UDC 620.9 DOI: 10.15222/TKEA2025.1-2.27

Vitalii FEDENKO, Bogdan DZUNDZA

Ukraine, Ivano-Frankivsk, Vasyl Stefanyk Precarpathian National University
E-mail: vitalii.fedenko.23@pnu.edu.ua

APPLICATION OF SOLAR TRACKING SYSTEMS FOR ENHANCING THE ENERGY YIELD OF PHOTOVOLTAIC MODULES: A REVIEW

This paper presents a classification of solar trackers, their types, and the advantages and disadvantages of various algorithms for tracking the Sun's daily movement. It is demonstrated that ensuring an optimal tilt angle of photovoltaic modules is one of the primary factors influencing the amount of electricity generated by solar power plants. Moreover, the economic benefits of their use are significant, as an increase in the generated electricity can enhance the profitability of investments in generation systems. The conducted studies indicate that efficiency improvements depend on the classification of the selected tracker based on its degrees of freedom, the tracking algorithm, and the installation site.

Keywords: solar tracker, sun tracking system, PV systems, solar energy, photovoltaic panels.

Ensuring an uninterrupted electricity supply to consumers is a fundamental component of modern society, forming the basis for technological progress, fostering sustainable development, and implementing innovative technologies. The use of renewable energy sources has become a key element in achieving global sustainable development goals. In recent decades, solar energy has experienced rapid growth; as of 2022, the industry accounts for 31,2% of renewable energy sources by installed capacity [1], underscoring the role of solar energy as a critical element in increasing electricity generation from renewables. The main advantages of photovoltaic converters include low maintenance costs, availability, the possibility of decentralized generation, and a positive environmental impact [2]. One of the most important factors directly affecting the electricity generated is the tilt angle of the photovoltaic modules relative to incoming solar rays [3].

The performance characteristics of a photovoltaic module can be represented by its *P–V* and *I–V* curves, which are influenced by temperature and insolation levels. Accordingly, an increase in temperature leads to reduced output power, while an increase in insolation enhances it [4]. Since the level of insolation depends on the installation location of the panels, developing methods to optimize the tilt angle through the use of automatic tracking systems is a current challenge in enhancing the efficiency of converting solar energy into electricity.

Solar trackers serve an important role in photovoltaic power plants by increasing electricity generation through the dynamic orientation of photovoltaic modules in accordance with the Sun's daily movement, following a predetermined operational algorithm [5]. The current produced by a photovoltaic module is directly correlated with the amount of absorbed light (**Fig. 1**). Assuming that the light intensity λ remains constant, that the angle θ represents the angle between the incoming light and the perpendicular to the module's surface, and that the value A represents the conversion limiting factor (since photovoltaic modules cannot convert 100% of absorbed radiation into electrical energy), the generated electrical energy *W* can be calculated using the formula [6]

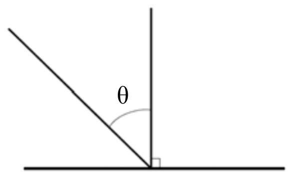

Fig. 1. Representation of the angle θ relative to the photovoltaic module's normal

$$W = A\lambda \cdot \cos\theta. \quad (1)$$

The efficiency of the photovoltaic module η_m can be determined using the formula [7]

$$\eta_m = \frac{P_o}{A_c G}, \quad (2)$$

where P_o — the output power of the photovoltaic module;
A_c — the area of the photovoltaic module;
G — the global horizontal solar irradiance.

For maximum efficiency, solar panels must be positioned perpendicular to the incoming solar radiation. Since the Sun's position changes throughout the day and year, photovoltaic modules installed on fixed structures lose some efficiency. Employing automatic positioning methods for these modules allows for optimal utilization of solar radiation, thereby increasing the amount of generated electricity.

This study reviews various publications in order to assess the level of increase in electricity generation achieved by the introduction of various solar trackers in comparison to stationary panels. Additionally, the study aims to assess the performance of various tracker designs based on their degree of mobility and selected tracking algorithms. Besides determining the energy gains, the work also evaluates the overall system efficiency, taking into account the costs associated with the installation and operation of tracking mechanisms.

Classification of Sun Tracking Methods

Passive Solar Trackers

Unlike active solar trackers, which incorporate electric motors and electronic components with programmed algorithms passive trackers typically rely on external physical conditions, such as temperature and solar irradiance, and therefore do not consume energy during operation [8]. This type of tracker can operate based on the principle of heating a liquid contained in cylindrical tubes under a certain pressure. As the liquid is heated, it vaporizes and transfers to another tube, creating a mass imbalance that, in turn, causes the panel to tilt (**Fig. 2**).

