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PERFORMANCE MONITORING OF HIGH-EFFICIENCY MAXEON™ BASED SUNPOWER PV PLANT IN THE COMPOSITE CLIMATE OF INDIA

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ABSTRACT: The real-time performance monitoring of the photovoltaic system provides useful data to validate performance modeling techniques. This paper presents a case study of long-term performance monitoring of high-efficiency Maxeon™ based SunPower solar plant installed at the National Institute of Solar Energy, Gurugram, India. The paper focuses on the suitability of high-efficiency SunPower solar technology in the composite climate of India by the analysis of the Performance Ratio (PR) and Thermal normalized PR (PR_{STC}). The estimation of the thermal factor, as well as the spectrum factor, is also done in the paper. The average PR and the PR_{STC} found to be maximum in June and minimum in December month. PR of the SPV system correlates with the four seasons and temperature of the SPV module, as the key feature of assessment. It has been found out that the range of PR is 0.94-0.96 during winter, 1-1.01 during summer, and 0.95-0.98 during the post-monsoon and 0.93-0.98 during Monsoon.

KEYWORDS

SunPower, IEC 61724, Seasonal Performance, Performance Ratio, Degradation

Introduction

Many countries in the world deployed solar energy into their daily consumptions as an alternative to conventional energy sources (Kabir et al., 2018). The National Solar Mission (NSM) formerly recognized as Jawaharlal Nehru National Solar Mission (JNNSM) is an ingenuity of the Indian Government and State Governments to increase renewable source utilization, exclusively solar energy in India. The mission under the guidance of Ministry of New and Renewable Energy (MNRE) will approve a 3-phase tactic, first year (up to 2012-13) of the 12th Plan as Phase 1, the Phase 2 as the 12th Plan (2013–17) and Phase 3 is the 13th Plan (2017–22) (Purohit and Purohit, 2018). The original 22GW solar energy target by 2022 under the JNNSM has been recently revised to 100GW, which would require rapid development in solar installations throughout the state in the upcoming age. India increased its cumulative solar power generation (Ground Mounted) capacity by about 21892.42 MW on 31st July 2018 (Purohit and Purohit, 2018), (*https://mnre.gov.in, 2017*). To endure economic growth, to come out of the energy scarcity situation and ensure that energy is usable in every township and village, India must use its huge potential in a sunlight-based generation (Pandey et al., 2016).

The solar module is evaluated under Standard Test Condition (STC), i.e., air mass 1.5 spectral distributions, an irradiance level of 1000W/m^2 and the temperature of module is 25^{o}C at 00 angles of incidence as per standard IEC 61215 (Wohlgemuth and Kurtz, 2014, IEC 61215). An environmental parameter like wind, humidity, ambient temperature, irradiation, and spectrum constantly changes with time which influences the output of the SPV modules installed in the field (Macalpine et al., 2016). Due to these altered conditions, the performance of SPV modules by standard testing condition may not be accurate and precise. Outdoor real-time performance analysis of the SPV module is important to recognize the viability and usability of the SPV modules in the different climatic conditions (Singh et al., 2018). The impact of the amount of wind flow, temperature variation, and electrical configuration over the functioning of building-integrated (BIPV) and building-applied (BAPV) SPV modules has been examined using experiments based on wind tunnel. The experiment has been done for four air gap thicknesses varying from 0cm (BIPV) to 5.5cm (BAPV) and five freestream approaching wind speeds from 1 to 5 ms^{-1} using with an inclined 3×2 SPV module. In the assessment, the BAPV module with the thickest air gap (5.5cm in this study) has been the optimum performance arrangement (Goossens et al., 2018). Gaglia et. al., 2017 has been presented a relevant data collection, utilizing a multi-crystalline PV array at the real-field experimental facility at the north of Athens. The SPV efficiency has been found out to be approximately 18% lesser than that under standard laboratory test conditions, under similar operating conditions (Gaglia et al., 2017). Balaska et al., 2017 has been done a performance evaluation of mono-crystalline heterojunction with an intrinsic thin layer (HIT), copper indium selenide (CIS), the tandem structure of amorphous silicon, microcrystalline silicon (a-Si_mc-Si), multi-crystalline and mono-crystalline back contact. It has been found out that a-Si_mc-Si and HIT performed much superior than the other SPV technologies. The annual average daily performance ratio of the a-Si_mc-Si module has been found out to be around 1.55% higher in comparison to HIT module and 2.04% in comparison to CIS module (Balaska et al., 2017). Singh et al., 2016 has been estimated the uncertainty in the measurements of power matrix values using indoor test conditions as per IEC 61853-1. During the experiment, it has been found out that the spectrum of the light source is changing with irradiation (Singh et al., 2016). Singh et al., 2015 has been done an analysis of the impact of series resistance on electrical parameters of HIT module. By increasing the series resistance of the modules, there is a decrement in the fill factor, power and Isc (Singh et al., 2015).

