Performance Evaluation and Comparison of Bifacial and Mono-Facial Crystalline Silicon PV Modules and Systems

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Abstract

The objective of the study is to evaluate the technical performance of a bifacial PV system & compare it with its mono-facial counterpart in outdoor conditions in India. It is found that the energy generation from the bifacial latitude tilt system is highest, followed by the mono-facial latitude tilt system and then the bifacial vertical tilt system. The quantum of excess energy generation depends on various parameters like ground albedo, GCR, GCH, module tilt angle etc. It is also found in the study that the bifacial gain is over 20% with natural vegetation & grass as the ground reflecting material and it increases further when SS-sheet was used as the ground reflecting material. The simulation study reveals that the LCOE from the bifacial system is comparatively lower than the equivalent mono-facial system when the albedo is 0.2 or above. The higher module cost of the bifacial module compared to its mono-facial counterpart is compensated by the extra energy generated by the bifacial system. The study further reveals that the albedo of the Ladakh region and desert of Rajasthan, India is naturally higher than the normal plain. Thus, these potential sites in India should be targeted for setting up MW-scale bifacial PV plants for higher energy yield and thereby, lower LCOE. Further, bifacial PV vertical systems can also be set up along the bunds of the agricultural land or the side of the national highways.

Keywords: bifacial, mono-facial, solar PV, bifaciality factor, bifacial gain, albedo, GCR, GCH, LCOE

1. Introduction:

In recent years, solar photovoltaic (PV) technology has gained prominence as a conventional energy source. Initially, mono-crystalline silicon (c-Si) PV modules were the dominant technology. Multi-crystalline silicon p-type solar cells with Aluminum Back Surface Field (Al-BSF) technology were widely used until 2015 [1]. However, the PV industry witnessed a shift in 2016 with the production of cost-effective mono-crystalline c-Si wafers. This encouraged the industry to explore innovative solar cell technologies such as Passivated Emitter Rear Contact (PERC), n-type Passivated Emitter Rear Totally-diffused (n-PERT), and heterojunction cells, which had previously only been developed in laboratories. Mono-facial PERC cells, known for their improved cell efficiency exceeding 22.5%, have reached their practical efficiency limit. However, to further increase energy output, the industry is transitioning to bifacial PERC cells. This transition doesn't significantly add to production costs. In the case of bifacial PERC cells, the traditional full-area Aluminum screen print on the rear side of mono-facial PERC cells is replaced with an optimized Aluminum/Silver finger grid, similar to the front side. Bifacial cell and module technology have gained popularity over the years. Bifacial modules harness energy from incident irradiance on both the front and rear sides of the module, resulting in higher energy generation in the field compared to mono-facial counterparts. With advancements in mono-crystalline Si PV cells, improved durability, reliability, and sturdy structures, many module manufacturers are adopting glass-glass panels, making bifacial solar technology an industry preference.

According to Kopecek, R. et al. [2], the global installed capacity of bifacial PV technology reached approximately 20 GW by the end of 2020, with significant installations in China, Chile, Mexico, and the Middle East. This capacity is expected to increase in the coming years. The International Technology Roadmap for Photovoltaic (ITRPV) 2021 suggests that bifacial cells, which accounted for about 30% of the market share in 2020, are projected to increase to approximately 80% in the next decade. Similarly, the market share of bifacial modules, which stood at around 18% in 2020, is forecasted to grow by 55% in the next decade [3]. In

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India, despite the dominance of Al-BSF multi-crystalline Si PV cells in the solar PV market, the potential of bifacial technology to produce more energy at nearly the same panel cost as mono-facial counterparts is making bifacial technology an attractive option for achieving lower Levelized Cost of Electricity (LCOE).

Section-1 of the paper presents the introduction of the study and describes the review of literature, Section-2 describes the objectives of the study, Section-3 depicts the methodology adopted to carry out the study, Section-4 illustrates the result and discussion, and Section-5 presents the conclusions and scope of further work.

Various literature on the performance of bifacial PV technology revealed that the daily power generation of the bifacial modules is more than mono-facial counterpart both on sunny and cloudy days. The bifacial gain on cloudy days is even higher than on sunny days due to the higher diffuse irradiance content in the global irradiance. Further, the energy generation of the bifacial system increases with higher ground albedo, tilt angle up to the optimum tilt, and module elevation. In general, it is observed in the literature that the optimum tilt angle of the bPV system is higher than the mPV system under the same external conditions. The optimization of module elevation is also important to trade-off between bifacial gain and system cost.

Wenbo Gu et al. [4] conducted an experimental study on bifacial PV modules under real conditions. They compared the electrical and thermal performance of bifacial modules with mono-facial modules, considering various installation parameters. Bifacial modules were found to produce more power than mono-facial modules due to their ability to collect more irradiance from the rear side. It concluded that higher ground albedo and specific tilt angles favoured bifacial modules. Long-term simulations showed a substantial annual bifacial gain of 14.77%. Suna Xingshu et al. [5] developed a physics-based model for optimizing bifacial solar PV modules on a global scale. Empirical equations derived from the model could estimate bifacial gain based on these parameters, facilitating quick evaluations. The study found that ground-mounted bifacial modules with higher ground albedo coefficients and elevated installations achieved higher bifacial gains, but the balance between gain and installation cost needed optimization.