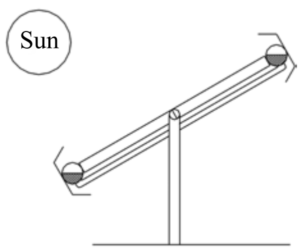

Fig. 2. Principle of a passive tracker with two identical tubes filled with liquid [9]

Passive trackers may also utilize shape memory materials. The authors of [10] describe an experimental model based on two shape memory alloy springs that act as opposing actuators. Upon heating, the springs contract due to the shape memory effect, causing the solar panel to rotate. Typically, passive tracker models struggle to return the panels to their original position before sunrise. The prototype developed by the authors of [11] employs a bimetallic strip deflector resistant to nocturnal temperature fluctuations. A key innovation is the ability for autonomous return to the original position, with the prototype demonstrating a 24,86% efficiency improvement compared to a fixed system.

Active Solar Trackers

The operation of active trackers is based on tracking the Sun's position, which is achieved through the use of integrated light intensity sensors or mathematical calculations. The collected data is processed by a microcontroller or a programmable logic controller, and based on the results, the system generates commands to drive the motor in the tracking direction. Active trackers provide higher efficiency compared to passive ones and are more commonly used in solar power plants; however, when implementing an active tracker, the system's own power consumption and maintenance costs must also be taken into account [12].

Algorithm Based on Light Sensor Readings

Trackers that rely on reading data from light sensors significantly improve the efficiency of solar energy collection by adjusting the panels' orientation throughout the day. The algorithm's operation is based on reading signals from light sensors, typically, these systems use photoresistors placed on the surface of solar panels. When one of the photoresistors receives a higher light intensity, its resistance decreases, allowing the microcontroller to detect the signal difference and, using a motor, rotate the panels in the required direction to minimize the error between the measured signal values [13, 14]. It should be noted that the algorithm's efficiency also depends on the accuracy of the sensors used. The system continuously tracks the Sun's position and regularly adjusts the photovoltaic modules to achieve maximum efficiency.

Algorithm for Determining the Sun's Position

The algorithm, based on astronomical calculations, utilizes mathematical models to determine the exact position of the Sun at any given moment. It is effective in solar trackers, allowing for precise orientation of solar panels to achieve maximum illumination. Additionally, this algorithm can be more efficient compared to systems that use photoresistors as light level sensors [15]. For tracker calibration, data regarding time, date, and geographical location (latitude and longitude) is required. The calculation of the Sun's position in the sky (**Fig. 3**) can be carried out following the methodology described in [16]. Here, the solar declination δ is calculated according to equation

$$\delta = -23,45\cos\left(\frac{360}{365}\cdot(n+10)\right), \tag{3}$$

where n is the ordinal number of the day in the year, counted from January 1

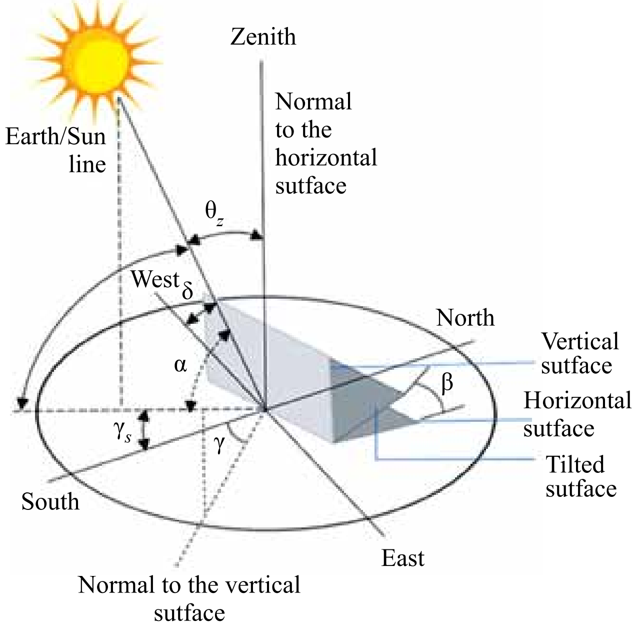

Fig. 3. Graphical representation of algorithm variables [16]

ISSN 3083-6530 (Print)
ISSN 3083-6549 (Online)

The zenith angle plays an important role in determining the Sun's position and the orientation of solar panels. Equation is used to calculate it

$$\theta_z = \cos^{-1}(\sin L_{st} \cdot \sin\delta + \cos L_{st} \cdot \cos\delta \cdot \cos ST), \quad (4)$$

where L_{st}, ST — the standard longitude (positive for the eastern region and negative for the western region) and the standard time.

