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Analysis of amorphous power in different photovoltaic system technologies

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Abstract.
This paper aims to analyse the amorphous power output of three different photovoltaic systems – fixed photovoltaic system, photovoltaic/thermal system and tracking photovoltaic system which are all located at the Institute of Energy Technology, Faculty of Energy Technology, University of Maribor. Over the course of a year, the production analysis is conducted at annual, monthly, and quarterly levels to determine which system achieves the highest electricity production across different time intervals. The analysis is based on 5-minute measurement data for each photovoltaic system, allowing for a detailed and comprehensive evaluation of production performance. In addition to the amorphous power output of individual photovoltaic systems, the paper investigates the availability factor, which represents the available power of each photovoltaic system as a function of the share of its nominal installed capacity. Based on the analyses of the electricity production, it is possible to determine which photovoltaic system achieves the highest energy yield by optimally utilizing the available solar energy under variable weather conditions throughout the year.

Key words. amorphous power, electrical energy, fixed photovoltaic system, tracking photovoltaic system, hybrid solar system

1. Introduction

The integration of photovoltaic (PV) systems is becoming an important strategy aimed at reducing reliance on conventional energy sources that contribute to greenhouse gas emissions in electricity production. Solar energy, recognized as an alternative energy source, is crucial in decarbonizing power systems. However, transitioning to alternative and renewable energy sources necessitates integrating various systems to ensure a stable and reliable electricity supply. Due to fluctuating weather conditions daily, PV systems exhibit variable electricity production, which is characterized as an amorphous form of energy, leading to seasonal discrepancies between production and electricity demand. With the increasing global trend of integrating diverse PV systems, advanced alternative technologies and systems are being developed in parallel to enhance the efficiency and output of PV installations, ultimately replacing conventional energy sources. Given the growing need for more efficient solar energy solutions, researches have explored various innovations in PV technology to improve energy yield and sustainability. The study in [1] explores innovations in PV technology and their significance in achieving sustainable energy production by 2050, identifying 15 innovative solutions that could contribute to sustainable development. Similarly, the authors in [2] investigate PV pavements, a fusion of PV and road infrastructure, to harness solar energy for electricity production. Their findings indicate that this technology remains in an early research phase, requiring improvements for large-scale deployment to attain economic and technical feasibility.
N. Amber et al. [3] presented the performance of a photovoltaic/thermal (PV/T) air collector by analyzing temperature distribution and the effects of inlet and outlet air temperature. The results showed that the air duct improved the electrical efficiency of the PV/T module by 13,67 %. The PV/T system enhanced overall efficiency and reduced efficiency variations throughout the day. J. Choi et. al [4] proposed a method for approximating the maximum power in a PV inverter system and an improved tracking method. Using tracking methods based on weather conditions improves electricity production by 50%, which they verified through experimental results.
The trend of increasing PV system installations is also evident in Slovenia. According to data from the National Transmission and Distribution System Operator (ELES), the total installed capacity of PV systems in Slovenia reached 1.36 GW by the end of 2024 [5].
For the purposes of analysing amorphous power production, this paper examines three types of PV systems: fixed PV systems, PV tracking systems, and PV/T systems. The paper is structured into four main sections: the introduction, a description of PV systems, the results of electricity production for each PV system, and a concluding section that summarizes the findings.

2. Description of photovoltaic systems

This section presents three different PV systems: fixed PV system, PV/T system and PV tracking system.

A. *Fixed PV system*

A fixed PV system is the most implemented type of PV system, which is permanently mounted on the supporting structure of a building. Due to its fixed positioning, the system does not allow for adjustments in tilt or orientation during operation. The surface area and, consequently, the number of PV modules depend on the available effective surface area and the electricity consumption of the building, assuming the user intends to rely solely on the fixed PV system for electricity production. The fixed PV system discussed in this paper is located at the Institute of Energy Technology, Faculty of Energy Technology, University of Maribor, and is shown in Figure 1.