Stein Joshua S. et al. [6] conducted a study to understand the performance factors of bifacial PV systems. They found that bifacial modules receive more irradiance on their rear surface, making traditional performance models for mono-facial modules inadequate. Factors like module height, tilt angle, azimuth angle, and ground albedo were studied. Results showed that bifacial modules produced more power than mono-facial modules under similar conditions. The annual energy production was highest for south-facing bifacial modules, but the annual bifacial gain was greatest for west-facing vertical modules due to cooler mornings. String-level performance analysis demonstrated varying bifacial gains with different tilt angles. Patel M. Tahir et al. [7] focused on temperature-dependent energy gain in bifacial PV farms on a global scale. They analyzed how temperature affected energy generation, the Levelized Cost of Electricity (LCOE), and compared standalone bifacial modules to solar farms with bifacial modules. Temperature-dependent cell efficiency was considered, and irradiance modelling was integrated for light collection. Bifacial modules, despite collecting more irradiance, could experience lower cell efficiency due to increased temperature. The study revealed that mutual shading in solar farms caused higher cell temperatures and reduced efficiency, particularly in hotter climates, impacting LCOE. They also found that bPV modules with lower temperature coefficients were more efficient and had higher power output. The study compared bifacial gain and LCOE for different module types and optimal elevation considerations.

Liang Tian Shen et al. [8] conducted a review of crystalline silicon bifacial photovoltaic (bPV) performance characterization and simulation. They discussed challenges in establishing standard test conditions for bPV cells/modules. Various methodologies were used to compare bPV and mono-facial PV (mPV) technology, including bifacial gain, equivalent efficiency, and bifacial STC rating. The review also highlighted different techniques for indoor and outdoor characterization of bPV cells and modules, emphasizing the importance of accurate optical modelling for bPV simulations. Additionally, the paper discussed the need for international standards and software tools for precise bPV performance evaluation. NREL [9] presented outcomes from the bifiPV2020 Bifacial Workshop, offering an overview of recent developments in bifacial solar PV technology. The report noted the increasing size of PV wafers and cells, as well as concerns about the long-term durability and reliability of bifacial modules. It highlighted the popularity of glass/glass bPV modules and the emergence of glass/transparent back sheets. The report also mentioned the shift towards n-type bPV technology and the importance of bifacial energy gain (BEG) as a key parameter for comparing bPV and mPV systems. Challenges related to tracking systems, standardization, and modelling were discussed, as well as the need for further research in various areas. Park Hyeonwook et al. [10] conducted an outdoor performance test of bifacial n-type silicon photovoltaic modules in South Korea. They evaluated the performance of bifacial modules and strings compared to mono-facial counterparts under different conditions, including varying ground albedo and the use of tracker systems. The study included indoor measurements under standard test conditions (STC) using mini-modules with different back sheet types. It found that the module with a white back sheet had the highest I_{SC}, while the transparent back sheet bifacial module exhibited high bifaciality factors. The outdoor tests revealed that bifacial modules performed significantly better than mono-facial modules, with higher annual energy yields and bifacial gains, especially in conditions with high-ground albedo. Asgharzadeh Amir et al. [11] conducted a study analyzing the impact of various installation parameters and system size on the energy yield and bifacial gain of photovoltaic (PV) systems. They used RADIANCE simulation software to investigate the effects of module elevation, ground albedo, tilt angle, and system size on PV system performance. The study considered three different system configurations: a single module, a row of five modules, and five rows of five modules. The simulation explored how changing module height, tilt angle, and ground albedo affected the performance throughout the year. Results indicated that the optimum tilt angle for bifacial modules varied with module height and time of year. Carlos D. Rodríguez-Gallegos et al.'s [12] paper, compared the cost-effectiveness of mono-facial and bifacial silicon-based PV modules across 55 locations worldwide. The study evaluated the levelized cost of electricity (LCOE) for various PV system configurations, considering factors like weather conditions, albedo, market conditions, and electrical performance. The research compared LCOE for mono-facial modules with different orientations, bifacial modules with standard orientation (AMO), and bifacial modules with vertical module orientation (VMO). Weather data from ground stations were used to estimate power generation, and cost parameters were adjusted based on the location. The study found that optimizing module orientation reduced LCOE and that mono-facial systems were more cost-effective at lower latitudes, while bifacial systems became more cost-effective at higher latitudes. Bifacial systems with AMO design were shown to deliver more energy in all locations, with increasing bifacial energy gain at higher latitudes. However, for ground albedos between 0.12 and 0.3, bifacial AMO systems were more cost-effective. Bifacial VMO systems became cost-effective at higher latitudes and near the poles, particularly with ground albedos between 0.29 and 0.57 [13], [14], [15].

However, these research studies have limitations. Most of these primarily focused on standalone bifacial modules, which may not reflect real-world installations with multiple modules and strings. Additionally, these studies mostly relied on satellite data from NASA rather than on-site measurements at various locations. Overall, these studies provide valuable insights into the performance, characterization, and challenges of bifacial photovoltaic technology, both indoors and outdoors, and emphasize the need for standardized testing and modelling approaches in the industry. However, some limitations of the study included the unavailability of accurate ground weather data for all locations, insufficient consideration of shading losses, land cost variations, transportation costs, policy and tax differences, and a limited system capacity.

Though many countries have been working on bifacial technology for decades, India is lagging in its development, deployment, and evaluation of performance at local conditions. The present paper aims to evaluate the performance of the bifacial system at latitude tilt & its comparison with the mono-facial system with latitude tilt and bifacial vertical tilt under outdoor conditions in India with estimation of bifacial gain at different albedo conditions, study of module temperature & its effect on energy yield and simulation study of bifacial PV power plant and optimization of various parameters to determine the minimum LCOE. The positive outcomes on the technical and financial fronts of the present study would help in the widespread acceptance and deployment of the bifacial PV technology.