Altitude angle α denotes the angle between the Sun's position in the sky and the observer's horizon, varying throughout the day:

$$\alpha = 90° - \theta_z. \quad (5)$$

Hour angle h indicates the Sun's position with respect to the observer's meridian and is measured in degrees:

$$h = 15° \text{ (solartime} - 12). \quad (6)$$

Azimuth angle is the angle between the projection of the Sun's center onto the horizontal plane and the south direction, and is determined according to equation

$$\gamma_S = \sin^{-1}\left(\frac{\sin h \cdot \cos\delta}{\sin\theta_Z}\right). \quad (7)$$

Classification of Tracking Systems by Degrees of Freedom

Single-Axis Solar Trackers

Single-axis trackers allow photovoltaic modules to rotate around a single axis, typically following the Sun in a horizontal or vertical direction throughout the day. This maximizes light collection and increases the amount of generated energy. Compared to dual-axis tracking systems, they are less efficient but feature a simpler design and are more cost-effective. Additionally, single-axis systems are easier to install and maintain, leading to lower operational costs. Their reduced mechanical complexity also enhances overall system reliability, making them a popular choice for large-scale solar installations.

Several design variants exist: horizontal single-axis trackers, vertical single-axis trackers, trackers with an inclined axis of rotation, and trackers with a polar-oriented axis of rotation [17, 18]. The principle of a single-axis tracker is illustrated in **Fig. 4**, where β denotes the panel's tilt angle.

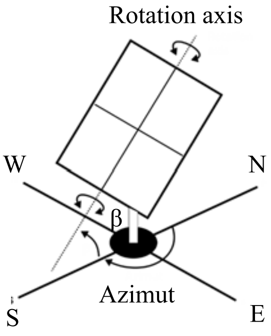

Fig. 4. Illustration of the operating principle of a single-axis tracker [18]

Results are presented in study [19] indicate an average output power of 17,15 W for a stationary system and 21,5 W for a single-axis tracker, corresponding to a 25% efficiency improvement. The prototype of a single-axis azimuth tracking system based on an ATmega328 microcontroller and a DC motor controlled by relay signals derived from light sensor readings is introduced in publication [20]. Measurement results for a latitude of 35.47° demonstrate an output power increase ranging from 18% to 25%.

The single-axis tracker model presented in [21] is implemented using a PIC 16F72 microcontroller, photoresistors, and a stepper motor. Experimental investigations reported a 15% efficiency improvement. The authors of [22] published the results of experimental studies on a single-axis tracker installation using a DC motor controlled according to signals from light sensors. In this case, the generated energy was 1742,88 Wh for the single-axis tracker compared to 829,6 Wh measured from a fixed solar panel (**Fig. 5**).

A single-axis tracker, operating by reading a database of the Sun's position and adjusting the required angle based on time and date, is presented by the authors in [23]. The main components of its design include a 40 W solar panel that rotates 180° around a horizontal axis, an Arduino microcontroller, and a servo motor. To evaluate its performance, researchers measured current and voltage every 30 min from 9:00 to 16:00; based on the results, the proposed model generated 15% more energy than a stationary panel.

Application of a single-axis tracker combined with Internet of Things (IoT) technology for information exchange via the Internet is proposed in [24]. The prototype utilizes a U-Blox GY-GPS6MV2 GPS module to determine latitude and longitude, which are transmitted to the Firebase service for calculating the optimal rotation angle. An MPU-6050 gyroscope is used to monitor the tracker's position and provide feedback to the control system. According to experimental measurements, energy production increased by 29.9%.

In [25], authors also examined how to control single-axis tracker parameters via IoT, exploring techniques that enable real-time monitoring and dynamic adjustment to optimize system performance. Their scheme is based on controlling a DC motor through an ATMega 2560 microcontroller to rotate a 30 W panel. An ESP8266

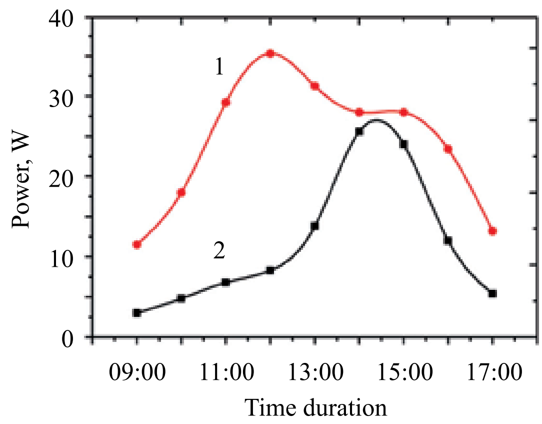

Fig. 5. Variation in output power throughout the day for a single-axis tracker (*1*) and a fixed solar panel (*2*) [22]

ISSN 3083-6530 (Print)
ISSN 3083-6549 (Online)

board, combined with a current and voltage sensor, provides real-time monitoring of these parameters via the online resource Thingview.

