JJEE

Volume 9 | Number 1 | March 2023 | Pages 31-41

Jordan Journal of Electrical Engineering

ISSN (print): 2409-9600, ISSN (online): 2409-9619

Homepage: jjee.ttu.edu.jo

Effect of Humidity on the Generation Capacity of Floating Solar Photovoltaic System

Anik Goswami*

University of Engineering and Management, Kolkata, West Bengal-700160, India
E-mail: anik91_go@rediffmail.com

Received: November 04, 2022 *Revised: December 11, 2022* *Accepted: December 16, 2022*

***Abstract*—** The continual search for new sources of renewable energy has resulted in the progress of floating solar photovoltaics (FSP). Since FSP system design and implementation are still in their early stages, efficiency, output and performance studies of FSP systems are not adequately acknowledged. FSPs operate on water; hence their performance differs from that of their equivalent land-based photovoltaics (LBP). The effect of water and humidity on the performance of FSP systems is not adequately discussed in the literature. Therefore, this paper investigates the effect of water - especially humidity - on the parameters and overall operation of FSP systems. For this purpose, an experiment is conducted with an FSP module, and the data obtained - over five months – are compared with similar LBP modules to determine the impact of water on the performance of the FSP system. The obtained results show that the FSP system is cooler than the LBP system by 7 °C. The relative humidity (RH) is found to be higher in the FSP system, and this impacted the performance ratio (PR) of the FSP system. Moreover, it is observed that - despite the fact that RH has an influence on the PR of the FSP system - the FSP system outperforms the LBP system in terms of energy output.

***Keywords*—** Floating solar PV; Performance ratio; Relative humidity; Power generation.

1. INTRODUCTION

The need for energy worldwide has been increasing steadily during the past decade due to population and industry growth. The majority of energy is derived from fossil fuel sources such as coal and petroleum. In addition to having a finite supply, fossil fuels impact the environment by releasing greenhouse gases [1]. The uncontrolled exploitation of conventional fuels has also resulted in the exhaustion of the earth's fossil fuel reserves. To address the issue of environmental preservation while meeting energy requirements, regulators are focusing on green and sustainable means of generating electricity. Sustainable energy sources are environmental friendly, clean, and green. Among all non-conventional sources, solar photovoltaic (PV) systems have become the most widely used due to their availability and simplicity.

PV systems generate the most energy of any renewable energy sources. PV systems produce no emissions and convert solar energy into electricity directly using PV cells [2]. Nearly, 25% of the world's energy requirements are predicted to be met by solar PV systems by 2030 [3]. To highlight PV power generation, decision-makers are offering a variety of incentives for grid-connected and independent PV systems. This has resulted in a massive increase in the use of PV systems in both the commercial and residential sectors. Srivastava et

* Corresponding author

Article's DOI: 10.5455/jjee.204-1667584023

al. [4] examined the various factors that must be considered while establishing solar utility systems. They proposed that temperature insolation and wind speed can be aptly calculated. A 1 MW PV system with the capacity to produce 1390 MWh of electricity yearly and cut CO_2 emissions by 818.7 tonnes was designed by Manoj Kumar et al. [5] and installed in Malaysia. The system supplied nearly 5% of the connected load. The variation in temperature and irradiance has an impact on the power production and functionality of PV modules. While conducting a feasibility assessment of PV systems, careful location selection is among the most crucial considerations. The amount of cloud cover in the sky also affects a solar power plant's production. Solar module partial shade is caused by the occurrence of dust, trees, and other barriers [6]. PV module efficiency is adversely affected by partial shading. Mostefaoui et al. [7] studied the problem of PV systems in the Sahara area being partially shaded. Due to partial shadowing, the PV modules' power production was lowered by 30%.

The power output from solar PV systems in real outdoor conditions is also affected by factors such as humidity, temperature, wind, and UV rays. A comprehensive review of PV system degradation was performed by de Oliveira et al. [8]. The authors found that moisture and humidity played an important role in degrading the efficiency of PV modules. The PV modules were mainly degraded due to moisture ingression and an increase in ionic paths. The power output of the PV module is also hampered by moisture and humidity-induced structural damage to the property of PV cells [9]. Han et al. [10] performed a study in China on PV modules working for 22 years. They found that due to moisture and humidity, the PV module has undergone corrosion of structures. Jordan et al. [11] also found that humidity is one of the major causes of delamination in PV modules. Thus, humidity plays an important role in degrading the performance of PV systems. Though the PV modules are tested for all weather-based corrosion before being commercially available, degradation still occurs in real outdoor conditions.