Fig. 1. Analysed fixed PV system

The fixed PV system shown in Figure 1 has a nominal installed capacity of 5.2 kW, a tilt angle of 10°, has been operational since 2016, and is oriented southward.

B. *Photovoltaic/thermal system*

A PV/T system, in addition to generating electricity, enables the dissipation of excess heat, positively impacting PV modules' efficiency and lifespan. This is achieved by using a heat exchanger, which effectively reduces the operating temperature of the system, thereby contributing to higher energy production and a lower degradation rate of components as the system is subjected to lower thermal stress. The heat absorbed by the heat exchanger medium can later be utilized for domestic hot water heating in combination with a thermal energy storage unit [6] and [7]. In addition to transferring heat to a storage unit, the absorbed heat can be used to warm the PV modules during winter, when frost or snow may accumulate on their surface at lower temperatures, reducing solar radiation absorption and, consequently, electricity production. A PV/T system located at the Institute of Energy Technology, Faculty of Energy Technology, University of Maribor, was examined to analyze electricity production, as shown in Figure 2.

Fig. 2. Analysed PV/T system

The analysed PV/T system shown in Figure 2 has a nominal installed capacity of 3.3 kW, a tilt angle of 45°, has been in use since 2021, and is oriented southward.

C. *Tracking photovoltaic system*

A PV tracking system incorporates a mechatronic system that integrates information, mechanical, and electronic technology to enable solar trajectory tracking, thereby increasing electricity production [8]. The authors in [9] compare electricity production between fixed and PV tracking systems using identical PV modules, concluding that a PV tracking system allows for higher electricity production within the same time interval. There are two primary control methods: closed-loop and open-loop systems. A closed-loop control system relies on sensors that detect the optimal solar potential and transmit this information to a controller, which adjusts the PV module orientation by activating a motor or actuator. On the other hand, an open-loop control system is based on mathematical algorithms that use precomputed geometric relationships between the Sun and Earth to determine the position of the motor and actuator. This approach eliminates measurement errors that may occur in closed-loop systems under unfavourable weather conditions, which can hinder accurate sensing. A PV tracking system located at the Institute of Energy, Faculty of Energy Technology, University of Maribor, was examined for the analysis of electricity production, as shown in Figure 3.

Fig. 3. Analysed PV tracking system

The analysed PV tracking system shown in Figure 3 has a nominal installed capacity of 5.2 kW, has an open-loop control system, has been in use since 2021, and is oriented southward.

3. Results

This chapter presents the analysis of electricity production for different PV systems at annual, monthly, and quarterly levels where the electricity production values are normalized by the nominal power of each PV system which represents W/W_p. The results help determine which PV system achieves the highest amorphous power production over the same time interval. The presented results offer a clear view of seasonal influences on the performance of each PV system.

A. Results for fixed PV system

Figure 4 presents the annual amorphous power produced by the fixed PV system.

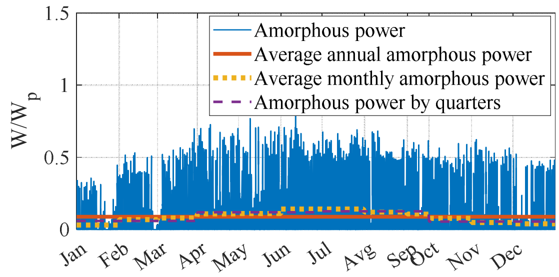

Fig. 4. Annual amorphous power of fixed PV system

Figure 4 clearly demonstrates that during the first quarter (January–March), the average amorphous power output was 0,088 W/W_p, with a notable increase towards the end of March, when the fixed PV system reached a peak value of 0,69 W/W_p. This significant rise in amorphous power production can be attributed to longer daylight hours and more stable weather conditions. The second quarter (April–June) was notably more favorable, with an average amorphous power value of 0,12 W/W_p. The third quarter (July–September) represented the optimal period for the fixed PV system, as the average amorphous power output increased to 0,13 W/W_p. The fourth quarter (October–December) saw an anticipated decrease in average amorphous power to 0,06 W/W_p, as shorter daylight hours and variable weather conditions adversely impacted electricity generation. In addition a more granular monthly analysis of the amorphous power produced by the fixed PV system was performed, as depicted in Figure 5.