The use of two photoresistors for measuring light intensity and constructing a prototype tracker that moves from east to west is presented in [26]. This tracker is based on an Arduino Uno 3 microcontroller and a servo motor that rotates a 20 W panel. The photovoltaic panel's parameters when connected to a resistive load were measured using a current and voltage sensor, with data recorded every 5 min on an SD card in CSV format. Based on the obtained results and their comparison with data from a panel without a tracker, the efficiency increase was 22%.

Dual-Axis Solar Trackers

Dual-axis trackers enable photovoltaic modules to maintain an optimal tilt angle by rotating on two distinct, perpendicular axes (**Fig. 6**). The primary advantage of dual-axis trackers is their ability to deliver higher efficiency compared to systems operating on a single axis. However, they feature a more complex mechanical design, require regular technical inspection and maintenance, and are more expensive than single-axis systems, necessitating greater initial investments. In addition, these trackers can continuously follow the Sun's trajectory in both azimuth and altitude, ensuring maximum exposure throughout the day. This dual-axis movement significantly enhances energy yield, particularly in environments with variable solar angles. Nonetheless, the increased mechanical complexity may lead to higher operational costs and a greater potential for component failures over time, making the overall cost-effectiveness dependent on specific installation conditions and maintenance practices. The following dual-axis tracker designs are distinguished: the tip-tilt dual-axis solar tracker and the azimuth-altitude dual-axis solar tracker.

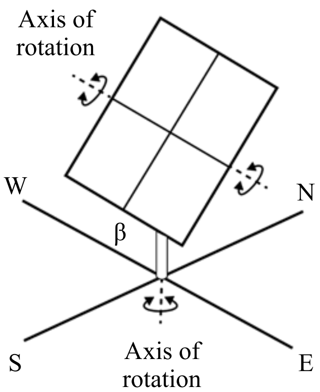

Fig. 6. Illustration of the operating principle of a dual-axis tracker [28]

The study [28] proposed a dual-axis positioning system that operates in conjunction with a maximum power point tracking controller, achieving an increase in output power of 28,8–43,6% depending on the season. An automatic dual-axis sun tracking system presented by the authors in [29] was developed with a closed-loop control system. The tracking strategy is based on a pseudo-azimuthal coordinate system for rotation around the primary (north-south) and secondary (east-west) axes. Analysis of the measurements demonstrated an efficiency increase of 44,89% compared to a fixed panel. A comparison of the output power for static, single-axis, and dual-axis systems presented in [30] indicates an efficiency improvement of 16,71% for the single-axis system and 24,7% for the dual-axis system, respectively (**Fig. 7**). The difference between the two systems was 8,26%, which may be significant over the long term.

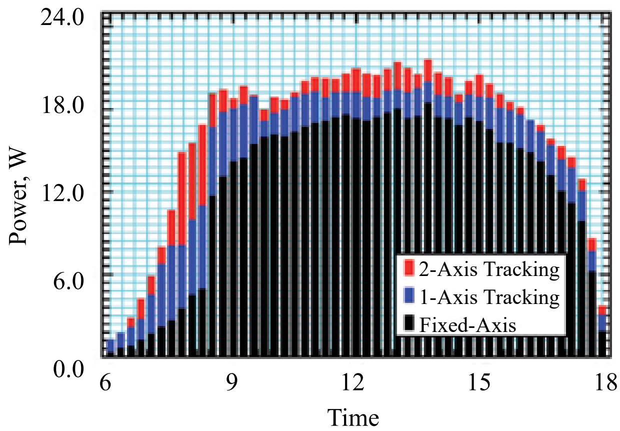

Fig. 7. Comparison of output power for different systems [30]

The application of a dual-axis tracker based on an algorithm that utilizes data from four photoresistors and is controlled by a microcontroller with stepper motors demonstrated a 40% efficiency increase [31]. The authors of [32] propose using a dual-axis tracking system combined with Internet of Things (IoT) technology based on the NodeMCU module. In this system, IoT technology enables 24-hour remote monitoring of the panels' output power and the storage of data for further analysis and performance verification. Experimental results [33] for a latitude of 35°, obtained from 9 AM to 4 PM, show an increase in electricity production of 25–40%. The dual-axis system model is based on an AVR ATmega328 microcontroller with photoresistors and employs two DC motors that operate along the azimuth and altitude axes. The developed hardware-software complex for dual-axis sun tracking [34], compared with a fixed panel tilted at 32° to the south, improved efficiency by an average of 41,34%. For remote monitoring of dual-axis tracker parameters, [35] proposes using a NodeMCU ESP8266 board and the BLINK IoT service. The proposed circuit is connected to an INA219 sensor via the I2C bus for reading current and voltage, and photoresistors together with a servo motor are used for tracker operation.