PV systems are ideal on broad and open land area to prevent shading effects from houses and other structures. For the establishment of major PV installations, a thorough examination of topography and the required amount of land is necessary. According to Kiesecker et al. [12], India needs between 55,000 km^2 and 125,000 km^2 of land to produce 175 GW of renewable energy and accordingly, 6000–10,000 km^2 of forest area and roughly 24,000–55,000 km^2 of agricultural land will be affected. In China, 1,832,000 m^2 of land was needed for the 50 MW PV system that Zhao et al. [13] designed. According to the findings, the cost of the land increased the plant's levelized cost of energy (LCOE) by 3.3%.

Solar photovoltaic systems have the greatest potential for energy production, but they also have certain drawbacks, including low dependability and efficiency [14]. The lack of available land is another significant drawback of PV power plants. Open land places are becoming more and more limited due to human growth. The design and implementation of utility-scale PV power facilities are further hampered by the rising land price. The cost of the land raises the plant's total cost, which in turn affects the LCOE. The installation of PV systems on water bodies is a practical alternative. Creating FSPs lowers the cost of land, which in turn lowers the capital cost of constructing a PV power plant. A 2 MW FSP system was designed by Singh et al. [15] to power the Indian city of Pondicherry. The proposed system has a yearly energy production capacity of 2,585 MWh. The initial 1,600,000 $ in expenses can be reclaimed in 6 years. The establishment of FSP systems on the reservoirs of hydroelectric power plants was suggested by Stiubiener et al. [16]. The authors discovered that the FSP systems can generate enough electricity to meet the local load using only 10% of the water's surface area. According to Lopes et al. [17] who carried out the FSP system's feasibility assessment in Brazil, the system produced 12 TWh of electricity utilizing a 70% coverage ratio.

Recent years have seen a rise in the importance of FSP systems, and policymakers are placing more emphasis on the construction of FSP power plants. The effectiveness and power production of large-scale FSP systems must be thoroughly understood before they can be developed. As FSP systems are floating over the water, the performance and power production are affected due to the cooling effect of water. The performance of FSP systems is also highly influenced by humidity because these systems are in contact with water. Literature survey investigating how dampness affects FSP modules is not widely available. This manuscript highlights the humidity analysis on the performance of FSP module. An experiment using FSP modules was carried out at Indian Institute of Technology (IIT), Dhanbad, India, to ascertain the impact of humidity. The performance of the experiment was recorded over the course of five months from January 2022 to May 2022. The experimental findings were contrasted with those of a related LBP system. The experiment's results were used to investigate how humidity affected the LBP system's performance output.

2. MATHEMATICAL ANALYSIS

The photovoltaic cell is a P-N junction that produces energy when exposed to sunlight. This is known as the photovoltaic effect. Through the use of electrical parameters and the single diode model [18], the physical characteristics of a PV module can be mathematically described. As depicted in Fig. 1, the solar module consists of a single current source, a resistance, and diodes linked in series and parallel with the load**.** The topography and weather of the area affect the PV cell's specifications. The effectiveness of the PV module is impacted by temperature and solar irradiation. Eqs. (1) to (5) are used to calculate the efficiency of the PV panel at any specific temperature (T) and irradiation (G) [19].

$$V_{FPV} = V_{FPV} + \mu_v(T - T_S) \quad (1)$$

$$I_{FV} = I_{FV}\left({}^{G}/_{G_S}\right) + \mu_i(T - T_S) \quad (2)$$

$$V_{mFPV} = V_{mpFV} + \mu_v(T - T_S) \quad (3)$$

$$I_{mFPV} = I_{pFPV}\left({}^{G}/_{G_S}\right) + \mu_i(T - T_S) \quad (4)$$

$$P_{mFPV} = V_{mFPV} \times I_{mFPV} \quad (5)$$

where V_{FPV} is the terminal voltage of PV module, T is the temperature, T_S is the temperature at standard test condition (STC), I_{FV} is the current, G is the irradiance, G_S is the irradiance at STC, μ_v is the voltage coefficient, μ_i is the current coefficient, V_{mFPV} is the maximum voltage, I_{mFPV} is the maximum current, and P_{mFPV} is the maximum power.