2. Objective:

The primary objective of this research is to conduct a comprehensive technical assessment of bifacial PV (bPV) systems in outdoor conditions within the Indian context. This assessment involves comparing their technical performance with that of mono-facial PV (mPV) systems and determining the Levelized Cost of Electricity (LCOE) across various scenarios relevant to the Indian market.

The specific objectives of this study encompass the following:

- ✓ Energy Generation Comparison: Analyzing and contrasting the energy output between mPV systems and b PV systems at their respective latitude tilt angles. Additionally, it assesses the energy production of bifacial PV systems at vertical tilt orientations.
- ✓ Bifacial Gain Measurement: Investigating the bifacial gain achieved under varying albedo conditions, including scenarios involving natural vegetation, soil, and other reflective materials.
- ✓ Performance Assessment of Vertical Bifacial Systems: Evaluating the performance of vertical bifacial PV systems and comparing it with both mono-facial and bifacial systems employing latitude tilt.
- ✓ Module Temperature Study: Examining the impact of module temperature on energy yield and overall system performance.
- ✓ Simulation Analysis: Conduct in-depth simulation studies on bPV power plants to understand their energy generation characteristics. This analysis will encompass the influence of parameters such as tilt angle, ground albedo, ground coverage ratio (GCR), module elevation above ground level, and other relevant factors. Additionally, the study will involve calculating the minimum LCOE for these systems.

In instant, this research aims to provide a rigorous technical assessment of bPV systems in Indian outdoor conditions, addressing key aspects of their performance and cost-effectiveness.

3. Methodology:

To realize the objectives, this research is structured into different sets of activities in Indoor and Outdoor evaluations, each outlined below in technical detail:

3.1 Indoor Performance Evaluation:

The indoor performance assessment of mono-facial and bifacial modules was carried out. Initially, the indoor measurements of both mono-facial and bifacial modules were conducted. Specifically, four mono-facial modules and six bifacial modules (three for each at latitude tilt and vertical tilt) were randomly selected for indoor testing. The current-voltage (I-V) characteristics of all modules, both mono-facial and bifacial, were measured under Standard Test Conditions (STC) utilizing a single light source solar simulator (Eternalsun Spire) available at the National Institute of Solar Energy (NISE). When one side of the bifacial module was exposed to light, the other side was covered with a black mask to prevent unintended contribution. Subsequently, the bifaciality factor (φ), defined as the minimum of the ratio between the rear side to the front side Isc and Pmax [min (φIsc, φPmax)], was determined. Using the bifaciality factor (φ), the bifacial power gain (BiFi) was calculated by illuminating the front side of the module with an equivalent irradiance (G_E) and noting the corresponding maximum power (Pmax). The equivalent irradiance was selected to achieve rear irradiances (Gri) close to three specific values: 100 W/m^2, 135 W/m^2, and 200 W/m^2. The graph between Pmax and corresponding Gri was plotted. The linear fit of data points passes the y-axis at Pmax, STC. The slope of this graph gives the bifacial power gain (BiFi). Finally, utilizing the bifacial power gain, the maximum power output of the modules was calculated, which represents the sum of the maximum output power of the front surface at STC and two values of rear irradiances, specifically 100 W/m^2 and 200 W/m^2.

3.2 Outdoor Performance Evaluation:

The second phase of the study involves evaluating the performance of mPV and bPV systems under outdoor conditions. The experimental setup consisted of three distinct systems: System-I, a 5 kWp bPV system at latitude tilt; System-II, a 5 kWp bPV system at vertical tilt; and System-III, a 10 kWp mPV system at latitude tilt. These systems were installed at the NISE in Gurgaon, India, and comprised mono-crystalline PERC cells as shown in the Fig. 1.

All three systems were grid-connected via individual grid-interactive inverters. Data regarding daily energy generation and module temperatures were recorded using data loggers. Days with grid-related issues, such as grid unavailability or overvoltage, were excluded from data analysis to focus solely on PV system performance.

The electricity generated by these three systems was compared, and the bifacial gain, representing the increase in energy output from the bifacial system compared to its mono-facial counterpart, was determined. This assessment included scenarios with natural ground cover (vegetation and soil) as well as stainless steel (SS) sheets as ground-reflecting materials.



System-I **System-II** **System-III**

Fig. 1: System-I: bPV system at Latitude Tilt, System-II: bPV system at Vertical Tilt, System-III: mPV system at Latitude Tilt

The study also examined solar power generation and bifacial gain on both sunny and cloudy days. Module temperature and its impact on energy yield were also investigated. Furthermore, the performance of vertically installed bPV systems was compared with bifacial systems at latitude tilt and mono-facial systems at latitude tilt.

3.3 Simulation Study:

Using the National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM), a simulation study was conducted to compare the energy generation capabilities of Systems I, II, and III under identical external conditions. Additionally, the levelized cost of electricity (LCOE) was simulated using SAM to assess the financial feasibility of bifacial technology within the Indian market context.

Finally, a comprehensive study was compiled, covering the indoor performance evaluation of both mono-facial and bifacial modules, the determination of maximum power output from bifacial modules, a comparative analysis of the three systems (System-I, II, and III) considering different ground albedo conditions, the bifacial gain achieved by System-I over its counterpart System-III, a simulation study of a bifacial technology-based PV power plant, and the calculation of its LCOE. The report concludes with key findings and recommendations for further research.

4. Results and Discussion:

Three distinct PV systems (System-I, II, & III) have been installed at NISE Gurgaon, India, employing mono-crystalline Passivated Emitter and Rear Cell (PERC) technology.