Study [36] presents the results of implementing a hybrid tracker. The electrical system is divided into three blocks: a sensor block designed to read time, position, and light intensity values; a control block that issues directional signals to the motors along the horizontal and vertical axes; and a motion regulation block based on two unipolar stepper motors. According to the publication, the hybrid tracking system achieves a 25.62% efficiency increase compared to a static system and 4.2% lower efficiency than a continuous tracking system. In the

ISSN 3083-6530 (Print)
ISSN 3083-6549 (Online)

hybrid tracker, one motor operates continuously to follow the Sun, while the other is activated once a month for seasonal adjustment; in contrast, both motors in a continuous tracking system operate constantly. This configuration resulted in a 44.44% energy savings when using the hybrid system. The implementation of a dual-axis tracker with IoT monitoring of solar panel data is described in [37]. The setup operates on an Arduino platform with servo drives capable of 180° rotation, along with light sensors. The monitoring system uses a Wi-Fi ESP8266 module to display graphs of voltage, current, and power on the Ubidots service.

Another publication [38] presented the results of fabricating a single-axis and a dual-axis tracker with 2 and 4 photoresistors used for each model, respectively. The system was controlled by a PIC18F4520 microcontroller, and provided the capability to record output parameters on an SD card. To measure voltage values, a voltage divider based on three 12 kΩ resistors connected to the microcontroller was proposed, with the voltage calculated according to the formula

$$\frac{R_3}{R_1 + R_2 + R_3} \times \text{Voltage}_{\text{panel}} = \text{Voltage}_{\text{controller}}. \quad (8)$$

In conclusion, it is stated that the dual-axis tracking system generates 8 – 12% more electricity compared to the single-axis system.

Cost-Effectiveness of Solar Tracking Systems

Analysis of the ratio between the increase in electricity production and the installation and operating costs of tracking systems allows for a comprehensive evaluation of the profitability of implementing this technology. This approach also provides key insights into the return on investment and helps compare the cost-effectiveness of various solar tracking systems. Furthermore, it supports decision-makers in identifying the most viable solutions that balance performance improvements with financial sustainability The technical-economic comparison conducted by the authors in [39] demonstrates that the average cost of electricity produced with a single-axis tracker ranges from 39 EUR/MWh to 79 EUR/MWh — approximately 20% lower compared to a fixed system — and features a payback period that is 9% shorter for the specified region.

An analysis comparing the performance and cost of three systems: fixed, single-axis, and dual-axis that operate under identical conditions and in the same location indicates significant advantages of movable structures over a fixed system [40]. The study reports an increase in electricity production of 24.367% for the single-axis system and 32.247% for the dual-axis system. An analysis of capital investments showed that the single-axis system reached payback 0.39 years sooner than the fixed system, while the dual-axis system did so 1.48 years sooner, leading to conclusions about the feasibility of implementing tracking systems.

The results presented in [41] also compare the three types of systems. They report that the single-axis system recovers its initial investment 20% faster than the dual-axis system and demonstrates an 8.5% higher internal rate of return. Although the dual-axis system produces the most energy, it requires a larger area, more complex installation, and higher initial investments. A comparative analysis of initial investments in tracking systems [42] indicates that total costs are 25% higher for a single-axis tracker and 33% higher for a dual-axis tracker compared to a fixed system. Consequently, the energy production increase is from 76 GWh to 98 GWh per year for single-axis systems and from 76 GWh to 101 GWh per year for dual-axis systems, as observed for the 50 MW Burnoye Solar-1 station.

The authors of [43] analyzed various cost and economic factors influencing the overall levelized cost of energy (LCOE) in solar tracker projects. The maintenance rate, along with initial capital expenditures and credit terms, plays the largest role in increasing the LCOE. At the same time, the increased energy production enabled by the tracker can significantly reduce the LCOE, as the same costs are spread over a larger volume of generated energy. Operating and maintenance expenses, as well as high interest rates on loans, can substantially extend the payback period, particularly in the presence of inflation. Thus, the success of the project depends on balancing the additional energy generation provided by the tracker against the extra costs of its acquisition and maintenance.