Performance evaluation of PV panels is crucial for PV power plant expansion and long-term functioning. The performance evaluation aids everyone in the distribution network in accurately estimating the project's size. The effectiveness of PV systems is influenced by three parameters; final yield, reference yield and performance ratio [20].

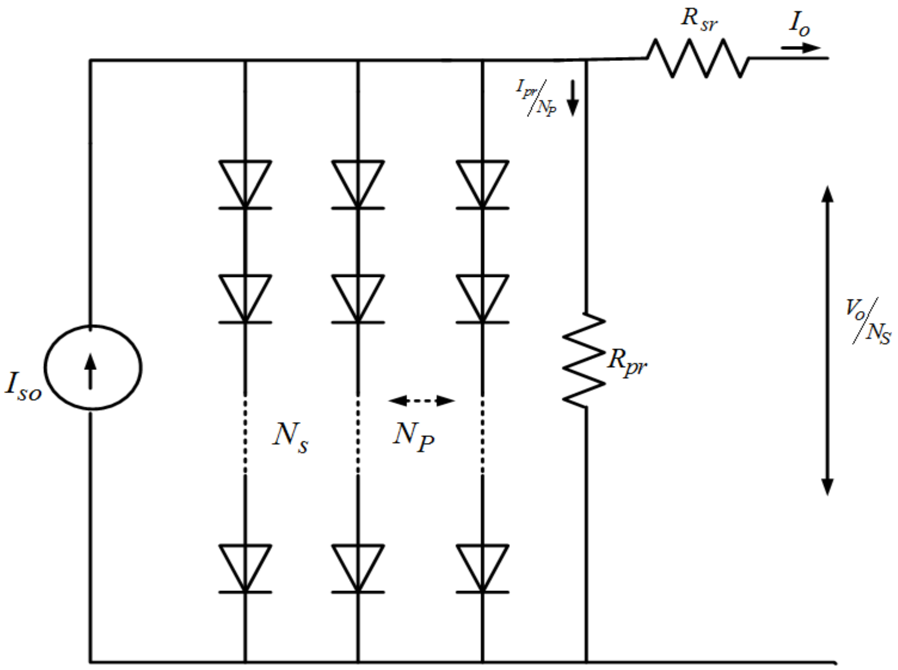

Fig. 1. Electrical model of the PV module.

Final yield (P_f) is the ratio of the quantity of energy that the PV system produces over a specific period of time (E_g) to the system's rated power output at STC.

$$P_f = \frac{E_g}{P_{mFPV}} \tag{6}$$

The solar insolation received on the PV panel's plane in relation to the reference irradiance of 1000 W/m² is known as the reference yield (P_r).

$$P_r = \frac{H}{G_s} \tag{7}$$

Performance ratio (PR) indicates the PV system's actual efficiency under actual outdoor settings. It indicates the entire amount of energy that the PV system can produce after accounting for all system losses. It also depicts the consequences on PV systems over the long term.

$$PR = P_f / P_r \tag{8}$$

Capacity utilization factor (CUF) is the actual amount of energy that a PV energy system produces over time, excluding the impacts of the environment. It is described as the proportion of the PV system's AC energy output (E_{ACFPV}) to the power produced when it is running at rated condition.

$$CUF = \frac{E_{ACFPV}}{P_{mFPV} \times 8760} \tag{9}$$

3. EXPERIMENTAL ANALYSIS

To ascertain the performance of the FSP module under actual outdoor circumstances, an experiment was carried out at the IIT, Dhanbad (23.8144° N, 86.4412° E). The LBP module was used in a similar experiment. An equivalent experiment was carried out with the LBP module. The experiment was conducted for five months, from January 2022 to May 2022. Table 1 presents the manufacturer parameters of the PV module.

Table 1. Manufacturer datasheet of the PV module.

