RESEARCH PAPER

Result-Based Comparative Analysis of Floating and Fixed-Mount Solar Photovoltaic Power Plants

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Abstract- The global solar photovoltaic (PV) sector has experienced unprecedented growth over the past decade and has emerged as a key pillar of the global energy transition. Decreasing technology costs, supportive government policies, climate commitments, and rising electricity demand have made solar PV the fastest-growing power generation technology globally. According to the International Energy Agency, solar PV installations have consistently outpaced all other electricity generation sources since 2019, signaling a decisive shift towards clean energy systems. By 2024, global solar power plant installed capacity will exceed 1.6 terawatts (TW), up from less than 40 GW in 2010. This rapid growth is primarily driven by China, which accounts for more than a third of global solar power capacity. Other major contributors include the United States, India, Germany, Japan, and Australia. Emerging economies in Southeast Asia, the Middle East, Africa, and Latin America are also rapidly expanding their solar energy portfolios, leveraging abundant solar resources to improve energy access and reduce dependence on fossil fuel imports.

Keywords- Global Energy Transition, Decreasing Technology Costs, Supportive Government Policies, Climate Commitments, Rising Electricity Demand, Solar PV Installations.

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.I. INTRODUCTION

One of the most important factors contributing to the growth of solar energy is the significant reduction in system costs. The global average price of large-scale solar power plants has fallen by approximately 85% since 2010, primarily due to cost reductions resulting from mass production, improved cell efficiency, advances in manufacturing processes, and competitive supply chains. According to the International Renewable Energy Agency, solar energy is now the cheapest source of electricity generation in many regions of the world, even without subsidies [1,]. Technological innovations are continually improving the performance and reliability of solar energy. Advances in bifacial modules, passivated emitter and rear contact (PERC) cells, heterojunction technology (HJT), and perovskite-based tandem cells are achieving conversion efficiencies exceeding 25% at commercial scale. Additionally, digital monitoring, artificial intelligence-based forecasting, and smart inverters are improving grid integration and operational efficiency. Floating solar PV, building-integrated PV (BIPV), and agrivoltaic systems are further expanding deployment opportunities by optimizing land and water use. From a policy perspective, solar energy plays a key role in national and international decarbonization strategies. Many countries have aligned their solar energy deployment targets with net-zero emissions targets set for 2050 or earlier. The European Union's Green Deal, India's National Solar Mission, and the US Inflation Reduction Act have significantly accelerated investment in solar energy production and deployment. Furthermore, the use of solar energy combined with battery energy storage systems (BESS) is rapidly increasing to address power vagaries and enhance grid stability. Despite rapid progress, challenges remain. Grid congestion, land availability, supply chain centralization, module recycling, and financing constraints in developing countries require coordinated approaches and technical solutions. However, projections from the World Energy Outlook indicate that solar PV will account for the largest share of global electricity generation capacity by 2030.

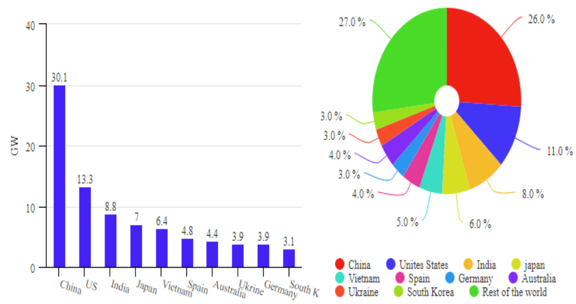
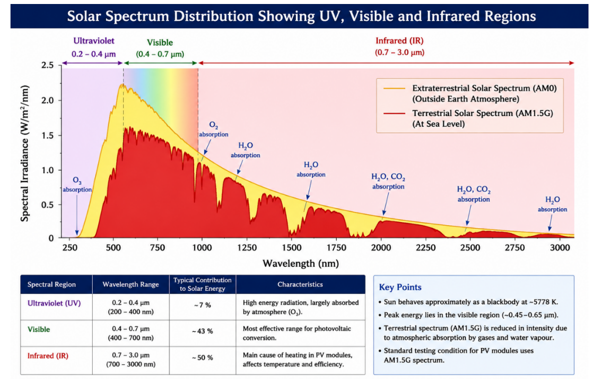