Conclusion

A review of studies indicates that dual-axis trackers achieve the highest efficiency; however, their drawbacks include higher initial investment costs and a more complex design, which result in additional challenges and expenses for maintenance. Single-axis trackers, on the other hand, have a simpler design and are less expensive, though they provide a smaller efficiency gain. Other important factors affecting the efficiency of tracking systems include the season and the location of installation. Therefore, the search for compromise solutions depends on the initial capital investment and system capacity. Research and implementation of tracking installations open up new opportunities for creating more efficient, economically advantageous, and environmentally sustainable systems capable of maximizing energy production, reducing operating costs, and minimizing environmental impact.

REFERENCES

1. IRENA. Available at: https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Technologies (accessed 10.03.2025)

2. Chen Y. M., Lee C. H., Wu H. C. Calculation of the optimum installation angle for fixed solar-cell panels based on the genetic algorithm and the simulated-annealing method. *IEEE Transactions on Energy Conversion*, 2005, vol. 20, iss. 2, p. 467. https://doi.org/10.1109/tec.2004.832093

3. Mamun M. A. A., Islam. M. M., Hasanuzzaman M., Selvaraj J. Effect of tilt angle on the performance and electrical parameters of a PV

module: Comparative indoor and outdoor experimental investigation. *Energy and Built Environment*, 2022, vol. 3, iss. 3, p. 278. https://doi.org/10.1016/j.enbenv.2021.02.001

4. Maghami M. R., Hizam H., Gomes C. et al. Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews*, 2016, vol 59, p.1307. https://doi.org/10.1016/j.rser.2016.01.044

5. Amelia A.R., Irwan Y.M., Safwati I. et al. Technologies of solar tracking systems: A review. *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 767, iss. 1, p. 012052. https://doi.org/10.1088/1757-899x/767/1/012052

6. Gupta P., Kumar B., Wankhade P. et al. Azimuth-altitude dual axis solar tracker. *IOSR Journal of Electrical and Electronics Engineering*, 2016, vol. 11, iss. 5, p. 2. https://doi.org/10.9790/1676-1105012630

7. Mahendran M., Ong H.L., Lee G. C., Thanikaikumaran K. An experimental comparison study between single-axis tracking and fixed photovoltaic solar panel efficiency and power output: case study in east coast Malaysia. *Sustainable Development Conference*, 2013, pp. 1–11.

8. Brito M. C., Pó J. M., Pereira D. et al. Passive solar tracker based in the differential thermal expansion of vertical strips. *Journal of Renewable and Sustainable Energy*, 2019, vol. 11, iss. 4, p. 043701. https://doi.org/10.1063/1.5100492

9. Clifford M. J., Eastwood D. Design of a novel passive solar tracker. *Solar Energy*, 2004, vol. 77, iss. 3, p. 269. https://doi.org/10.1016/j.solener.2004.06.009

10. Degeratu S., Rizescu S., Alboteanu L. et al. Using a shape memory alloy spring actuator to increase the performance of solar tracking system. *Annals of the University of Craiova, Electrical Engineering series*, 2014, vol. 38, p. 116.

11. Alemayehu M., Admasu B. T. Passive solar tracker using a bimetallic strip activator with an integrated night return mechanism. *Heliyon*, 2023, vol. 9, iss. 7, p. 18174. https://doi.org/10.1016/j.heliyon.2023.e18174

12. Pulungan A. B., Son L., Syafii. A riview of solar tracking control strategies. *EECSI*. Malang, Indonesia, 2018, p. 631–635.

13. Salgaonkar N.K., Shirodkar N.A., Yedurkar N. A., Mohite N.A. Automated dual axis solar tracking system using LDR sensors. *International Journal of Engineering Research & Technology*, 2017, vol. 6, iss. 07, pp. 279–282. https://doi.org/10.17577/ijertv6is070189

14. Ya'u M. J. A review on solar tracking systems and their classifications. *Journal of Energy, Environmental & Chemical Engineering*, 2017, vol. 2, iss. 3, p. 46. https://doi.org/10.11648/j.jeece.20170203.12

15. Kuttybay N., Saymbetov A., Mekhilef S. et al. Optimized single-axis schedule solar tracker in different weather conditions. *Energies*, 2020, vol. 13, iss. 19, p. 5226. https://doi.org/10.3390/en13195226

16. Musa A., Alozie E., Suleiman S. A. Et al. A review of time-based solar photovoltaic tracking systems. *Information*, 2023, vol. 14, iss. 4, p. 211. https://doi.org/10.3390/info14040211

17. Shankar G., Singh R. S. A review of solar energy tracker and models. *Journal of Basic and Applied Engineering Research*, 2014, vol. 1, iss. 9, pp. 110–114.

