electron charge, V_1 is the voltage on the G_d source, V_{go} is the voltage corresponding to the width of the silicon energy gap, J_{0R} is the density of the generation component of the saturation current, and n_R is the emission coefficient of the generation component of the current.

R_{sh} is the leakage resistance of the photovoltaic modules, and R_S is the series resistance of the series-connected photovoltaic cells at temperature T_0 . The controlled voltage source, E_{RS} , models the effect of temperature on the series resistance of the photovoltaic cell. The voltage across this source is described by the formula of the following form:

$$E_{RS} = I_{PV} \cdot R_S \cdot \alpha_{RS} \cdot (T_j - T_0) \quad (3)$$

where the I_{PV} current is marked in Figure 1 and α_{RS} is the temperature coefficient of series resistance.

The E_{MPPT} controlled voltage source imposes a voltage corresponding to the maximum power produced by the photovoltaic modules, taking into account the effect of temperature on this voltage. The voltage across this source is described by the following formula:

$$V_{MPPT} = V_{MPPT0} \cdot (1 + \alpha_{MPPT} \cdot (T_j - T_0)) \quad (4)$$

where V_{MPPT0} is the value of the V_{MPPT} voltage at temperature T_0 , and α_{MPPT} is the temperature coefficient of this voltage.

The controlled voltage source, E_{Inv} , allows for the determination of the power generated by the photovoltaic installation. The voltage at this source is the product of the V_{MPPT} voltage and the I_{PV} current.

The controlled voltage source E_T is used to calculate the junction temperature of photovoltaic modules. This temperature value is given by the following formula:

$$T_j = T_a + R_{th} \cdot \left(\frac{V_{MPPT} \cdot I_{PV}}{m} \cdot k + E \cdot S \cdot k \cdot a\right) \quad (5)$$

where T_a is the ambient temperature, R_{th} is the thermal resistance of the photovoltaic module, k is the number of photocells in the module, and a is the infrared radiation absorption coefficient.

3. System Description

This section provides information on the construction of the studied photovoltaic micro-installations. They are located in the immediate vicinity of each other in northern Poland.

The first installation under consideration is hereinafter referred to as the stationary installation. The next is the tracking photovoltaic installation. The geographical coordinates of these installations are as follows: $53^{\circ}56'4''$ N, $18^{\circ}16'21''$ E. The site chosen for both PV installations is characterized by good exposure conditions. In the immediate vicinity, there are only isolated, low trees (up to approximately 6 m in height) located approximately 40 m from the installations. Dense forest complexes begin only at a distance of approximately 100 m. This spatial arrangement provides excellent sunlight exposure and a low risk of shading. These conditions allow for a fair comparison of the efficiency of the tracking and stationary installations under similar environmental conditions.

Figure 2 shows a map fragment with the approximate location of the stationary FT (fixed-tilted) and TR (tracker) installations. The circle segment with marked azimuths shows the operating range of the TR installation, which is in the range of 60° – 300° .

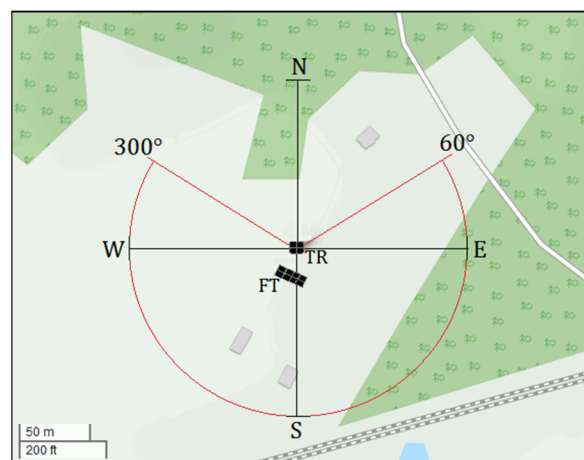


Figure 2. Location of PV installations (© OpenStreetMap contributors).

We used two existing PV installations because they operate under nearly identical environmental conditions, allowing for a reliable comparison of stationary and tracking systems under actual operating conditions. The main limitation of this approach is that the installations have different rated powers. To account for this difference, all energy production results were normalized to the rated power (expressed as time of use).

3.1. Stationary Installation

The stationary PV micro-installation is shown in Figure 3. Bilateral PV modules from JA SOLAR, type 60D20 380/MB [32], were used to construct the stationary photovoltaic installation. These modules were mounted in two horizontal rows on a frame made of steel profiles mounted on supports anchored in the ground.

The top row contains nine PV modules, and the bottom row contains eight modules. The modules are connected in a single-series string. The azimuth of the installation was set at approximately 195° , which is approximately 15° west of the optimal south direction. This decision was based on aesthetic considerations—the installation was aligned parallel to the plot boundary—and to reduce the risk of shading from the short trees on the neighboring plot. The module tilt angle was set at 35° , measured from the ground level.



Figure 3. Stationary PV installation.

3.2. Tracking PV Installation

Figure 4 shows a tracker photovoltaic installation starting operation on a frosty November morning.



Figure 4. Tracking PV installation.

The following assumptions were made in the process of designing the tracking installation:

- Increasing energy yields at low solar radiation angles (early morning, late afternoon, especially from spring to autumn);
- Increasing the yields of micro-installations with a capacity below 10 kWp;
- High resistance of the system to violent atmospheric phenomena frequently occurring in the region (storms, strong gusts of wind);
- Tracking the azimuthal position of the Sun in the range from 60° to 300° ;
- Use of a simplified control system based on an astronomical calendar, allowing the position of the Sun to be determined solely on the basis of the current time (date and time) and the location of the installation, without the need to use Sun sensors;
- Optimization of energy yields by introducing a dynamic correction of the modules' tilt angle by approximately 20° during azimuth rotation, achieved by tilting the rotation axis towards the north;
- Application of a step-by-step positioning mode for PV modules, in which their position is corrected by changing the azimuth by 30° every two hours;
- Possibility of calibrating the mechanism and tracker controller;
- Adjustable DC motor speed enabling smooth starting and braking;
- Use of electromechanical limit switches limiting the movement of the mechanism to permissible working positions;

- Minimizing financial outlays through maximum use of existing material resources and secondary resources.

The photovoltaic installation with a solar tracker utilized eight bifacial PV modules from LONGI, type LR4-72HBD-440M [33], with a total power of 3.52 kWp. The PV modules were mounted on a frame made of dedicated profiles used in ground-mounted photovoltaic installations. The frame base was bolted to the hub of the reduction gear described above. The PV modules were arranged vertically in two rows (four in each row) and connected in series to form a single string. The module tilt angle was set to 35°. In the analyzed tracking system, this angle is defined relative to the ground plane, assuming an azimuth setting of 180°.