4.1 Indoor measurements of mono-facial modules:

To carry out indoor measurements, four mono-facial modules were selected (out of the modules of System-III) randomly. The current-voltage (I-V) characteristics of all four modules were measured under STC using a single light source solar simulator (Eternalsun Spire). The mean and median values of maximum power (Pmax) of mono-facial modules are found to be 352 W and 352.2 W respectively.

4.2 Indoor Measurements of Bifacial Modules:

Similarly, six bifacial modules were randomly chosen for indoor measurement. Current-voltage characteristics for both the front and rear sides of these six modules were recorded under Standard Test Conditions (STC) using a single light source solar. When one side of the module was illuminated, the other side was shielded with a black mask to prevent any unintended contribution from that side.

4.2.1 Determination of Bifaciality Factor at STC:

The performance of the rear side with respect to the front side of the bifacial module is called bifaciality factor (φ). The bifaciality factors of all six modules for different parameters (Isc, Voc and Pmax) were calculated. The average value calculated of φIsc, φPmax and φVoc is 0.82, 0.81 and 0.99 respectively. The minimum of (φIsc, φPmax) is considered as the bifaciality factor. Therefore, the average bifaciality factor considered for the study is 0.81.

4.2.2 Determination of Bifacial Power Gain Driven by Rear Irradiance and Maximum Output Power:

The equivalent irradiance (G_E) method was used to find out the bifacial power gain (BiFi) using a single-side illumination solar simulator. The mean and median values of maximum power for rear irradiance 100 W/m^2 are 384.4W and 384.1W respectively. Similarly, the mean and median values of maximum power for rear irradiance 200 W/m^2 are 410.7 W and 409.9 W respectively.

4.3 Outdoor measurements:

4.3.1 Measurement of bifacial gain with natural vegetation and soil as the ground reflecting material:

The collection of generation data started with natural vegetation and soil as the ground reflecting material with an estimated ground albedo coefficient of 0.25[5]. The module elevation/ground clearance height, measured at the centre of System I and System III at latitude tilt is 1.0 meters and for System II, it is 0.2 meters. All three systems were connected to the grid through individual grid-interactive inverters. During the collection of data, the days with no grid or grid over-voltage were filtered out while aggregating the electricity generation at the system level to differentiate based on PV system performance only.

The electricity fed into the grid from 12-11-2021 till 24-02-2022 (after filtering out the days with partial no grid or grid over-voltage; the effective data is for 54 days) by individual systems (I, II and III) is given in Fig. 2. The generation data from System-III is normalized to 5 kWp equivalent system.

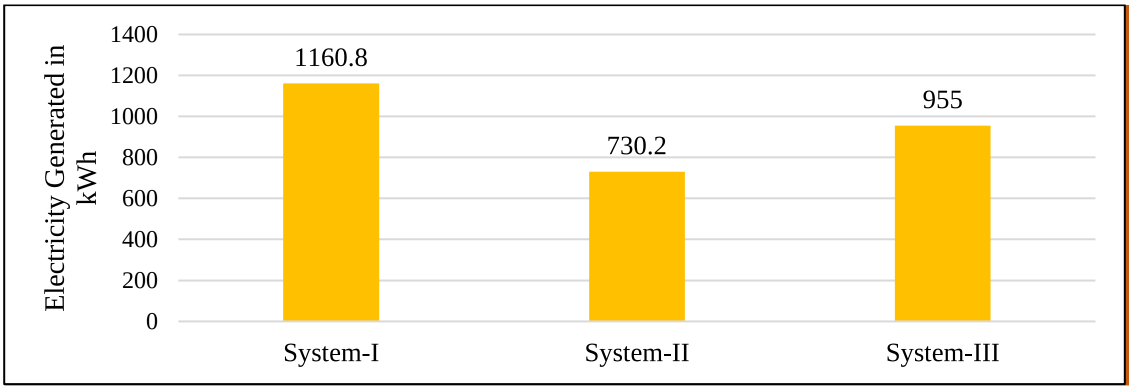


Fig. 2: Electricity fed into the grid by the three systems with natural vegetation and soil as the ground reflecting material

The bifacial gain (%) of the bPV system with latitude tilt (System-I) compared to its mono-facial counterpart (System-III) is calculated. Bifacial Gain = {(Energy generated by bPV system – Energy generated by the mPV system) * 100}/ Energy generated by the mPV system = {(1160.8 – 955) *100}/955 = 21.5%.

This bifacial gain obtained during November, December, January and most of the days of February is clearly due to the additional radiation available due to the natural vegetation and soil as the ground reflecting material which can be converted only by the bifacial modules. The bifacial gain of 21.5% appears to be higher compared to the data in the available literature. This higher gain may be due to higher system elevation and limited system size.

4.3.2 Measurement of bifacial gain with stainless steel (SS) sheet as the ground reflecting material:

System-I

System-II

Fig. 3: System-I with SS-sheet as ground reflecting material, System-II with SS-sheet as ground reflecting material

The same experimental set-up is used to find out the bifacial gain using SS-sheet as the ground reflecting material. The SS-sheet for System I and II was placed on 25-02-2022. The System-III being mono-facial, only natural vegetation and soil are used as the ground reflecting material. The System I and System II are shown in Fig. 3.

The electricity fed into the grid from 25-02-2022 till 20-05-2022, after filtering out the days with partial/no grid or grid over-voltage; the effective data available is for 33 days) by the individual system (I, II and III) is given in Fig. 4. The generation data from System-III is normalized to a 5 kWp equivalent system.