Figure 1- Global Solar Photovoltaic (PV) installed capacity and their percentage

II. EFFECT OF LOCATION AND SEASONAL SOLAR PATH ON PV PERFORMANCE

The geographical location of a solar PV installation significantly affects its thermal and electrical performance. Latitude determines solar path variation, solar altitude angle, and daylight duration, thereby influencing the quantity of solar radiation available for photovoltaic conversion. Seasonal variation alters: irradiance intensity, solar incidence angle, atmospheric conditions, humidity, andambient temperature. These parameters collectively influence photovoltaic operating temperature and electrical behavior. In Fixed Ground Mount systems, module temperature generally increases significantly during high irradiance summer conditions because heat dissipation occurs primarily through natural air convection. Elevated module temperature reduces open-circuit voltage and overall conversion efficiency. In contrast, Floating Solar PV systems experience enhanced cooling due to the presence of the underlying water surface. Water-induced evaporative cooling and convective heat transfer reduce module operating temperature, thereby improving voltage stability and electrical efficiency under identical irradiance conditions. Consequently, the thermal response of floating solar PV systems differs significantly from conventional ground-mounted systems, particularly during peak summer conditions. Therefore, accurate solar radiation and solar geometry modeling become essential for understanding seasonal performance variation and establishing reliable comparative analysis between Fixed Ground Mount and Floating Solar PV systems.



Spectral Region	Wavelength Range	Typical Contribution to Solar Energy	Characteristics
Ultraviolet (UV)	0.2 – 0.4 μm (200 – 400 nm)	~7 %	High energy radiation, largely absorbed by atmosphere (O_3).
Visible	0.4 – 0.7 μm (400 – 700 nm)	~43 %	Most effective range for photovoltaic conversion.
Infrared (IR)	0.7 – 3.0 μm (700 – 3000 nm)	~50 %	Main cause of heating in PV modules, affects temperature and efficiency.

Figure 2- Solar Spectrum Distribution Showing UV, Visible and Infrared Regions

III. RESEARCH METHODOLOGY

(i) Semiconductor Theory- Photovoltaic cells are fabricated using semiconductor materials capable of converting incident solar radiation into electrical energy. A semiconductor is a material whose electrical conductivity lies between that of a conductor and an insulator. The electrical properties of semiconductors can be controlled through the process of doping, where small quantities of impurity atoms are intentionally introduced into the crystal structure. The most widely used semiconductor material in photovoltaic technology is silicon due to its: suitable band-gap energy, high abundance, thermal stability, mechanical durability, and mature manufacturing technology.

(ii) p–n Junction Formation and Photovoltaic Effect- At the junction between p-type and n-type semiconductor layers, electrons from the n-region diffuse toward the p-region while holes from the p-region diffuse toward the n-region. This carrier diffusion creates a depletion region near the junction, where immobile ions generate an internal electric field. The internal electric field prevents further carrier diffusion and plays a critical role in photovoltaic energy conversion. When solar radiation falls on the photovoltaic cell, incident photons with energy greater than the semiconductor band-gap energy excite electrons from the valence band to the conduction band, thereby generating electron–hole pairs. The built-in electric field across the depletion region separates these charge carriers: electrons move toward the n-region, and holes move toward the p-region.

(iii) Electron–Hole Generation Mechanism- The generation of electron–hole pairs depends primarily on: incident solar irradiance, spectral distribution of sunlight, semiconductor band-gap energy, and cell temperature. When photons possessing sufficient energy strike the semiconductor surface, electrons absorb photon energy and transition from the valence band to the conduction band. This process leaves behind vacancies known as holes. The number of generated charge carriers increases with increasing solar irradiance, resulting in higher photovoltaic current generation. Therefore, the short-circuit current of a PV cell is approximately proportional to incident irradiance. However, not all generated charge carriers contribute to electrical power generation. Some carriers recombine before reaching the external circuit, reducing conversion efficiency.

(iv) Recombination Losses in Photovoltaic Cells- Recombination losses occur when generated electrons and holes recombine before contributing to useful electrical current. Recombination significantly reduces photovoltaic efficiency and is one of the major limitations affecting solar cell performance. The primary recombination mechanisms include:

- Surface Recombination
- Bulk Recombination
- Junction Recombination

(v) Temperature Coefficient and Thermal Effects- Photovoltaic electrical characteristics are highly sensitive to operating temperature. As module temperature increases, semiconductor carrier activity increases, resulting in: reduction in open-circuit voltage, increased recombination losses, and reduced conversion efficiency. The effect of temperature on photovoltaic performance is represented using temperature coefficients. The short-circuit current temperature dependence is expressed as:

$$I_{PH} = [I_{SCr} + K_i(T - T_r)] \times \frac{G}{G_r}$$

Where:

I_{PH}= Photo-generated current
I_{SCr}= Reference short-circuit current
K_i= Temperature coefficient of current
T= Cell temperature
T_r= Reference temperature
G= Solar irradiance
G_r= Reference irradiance

An increase in temperature causes only a slight increase in current but produces a significant reduction in voltage, thereby reducing overall power output. In Fixed Ground Mount systems, module temperature rises considerably under high irradiance conditions due to limited heat dissipation. In contrast, Floating Solar PV systems benefit from evaporative and convective cooling from the water surface, resulting in lower module temperature and improved electrical performance.