18. Tudorache T., Kreindler L. Design of a solar tracker system for PV power plants. *Acta Polytechnica Hungari-ca*, 2010, vol. 7, iss. 1, pp. 23–39.

19. Rinaldi R., Aprillia B. S., Ekaputri C., Reza M. Design of open loop single axis solar tracker system. IOP Conference Series: *Materials Science and Engineering*, 2020, vol. 982, iss. 1, p. 012016. https://doi.org/10.1088/1757-899x/982/1/012016

20. Akbar H. S., Fathallah M. N., Raoof O. O. Efficient single axis sun tracker design for photovoltaic system applications. *IOSR Journal of Applied Physics*, 2017, vol. 09, iss. 02, pp. 53–60. https://doi.org/10.9790/4861-0902025360

21. Prodhan M. M. H., Hamid M. K., Hussain D., Huq M. F. Design, construction and performance evaluation of an automatic solar tracker. *Published online January 1*, 2016, vol. 8, iss. 1, pp. 1–12. https://doi.org/10.3329/jsr.v8i1.23357

22. Mehdi G., Ali N., Hussain S. et al. Design and fabrication of automatic single axis solar tracker for solar panel. *2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, 2019, pp. 1–4. https://doi.org/10.1109/icomet.2019.8673496

23. Chaijum N., Cheunchantawong L., Siriram T. Single-axis solar tracking system referring to date and time. *Journal of Physics*: *Conference Series*, 2021, vol. 2145, iss, 1, p. 012052. https://doi.org/10.1088/1742-6596/2145/1/012052

24. Gutierrez S., Rodrigo P. M., Alvarez J. et al. Development and testing of a single-axis photovoltaic sun tracker through the internet of things. *Energies*, 2020, vol. 13, iss. 10, p. 2547. https://doi.org/10.3390/en13102547

25. Pulungan A. B., Purwanto W., Maksum H. et al. Design and development of real time monitoring single axis solar tracker by using internet of things. *International Journal of GEOMATE*, 2020, vol. 18, iss. 69, pp. 81–87. https://doi.org/10.21660/2020.69.25863

26. Rosma I. H., Putra I. M., Sukma D. Y. et al. Analysis of single axis sun tracker system to increase solar photovoltaic energy production in the tropics. *2nd International Conference on Electrical Engineering and Informatics (Icon EEI). IEEE*, 2018, pp. 183–186. https://doi.org/10.1109/icon-eei.2018.8784311

27. Ghodasara A., Jangid M., Ghadhesaria H. et al. IOT based dual axis solar tracker with power monitoring system. easychairorg. *EasyChair Prepringt 5063*, 2021.

28. Fathabadi H. Novel high accurate sensorless dual-axis solar tracking system controlled by maximum power point tracking unit of photovoltaic systems. *Applied Energy*, 2016, vol. 173, 448–459. https://doi.org/10.1016/j.apenergy.2016.03.109

29. Jamroen C., Komkum P., Kohsri S. et al. A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. *Sustainable Energy Technologies and Assessments*, 2020, vol. 37, p. 100618. https://doi.org/10.1016/j.seta.2019.100618

30. Thungsuk N., Tanaram T., Chaithanakulwat A. et al. Performance analysis of solar tracking systems by five-position angles with a single axis and dual axis. *Energies*, 2023, vol. 16, iss. 16, p. 5869. https://doi.org/10.3390/en16165869

31. Kumar S., Singh B., Banerjee S. et al. Performance comparison between arduino based dual axis solar tracker and fixed module. *Journal of Information and Optimization Sciences*, 2022, vol. 43, iss. 3, pp. 475–480. https://doi.org/10.1080/02522667.2022.2044000

32. Muthukumar P., Manikandan S., Muniraj R. et al. Energy efficient dual axis solar tracking system using IOT. *Measurement: Sensors*, 2023, vol. 28, p. 100825. https://doi.org/10.1016/j.measen.2023.100825

33. Akbar H. S., Siddiq A. I., Aziz M. W. microcontroller based dual axis sun tracking system for maximum solar energy generation. *American Journal of Energy Research*, 2017, vol. 5, iss. 1, pp. 23–27. https://doi.org/10.12691/ajer-5-1-3

34. Abdallah S., Nijmeh S. Two axes sun tracking system with PLC control. *Energy Conversion and Management*, 2004, vol. 45, iss. 11–12, pp. 1931-1939. https://doi.org/10.1016/j.enconman.2003.10.007