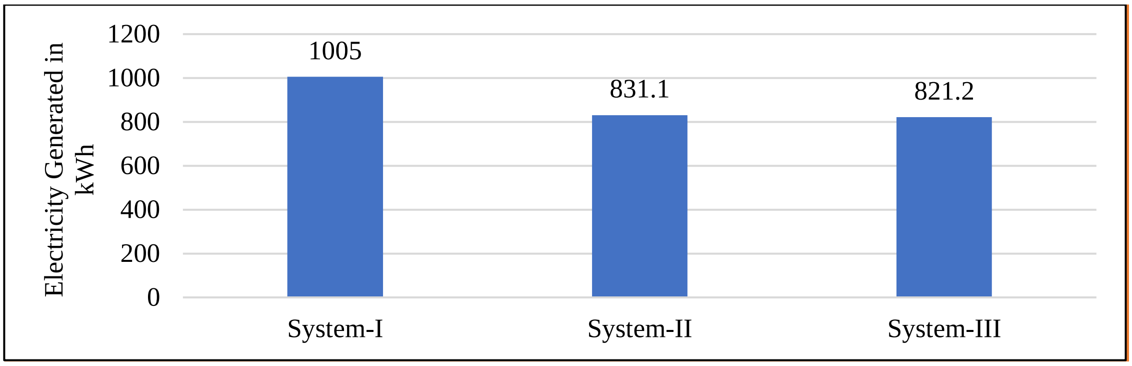


Fig. 4: Electricity fed into the grid by the three systems with SS-sheet as the ground reflecting material

The bifacial gain (%) of the bPV system with latitude tilt (System-I) compared to its mono-facial counterpart (System-III) is calculated. Bifacial Gain = {(Energy generated by bPV system – Energy generated by the mPV system) * 100}/ Energy generated by the mPV system = {(1005 –821.2) *100}/821.2 = 22.4%

This bifacial gain of 22.5% obtained is clearly due to the additional radiation available when SS-sheet is used as the ground reflecting material, which can be converted only by the bifacial modules. The bifacial gain obtained is ~ 1% higher as compared to the bifacial gain obtained (21.5%) when natural vegetation and soil are used as ground reflecting material.

4.3.3 Solar Power Generation and Bifacial Gain on an Arbitrary Sunny Day:

The generation of solar power from all three systems of capacity 5 kWp (the System-III is normalized to 5 kWp equivalent system) on an arbitrary sunny day (02nd Jan. 2022) was considered and depicted in Fig. 5 below.

It was observed that the power generated from System-I is highest followed by power generated from the System-III and then System-II. It was also observed that in the case of System-II, the maximum power output occurs two times a day, once in the morning and another in the evening and the power output was minimal during solar noon. The bifacial gain (%) of the system-I compared to its system-III on that particular day was calculated: {(21.9 – 18.2) *100}/18.2 = 20.3%

4.3.4 Solar Power Generation and Bifacial Gain on an arbitrary cloudy day:

The generation of solar power from the three individual systems of capacity 5 kWp each, throughout an arbitrary cloudy day (28th Dec. 2021) was considered and depicted in Fig. 6.

As expected, the power generated from System-I is highest followed by power generated from System-III and then System-II. The bifacial gain (%) of the system-I to system-III on that day is calculated which is {(3.9 – 3.2) *100}/3.2 = 21.9%.

Thus, the bifacial gain was higher on a cloudy day (21.9%) compared to a sunny day (20.3%). The increase in bifacial gain with the decrease in sky clearness index is due to the increased absorption of diffused radiation by the rear surface since on cloudy days the content of diffuse irradiance in the global irradiance is higher. It also indicates bPV technology is advantageous in fluctuating weather conditions with low irradiance levels. It is also important to mention that the difference in energy generation between a bifacial vertical system and a mono-facial latitude tilt system is less on a cloudy day compared to a sunny day.