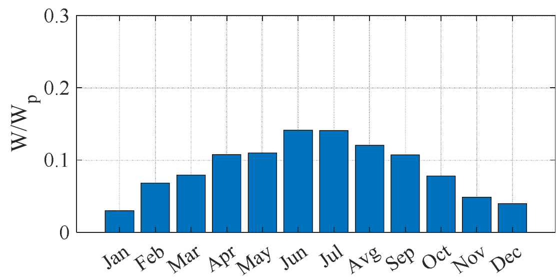

Fig. 5. Monthly amorphous power of fixed PV system

Figure 5 shows that the most favorable month was June, when the average amorphous power reached 0,14 W/W_p. In contrast, January was the least favorable month, with an average amorphous power of only 0,03 W/W_p. This can be attributed to shorter daylight hours and unfavorable weather conditions, significantly reducing electricity production during this period. The electricity production of the fixed PV system, relative to its nominal capacity, is graphically represented in Figure 6.

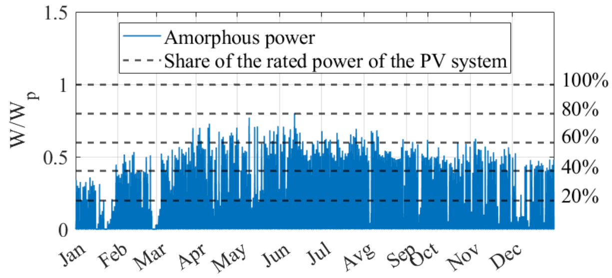

Fig. 6. Availability of the fixed PV system depending on the share of nominal power

In Table 1, the availability factor of the fixed PV system is presented in relation to its nominal capacity, which the fixed PV system can theoretically achieve.

Table I. – Availability factor of the fixed PV system

Share of nominal power [%]	Availability factor [%]
20	81,49
40	10,72
60	7,62
80	0,16
100	0

Figure 6 and Table 1 show that the fixed PV system has the highest availability factor at 20 % of its nominal capacity. In contrast, the availability factor is nearly negligible at 80% of the nominal capacity. The fixed PV system never reaches 100 % of its nominal power, which can be attributed to an unfavourable tilt angle (10°) and the degradation of the PV system, which has been in operation for nine years. Based on the results, it can be concluded that the system has a low availability factor relative to its nominal capacity.

B. Results for photovoltaic/thermal system

Figure 7 presents the annual amorphous power produced by the PV/T system.