The tracker was intentionally designed to operate in discrete 30° steps every two hours to reduce the energy consumption of the drive system and simplify both the mechanical design and the control algorithm. This operating mode also enables the use of a less demanding drive and transmission system compared with continuous tracking. Since the objective of this paper was to evaluate a simple and low-cost tracking solution, stepwise operation was considered an appropriate compromise between energy yield and system complexity.

During operation of the rotation mechanism, as the azimuth of the PV modules changes, their angle of inclination relative to the ground also changes. This change in inclination angle is a natural consequence of the main gearbox's rotation axis being 13° from the vertical northward. This means that at 90° E or 90° W, the inclination angle increases to 48°. This angle increases to approximately 54° at the extreme azimuth positions, i.e., at 60° and 300°, respectively. It is also important to note the negative consequences of tilting the solar tracker's gearbox rotation axis. The first is aesthetics. In azimuth positions other than 180°—especially when facing west, east, and at the extremes—the structure may appear unstable.

Another consequence of tilting the rotation axis is a temporary reduction in the height of the outermost PV modules relative to the ground. This results in a slightly shorter total operating time of the installation at optimal power during the day. The lowest modules may be shaded just after sunrise and just before sunset, which also reduces the efficiency of the remaining modules connected in a series chain [26].

Seasonal adjustment of PV panel tilt is a simple strategy to increase annual energy yield, particularly in fixed installations. This approach takes advantage of the fact that the Sun's altitude changes throughout the year, being lower in winter and higher in summer. Simulation studies have shown that adjusting the panel angle according to the season can improve solar energy capture by several percent annually, with higher tilt angles in winter and lower angles in summer [21,34,35]. Seasonal tilt adjustment is therefore one of the strategies, similar to solar-tracking systems, that can enhance energy yield without the need for more complex and costly tracking technology. In contrast, the fixed-tilted (FT) systems analyzed by the authors do not allow for such seasonal adjustment, which limits their ability to optimize energy yield throughout the year.

3.3. Inverter and Electrical Protection of the PV Installation

Both PV installations contain the same basic components, but the analyzed and utilized PV modules from different manufacturers reflect the dynamically changing market—at the time the tracker installation was designed, JA SOLAR 60D20 modules were no longer available. To account for differences in nominal power, additional calculations were performed using data from a day with high solar radiation, during which the tracker was positioned at an azimuth similar to the orientation of the stationary installation.

The photovoltaic installation under consideration contains the following components:

- PV module string;
- Solis inverter;
- DC protection box—containing overcurrent and overvoltage protection on the DC side, protecting the installation and the inverter;
- AC protection box—contains overcurrent and overvoltage protection on the AC side, protecting the installation and the network;
- Logging device—a device monitoring the operation of the inverter and the entire installation, transmitting data via WiFi to the database (Solis Cloud) for performance analysis and online diagnostics.

The presented photovoltaic installation is connected to a three-phase power grid.

Solis inverters [36] are equipped with a built-in energy meter and an external WiFi logger module. These modules enable remote monitoring of the installation via the SolisCloud platform. Data is recorded every 5 min and includes DC/AC currents and voltages, instantaneous power, daily energy production, and other PV installations operating parameters. The collected data was imported from the SolisCloud system in the form of spreadsheets for further analysis.

Table 1 summarizes selected parameters [32,33] of the PV modules of the discussed installations. Table 2 lists the equipment, including inverters [36] and selected parameters of the discussed installations.

Table 1. Parameters of PV modules and array.

	Stationary Installation	Tracking Installation
Module model	JA SOLAR 60D20 380/MB (Jinko Energy, Wuxi City, China)	LONGI LR4-72HBD-440M (Longi, Wuxi City, China)
Module type	half-cell, PERC, bifacial	half-cell, bifacial
Maximum power	0.38 kWp	0.44 kWp
Efficiency	20.4%	20.7%
Module dimensions	1774 × 1052 × 35 mm	2094 × 1038 × 35 mm
Number of modules	17 pcs.	8 pcs.
PV Array dimensions	8.5 × 4.2 m	4.2 × 4.2 m
Total PV power	6.460 kWp	3.520 kWp

Table 2. Equipment and parameters of the PV installation.

	Stationary Installation	Tracking Installation
Module tilt angle	35°	35–55°
Azimuth position	195°	60–300°
Mounting structure	Ground-mounted steel structure	Ground-mounted steel structure with gearbox and DC motor
Inverter model	SOLIS 3P-6K-4G (Ginlong Technologies, Ningbo, China)	SOLIS 3P-4K-4G (Ginlong Technologies, Ningbo, China)

Both installations use the PV monitoring platform SolisCloud and the data logger SOLIS WiFi, and the power is measured using an inverter-integrated meter.

3.4. Tracker System Controller

The controller utilizes an STM32F411 microcontroller equipped with a battery-backed real-time clock (RTC). The RTC enables operation according to the astronomical calendar. The horizontal position of the Sun (azimuth) is determined based on data averaged for the

middle of each month. This control method allows for simplified yet stable operation of the tracker without the need for light sensors. The drive is provided by a DC motor.

Changing the rotation direction is accomplished via a relay that switches the motor's power supply polarity. An incremental encoder is installed on the motor axis to track the current azimuth position. The controller calibrates the positioning each time the power is applied. Limit switches mounted on the structure protect the mechanism and limit movement in the azimuth axis to a range of 60–300°. These limit switches prevent accidental overshooting of the permissible positions and protect the PV system's DC cables from breaking due to software errors or controller failures. The switches also play a key role in calibrating the positioning algorithm. The power supply and charging system maintains the proper charge level of the buffer battery, which sustains the controller during power outages. This allows, among other things, for the safe repositioning of the tracker to a protective position, for example, in the event of strong winds. The simplified control system is functional, energy-efficient, and ensures reliable positioning and quick calibration in the field. Figure 5 shows a graph of the PV module tilt angle versus the azimuth, which is changed by the tracking system every two hours.

