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A comparative analysis of polycrystalline and bifacial photovoltaic module under various partial shading condition

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ABSTRACT

A bifacial photovoltaic module (BPVM) has gained prominence over the last decade due to its high efficiency due to the arrangements to grab the photon on both sides of the module. It has been shown that partial shading substantially affects the performance of polycrystalline photovoltaic module (PPVM) and BPVMs. A comparison of the performance of PPVM and BPVMs under different partial shading conditions is presented in this paper. Experiments were conducted on polycrystalline and BPVM with 320 W and 395 W, respectively. Module performance is analyzed in terms of percentage power extraction, percentage power loss, and power extraction per square meter. A partial shading for the front and rear side of BPVM has been developed and the results are presented. Based on the results, the average loss due to frontside partial shading is 26% lower in BPVM than in polycrystalline.

1. Introduction

The extensive use of fossil fuels and greenhouse gases has polluted the environment which in turn promotes the development of renewable energy sources such as solar, wind, tidal. Aside from its affordability, solar photovoltaic (PV) power generation has gained considerable attention because of subsidies from governments and innovative business models that have allowed prices to drop [1]. PV modules made from silicon have the largest market share of 95% among commercialized technologies [2]. In comparison to traditional PV modules, BPVM can perform better because solar irradiation is absorbed from both sides of the cells [3].

The installation of PV has attained an exponential increase and reached a total installed capacity of 402.5GWp by the end of 2017. In 2017, the contribution of PV systems was about only 2.14% of total electricity demand worldwide and its share keeps increasing [4]. By 2030, the total installed capacity of PV systems is expected to be between 1760GWp and 2500GWp [5]. Over 90% of PV cells available in the current market are made up of Si crystalline (IEA, 2016). This can be categorized into the aluminum back surface field has a market share of 70% followed by the Passivated Emitter and Rear Contact (PERC) / Passivated Emitter with Rear Locally Diffused Cells (PERL)/ Passivated Emitter Rear Totally Diffused- Cells (PERT) technologies by 20% [6]. The PPVM is composed of AL-BSF and the BPVM is prepared by PERC/ PERL/ PERT technologies. The BPVM has gained attraction because of light absorption occurring on the front and rear sides of the module.

Polycrystalline cells collect the photons from the sunlight only from the front side of the module. In the BPVM, photons are collected on the front and rear sides of the module. A transparent back sheet allows partial sunlight to reach the module from the rear side as it is reflected from the ground surface. This phenomenon of bifacial cells can increase the energy yield and thereby reduction in the cost of energy is achievable [7]. Luque et al, has developed an experimental setup using a concentrator device to collect the incident and albedo light to improve the power generation. The results showed that the albedo light improved the output power by 50%. Because of higher energy density in the BPVM, it generates higher output power compared to the PPVM for the same area. Because of the higher energy yield, the BPVM has a lower payback period. The lifetime of the BPVM with is improved because of the lesser sign of degradation due to moisture, light-induced and potential induced degradation [8]. The main advantages of the BPVM are the lower operating temperature due to the increase in open-circuit voltage. By reducing parasitic absorption and increasing recombination at the interface of the aluminum back surface field, losses are decreased. The absenteeism of metallization on the back surface of the cell lowers the infrared absorption and reduces the operating

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temperature. Therefore, the bifacial cells operate at a lower temperature compared to the polycrystalline cells, resulting in enhanced power output [9,10].

In the BPVM, the introduction of a glass back sheet improves the durability compared to the PPVM with glass back sheet module construction [11,12]. The glass-glass structured BPVMs reduce the operating cost and therefore it is on the verge of emerging as a significant technology for electricity generation through solar energy. However, the performance of the BPVM relies on the module tilt, spacing and elevation. Among bifacial and polycrystalline structures, the rear exposer is the most significant difference. In a polycrystalline solar cell, the back contact is coated with silver and aluminum as a spate layer. For the bifacial solar cell, the back contacts are fabricated in the shape of an open metallization grid. The presence of a metallization grid facilitates the solar cells absorbing irradiation from the rear surface. Depending on the installation, the BPVM can improve the output power by 20% compared to the PPVM. Recently, the cost difference of the bifacial and PPVMs has decreased significantly [13]. By 2028, the share of the BPVM is expected to reach 40%. The efficiency of bifacial cells is calculated by separately defining the rear and front side efficiencies [14].

The factors that affect the efficiency of the BPVM are installation parameters, irradiance components and mismatch effect. The occurrence of inhomogeneous irradiance results in a mismatch effect, which affects the reliability of the power generation. When the mismatched cell is reverse biased and acts as a load. It dissipates power in the form of a heating effect and increases the operating temperature leading to delamination of encapsulated materials. Therefore, it is essential to compare the performance of the BPVM with the PPVM.