Material	**Band Gap (eV)**	**Efficiency Range**	**Advantages**	**Limitations**
Mono-crystalline Silicon	1.12	High	High efficiency	Higher cost
Poly-crystalline Silicon	1.10	Moderate	Lower cost	Lower efficiency
Thin Film CdTe	1.45	Moderate	Lightweight	Toxicity concerns
Amorphous Silicon	1.7	Low	Flexible	Lower stability

Table 1- Comparative Characteristics of Common Photovoltaic Semiconductor Materials

IV. PROPOSED MATHEMATICAL MODELING OF PHOTOVOLTAIC SYSTEM

The electrical performance of photovoltaic (PV) systems is governed by nonlinear relationships between solar irradiance, operating temperature, semiconductor behavior, and environmental conditions. Accurate mathematical modeling is therefore essential for predicting photovoltaic output characteristics, analyzing thermal effects, evaluating seasonal performance variation, and establishing comparative relationships between Fixed Ground Mount (FGM) and Floating Solar Photovoltaic (FSPV) systems. In conventional photovoltaic studies, electrical output is often estimated using simplified irradiance-based models without adequately considering thermal interaction, environmental dependency, and dynamic operating conditions. Such simplified approaches are insufficient for realistic comparative performance analysis because photovoltaic systems are strongly influenced by temperature variation, humidity, wind conditions, and mounting configuration. In particular, Floating Solar PV systems exhibit different thermal behavior due to water-induced cooling effects, resulting in significant variation in electrical characteristics relative to conventional ground-mounted installations. To address these limitations, the present research develops an integrated thermo-electrical mathematical modeling framework capable of correlating irradiance, temperature, humidity, wind interaction, and mounting conditions with photovoltaic output characteristics. The proposed methodology combines conventional photovoltaic electrical modeling with newly developed thermal difference and unified performance relationship models for comparative techno-commercial analysis. The mathematical formulations presented in this section constitute the analytical foundation for: thermal performance evaluation, electrical output prediction, relationship fitting, optimization analysis, and statistical validation presented in subsequent chapters.

Symbol	Parameter	Unit
G	Solar irradiance	W/m²
T	Module temperature	°C
H	Relative humidity	%
V_w	Wind velocity	m/s
P	Output power	W
R_s	Series resistance	Ω
R_{sh}	Shunt resistance	Ω

Table 2- Parameters Used in Mathematical Modeling

V. PERFORMANCE-BASED COMPARATIVE ANALYSIS OF FIXED-GROUND-MOUNTED AND FLOATING SOLAR PHOTOVOLTAIC PLANTS

The analysis of I–V and P–V characteristics forms an essential foundation for comparative thermo-electrical evaluation between Fixed Ground Mount and Floating Solar PV systems. The comparative analysis of these characteristics provides the basis for: thermal performance evaluation, optimization modeling, regression fitting, and techno-commercial assessment presented in later chapters.

Parameter	Fixed Ground Mount	Floating Solar PV
Module Temperature	Higher	Lower
Open-Circuit Voltage	Lower at high temperature	Improved stability
Thermal Losses	Higher	Reduced
Fill Factor	Moderate	Improved
Power Output	Reduced under thermal stress	Higher stability
Seasonal Performance	Temperature sensitive	Better summer performance

Season	FGM Performance	Floating PV Performance
Summer	Higher thermal losses	Improved cooling and efficiency
Winter	Improved voltage	Stable performance
Rainy Season	Reduced irradiance response	Better thermal stability