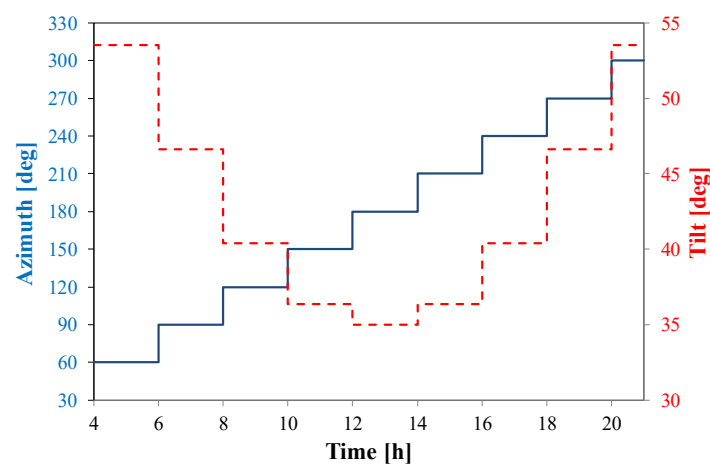


Figure 5. Dependence of the module inclination angle (dashed line) and azimuth (solid line) on time.

It can be seen that the mechanical structure of the tracking system moves throughout its operating azimuth range throughout the day. In turn, the system's tilt angle relative to the ground varies from 34 to 54 degrees. This angle is smallest at noon and largest at sunrise and sunset.

4. Description of Irradiation on the Surface of the Tested Installations

In the case of a tracking system, its orientation relative to the Sun and the ground changes abruptly, which means that the irradiance on its surface changes differently than on the surface of a stationary system. To obtain the time course of irradiance on the surface of these modules, it is necessary to determine irradiance curves for each of the system's orientations and then select a segment from each curve corresponding to the time interval over which the system's properties are described. After combining the selected segments of the irradiance curves, a time course of irradiance on the surface of the tracking system is obtained.

Using a script based on the Python 3.14.6 pvlib library, a set of irradiance waveforms (POA—Plane of Array) was generated for various components: front, back, and global (BF) at a given location (TR), assuming time discretization every 2 h. This resulted in a family of characteristics describing the variability in solar radiation conditions over time, which were then combined into a single function corresponding to the V_{sun} source waveform used in

the simulation model. The POA segments were used only for modeling the irradiance of the tracking installation and were not used to control its operation.

This approach allows for a more realistic representation of photovoltaic system operating conditions in the Spice tracker simulation, as it accounts for both temporal variations in irradiance and various radiation components (direct, reflected, and diffuse, as well as the influence of the module's backside). An additional advantage is modularity—individual POA waveforms can be easily modified, scaled, or compared for different scenarios (e.g., different locations, installation geometries, or atmospheric conditions). This makes the model more flexible and better suited for comparative analysis and long-term simulations of PV system performance.

Figure 6 shows the time-varying effect of radiation falling directly on the back of the panels, particularly during the hours corresponding to the tracker's east- and west-facing positions. Appropriately superimposing fragments of the characteristics for subsequent tracker settings allows for the reconstruction and understanding of the final, daily irradiance characteristic. As a result, the obtained curve is not just a simple solar irradiance profile, but the result of superimposing several different system settings, which better reflects the actual operating conditions of the photovoltaic installation during the day.

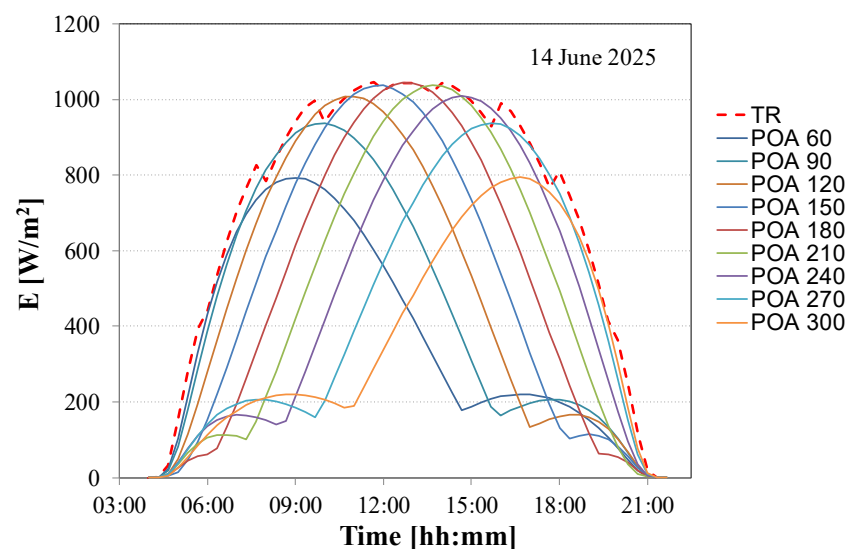


Figure 6. Time course of irradiance on the surface of the tested tracking installation for 14 June 2025.

Individual solid lines correspond to the irradiance curves at the site of the considered installation at various azimuthal angles. The dashed red line represents the resultant irradiance curve after taking into account the abrupt changes in azimuthal angle. It can be seen that the energy of light radiation incident on the surface of the mobile installation is significantly greater than that of a stationary station positioned relative to the Sun at any chosen azimuthal angle.

Analogous curves were determined for selected days of the year for both the mobile and stationary installations. The obtained irradiance curves for three days of the year are summarized in Figure 7, where Figure 7a concerns the tracking installation and Figure 7b the stationary installation.

Comparing the irradiance curves obtained for the days under consideration, it can be seen that the shapes of these curves obtained for individual days are similar for the stationary installation. The differences concern only the duration of illumination of the photovoltaic modules and the maximum E value. Of course, the module illumination time is longest in June and shortest in December. These two differ by as much as two-fold, as do the amplitudes of the considered curves.