The hot spot phenomenon can occur in a PV module when the reverse voltage across the PV module exceeds the breakdown voltage and large concentrated current concentrates in a limited area. The cells may be irreversibly damaged by the thermal breakdown. The occurrence of the mismatch effect in a BPVM can be categorized as the front-side and rear-side mismatch. The mismatch effect on the front-side of the module is caused by the passing cloud, nearby building or soiling. The mismatch effect on the front-side of the PPVM is similar to that on the BPVM. The occurrence of the mismatch effect on the front-side of the PPVM focuses on the reverse characteristics of the cell, shading ratio and influence of the bypass diode.

The electrical and thermal performances of the BPVM differ with the rear-side irradiance under the same front-side shading condition. The rear-side mismatch is caused by the inhomogeneous irradiance because of the self-shading effect of the module and installation parameters such as the junction box on the rear side, mounting frame and bracket. The rear-side irradiance inhomogeneity plays a significant role in evaluating the power and reliability. Koen et al, has conducted a simulation study on the current - voltage characteristics of the BPVM on both sides. The results show that the 0.2% power loss was caused by inhomogeneous irradiance. The author found that the mismatch effect on the rear-side would not lead to hotspots, but it affects the reliability of the module. Several researchers have analyzed the influence of the inhomogeneous irradiance on the rear-side only through simulation studies. Therefore, it is essential to explore the inhomogeneous irradiance on the rear side by the field test [15].

Analysing the effects of front side irradiance and rear-side inhomogeneous irradiance on BPVM performance is presented using ray tracing simulations with a cell-level electrical circuits model. A linear model for predicting the mismatch loss of BPVM has been developed in this study. Based on the model, mismatch losses have been discussed in a 3x3 bifacial PV array, thus illustrating their impact on overall system performance due to rear inhomogeneity [16]. A horizontal single-axis tracker (HSAT) and a fixed racking bifacial system are discussed. For different racking configurations, a shading factor and mismatch loss is provided, as well as a demonstration of the distance effect on model, which provides principles for further improving the mounting systems and determining accurate parameters for PVsyst modelling [17]. The irradiance mismatch can result from two factors: partial shading on the front side and inhomogeneous irradiance on the rear side. The performance of BPVM were investigated in this experimental study to study the effect of these two factors. Under different shading conditions, BPVM and PPVM were compared for the effect of front-side partial shading. A BPVM was analysed under certain typical installation conditions under the influence of rear-side inhomogeneous irradiance [18]. In shaded conditions, BPVM generates more power than mono-facial PV modules based on an analysis of power loss. Shaded areas, functioning status of bypass diode, and module temperature are considered in a modelling approach to predict the power of a bifacial PV module in a shaded environment. As a result, the BPVM has relatively low power loss as compared to the mono-facial PV module. The mathematical modelling of both the PV modules are shown in the below figure. The current source is parallelly connected with the diode is the equivalent circuit of the general solar PV module. In the given Fig. 1(a) represents the single diode model for the one bifacial PV module. In the diode modelling, f represents the front face of the PV cell and the r denotes the rear side of the bifacial cell. The Fig. 1(b) indicates the single diode equivalent circuit of the mono-facial (polycrystalline) solar PV module. Both the equivalent circuits are developed and simulated in the MATLAB / SIMULINK platform to validate the experimental results [19]. An analysis of BPVM is presented using a simulation model. A software tool has been developed for the application of this model, which has been tested on various relevant configurations (diffuse irradiation fraction, module height, module tilt, ground albedo). As simulation result shows, vertically mounted BPVM at higher latitudes can be expected to generate high annual energy yield than south-facing mono-facial modules [20].

The mathematical output current equations are given below for both the solar PV modules.

The current equation of the BPVM is expressed as.,

$$I_{pv} = \left(\frac{G_{front}}{G_{STC}}\left(I_{mpp,n} + K_I\Delta T\right)\left(1 - \frac{SR_f}{100}\right)\right) + \left(\frac{G_{rear}}{G_{STC}}\left(I_{mpp,n} + K_I\Delta T\right)\varphi_{I_{sc}}\left(1 - \frac{SR_r}{100}\right)\right) \tag{1}$$

$$SR_r = \frac{SD_r}{A_{cell}}.100\% \tag{2}$$

were,

SR_r is the shading ratio on the concern PV module.