Particulars	Value
Manufacturer	Waaree
Voltage	14.9 V
Short-circuit current	8.5 A
Peak voltage	12.16 V
Peak current	8.25 A
Efficiency	13.21 %
Cells per module	24
Resistance (parallel)	178.60 Ω
Resistance (series)	0.147 Ω

The module has an area of 1.03 m^2 and the voltage and power coefficients are; -0.3095 %/k and 0.0398 %/k, respectively. A digital anemometer is used to measure meteorological data such as wind speed. A solar power meter is used to measure solar irradiance. The current-voltage characteristics of the modules are determined using a solar power analyzer. An infrared thermometer is used to measure the ambient and module temperatures. Humidity is measured using a humidity sensor kept near the FSP system. The PV modules were installed with a south-facing orientation and a tilt angle of 24°, corresponding to the latitude of the location. Fig. 2 presents the experimental setup of the system.

(a) (b)

Fig. 2. Experimental setup: a) FSP system; b) LBP system.

4. RESULTS

Fig. 3 shows the day-to-day temperature fluctuation for both the FSP and the LBP modules. Since the air temperature is low in the morning, the temperatures of both modules are almost identical. The temperature differential between the modules is seen when the ambient temperature rises. The FSP module maintains a lower temperature than the LBP system. As water takes longer to heat due to its large specific heat capacity, the FSP module in contact with water stays cooler. During the time period of the experiment, it was observed that the FSP module is 7 °C cooler than the LBP system. The temperature of the LBP module is greater because heat is trapped in the soil and the panel.

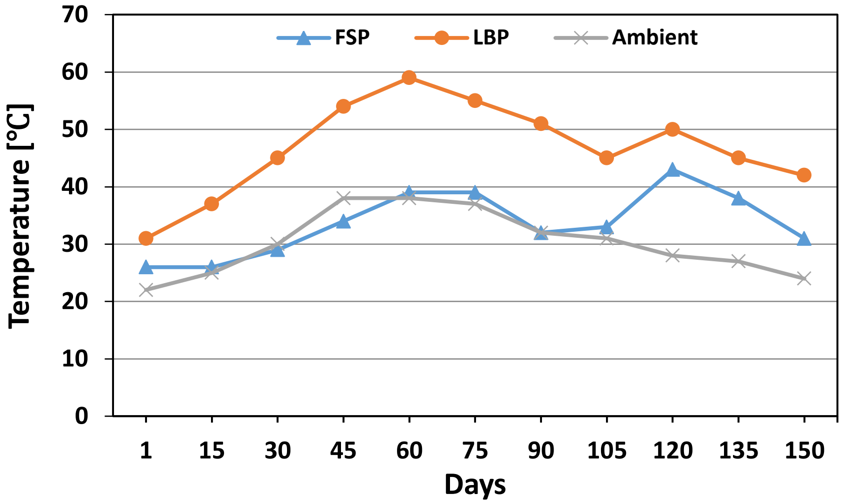

Fig. 3. Temperature variation of FSP and LBP modules.

4.1. Effect of Humidity

As FSP systems are floated over water, relative humidity (RH) plays an important role in judging the performance output of the system. Fig. 4 presents the comparison of the power output and the relative humidity between the LBP and FSP modules (E denotes experimental value and C denotes calculated values). The solar module generates power by converting solar insolation to electricity. During the winter, both modules produce the most electricity. From the experiment, it is seen that the FSP module has an average output of 79 W, whereas the LBP module has an average output of 69 W. Winter months feature low cloud cover, high solar irradiance, and cooler temperatures, all of which contribute to higher PV power production. The lower temperature of the FSP module leads to increased generation. The calculated values also follow a similar trend where the FSP power is higher than the LBP power. The average FSP and LBP power output calculated was 83 W and 74 W. The experimental power output of both systems is low as various environmental and operational losses are encountered while performing the experiment in real outdoor conditions.