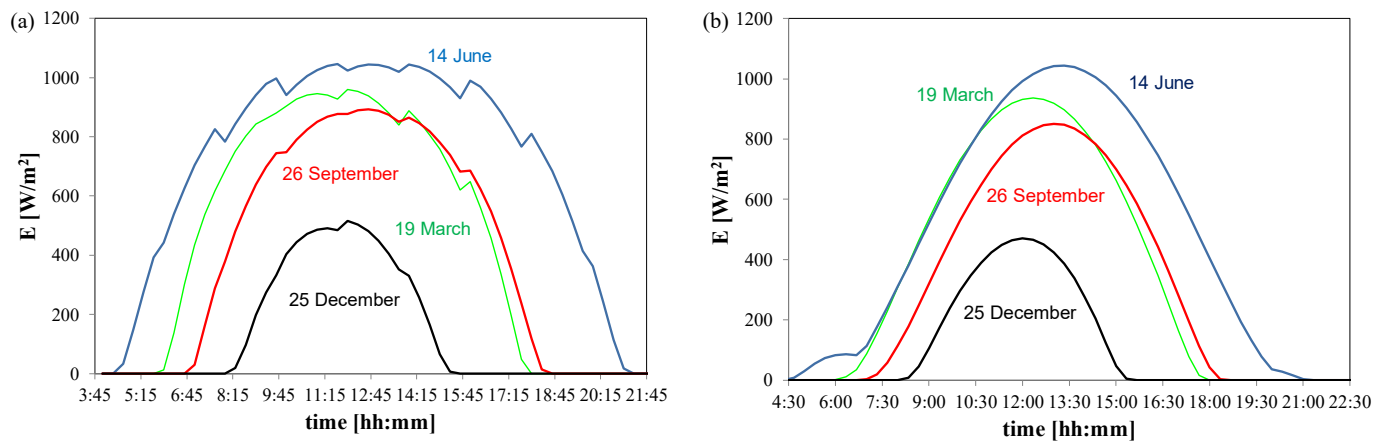


Figure 7. Time histories of irradiance on the surface of the tested tracking (a) and stationary (b) installations for selected days.

Compared to the stationary system, the tracking system clearly extends the time during which the radiation power density is close to its maximum. In June, this time even exceeds 8 h. The system's illumination time on each day under consideration also increased. This is most noticeable in June and least noticeable in December.

The simulation model for a bifacial photovoltaic system uses a voltage source representing two independent solar radiation profiles: radiation incident on the front side of the module (POA Front) and radiation incident on the back side of the module (POA Back). This allows for the representation of actual variations in lighting conditions over time throughout the entire operating day.

The V_{sun} source calculates the effective irradiance level used by the photovoltaic cell model. This value is determined as the sum of the radiation incident on the front side of the module and the appropriately scaled back radiation. Scaling is performed using two parameters describing the properties of the bifacial panel. The β coefficient determines the relative efficiency of the module's back side relative to the front side, while the k_{back} coefficient is the back loss factor, which accounts for additional losses resulting from factors such as mounting geometry, shading by structural elements, and uneven radiation reflection.

Finally, the irradiance value is calculated according to the following formula:

$$V_{sun} = G_{front} + \beta \cdot k_{back} \cdot G_{back} \quad (6)$$

where G_{front} denotes the radiation incident on the front side of the module, and G_{back} is the radiation incident on the back side of the module.

In the analyzed model, the bifaciality coefficient was assumed to be: $\beta = 0.7$ and the back side loss coefficient $k_{back} = 0.6$, which means that the energy reaching the back side of the module generates about 42% (which results from the product $0.6 \times 0.7 = 0.42$) of the energy effect relative to the radiation incident on the front side.

The product $\beta \times k_{back} = 0.42$ does not mean a 42% increase in total generated power, but rather determines the efficiency of utilizing the radiation incident on the module's back side. Because the level of back radiation (POA Back) is significantly lower than the radiation incident on the front side, the actual energy contribution from the module's back side remains relatively small and typically ranges from a few to a dozen or so percentage points of the total generated energy.

The use of a V_{sun} source allows for the direct use of the determined effective irradiance in the photovoltaic cell model, without the need to modify the photocurrent source equation itself. This solution allows for the preservation of the model's modular structure and easy

parameterization of bifacial module properties. This approach also simplifies the analysis of the influence of the β and k_{back} parameters on the module's electrical characteristics and the operation of the MPPT algorithm.

The model prepared in this way enables realistic simulation of the operation of bifacial modules in variable environmental conditions while maintaining relatively low computational complexity.

5. Evaluation Methodology

This section presents the methodology for evaluation of the usefulness of the proposed model of the PV installations and comparing the properties of the installations under consideration. The aim of the analysis was to obtain reliable information on seasonal and daily energy production, taking into account differences in nominal power, the type of PV modules used, the installation method, and local operating conditions. The methodology for collecting and processing measurement data, the criteria for selecting representative measurement days for each season, the comparative indicators used, and the analysis tools are described. Steps were taken to enable comparison of both installations regardless of their nominal power and design features.

To fairly compare the performance of both photovoltaic installations, one day was selected from the first month of each season. The selection criteria included:

- High level of solar radiation—days with maximum total energy reaching PV modules;
- No or very little cloud cover—ensuring smooth power output throughout the day.

To ensure a meaningful comparison between the stationary installation (FT) and the tracking installation (TR), the following indicators were adopted:

- Instantaneous power normalized to 1 kWp P_{norm} —enables comparison of systems with different installed power:

$$P_{norm} = \frac{P_{meas}}{P_{inst}} \quad (7)$$

where: P_{norm} is the instantaneous power normalized to 1 kWp; P_{meas} —measured instantaneous power [kW]; P_{inst} —nominal power of the PV installation [kW].

- Daily/monthly/annual time of use—used to assess the seasonal and annual normalized energy yield of the PV installation;

$$Y = \frac{E_d}{P_{inst}} \quad (8)$$

where E_d is the daily produced energy [kWh].

- Relative difference in the time of use—indicates the percentage advantage of one installation over the other:

$$\delta Y = \frac{Y_{TR} - Y_{FT}}{Y_{FT}} \cdot 100\% \quad (9)$$

where δY is the relative difference in the time of use of both installations; Y_{TR} —the time of use for the tracking installation [kWh/kWp]; Y_{FT} —the time of use for the stationary installation [kWh/kWp].

Data analysis was based on logs of both systems, recorded every 5 min throughout the day for 12 months. The data was pre-processed in a spreadsheet, including:

- Normalization of produced energy to 1 kWp, and calculation of the difference in the time of use between systems;

- Data compilation to obtain graphs of daily, monthly and seasonal changes in P_{norm} , Y and δY .

The results of measurements and computations are presented as instantaneous power time histories, monthly bar graphs, and seasonal and annual comparison tables. This approach allows for the assessment of the impact of system design, module age/type, and local operating conditions on the energy efficiency of the tested installations.

6. Results

The first part of this section focuses on the best electricity yields from stationary and rotating installations. One day (the best in terms of electricity yields) was selected for comparison for each of the first months of the four seasons. The second part of the section compares the results of stationary and tracker photovoltaic installations over the next twelve months. This comparison will be helpful in drawing conclusions regarding the economic viability of building and operating a solar-tracking PV installation.

The following section presents equations for normalizing energy production and determining the relative difference, along with the calculations performed. Based on the measured characteristics, the energy produced by each installation over the course of a day was determined. This energy value was then normalized to the rated power of each installation. The obtained values were 6.46 kWh/kWp for the stationary installation and 6.65 kWh/kWp for the tracking installation. Therefore, the difference in the normalized values is 2.9%.