Table 3- Seasonal Comparative Performance Trend of FGM and FSPV Systems

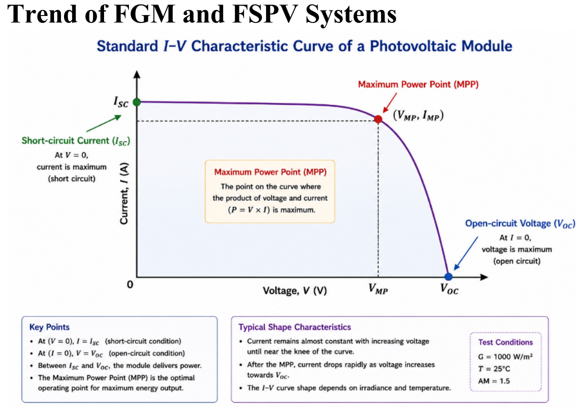


Figure 3- Standard I–V Characteristic Curve of a Photovoltaic Module

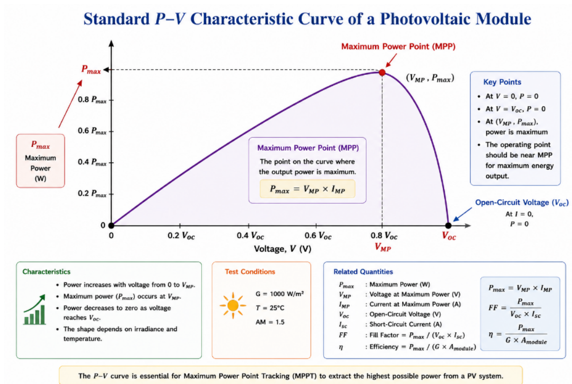


Figure 4- Standard P–V Characteristic Curve of a Photovoltaic Module

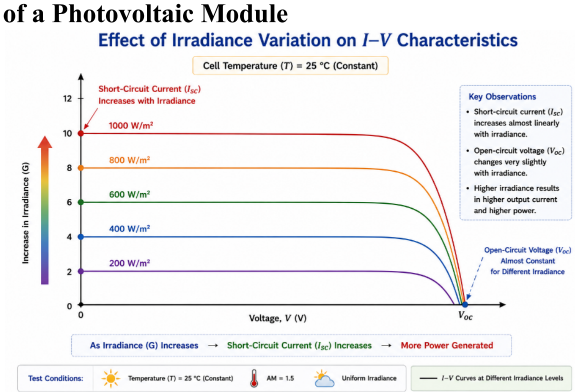


Figure 5- Effect of Irradiance Variation on I–V Characteristics

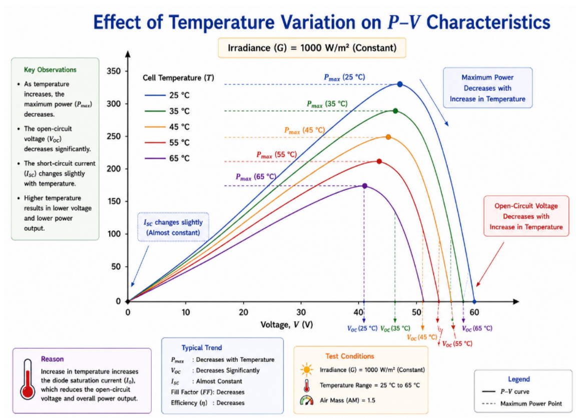


Figure 6- Effect of Temperature Variation on P–V Characteristics

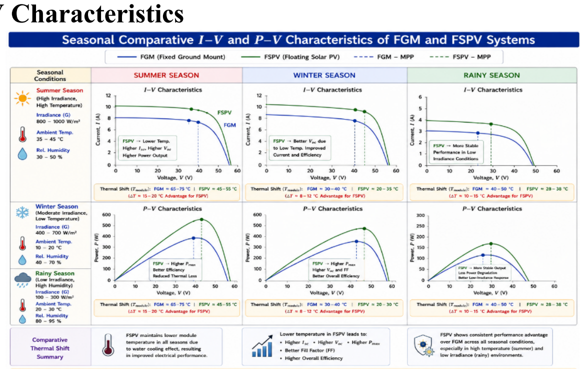


Figure 7- Seasonal Comparative I–V and P–V Characteristics of FGM and FSPV Systems