From the above literature review, a comprehensive investigation of the performance monitoring of SPV system needed to be done for the forecasting and modeling of solar power plant system. It is also beneficial in the future to improve the power plant scheme development and the demand side management. Dependability analysis of the SPV module enables us to guarantee the commercial feasibility at a specific position. The performance of the SPV system, installed in different climatic zones is a function of the environmental and native conditions. Unless a detailed examination is carried out for the site, it is difficult to foresee the performance and energy production competence. It becomes important to carry out outdoor field test and scientific investigation of the statistics for the site-specific power plant.

The present work demonstrates the real-time performance monitoring of high-efficiency Maxeon™ based SunPower SPV plant in the composite climate of India. The aims are to evaluate the suitability of high-efficiency SPV technologies under Indian climatic conditions. Performance of Maxeon™ based SunPower technology SPV plant in the composite climate zone of India has been analyzed by performance ratio (PR), the spectrum and thermal normalized PR (PR_{STC}). The varying performance based on the monthly data has been also presented in the paper.

Materials & Methods

The 3.2 Kwp SunPower system is installed at the National Institute of Solar Energy, Gurugram, India (Latitude 280 37 N, Longitude 7704 E). The average ground altitude is 217 meters (712 ft) above sea level. Gurugram encounters a monsoon-influenced Composite climate by the Köppen climate classification (Singh et al., 2018).

Materials

To examine the real-time outdoor conditions, an experimental test-bed facility of high-efficiency SunPower array containing 5 SPV modules at NISE, Gurugram is shown in Fig 1.

The test-beds are installed for testing, performance evaluation, and validation of suitable SPV module for a specific climatic situation. The details of the I-V tracer along with the temperature and radiation sensor accuracy is provided in Table 1.

Model	PVPM2450C
Voltage DC (V)	Accuracy ± 2% for voltage
Current DC (A)	Accuracy ± 2% for current
Temperature	-40°C - +120°C with pt1000
Irradiance	Model: SOZ-03, 0-1300 W/m^2

TABLE 1. TI-V tracer along with the temperature and radiation sensor accuracy

FIGURE 1. A testbed of The Maxeon™ based SunPower technology along with I-V curve tracer PVPM

The array consists of five SPV modules connected in series with each other, an I-V tracer for continuous data logging of electrical output, along with a reference cell having same tilt with the tilt of modules to measure in-plane global radiation and a temperature sensor attached to the back of the module to record the module temperature data. Each SPV module comprises 96 cells having single cell area of 156.25 sq.mm. The SPV modules specification are given in Table 2.

Modules Parameter	Specifications
Technology Make	SunPower Technology
No. of solar cells in series	96
Maximum power (W)	327
Maximum voltage (V)	54.7
Maximum current (A)	5.98
Open circuit voltage (V)	64.9
Short circuit current (A)	6.46
Temperature coefficient of voltage	- 176.6 mV/K
Temperature coefficient of current	3.5 mA /K
The temperature coefficient of power	- 0.38 %/K
Cell Efficiency	22.5%

TABLE 2. Technical specification of the Maxeon™ based SunPower SPV module

Electrical and environmental data are recorded at every single 10 second interval of time using four probe connectors. The spectrum data is calculated using The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) software provided by the National Renewable Energy Laboratory (NREL). All modules are cleaned regularly to avoid dust deposition or other dirt like the bird dropping effect on the output.