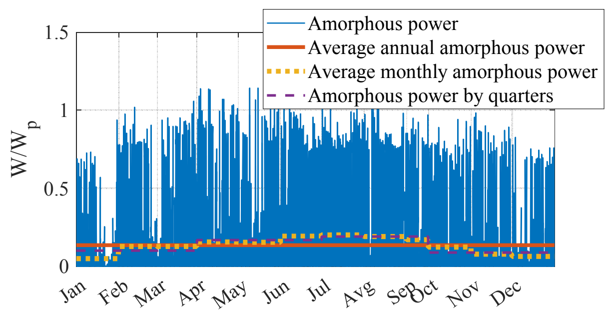

Fig. 7. Annually amorphous power of PV/T system

Figure 7 presents a more detailed quarterly analysis, revealing seasonal fluctuations in the PV/T system, which operated with an average annual amorphous power of 0,13 W/W_p. In the first quarter (January–March), the PV/T system achieved an average amorphous power of 0,09 W/W_p. In the second quarter (April–June), the system improved, with an average amorphous power increase to 0,17 W/W$_p$. The transition into the spring period brought longer days, higher temperatures, and more stable weather conditions, which positively impacted electricity production. The PV/T system performed at its best in terms of amorphous power production during the third quarter (July–September), reaching the highest average value of 0,19 W/W$_p$. Stable and high solar irradiation during this period resulted in significantly fewer production dips. Notably, electricity production of the PV/T system was often recorded to exceed 1 W/Wp from March to August. Since the installed capacity is measured under standard test conditions (STC), it can be inferred that actual operating conditions during these months were more favorable for electricity generation. The least favorable period for the PV/T system was the fourth quarter (October–December), where amorphous power decreased to 0,087 W/W$_p$. Despite the cooling and heating functionalities of the PV/T modules, this technology did not significantly enhance electricity production during this period. Figure 8 illustrates the monthly distribution of amorphous power production in the PV/T system.

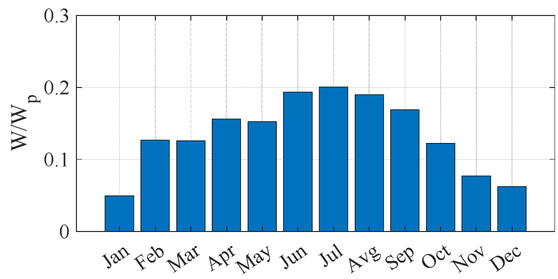

Fig. 8. Monthly amorphous power of PV/T system

Figure 8 illustrates the monthly produced amorphous power of the PV/T system, with July standing out as the month with the highest amorphous power output, reaching 0,2 W/W$_p$. In contrast, January, with an amorphous power value of 0,05 W/W$_p$, represents the month with the lowest output. Transitional months, such as April, May, September, and October, show an increasing trend in production during spring and a decreasing trend in autumn regarding amorphous power production. The integration of the heat exchanger enhances the system's operating conditions compared to a conventional PV system, as it mitigates extreme operating temperatures, resulting in improved electricity production in both summer and winter. Figure 9 and Table 2 present the availability factor of the PV/T system in relation to its nominal capacity.

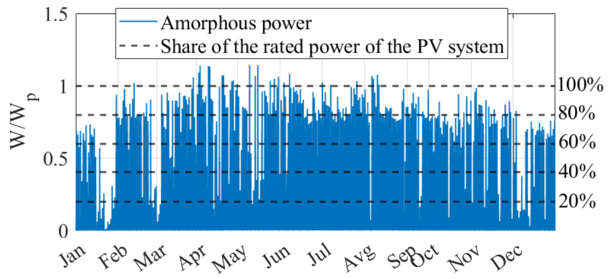

Fig. 9. Availability of the PV/T system depending on the share of nominal power

Table II. – Availability factor of the photovoltaic/thermal system

Share of nominal power [%]	Availability factor [%]
20	77,77
40	7,71
60	5,36
80	7,36
100	1,74

Table 2 and Figure 9 show that the PV/T system exhibits a relatively better-distributed availability factor. At 80 % of its nominal capacity, it achieves an availability factor of 7.36 %. The PV/T system occasionally reaches 100 % of its nominal capacity; however, the availability factor at this level is negligibly low, at only 1.74 %. The highest availability factor, 77.77 %, is observed at 20 % of the nominal capacity. This can be attributed to the lower degradation rate of the PV/T system, as it has been in operation for only four years, and the optimal tilt angle of the PV modules (45°), which enhances the efficiency of amorphous power production. Compared to the monthly production of the fixed PV system, the PV/T system achieves relatively higher amorphous power production during transitional months (February, October, and November).

C. Results for photovoltaic tracking system

Figure 10 presents the annual amorphous power production by the PV tracking system.