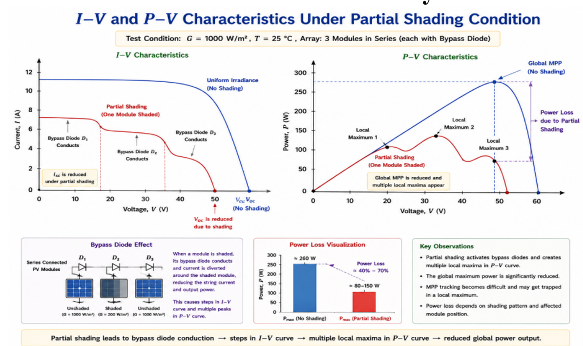


Figure 8- I–V and P–V Characteristics under Partial Shading Condition

VI. RESULTS ANALYSIS OF PROPOSED WORK

The analysis of the results presented in this study focuses on the detailed evaluation of the performance of two different solar photovoltaic installations, namely Fixed Ground Mount (FGM) Solar PV System and Floating Solar PV**,** two systems operated under similar climatic conditions over an extended observation period were studied. The main objective of this analysis was to investigate, compare, and explain the electrical, thermal, and performance behaviour of both systems under realistic outdoor conditions. The study aimed to uncover the impact of installation configuration and operating environment on the overall performance of a photovoltaic system by analysing experimentally measured parameters such as solar radiation, ambient temperature, photovoltaic module temperature, output voltage, current, power, efficiency ratio, capacity factor, fill factor, and conversion efficiency.

(i) Performance Analysis 12 month September 2023 to August 2024 Fixed Ground Mount Solar PV system - Performance analysis. Fixed Ground Mount (FGM) Solar PV System Continuous 12-month period from September 2023 to August 2024 Under realistic outdoor operating conditions, the results clearly demonstrate how solar radiation, ambient temperature, and photovoltaic cell temperature affect power generation and system performance. Throughout the months, solar radiation follows a similar diurnal pattern, increasing in the morning and peaking in the evening.12:00 and 13:00Solar radiation levels peak in the morning and then gradually decrease in the evening. This radiation trend directly controls the output current and power of photovoltaic systems, ensuring the strong dependence of photovoltaic power generation on solar radiation. Especially during the summer months of April and May, high radiation levels can cause peak current values to exceed the prescribed limits.7.5 A and maximum power output approx.125–

128 watts As per the information given in the relevant tables.

Hr	Irrad. (W/m²)	Amb. (°C)	FGM_Tcell (°C)	FGM_V (V)	FGM_I (A)	FGM_P (W)	FGM_PR	FGM_CF	FGM_FF	FGM_Eff (%)
10 AM	521.57	25.24	41.54	18.13	4.3	77.93	0.93	0.49	0.794	14.9414
11 AM	632.9	28.01	47.79	17.78	5.18	92.03	0.91	0.58	0.7883	14.541
12 PM	703.83	29.3	51.3	17.57	5.73	100.77	0.89	0.63	0.785	14.3174
13 PM	659.79	31.23	51.85	17.54	5.37	94.23	0.89	0.59	0.7845	14.2818
14 PM	599.11	30.73	49.45	17.68	4.89	86.48	0.9	0.54	0.7867	14.4347
15 PM	446.63	29.04	43	18.05	3.67	66.31	0.93	0.41	0.7926	14.8467
16 PM	320.08	27.49	37.49	18.37	2.65	48.65	0.95	0.3	0.7975	15.1993

Table 4- Experimental Output Results Fixed Ground Mount Solar PV system dated 11 September 2023, Day (Monday)

(ii) Performance Analysis 12 month September 2023 to August 2024 Floating Solar PV system- The experimental results of the Floating Solar Photovoltaic (FSPV) system were analyzed over a twelve-month period from September 2023 to August 2024 to evaluate its electrical and thermal performance under real outdoor operating conditions. Hourly data recorded between 10:00 AM and 4:00 PM demonstrate a consistent diurnal trend in solar irradiance, with values gradually increasing during the morning, reaching a maximum around solar noon, and decreasing thereafter. Peak irradiance values exceeding 950 W/m² were observed during summer months, while comparatively lower irradiance levels were recorded during winter and monsoon periods. This irradiance variation directly governs the current generation and output power of the floating PV system.

Hr	Irrad. (W/m²)	Amb. (°C)	Float_Tcell (°C)	Float_V (V)	Float_I (A)	Float_P (W)	Float_PR	Float_CF	Float_FF	Float_Eff (%)
10 AM	521.57	25.24	35.02	18.51	4.33	80.1	0.96	0.5	0.7997	15.3575
11 AM	632.9	28.01	39.88	18.23	5.22	95.24	0.94	0.6	0.7955	15.0482
12 PM	703.83	29.3	42.5	18.08	5.79	104.73	0.93	0.65	0.7932	14.88
13 PM	659.79	31.23	43.6	18.02	5.42	97.71	0.93	0.61	0.7921	14.8093
14 PM	599.11	30.73	41.96	18.11	4.93	89.36	0.93	0.56	0.7937	14.9155
15 PM	446.63	29.04	37.42	18.37	3.7	67.91	0.95	0.42	0.7976	15.205
16 PM	320.08	27.49	33.49	18.59	2.66	49.47	0.97	0.31	0.801	15.4555