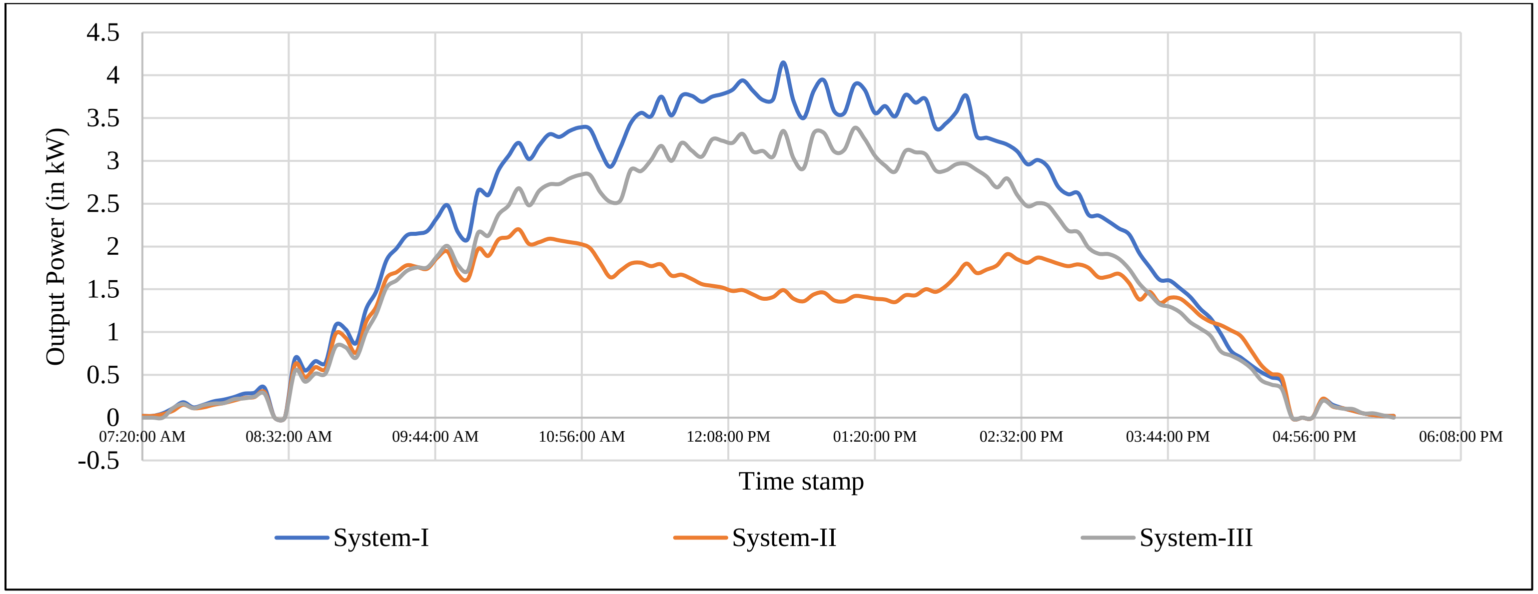


Fig. 5: Solar Power Generation from three systems throughout a sunny day *(02nd Jan. 2022)*

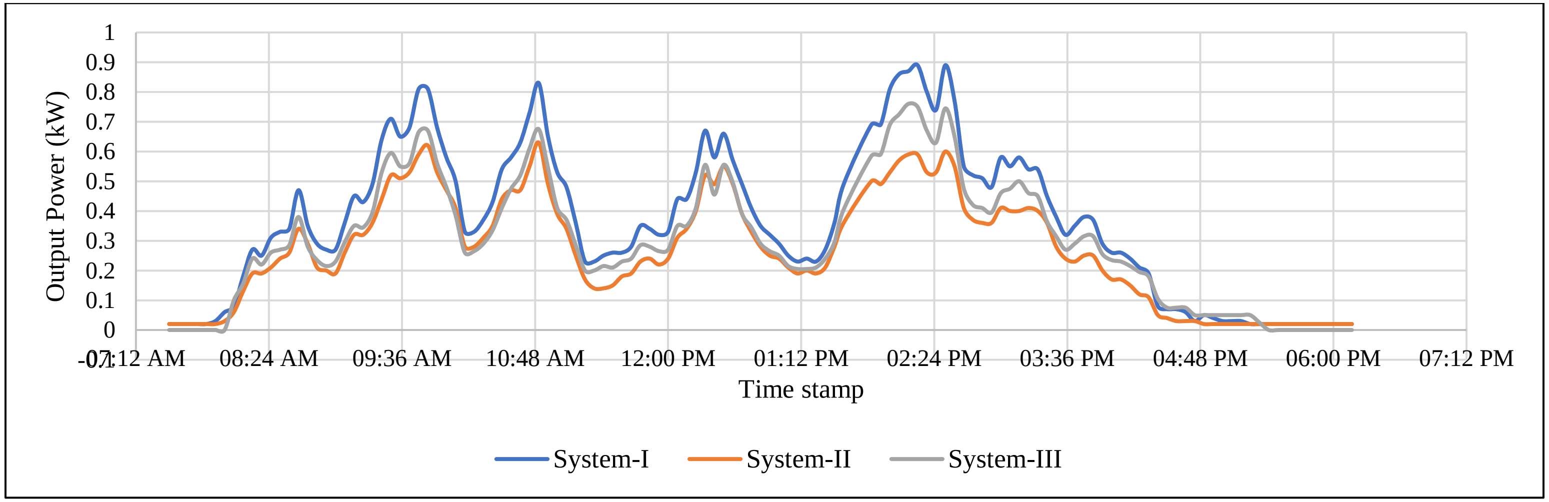
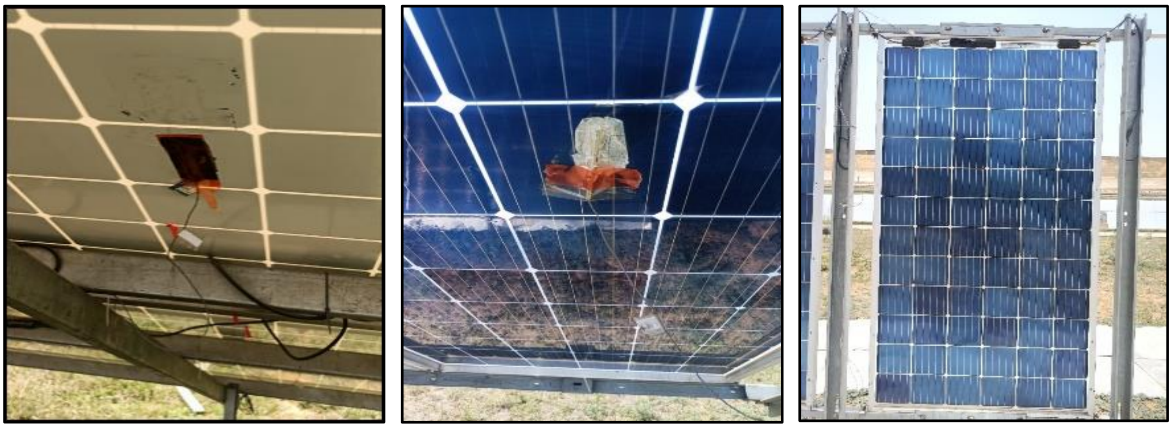


Fig. 6: Solar Power Generation from three systems throughout a cloudy day *(*28th Dec. 2021)

4.3.5 Module temperature study and its impact on energy yield:

Module temperatures of the three systems were measured daily at an interval of 10-minute time stamps. The monthly average temperatures are then determined to study the module temperature variations in various months. The temperature sensors are placed at the rear side of mono-facial and bifacial modules as shown in Fig. 7 (a, b & c) below.