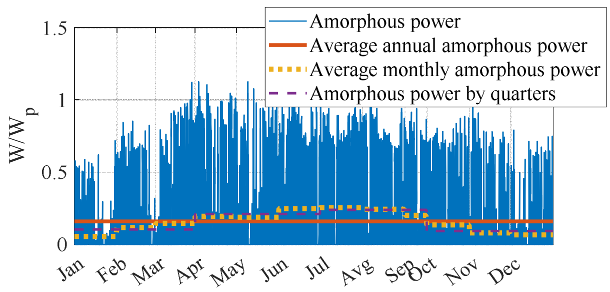

Fig. 10. Annually amorphous power of photovoltaic tracking system

Figure 10 shows that the average annual amorphous power was approximately 0,16 W/W$_p$, with the summer months (June, July, and August) standing out as the period with the highest production, where daily power peaks frequently exceeded 0,96 W/W$_p$. Production fluctuated during the transitional months (March, April, September, and October), with the average monthly power ranging between 0,16 W/W$_p$ and 0,21 W/W$_p$. The winter months exhibited lower average values, with an average quarterly power of 0,10 W/W$_p$, and daily power peaks during this period rarely exceeded 0,19 W/W$_p$, indicating limited solar irradiation. A quarterly production analysis confirms that the third quarter was the most favorable for electricity production, with the highest amorphous power recorded at 0,24 W/W$_p$. Electricity production from the PV tracking system also exceeded 1 W/Wp during the same periods as the PV/T system, confirming more favorable conditions than STC. Conversely, the lowest average quarterly amorphous power was observed in the first quarter, with a value of

0,10 W/W$_p$, which is still 0,06 W/W$_p$ higher than that of the fixed PV system during the same period in the analyzed year. Figure 11 shows the monthly amorphous power production of the PV tracking system.

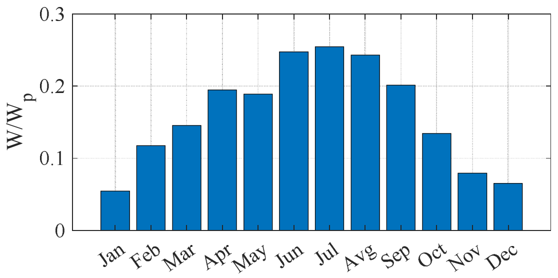

Fig. 11. Monthly amorphous power of photovoltaic tracking system

Figure 11 shows that the highest monthly amorphous power production of the PV tracking system occurred in July, with an average amorphous power of 0,25 W/W$_p$. The summer season, including June and August, represents the peak production period due to optimal summer conditions characterized by more stable weather patterns. In contrast, the spring months (April and May) demonstrate a gradual increase in production, with average amorphous power reaching 0,19 W/W$_p$ in May. A decline in electricity production is observed in September and October, where amorphous power values drop to 0,12 W/W$_p$. The lowest production values, as expected, are seen in December, January, and February, with the lowest average amorphous power recorded at just 0,05 W/W$_p$. The analysis confirms that the PV tracking system achieves its highest production in the summer months while maintaining relatively stable output even under less favorable conditions. Figure 12 and Table 3 present the availability factor of the PV tracking system in relation to its nominal capacity.

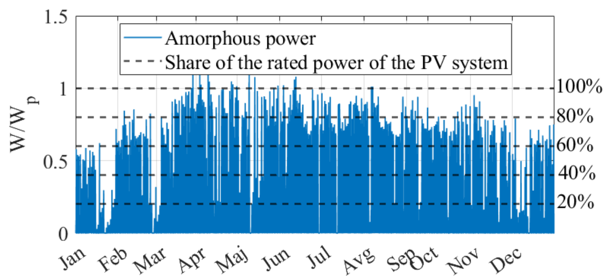

Fig. 12. Availability of photovoltaic tracking system depending on the share of nominal power

Table III. – Availability factor of photovoltaic tracking system

Share of nominal power [%]	Availability factor [%]
20	74,27
40	7,29
60	5,63
80	11,10
100	1,66

Based on the data presented in Table 3 and Figure 12, the analysis indicates that the PV tracking system achieves its highest availability factor at 20 % of its nominal capacity, reaching 74 %. As the nominal amorphous power increases, the availability factor declines rapidly but rises again slightly at 80% of the nominal capacity, reaching 11 %. The lowest value is observed at full nominal capacity, where the availability factor drops to 1.66 %. The analysis confirms that the PV tracking system, due to its ability to adjust orientation, offers higher availability than the fixed PV and PV/T systems.