Table 5- Experimental Output Results Floating Solar PV system dated 11 September 2023, Day (Monday)

(iii) Comparison analysis of Fixed Ground Mount Solar PV system Vs Floating Solar PV system Dated 6th December 2023 (Winter Seasons)- The results presented in Figures 4.1 to 4.10 provide a comprehensive comparative performance analysis of the Fixed Ground Mount (FGM) Solar PV system and the Floating Solar PV system for 6 December 2023. The analysis captures the influence of environmental conditions on electrical output and key performance indicators throughout the daytime operating hours (10:00 AM –16:00 PM).

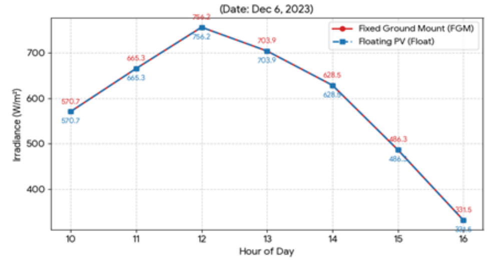


Figure 9- Irradiance comparison analysis of Fixed Ground Mount Solar PV system Vs Floating Solar PV system Dated 6th December 2023 (Winter Seasons)

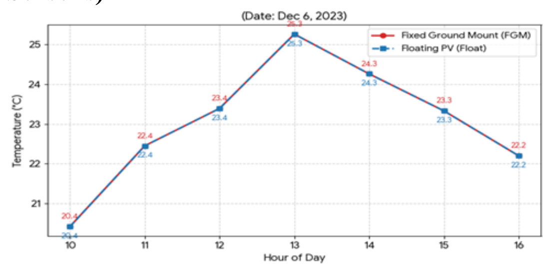


Figure 10- Ambient Temperature comparison analysis of Fixed Ground Mount Solar PV system Vs Floating Solar PV system Dated 6th December 2023 (Winter Seasons)

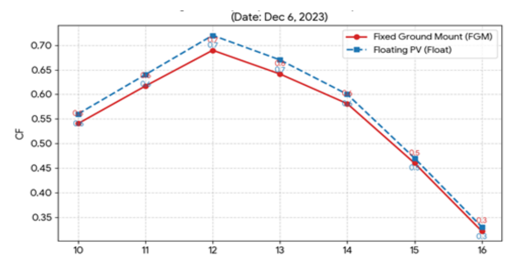


Figure 11- Capacity Factor (CF) comparison analysis of Fixed Ground Mount Solar PV system Vs Floating Solar PV system Dated 6th December 2023 (Winter Seasons)

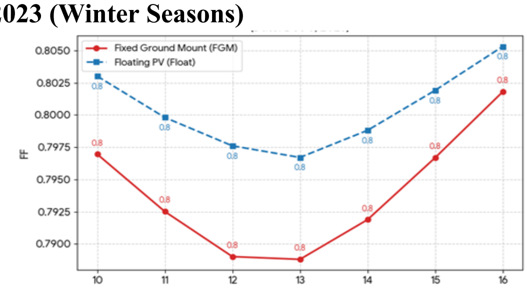


Figure 12- Fill Factor (FF) comparison analysis of Fixed Ground Mount Solar PV system Vs Floating Solar PV system Dated 6th December 2023 (Winter Seasons)

COLCLUSION

The obtained results conclusively demonstrate that solar irradiance acts as the primary driving parameter governing photovoltaic current generation and output power in both FGM and Floating Solar PV systems. Since both systems were operated under identical environmental conditions with nearly identical irradiance and ambient temperature profiles, the observed differences in electrical and thermal behavior are directly associated with mounting configuration, thermal interaction, and cooling characteristics of the surrounding environment.

The experimental analysis clearly establishes that although both systems follow similar seasonal and diurnal irradiance trends, their thermal response and electrical performance characteristics differ significantly. The Fixed Ground Mount Solar PV system demonstrated stable and reliable operation throughout the year with comparatively good performance indicators. The system maintained-Performance Ratio (PR) values between 0.81 and 0.97, Fill Factor (FF) values between 0.76 and 0.80, and stable power generation under varying climatic conditions.

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