(a) (b) (c)

Fig. 7: (a) mPV module temperature sensor, (b) bPV latitude tilt module temperature sensor, (c) bPV vertical tilt module temperature sensor

In the case of a mono-facial system, two temperature sensors were placed at the rear side of two modules and their average was taken for the study. In the case of the bifacial latitude tilt and vertical tilt system, the temperature sensors were placed at the rear side of one module of each system. The maximum temperatures of the three systems were taken separately for every month of the study (from Nov-2021 to April-2022) and are shown in Fig. 8.

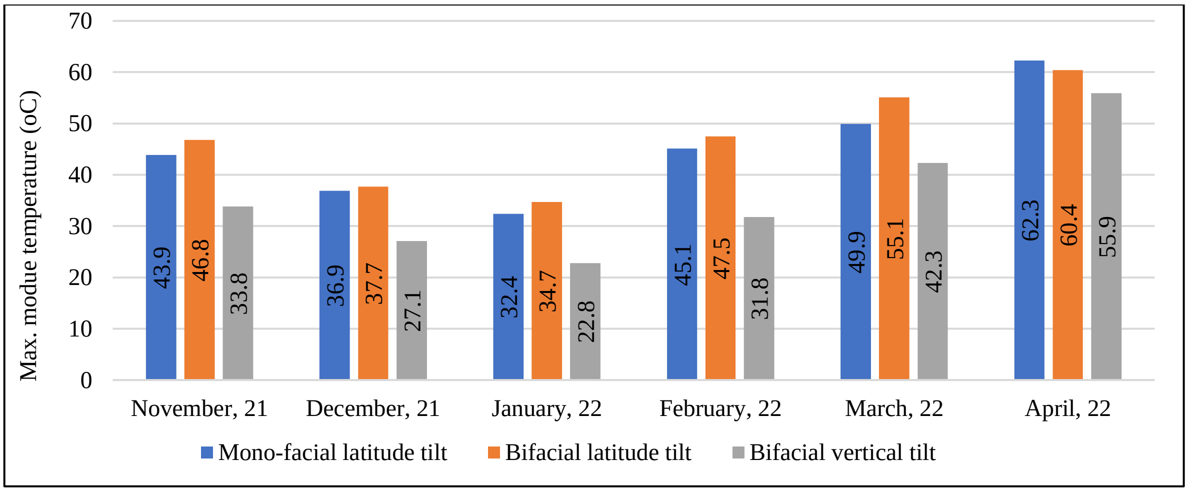


Fig. 8: Maximum module temperatures of three systems in different months

From the above study, it was evident that the module temperature of the bifacial latitude tilt system was comparatively higher (~ 2^0C - 5^0C) than that of the mono-facial latitude tilt system in various months. The higher module temperature of the bifacial latitude tilt system is possibly attributed to the absorption of higher total irradiance compared to the mono-facial latitude tilt system. Absorption of higher total irradiance by the bifacial latitude tilt system results in the generation of more solar electricity and thereby, an average bifacial gain of over 20%.

It was also observed that although the morning and evening temperatures of bifacial vertical modules were higher, the average module temperature of this system (System-II) was lower (~ 10^0C) compared to both bifacial and mono-facial systems with latitude tilt. The less absorption of light in the vertically installed system (around noon time) is the possible reason for the lower temperature in the vertically installed system. The reduction in absorption of incident light for vertical systems also results in a lower generation of solar electricity compared to mono-facial and bifacial systems with latitude tilt.

4.3.6 Performance study of the vertically installed bifacial system:

The energy generation from the vertically installed bPV system (System-II) was comparatively lower than both bPV and mPV systems with standard tilt (System-I & System-III respectively). It was observed that the daily average specific energy yield from System-II is around 37% and 23% lower than System-I and System-III respectively from Nov to Feb when the ground reflecting material is natural vegetation and grass; while it was around 17% lower than System-I and 1.2% higher than System-III during March to mid of May, when the ground reflecting material was SS-sheet. The higher daily specific average energy yield of the bifacial vertical tilt system is due to the change in ground reflecting materials and with the increase in ground reflection (with special preparation), it is possible to achieve similar energy output compared to mPV systems as can be seen in the experimental data with SS sheet.

It was observed that the bifacial modules supplied by the vendor were with standard frame (as in mono-facial modules) as shown in Fig. 9, which was causing significant shading on the rear side especially when the rear side of vertically installed modules were facing the sun. That was a possible reason for the lower energy yield from the vertical bifacial system especially in the second half of the day. Thus, for a vertical bifacial module, it is recommended to use specially designed frames to avoid the shading on the rear side and the module should be with high bifaciality. It was also observed that the daily average maximum module temperature of the bPV vertical system was comparatively lower than both bPV and mPV systems with latitude tilt.

Fig. 9: Standard frame shading the rear side of a bPV module

The bifacial vertical system can be set up along the bunds of the agricultural land or along the side of the national highways. Thus, it can save the cost and hassle of acquiring land for setting up solar PV projects. Even though the energy generation is comparatively lower, a bifacial vertical system is very useful for Agro-PV or PV systems installed along the highways.