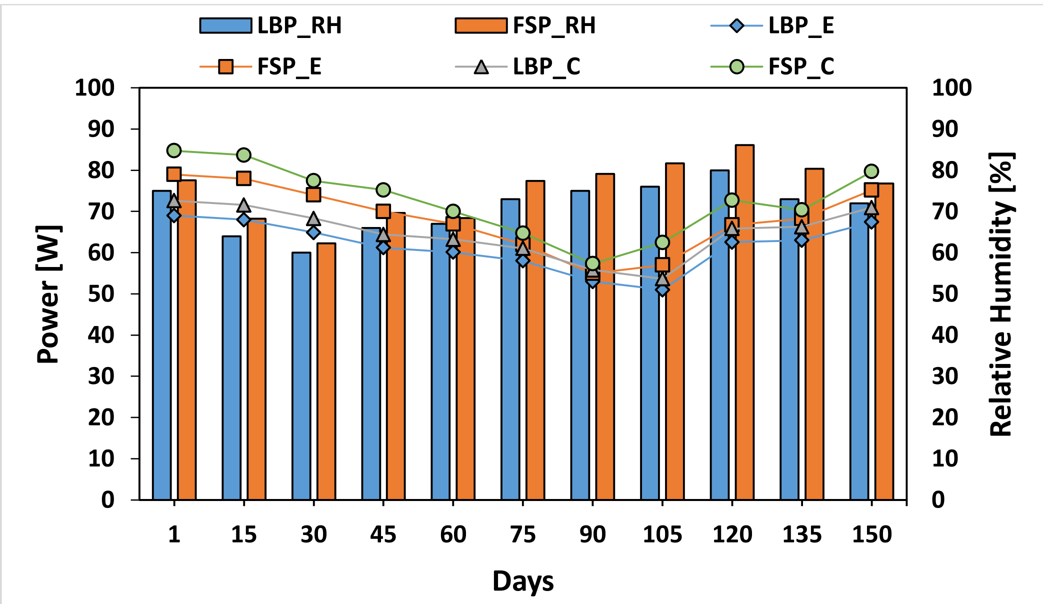

Fig. 4. Power output and relative humidity of FSP and LBP modules.

Again from Fig. 4, it is observed that the RH of the FSP system is higher than the similar LBP system as the FSP system is always in contact with water. In the initial days of the experiment (1-60 days), the average RH difference between the FSP and LBP systems was 3.2%. In the later part of the experiment, the RH difference increased to 5.6%. From the experiment, it can be seen that -over time- RH increases for the FSP system. To determine the effect of the increased RH on the performance of the FSP system, the PR of both systems are compared.

The comparison of the experimental and the calculated PR between the FSP and LBP systems is given in Fig. 5 (E denotes experimental value and C denotes calculated values).

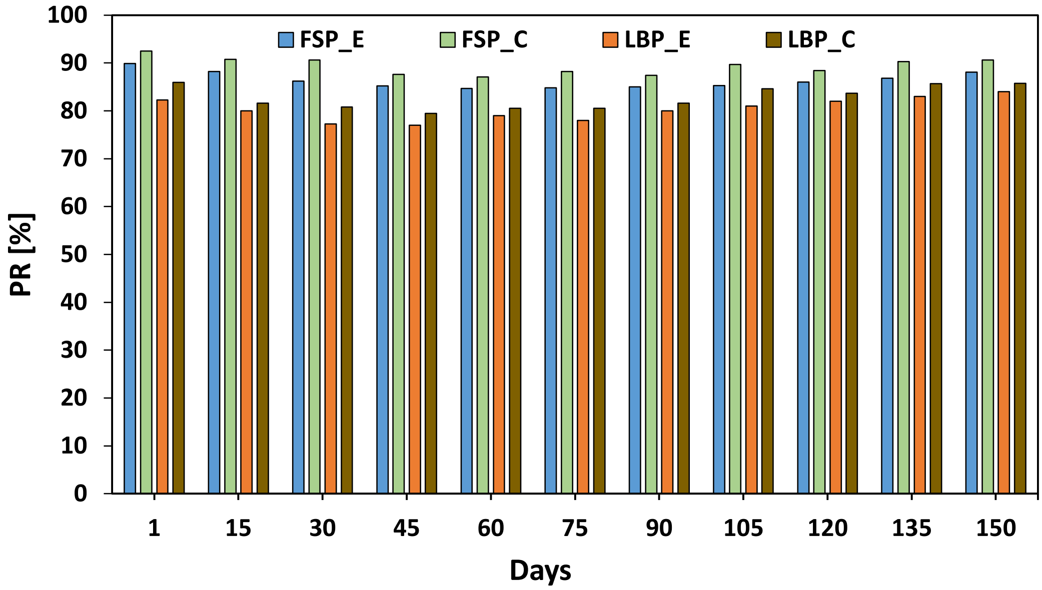

Fig. 5. PR of FSP and LBP modules.