6.1. Comparison of Yields for Four Representative Days

To objectively evaluate the performance of both photovoltaic installations, one day with the most favorable solar radiation conditions was selected for each season. These selected days were characterized by high levels of solar radiation, minimal cloud cover, and stable weather conditions, allowing for analysis of energy yields under near-ideal conditions. To ensure a meaningful comparison of both installations, their energy yields were normalized to their nominal power.

The following sections present the test results for the stationary installation (FT) and the tracking installation (TR). The following dates were selected for comparison: 25 December 2024, 19 March, 14 June, and 26 September 2025. The time histories of power production presented in the following sections illustrate the differences in the operating profile of both installations during different seasons.

In the following figures, solid lines indicate measurement results, and dashed lines indicate the calculation results. The results for the tracking system are shown in red, and those for the stationary system are shown in blue.

Figure 8 shows the daily changes in the power produced on 25 December 2024.

As can be seen, the tracker's advantage in winter is small. The increased yield is primarily due to its ability to capture radiation at low solar elevation angles. The graph shows that energy production begins around 9 a.m. and ends before 3 p.m. The standardized energy output of the stationary installation was 2.12 kWh/kWp, while for the tracking installation, it was 2.36 kWh/kWp. This translates to an 11.2% advantage for the tracking installation.

The graph in Figure 8 shows anomalies: shading of the stationary installation from nearby trees around 9 o'clock, and shading of the lower part of the tracker modules by the corner of the stationary installation (from the west) between 1 and 2 p.m.

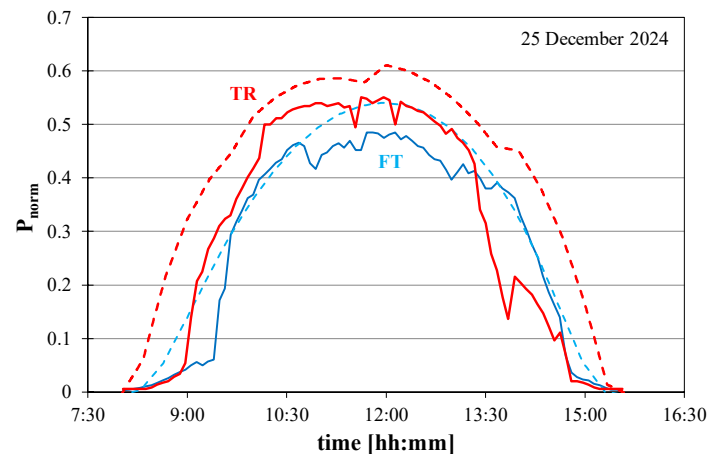


Figure 8. Comparison of the performance of the stationary system and the tracking system on 25 December 2024.

Figure 9 shows the daily changes in the power produced on 19 March 2025.

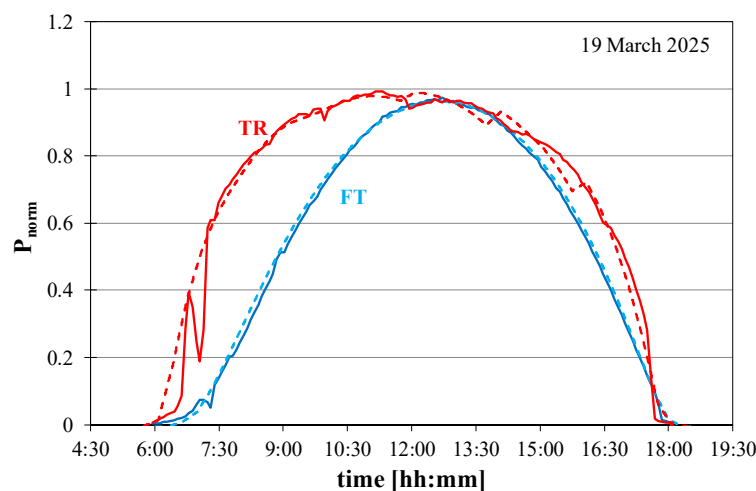


Figure 9. Comparison of the performance of the stationary system and the tracking system on 19 March 2025.

As can be seen, electricity production lasts from 6:30 a.m. to 5:30 p.m. The tracking installation shows increased production, particularly from 6:30 a.m. to 11:00 a.m. and from 3:00 p.m. to 5:00 p.m. Around noon, the differences in power production by both installations are negligible. The standardized value of energy produced by the stationary installation was 6.9 kWh/kWp, while for the tracking installation, it was 8.86 kWh/kWp. This means a 28.4% advantage for the tracking installation. Momentary shading of the PV modules in the tracking installation around 7 a.m. is visible, as are momentary drops in power production caused by the tracking system correcting the PV module position.

Figure 10 shows the daily changes in the power produced on 14 June 2025.

It can be seen that in June, electricity production lasts from 5:30 a.m. to 8:30 p.m. The greatest advantage of the tracking system is visible from 5:20 a.m. to 12:00 p.m. and from 3:30 to 8 p.m., i.e., in the early morning hours and before sunset. At noon, both installations achieved values close to their nominal power. The standardized value of energy produced by the stationary installation was 8 kWh/kWp, while for the tracking system, it was 12.16 kWh/kWp. This means a 51.4% advantage for the tracking system.

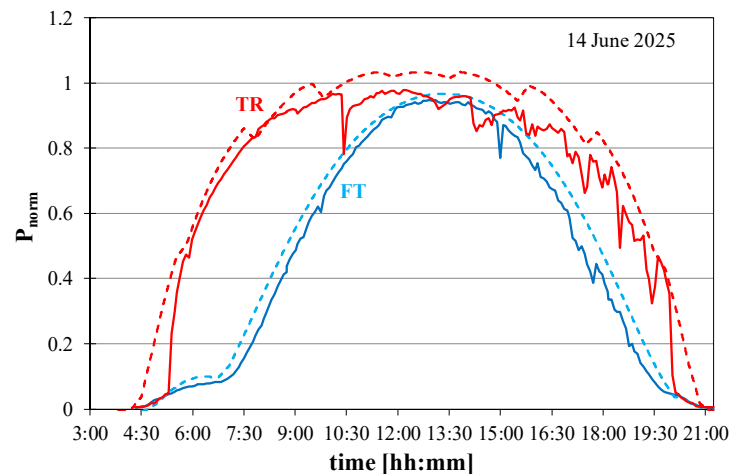


Figure 10. Comparison of the performance of the stationary system and the tracking system on 14 June 2025.