35. Anshory I., Jamaaluddin J., Fahruddin A, et al. Monitoring solar heat intensity of dual axis solar tracker control system: New approach. *Case Studies in Thermal Engineering*, 2024, vol. 53, p. 103791. https://doi.org/10.1016/j.csite.2023.103791

36. Ferdaus R. A., Mohammed M. A., Rahman S. et al. Energy efficient hybrid dual axis solar tracking system. *Journal of Renewable Energy*, 2014, vol. 2014, pp.1–12. https://doi.org/10.1155/2014/629717

37. Jumaat S. A., Said M. N. A. M., Jawa C. R. A. Dual axis solar tracker with IoT monitoring system using arduino. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 2020, vol. 11, iss. 1, p. 451. https://doi.org/10.11591/ijpeds.v11.i1.pp451-458.

ISSN 3083-6530 (Print)
ISSN 3083-6549 (Online)

38. Mohaimin A. H., Uddin M. R., Law F. K. Design and fabrication of single-axis and dual-axis solar tracking systems. *IEEE Student Conference on Research and Development (SCOReD)*, 2018, pp. 1–4. https://doi.org/10.1109/scored.2018.8711044

39. Gol A. E., Scasny M. Techno-economic analysis of fixed versus sun-tracking solar panels. *International Journal of Renewable Energy Development-IJRED*, 2023, vol. 12, iss. 3, pp. 615–626. https://doi.org/10.14710/ijred.2023.50165

40. Demirdelen T., Alıcı H., Esenboğa B., Güldürek M. Performance and economic analysis of designed different solar tracking systems for Mediterranean climate. *Energies*, 2023, vol.16, iss.10, p. 4197. https://doi.org/10.3390/en16104197

41. De Simón-Martín M., Alonso-Tristán C., Díez-Mediavilla M. Performance indicators for sun-tracking systems: A case study in Spain. *Energy and Power Engineering*, 2014, vol. 06, iss. 09, pp. 292–302. http://dx.doi.org/10.4236/epe.2014.69025

42. Praliyev N., Zhunis K., Kalel Y., Dikhanbayeva D. Impact of One-and Two-axis Solar Tracking on Techno-Economic Viability of On-Grid PV Systems: Case of Burnoye-1, Kazakhstan. *International Journal of Sustainable Energy Planning and Management*, 2022, vol. 29, pp. 79–80. https://doi.org/10.5278/ijsepm.3665

43. Liu Q., Wan. LCOE Analysis of Solar Tracker Application in China. Computational Water, *Energy, and Environmental Engineering*, 2020, vol. 09, iss. 04, pp. 87–100. ttps://doi.org/10.4236/cweee.2020.94007

Received 10.03 2025

DOI: 10.15222/TKEA2025.1-2.27
УДК 620.9

Віталій ФЕДЕНЬКО, Богдан ДЗУНДЗА

Україна, м. Івано-Франківськ,
Прикарпатський національний університет
імені Василя Стефаника

E-mail: vitalii.fedenko.23@pnu.edu.ua

ЗАСТОСУВАННЯ ТРЕКЕРНИХ СИСТЕМ ДЛЯ ПІДВИЩЕННЯ РІВНЯ ГЕНЕРАЦІЇ СОНЯЧНИМИ ФОТОЕЛЕМЕНТАМИ: ОГЛЯД

У цьому дослідженні зроблено огляд публікацій з метою оцінки рівня збільшення вироблення електроенергії в результаті впровадження різних трекерних систем стеження за Сонцем порівняно зі стаціонарними панелями. Крім того, проаналізовано загальну ефективність системи, беручи до уваги витрати, пов'язані з установкою та експлуатацією механізмів стеження.

В роботі описані одно- та двовісьові сонячні трекери різних конструкцій та можливі алгоритми відстеження руху Сонця впродовж дня. Встановлено, що забезпечення оптимального кута нахилу фотоелементів є одним з ключових факторів, які впливають на кількість генерованої сонячними електростанціями електроенергії. Застосування трекерних систем стеження дозволяє оптимізувати площу встановлених панелей, що є особливо важливим у місцях з обмеженим простором. Також їх можна налаштувати для роботи в різних географічних умовах, тобто в широкому спектрі локацій. Важливим є також і економічний ефект від застосування, оскільки збільшення кількості отриманої електроенергії може покращити рентабельність інвестицій у системи генерації. Аналіз показав, що ефективність застосованої системи залежить від ступеней свободи руху вибраного трекера та алгоритму стеження, а також місцевості його встановлення.

Ключові слова: сонячний трекер, системи відстеження сонця, фотоелектричні системи, сонячна енергетика, фотоелектричні панелі.