It can be seen from Fig. 5 that the FSP module has higher PR than the LBP module due to lower module temperature. At the beginning of the experiment, the PR difference was near about 11% but as the experiment progressed, the PR difference reduced to 6.6%. The calculated PR difference between the FSP and LBP modules was around 8.2%. The FSP module's PR reduced over time and the main reason behind this is the increment in RH. Thus, it can be observed that humidity has a major impact on the performance of the FSP system. The degradation and PR loss of PV systems for previous works are given in Table 2 and compared with the present work.

Table 2. Performance loss of PV systems for previous and current works.

Area	Capacity	Performance Loss	Reference
Morocco	5.94 kW	6-8%	[21]
Northern India	200 kW	9.6%	[22]
India	5 MW	8%	[23]
Ghana	20 kW	8-13 %	[24]
Present System	100 W	FSP – 10.1% LBP – 8.2%	-

In the prior art, the effect of humidity on the performance of FSP systems is not discussed. This paper presents the effect of humidity on the power output of FSP systems. Comparing the previous literature, it is seen that the PR of land-based systems generally degrades by 8-10%. As seen in Table 2, a study conducted in Morocco on a 5.94 kW system showed that the PR loss is around 6 to 8%. Similarly study in India showed that the PR loss is 8-10%, while in Ghana the output of the PV system degraded by 13%. In this paper, the effect of humidity on the power output of the FSP system is studied. Results showed that the FSP system had undergone higher PR loss than the LBP system due to humidity

Though the PR of the FSP system has decreased due to humidity, the average PR of the FSP system is still higher than the LBP system, as seen in Table 3. Thus, it can be concluded that even though the FSP system's generation capacity is hampered due to RH, the overall performance is still higher than similar LBP system.

Table 3. Performance of investigated FSP and LBP systems.

Days	LBP		FSP	
	RH [%]	PR [%]	RH [%]	PR [%]
1	75	82.3	78	89.9
60	68.4	79	64.3	84.7
150	76.8	84	72	88.1

4.2. Factors Affecting PV Performance

To determine the effect of other parameters on the performance output of the PV system, the fill factor (FF) and the ideality factor (IF) of both the FSP and LBP systems were observed. Fig. 6 presents the variation of the fill factor over the period of the experiment. From Fig. 6, it can be observed that the average FF of the FSP module was 64.8% while the average FF for the LBP module was 65.3%. The FSP module displayed lower FF than the similar LBP module, and one of the main reasons is water-based degradation due to corrosion and humidity.

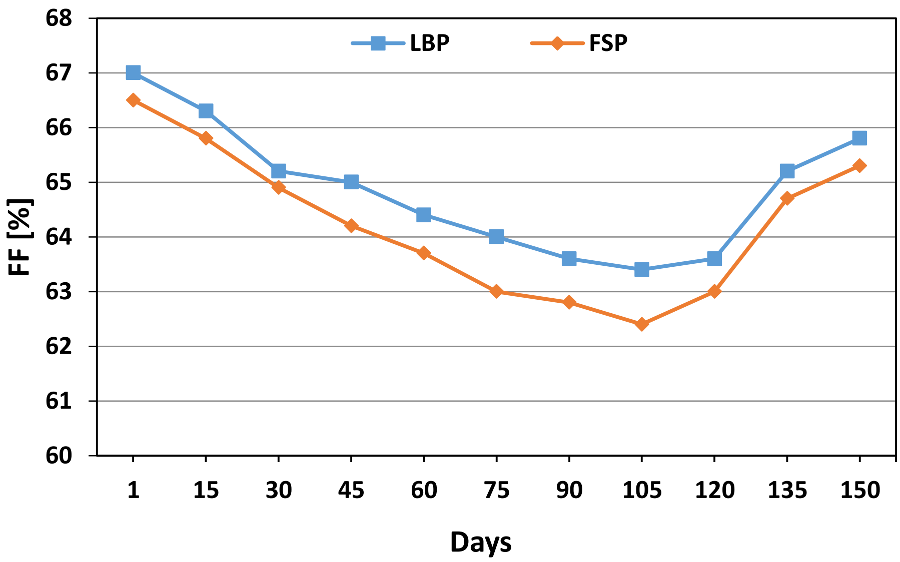

Fig. 6. Variation of FF in the time period of the experiment.