Figure 11 shows the daily changes in the power produced on 26 September 2025.

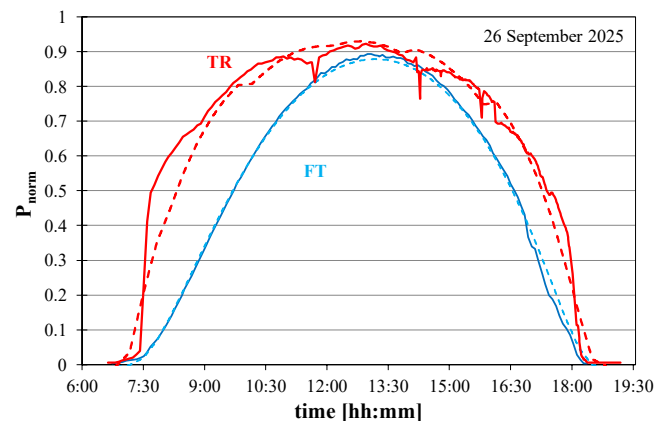


Figure 11. Comparison of the performance of the stationary system and the tracking system on 26 September 2025.

As can be seen, electricity production lasts from 7:30 a.m. to 6:00 p.m. The tracking installation shows increased production, particularly from 7:30 a.m. to 12:00 p.m. and from 3:00 p.m. to 5:30 p.m. Around noon, the differences in power production by both installations are negligible. The standardized value of energy produced by the stationary installation was 6.18 kWh/kWp, and for the tracking installation, it was 8.12 kWh/kWp. This means a 31.4% advantage for the tracking installation. Momentary shading of the PV modules in the tracking installation around 7 a.m. is visible, as are momentary drops in power production caused by the tracking system correcting the PV module position.

The calculation and measurement results presented in Figures 8–11 are evident. These differences are characterized by the root mean square error (RMSE) normalized to the average value of the power produced. The values of this error calculated for the considered days for each installation are summarized in Table 3.

As can be seen, the modeling error obtained for the stationary installation is always smaller than for the tracking installation. The smallest error values (approximately 3% for the FT installation and approximately 8% for the TR installation) were obtained in March and September, and the largest (over 18% for the FT installation and over 32% for the TR installation) in December. It should be noted that the calculation results are generally overestimated compared to the measurement results. The discrepancies between

the calculation and measurement results are smaller the shorter the period during which the installation is partially shaded (visible distortions of the time course of power).

Table 3. Values of RMSE for the tested installations in selected days.

Date	24 December 2024	19 March 2025	14 June 2025	26 September 2025
FT installation	18.35%	2.77%	10.57%	3.30%
TR installation	32.5%	7.79%	12.68%	8.36%

The modeling results presented above refer to days with cloudless skies. Figure 12 shows the measurement and modeling results for a spring day with heavy cloud cover.

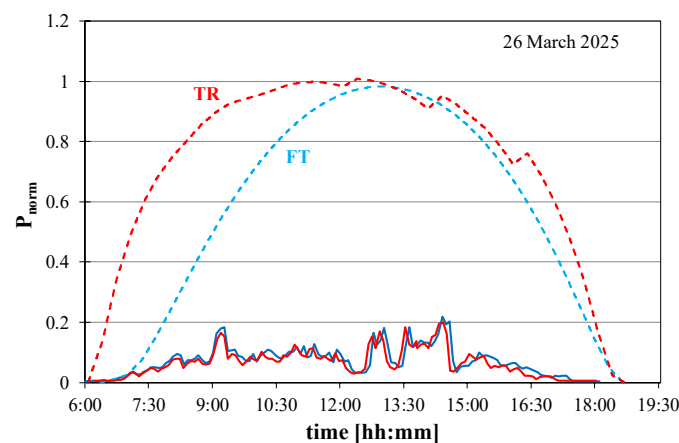


Figure 12. Comparison of the performance of the stationary system and the tracking system on 26 March 2025.

On the day in question, the average power output reached only 10% of the rated value. Unfortunately, the solar radiation model used does not account for cloud cover. Therefore, the calculation and measurement results differ significantly, with differences exceeding 90%. This indicates that the proposed model's applicability is limited to days with low cloud cover.

Figure 13 shows the time of use [kWh/kWp] of both tested photovoltaic installations for representative high-performance days in each season. In this figure, full bars present the results of measurements, whereas empty bars present the results of calculations.

Figure 13 shows that the tracking system is more productive than the stationary system on each of the days considered. The advantage of the tracking system becomes more pronounced with the length of the day. Therefore, the value of standardized energy produced by the tracking system is only 11% higher than for the stationary system at the end of December and as much as over 50% higher in mid-June. It is also worth noting that there are significant seasonal changes in the amount of energy produced. For the stationary system, energy produced on a June day is four times greater than on a December day, while for the tracking system, it is as much as six times greater. The calculated Y values are close to the measured values, and the value of RMSE divided by the average value of Y is below 6.45% for the FT installation and below 8.1% for the TR installation.

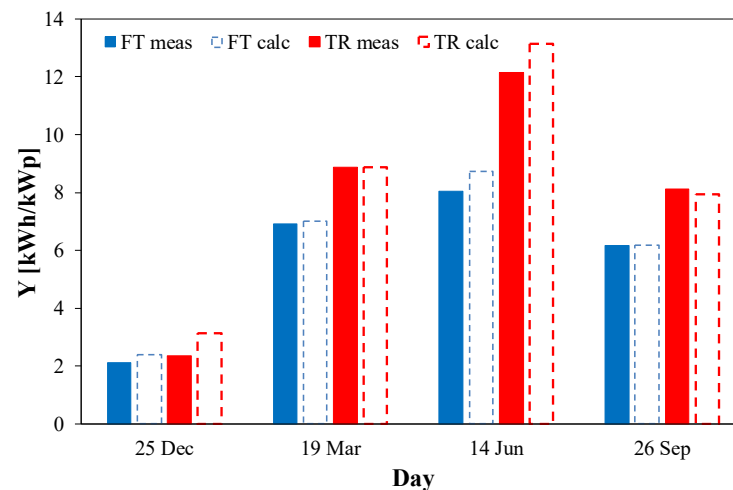


Figure 13. Summary of the times of use from both installations for selected days.

6.2. Comparison of Yields for Individual Months

Analysis of data from the last 12 months revealed significant differences in the efficiency of both PV micro-installations. Annual energy production from the stationary installation was 7573 kWh, while the tracking installation generated 5177 kWh. After normalizing these values to the rated power, the time of use for the stationary installation was 1204 kWh/kWp and for the tracking installation, it was 1505 kWh/kWp. This corresponds to a 25% higher time of use for the tracking installation.