The current equation of the PPVM is expressed as.,

$$I_{pv} = I_{ph} - I_D\left[-exp\left(\frac{V_{pv} + R_sI_{pv}}{A}\right) - 1\right] - \left[\frac{V_{pv} + I_{pv}R_s}{R_{sh}}\right] \tag{3}$$

From the literature survey only deals with the performance assessment of front side partial shading effect in the PPVM and BPVM. In some literature work relates the rear side partial shading effects in the BPVM. Still there is a lack of research in the consideration of combined shadowing effect on both sides (front and rear). These shadowing scenarios may greatly affect the performance of the BPVM when compared with the PPVM respectively. Hence, in this present study, the various partial shading scenarios has been discussed to validate the performance of the polycrystalline and the bifacial PV module. The rear side shading conditions will be greatly decreasing the performance of the bifacial module to the polycrystalline module when compared with the front side shading cases. In this proposed work, mainly focus on the impact of the real-time rear side shading, both side shading cases with same location and different locations are compared with the conventional polycrystalline module. Also, its performance is compared with the PPVM in terms of the percentage of power extraction, percentage power loss, power extraction per meter square. The activation of bypass diodes concern with the percentage of shading on the PV module is also discussed in this study.

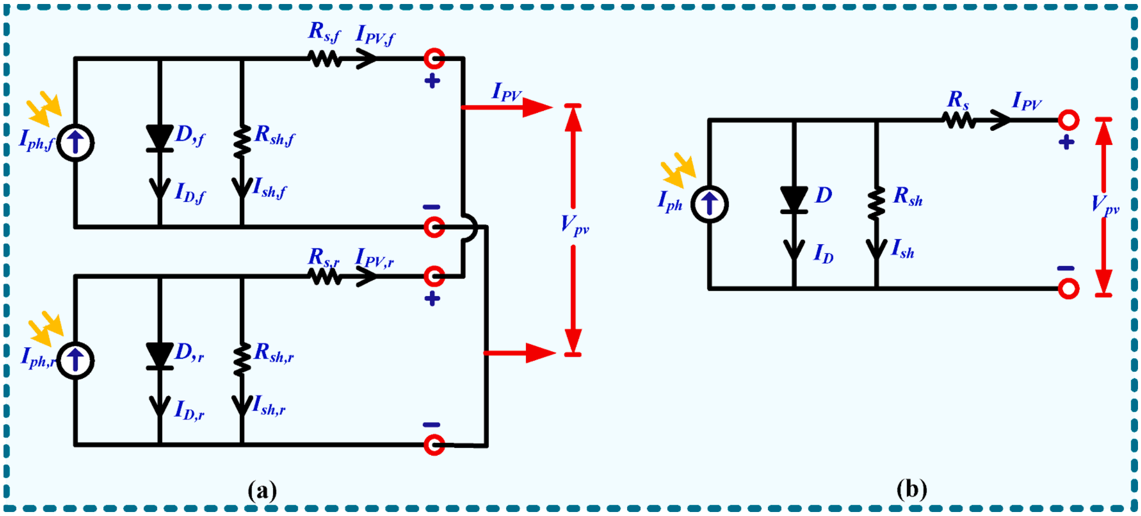


Fig. 1. Single diode equivalent circuit of a solar PV module (a) Bifacial Photovoltaic module, (b) Polycrystalline photovoltaic module.

This paper is organized as follows. Section 2 demonstrates the experimental setup of the polycrystalline and BPVM. Section 3.1 discusses the partial shading scenario considered for the study. Section 3.2 describes the performance parameters for analyzing the performance of polycrystalline and BPVMs. Results are analyzed in section 4 and followed by a conclusion in Section 5.

2. Experimental setup

An experimental setup was conducted to investigate the impact of partial shading on the performance of polycrystalline and BPVMs. Fig. 2 illustrates the experimental setup consisting of polycrystalline and BPVMs installed at Kamaraj College of Engineering and Technology, (9.6728° N, 77.9659° E), Virudhunagar, Tamil Nadu, India.

The BPVM and PPVMs are installed with a same tilt angle of 9.6° N (south facing). Both the modules consist of 72 cells connected in series along with three bypass diodes. Each module consists of six columns, with twelve cells are connected in series with three bypass diodes. The polycrystalline and BPVMs are connected to a resistive load of 4.17 Ω and 4.06 Ω, to obtain the peak power of 320 W and 395 W. The electrical

Table 1
Electrical characteristics of PPVM and BPVM.

Parameters	PPVM	BPVM
Maximum Power (P_{max})	320 W	395 W
Maximum Power Voltage (V_{mp})	36.58 V	38.3 V
Maximum Power Current (I_{mp})	8.76 A	9.42 A
Open Circuit Voltage (V_{oc})	45.92 V	46.8 V
Short Circuit Current (I_{sc})	9.12 A	10.97 A
Number of cells connected in series	72 Nos	72 Nos