D. Analysis of average amorphous power among PV systems

In this subsection, the power output of amorphous PV systems is analyzed on both monthly and annual scales. The average annual and monthly amorphous power outputs of each PV system within the same time period are presented in Figures 13 and 14.

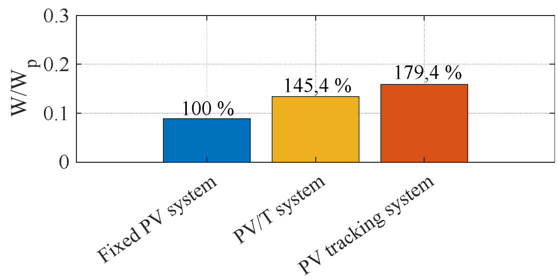

Fig. 13. Average annual amorphous power of PV systems compared to fixed PV system

From Figure 13, it is evident that the fixed PV system achieved the lowest average amorphous power output, at 0,089 W/W$_p$, while the PV tracking system recorded the highest average amorphous power output, at 0,16 W/W$_p$, representing a 79.4 % higher production over one year compared to the fixed PV system. The PV/T system achieved an average amorphous power of 0,13 W/W$_p$ over the year, corresponding to a 45,4 % higher production than the fixed PV system. Similar to annual electricity production, the PV tracking system also leads in average monthly amorphous power, as shown in Figure 14.

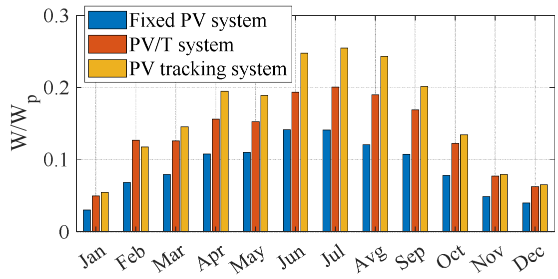

Fig. 14. Average monthly amorphous power of PV systems

Figure 14 shows that the PV/T system achieved a higher or nearly equal average amorphous power than the PV tracking system during winter (January, February, November, and December). Due to the fixed tilt and azimuth angles, the electricity production of the fixed PV system is noticeably lower, by approximately 55%, compared to the other two PV systems. Both the PV tracking system and the PV/T system adapt to increasing electricity production by tracking the sun and regulating PV/T module temperatures through cooling or heating. In contrast, the fixed PV system remains limited by its predetermined tilt and azimuth angles.

4. Conclusion

This paper focused on analyzing amorphous power output across three different PV systems: fixed PV system, PV/T system, and PV tracking system. Amorphous power serves as a key metric for evaluating the efficiency of these PV systems in utilizing available solar energy under varying weather conditions. The results demonstrated that the PV tracking system achieved the highest average annual amorphous power of 0,16 W/W_p, significantly outperforming the fixed PV system (0,089 W/W_p) and the PV/T system (0,13 W/W_p). The PV tracking system also showed the most balanced availability factor, reflecting its adaptability to changing weather conditions on an annual, quarterly, and monthly basis. However, integrating energy storage systems into these PV systems could enhance energy utilization by enabling the storage of surplus energy produced during periods of high operational hours (particularly in the second and third quarters) for use during morning demand peaks. This approach would reduce grid dependency and increase energy self-sufficiency, making these systems even more effective in sustaining energy demands. However, for a comprehensive assessment of the efficiency of such systems, it is also essential to examine the economic aspect, which is crucial in determining the viability of the investment. While the PV tracking system achieves higher energy production, its initial investment and maintenance costs can be significantly higher than those of a fixed system. Therefore, evaluating whether the additional energy production justifies the higher costs in the long run is important or if the cost-benefit ratio balances out with the fixed system is important.

Acknowledgment

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