4.4 Simulation Study for Levelized Cost of Electricity (LCOE):

The LCOE was simulated for the three systems configurations each having capacity of 1 MW_{dc}. The LCOE calculator of NREL's System Adviser Model was used for the above assessment. The site selected for carrying out the study was Bhadla (27.55^{0}N, 71.95^{0}E), District Jodhpur, Rajasthan. The bifaciality = 0.81, albedo = 0.3, ground coverage ratio = 0.3 and ground clearance height = 0.6 meters have been considered for the calculation of LCOE. The capital cost of the projects has been considered as per the current market trends. The various assumptions made for the study including the land cost for the bPV vertical system were assumed to be zero as vertical plants are generally hosted on the bunds of agricultural fields or along the side of highways. MW-size vertical PV plants are generally not installed on open fields. This is why the system cost of the bifacial vertical system is considered the lowest among the three system configurations. The cost of bifacial module was assumed to be USD cent 0.50/Wp higher than its mono-facial counterpart. Therefore, the system cost including cost of installation is highest for bPV latitude tilt system followed by mPV latitude tilt system and then bPV vertical tilt system.

The LCOE calculator of SAM uses the fixed-charge rate (FCR) method to calculate the project-levelized cost of electricity. The FCR is the revenue required per amount of investment to recover the investment made. After simulation, the results obtained for all three configurations are tabulated in Tab. 1.

Thus, LCOE= {(FCR x Capital Cost + Annual O&M cost)/Annual Electricity Production} + Variable Operating cost (if any)

Tab. 1: Simulated results for LCOE

Results	bPV system with latitude tilt	m PV system with latitude tilt	bPV system with vertical tilt
Annual energy production	18,14,446 kWh	15,85,615 kWh	15,21,172 kWh
Capacity Factor	20.7%	18.1%	17.3%
Energy yield	1,816 kWh/kW	1,587 kWh/kW	1,519 kWh/kW
LCOE (Exchange rate 1 USD= INR 74 during that time)	USD Cent 2.53/unit or INR 1.87/unit	USD Cent 2.86/unit or INR 2.12/unit	USD Cent 2.92/unit or INR 2.16 unit

Bifacial Gain = {(Energy yield from bPV system with latitude tilt - Energy yield from mPV system with latitude tilt)/Energy yield from mPV system with latitude tilt} = {(1816 - 1587)/1587} = ~14%

Thus, it is observed that LCOE is minimum for the bPV system with latitude tilt followed by LCOE for the mPV system with latitude tilt and then the bPV system with vertical tilt. The LCOE for the bPV system with latitude tilt is ~12% lower than the mPV system and the LCOE for the bPV system with vertical tilt is ~ 2% higher than the mono-facial PV system with latitude tilt. Though the LCOE of the bifacial PV with vertical tilt is the highest among the three configurations, it is useful for niche applications like Agro-PV, fencing, noise barriers etc.

Further, the LCOE for bifacial PV systems with latitude tilt depends on various parameters like tilt angle, albedo, ground coverage ratio (GCR), ground clearance height or elevation of the modules from the ground etc.

4.4.1 Optimized parameters for minimum LCOE:

The optimized various parameters for the minimum LCOE of a bPV power plant (1 MWdc) located at Bhadla, District-Jodhpur, Rajasthan are given in Tab. 2 as:

Tab 2: Optimized values of various parameters for minimum LCOE

Various parameters	Optimized value
Sub-array tilt angle	35^0
Ground coverage ratio	0.3
Ground clearance height	1.2 meter
Ground albedo for desert sand	0.3

With the above-optimized parameters, the energy yield and minimum LCOE for 1 MWdc bPV system are given in Tab. 3 as under:

Tab. 3: Energy Yield and Minimum LCOE for 1 MWp optimized system

Various parameters	Value
Annual Energy	18,61,280 kWh
Capacity Utilization Factor	21.3%
Energy Yield	1863 kWh/kW
Performance Ratio	0.82
Levelized Cost of Electricity (1 USD =INR 74)	USD Cent 2.51/kWh or INR 1.857/kWh

5. Conclusions and Scope of Further Work:

The bPV modules and system undoubtedly generate more energy than their mono-facial counterpart. The quantum of excess energy generation depends on various parameters like ground albedo, ground coverage ratio, ground clearance heights, module tilt angle etc. In this study, it is found that the bifacial gain is over 20% with natural vegetation and grass as the ground reflecting material which increases further when SS-sheet is used as the ground reflecting material.

The slightly higher module cost of the bifacial module compared to its mono-facial counterpart is compensated by the extra energy generated by the bifacial system. The simulation study reveals that the LCOE from the bPV system is comparatively lower than the equivalent mPV system when the albedo is 0.3 or above. The albedo of the Ladakh region and desert of Rajasthan is naturally higher than the normal plain as the Ladakh region is covered with snow for most of the time round the year and the desert areas of Rajasthan are covered with sand. Thus, these are the natural potential sites in India for setting up MW-scale bPV plants with higher energy yield and thereby, lower LCOE. Though it is not economically feasible and advisable to change the ground-reflecting material of the entire solar field, it may be possible for a rooftop solar system. The rooftop may be white painted once a year to harness more energy from the bPV rooftop solar systems. Thus, the bifacial modules can also become useful for rooftop solar systems as India has an ambitious target of 40 GW of rooftop solar systems.

The bPV vertical tilt system is also very useful and it has wide applications. Though it generates comparatively lower energy than the mPV latitude tilt system, it can be set up along the bunds of the agricultural land or along the side of the national highways. Thus, it can save the land cost and hassles of acquiring land for setting up solar PV projects. Therefore, a bifacial vertical system is very useful for Agro-PV or PV systems installed along the highways.

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