Methods

To analyze the performance monitoring of SPV plant, performance indicators i.e. performance ratios, reference yield, and final yield are calculated as endorsed in IEC 61724 standard (IEC 61724).

Performance monitoring of the SPV system

The International Electro-Technical Commission (IEC) printed the international standards in 1998 which described parameter for the performance monitoring. As well-defined in IEC 61724 the performance ratio specifies the total impact of failures on the PV system rated due to array temperature, inadequate utilization of the radiation and component inadequacies or breakdowns. The final yield of the PV module is expressed as the ratio of the final or actual energy output of the to the total power of the SPV module under STC. The expression of the final yield is expressed as,

$$\text{Final Yield } (Y_f) = \frac{\text{Final Energy Output (kWh)}}{\text{Maximum Power},_{STC}\ \text{(kW)}} \quad (1)$$

The reference yield (Y_r) is described as the ratio of total in-plane irradiance to that of the irradiance in a unit area defined under STC and is expressed with below;

$$\text{Reference Yield } (Y_r) = \frac{\text{Total in-plane Irradiance} \left(\frac{kWh}{m^2}\right)}{1000 \left(\frac{kW}{m^2}\right)} \quad (2)$$

The SPV reference irradiance at the STC is equivalent to the 1000 W/m^2. From the above equation, the reference yield is a site-specific factor. The performance ratio (PR) is defined as the ratio between the final yield of the system (Y_f) to the reference yield (Y_r). PR has been used for the comparative study and performance monitoring of the SPV system in different climatic zones. The expression of the PR is as follows,

$$\text{Performance Ratio (PR)} = \frac{\text{Final Yield } (Y_f) = \dfrac{\text{Final Energy Output (kWh)}}{\text{Maximum Power}_{STC}\text{ (kW)}}}{\text{Reference Yield } (Y_r) = \dfrac{\text{Total in-plane Irradiance } \left(\frac{kWh}{m^2}\right)}{1000 \left(\frac{kW}{m^2}\right)}} \tag{3}$$

For simplification of the understanding, it may be written as,

$$\text{Performance Ratio (PR)} = \frac{\text{Final Yield } (Y_f)}{\text{Reference Yield } (Y_r)} \tag{4}$$

The PR offers the part of the yield of an SPV system in outdoor climatic circumstances concerning the yield at STC normalized input solar radiation. In this manner, the PR has been standardized to PR at STC (PR) with module temperature using the thermal factor (T_f) and spectrum using spectrum factor (S_f).

$$T_f = \frac{1}{1 + \gamma_p (T_m - T_{STC})} \tag{5}$$

Where T_f is a thermal factor, T_m is the temperature of the module, T_{STC} is a standard test condition temperature and γ_p is the temperature coefficient of power at the maximum power point of SPV the module.

$$S_f = \frac{\int \zeta STC(\lambda) . SR(\lambda) \,/ \int \zeta(\lambda) . SR(\lambda) d\lambda}{\int \zeta STC(\lambda) . d\lambda \,/\, \zeta(\lambda) d\lambda} \tag{6}$$

Where S_f is spectrum factor, ζSTC is standard spectrum at STC, ζ is the solar spectrum of the place, SR is the relative spectral response of the SPV technology, and λ is the wavelength (nm). The PR_{STC} of SPV module can be determined by

$$PR_{STC} = PR \times T_f \times S_f \tag{7}$$

The methodology followed for the data collection, filtration and for the calculation of the performance ratio and thermal normalized performance ratio is shown in Fig 2.

Results and Discussion

The experimental data have been collected for one complete year. The data have been filtered on the basis of a predetermined factor for the calculations presented in Fig. 2. Based on the experimental data, the performance ratio, thermal factor, spectrum factor and the normalized performance ration has been calculated using IEC 61724.