Next, the variation of the IF for both the FSP and the LBP modules is observed during the time period of the experiment and is given in Fig. 7.

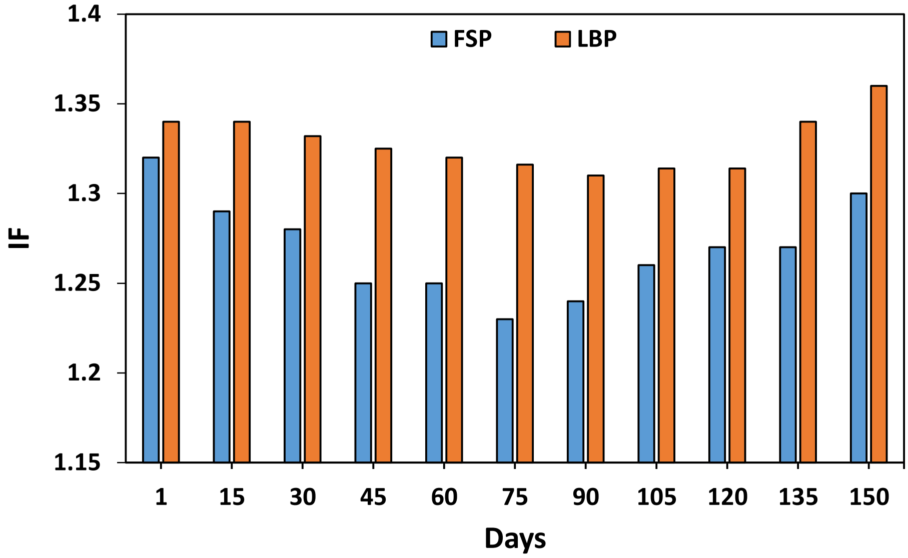

Fig. 7. Variation of IF in the time period of the experiment.

From Fig. 7, it is seen that the IF of the FSP module is lower than the IF of the LBP module. The IF of the FSP module was lower than the LBP module by nearly 4.6%. The lower IF is attributed due to the higher degradation of the FSP module. The FSP has higher degradation due to water-based corrosion and water ingression.

Though the FSP module displays higher degradation due to water-based corrosion, the power output of the FSP module is still higher than the LBP module due to the cooling effect of water.

5. CONCLUSIONS

The scarcity of open lands and rising land costs has resulted in the recent introduction of FSP systems for energy generation. The influence of relative humidity on the FSP module performance under real-world circumstances is investigated in this paper. To determine the effect of humidity, an experiment was performed at Indian Institute of Technology (IIT), Dhanbad for five months (January-May, 2022) with FSP and LBP modules. The results showed that the average temperature of the FSP module was lower than the similar LBP module by 7 °C as the FSP module was in contact with water. Due to lower temperatures, the power output of the FSP system is also higher. It was observed that the average output of the LBP module was 69 W while the output for the FSP module was 79 W. Similarly, the calculated power of the FSP system was also higher than the LBP system. Again, from the five months of the experiment, it was observed that the RH of the FSP is higher than the LBP system. Due to the effect of RH, the PR of the FSP system was also hampered. In the 150 days, the PR difference between the FSP and LBP systems had decreased by 6.6%, which denotes the loss in performance, especially for the FSP system. Other PV parameters such as FF and IF were also examined to have a better idea about the PV performance degradation. Results showed that the FF and IF of the FSP system were lower than the LBP system by 0.5% and

4.6%, respectively. The main reason behind the performance loss is the degradation of the FSP module due to moisture, water ingression and water-based corrosion. Though RH is impacting the PR of the FSP system, the power output of the FSP system is still better than the LBP system; thus, making the FSP system a feasible and green alternative to PV power production.

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