The energy consumption of the tracker drive was estimated at approximately 15 kWh per year, which represents only 0.3% of the energy produced by the tracking system. This means that its impact on the annual energy balance is negligible. A comparison of monthly energy production values from the stationary and tracking systems, normalized to their rated power (the time of use), is shown in Figure 14.

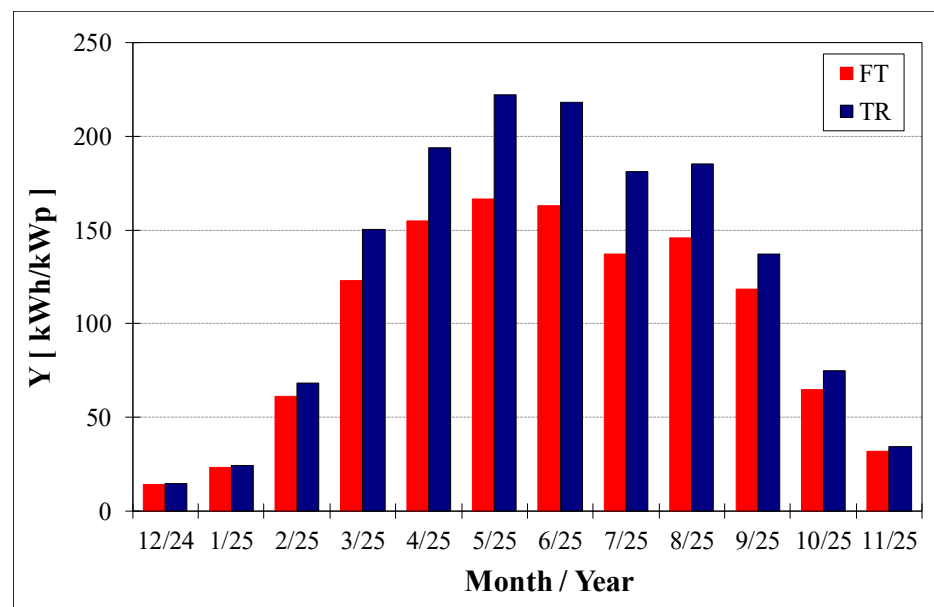


Figure 14. Summary of monthly values of energy produced by both installations, normalized to their rated power.

From this figure, it can be concluded that energy production in the tracking system is greater than in the stationary system year-round. The benefits of using the tracking

system are particularly significant in the period from March to September, when day length exceeds 12 h. The tracking system demonstrates an advantage particularly in May, June, and July, achieving 33.5%, 33.6%, and 32.4% higher yields per unit of rated power than the stationary system, respectively.

Figure 15 shows the time of use and the corresponding relative differences between the productivity of both photovoltaic installations.

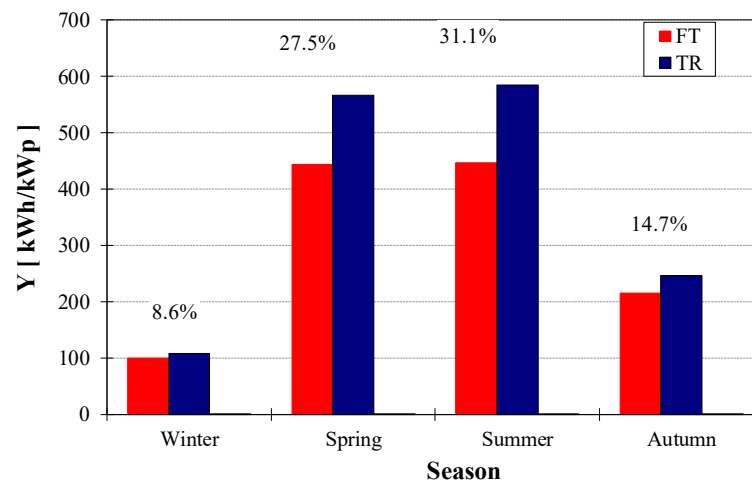


Figure 15. Summary of the time of use of both installations for the 4 seasons.

In the spring and summer months, the differences between installations are greatest. This is due to the high altitude of the Sun above the horizon and longer days. In autumn and winter, the difference in yields between installations decreases significantly, ranging from 8.6% to 14.7%. This is due to heavy cloud cover, a low solar trajectory, and the limited effect of PV module orientation on the level of radiation reaching the photovoltaic cells. The presented analysis confirms the seasonal variability in yields for photovoltaic installations—the highest production values are observed from April to August, while the lowest are from November to January [37]. The tracker installation demonstrates a particularly clear advantage in the spring and summer period, when extended sunlight duration allows for better exposure of PV modules in the morning and afternoon. Another significant factor influencing yields in the spring and summer season is the ability of the prototype tracker system to operate at a wider range of tilt angles. As mentioned earlier, this is due to the greater operating range in the azimuth axis during the longest days of the year, which allows for a longer period of time—compared to typical single-axis systems—to maintain the favorable orientation of PV modules towards the Sun.

7. Profitability Analysis of the Implementation of a Tracking Installation

This section compares the costs of implementing a stationary photovoltaic system and a tracking installation. The analysis was conducted based on the assumption that both systems would be built independently using PV components currently available on the market, taking into account estimated labor costs. To maintain comparability, the detailed cost structure was not disclosed, except for information regarding the use of components used in one of the tracking system variants.

Three installation variants were adopted for analysis:

- A stationary installation as a reference variant;
- A tracking installation made entirely of new components;
- A tracking installation made using used parts and recycled materials.

The stationary installation is built on a support structure anchored directly to the ground. The tracking installation is built on a foundation and uses a heavy-duty gearbox.

It should be noted that in the case of fixed-tilted installations, the cost structure exhibits relatively low variability, as it is dominated by standard components that are widely available on the market and have relatively stable unit prices. A different situation occurs in the case of installations equipped with tracking systems, where the type of mechanical components and their degree of wear have a significant impact on the final investment cost. In particular, this applies to heavy-duty gearboxes, and supporting structures, whose cost in the variant based on new components substantially increases the overall investment outlay.

The construction costs (estimated calculation basing on the market costs) of the analyzed installations are:

- Stationary installation mounted by professional company: €3600;
- Tracking installation mounted by one of the authors (new components): €8400;
- Tracking installation mounted by one of the authors (recycled components): €4000.