Using the thermal factor and spectrum factor the normalized performance ratio has been calculated for twelve months. The difference in the PR between the PR_{STC} has been calculated and shown in Fig. 3, and it has been found out that PR_{STC} is higher than the PR due to normalization of the thermal effects occurring over the module surface. The experimental results reveal that the performance of the SunPower modules is stable throughout the year, however, lowest performance has been observed in the may due to the high temperature. The highest performance is observed during the winter season when the surface of the SPV module is low.

From Fig. 3, the year PR of the SunPower is higher than the 0.90 which is quite good for outdoor field-based technology. The most constant PR values are 0.965 on a yearly basis. There is a significant impact of the irradiance and the temperature over the solar PV plant, however, the results presented here were normalized in case of PR_{STC}.

The calculated data has been divided into four seasons, i.e. winter from mid-November to mid-March, summer from mid-March to end-June, and the monsoon from starting-July to mid-September, post-monsoon from mid-September to mid-November. The performance ratio of each season has been shown in Fig. 4.

The performance ratio has been found out that in the range of 0.94-0.96 during winter, 1-1.01 during summer, and 0.95-0.98 during Post-monsoon and 0.93-0.98 during Monsoon. Change in the module temperature gained by the SPV modules in a different season is one of the key reasons for a varying performance over a year.