The difference in investment costs between a stationary and a tracking installation is mainly due to the use of mechanical components of the drive system with increased durability.

The return-on-investment analysis was conducted based on energy yield for both installation variants discussed. The reference point was an annual energy production of 1000 kWh/kWp·year in the stationary installation, which corresponds to approximately 3600 kWh/year for the analyzed rated power of 3.6 kWp.

Based on measurement data, including systematic corrections (resulting from differences between nominal power generated by each installation), it was estimated that the tracking installation generates approximately 22% higher energy yield than the stationary installation, which corresponds to an additional energy production of approximately 792 kWh/year. The cost effectiveness assessment was performed using the simple payback time method. The electricity price was assumed to be €0.25/kWh, corresponding to the approximate cost of electricity for the end user in Poland in 2025. The additional annual value of energy obtained through the tracking installation is approximately €198/year.

On this basis, the simple payback time was estimated:

- Tracking installation (new components): approximately 24.2 years;
- Tracking installation (used components): approximately 2 years.

The obtained results indicate that the use of a tracking system made of new components leads to a significantly longer payback period, approaching the expected durability of the system's mechanical components. This option is therefore characterized by limited economic attractiveness for prosumer micro-installations. In contrast, the use of used components and recycled materials significantly reduces investment costs, resulting in a radically shorter payback period. In this case, a tracking system can be an economically viable alternative, provided that the mechanical components are maintained in good condition. It should be noted that investors without experience in the construction of mechanical structures and controllers will not be able to install or maintain a tracking system themselves. Outsourcing this work to specialists will involve additional costs that may undermine the investment's profitability. The ultimate cost effectiveness of using a tracking mechanism should be assessed individually, taking into account local conditions, construction and maintenance costs, and potential losses resulting from component failure or wear.

8. Discussion of Results

Analysis of normalized yields for the stationary (FT) and tracker (TR) installations revealed clear seasonal differences resulting from different solar-radiation-tracking methods. In each of the four seasons, the TR installation achieved higher specific yields than the FT installation, but the measure of its advantage varied depending on the season. The greatest benefits from tracker use were observed during high-solar-radiation seasons—spring and summer, where the relative differences were 27.6% and 31.1%, respectively. This is due to the fact that during these periods, the Sun travels along a high trajectory, and the tracker mechanism can maintain the modules in an orientation that maximizes the radiation power density on the PV module surface for most of the day. The increased share of radiation incident at the optimal angle is particularly favorable for installations with monocrystalline modules that are highly sensitive to deviations from the angle of incidence from the normal [38].

During periods of lower solar irradiance, i.e., winter and autumn, the differences between the energy produced by both installations were smaller. In winter, the system's productivity is further limited by the Sun's low position above the horizon and the greater share of diffuse radiation, to which the tracker system responds less. In autumn, tracker efficiency improves due to the greater solar angle, but shorter days and more frequent cloud cover result in lower productivity compared to the summer months. A comparison of the measurement data shows that the year-round advantage of the tracker system is clear, and the seasonal distribution of benefits reflects the geometric and atmospheric conditions of solar radiation availability. The greatest relative benefit occurs when the tracker can more fully utilize the Sun's diurnal motion, whereas in conditions of low solar angle and a predominance of diffuse radiation, the advantage of the tracker system decreases. The obtained results confirm that the use of a solar tracker provides the greatest energy benefits from spring to early autumn, which should be taken into account when analyzing the profitability of the investment.

The impact of bifacial modules: in installations with bifacial modules, additional electricity production comes from the backside of the modules (bifacial gain). Its value depends mainly on the ground's reflectance coefficient (albedo), mounting height, structural shading, and—in the case of a stationary installation—its azimuth. A stationary system can significantly increase yield in the early morning hours and just before sunset, when the backside of the modules is directly illuminated by sunlight. Typical annual yield increases for installations with bifacial modules are of up to 30% [39]. However, it should be noted that tracker installations are never directly illuminated by the Sun from behind. This fact may reduce the relative advantage of the tracker on the longest sunny days of the year. Therefore, it is reasonable to consider the backlight effect in comparative analyses of FT vs. TR with bifacial modules.

9. Conclusions

The presented photovoltaic system model allows for the correct modeling of both stationary and tracker photovoltaic systems. Using available solar radiation models in the literature allows for the correct modeling of both systems' characteristics. However, significantly better modeling accuracy was achieved for the stationary system. The largest differences between the calculation and measurement results occur in summer and winter. The value of RMSE normalized to the daily average value of produced power does not exceed a few percentage points in sunny days, but in cloudy days, this error can exceed even 90%.

The conducted research confirms that the considered tracking system can significantly increase annual energy production compared to a stationary installation. The tested track-

ing system provides higher yields in all seasons, with the greatest benefits noted during months with high irradiance (spring and summer). In winter and autumn, the advantage of the tracking system was smaller, indicating a strong seasonal effect. Taking into account design differences and potential confounding factors (e.g., azimuth, module age, and contamination), the normalization of the obtained results was carried out, which allowed for a more reliable comparison of the tested installations. After normalization, the tracking system still shows a significant advantage, indicating that the change in module alignment geometry alone is the main source of the yield increase.

The analysis performed for one year also showed that for small prosumer installations, trackers can be an effective tool for increasing production, especially in locations with limited shade and in regions with highly variable solar radiation angles. Constructing a solar tracker using recycled components significantly reduces investment costs. It also allows for customization of the structure to individual needs and the acquisition of practical skills. However, this type of installation requires regular maintenance. The steel structure requires maintenance every few years to prevent corrosion. The height of trees and vegetation around the installation should also be monitored to ensure full solar exposure. A need for the controller to measure wind direction and speed is apparent. This would enable the tracker to be positioned safely during strong gusts.

In the European market, prices for commercial tracker designs range from several thousand to several dozen thousand euros, depending on performance. Typically, implementing a tracker with a power output exceeding 2 kWp requires the purchase of several smaller trackers, which can lead to mutual shading of neighboring installations and requires a significantly larger site. Additionally, there are the costs of cabling, earthworks, and complications related to inverters and AC/DC protection systems. Investors without experience in mechanical construction and controllers will be unable to install or maintain a tracking system themselves. Outsourcing this work to specialists will entail additional costs that may undermine the investment's profitability.

The results of the conducted research can provide practical guidance for prosumers and designers considering the cost effectiveness of using or building their own trackers in PV micro-installations. Ultimately, the cost effectiveness of using a tracking mechanism should be assessed individually, taking into account local conditions, construction and maintenance costs, and possible losses resulting from component failure or wear.

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