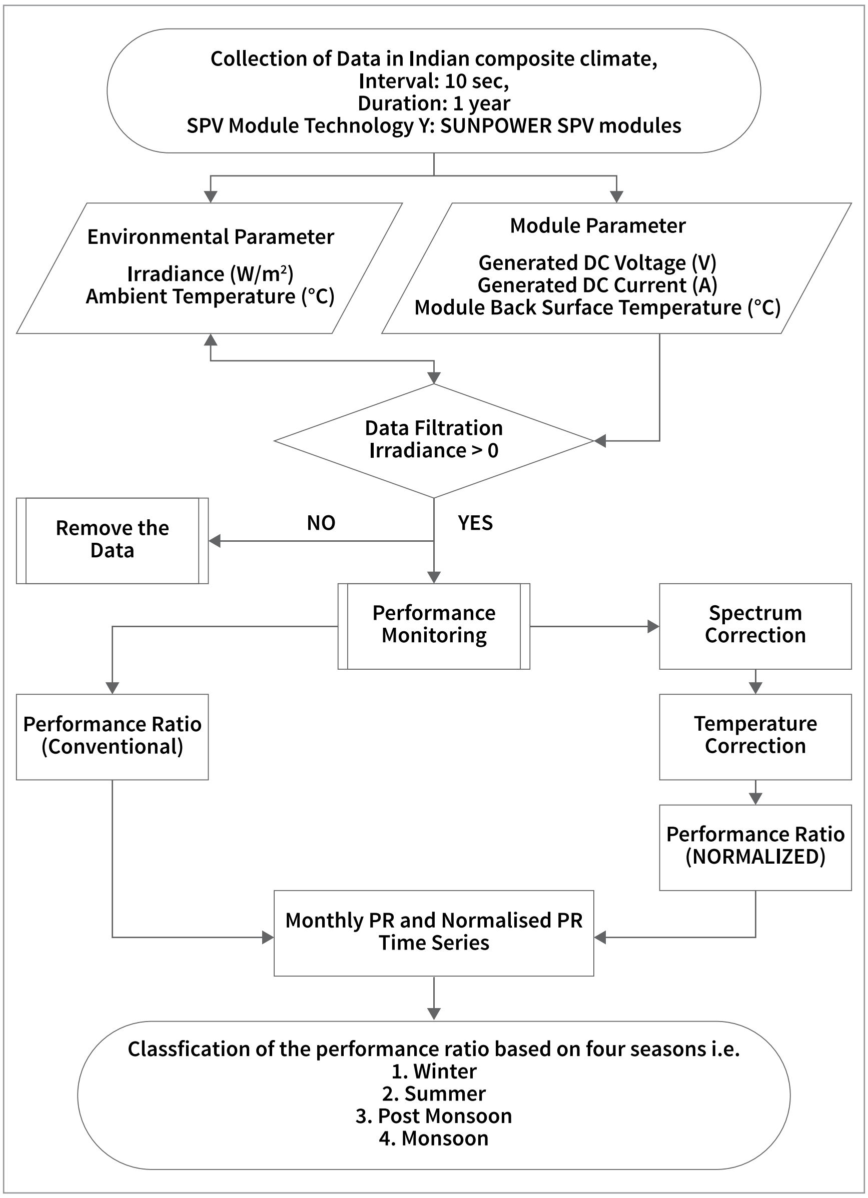

FIGURE 2. Flow-chart of the procedure followed for the performance monitoring

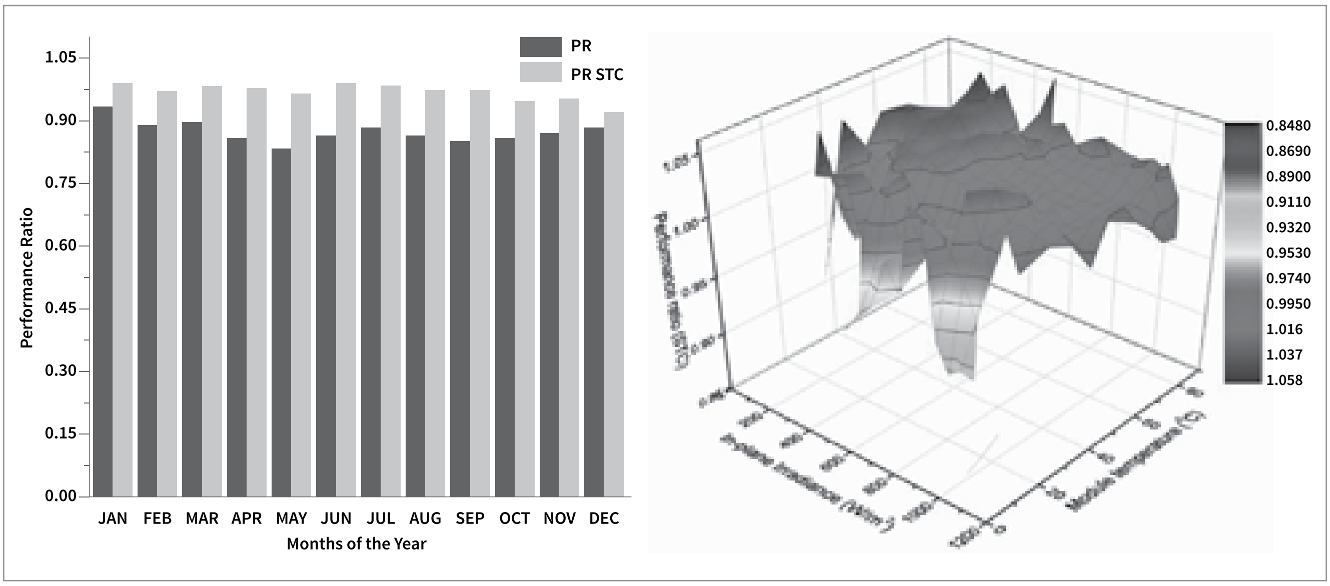

FIGURE 3. (a) Monthly average daily performance ratio and (b) Yearly performance ratiomonitoring

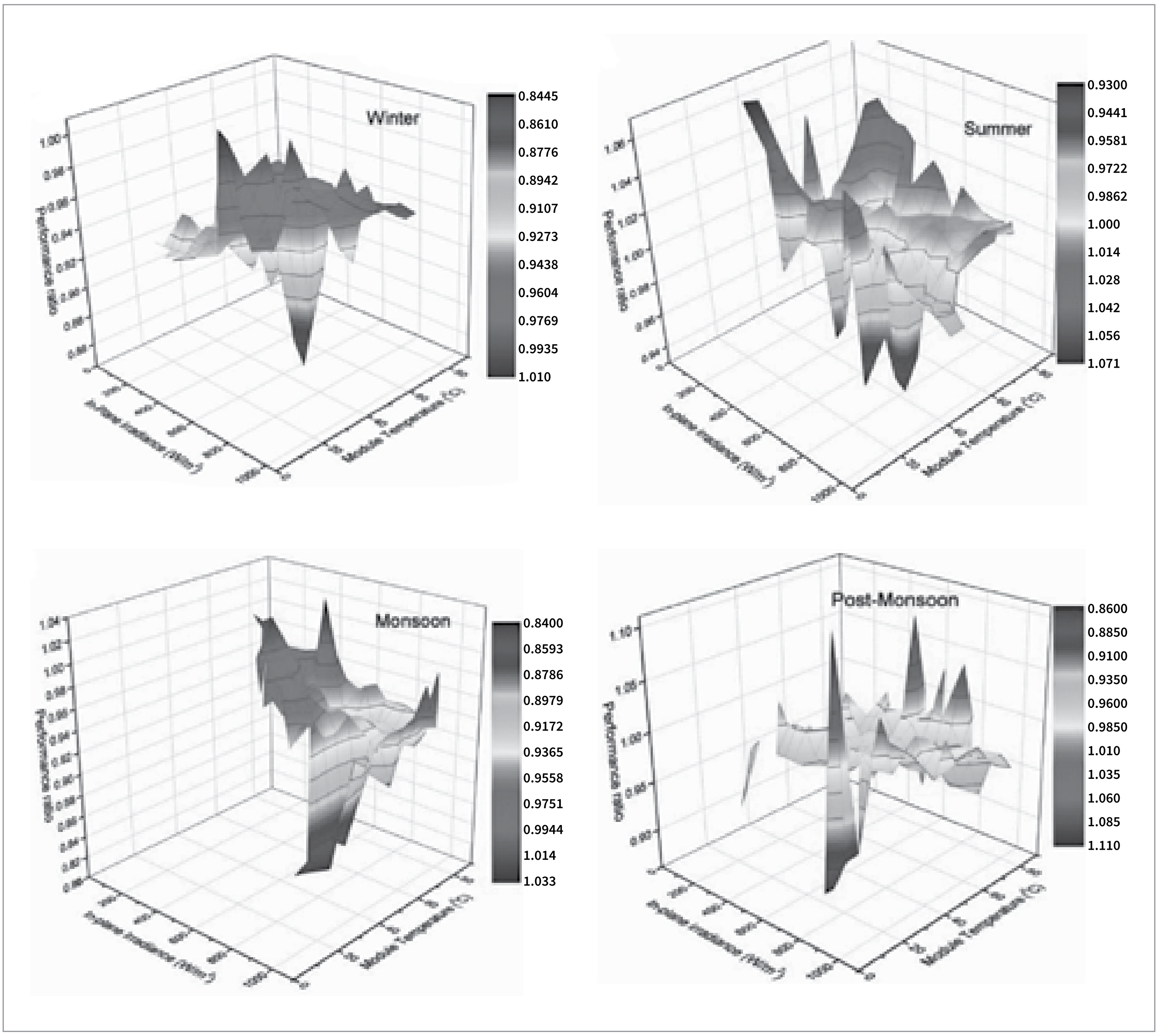

FIGURE 4. Seasonal variations in the performance ratio of the SunPower SPV Plant

Conclusion

Energy generation and utilization of the renewable sources, mainly SPV system would result in a positive impact on the environment. The paper focuses on the suitability of high-efficiency SunPower solar technology in the composite climate of India based on the Performance Ratio (PR), Thermally normalized PR (PR_{STC}). The high efficiency of the plant has been observed in the higher range of irradiance. The SunPower technology is well suited to the climatic zone having normal to high irradiance and temperature.

The analysis of the SPV performance under outdoor field conditions takes into account an ideal evaluation and forecasting the energy output. The proposed associations take into account the seasonal variation of irradiance and temperature that can be used to estimate the performance of SPV power plant under composite climate, thus reducing the probability of over or under sizing the plant design.

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