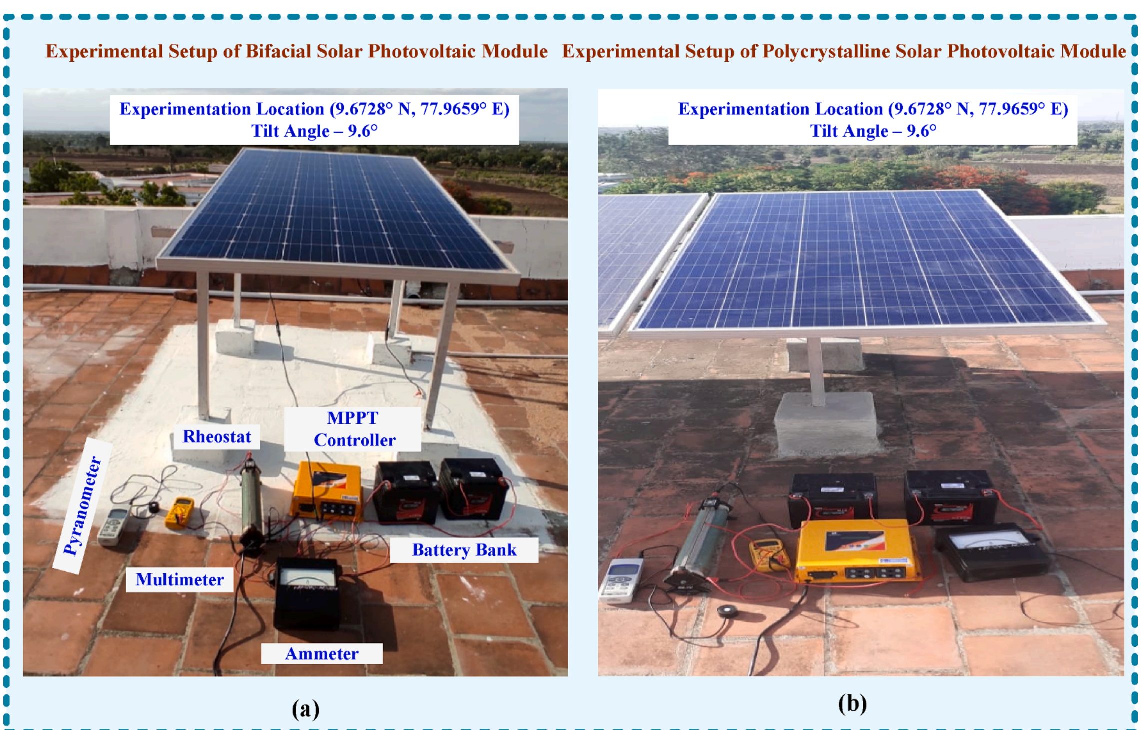


Fig. 2. Experimental verification (a). PPVM (b). BPVM.

characteristics of the polycrystalline and BPVMs are presented in Table 1.

An experiment was conducted to analyze the impact of partial shading on both modules.

The partial shading effect is obtained using cardboard sheet to reduce the incident irradiation on the module. At the time of the experiment, the entire module was subjected to irradiation of 900 W/ m^2. In the PPVM, a partial shading effect is created on the front side, whereas in the BPVM, it is created on the front and rear sides. To maximize the albedo effect, the surface beneath the BPVM is kept white to enhance the light reflection. The incident irradiation on the module was measured using a Meco 936 solar meter. For the different partial shading conditions, the voltage of the module and current are recorded. The wall mounted MPPT Smarten PWM solar charge controller rated as 24 V / 48 V & 50 A is used to validate the results taken by varying the rheostat.

3. Experimental procedure

3.1. 1. Partial shading scenario

In this study, the effectiveness of the polycrystalline and BPVMs is verified by comparing their performance under different partial shading conditions. The partial shading pattern is analyzed in terms of different shading ratios in the PPVM. The implementation of the partial shading scenario is shown in Fig. 3.

The partial shading conditions considered for this study are shading on the polycrystalline and front side of the BPVM, shading only on the rear side of the BPVM, shading on the PPVM and identical shading patterns shading on the front and rear side with identical shading ratios and different pattern of shading on the front and rear side with different shading ratio. The different shading patterns considered for the study are row shading, column shading, single cell distributed shading and distributed short column shading. Fig. 4 illustrates the pictorial representation of the real time possibility of occurrence of partial shading conditions for both PPVM and BPVM.

The occurrence of the shading ratio on the module considered for the study varies between 0% and 100%. The performance of the modules is analyzed in terms of the percentage of power extraction, percentage power loss and power extraction per meter square.

3.1.1. Case 1

For case 1, various shading patterns are considered with different shading ratios on the polycrystalline and front side of the BPVM, as shown in Fig. 5(ca- cn). The rear side of the BPVM was considered unshaded.

3.1.2. Case 2

For case 2, various shading patterns are created with different shading ratios on the rear side of the BPVM, as shown in Fig. 6(ca – cn). The front of the polycrystalline and BPVM is considered unshaded.

3.1.3. Case 3

For case 3, various shading patterns are considered with a similar shading ratio on the front and rear sides of the BPVM as shown in Fig. 7 (ca - cn). Here, a similar shading pattern is assumed to occur on the PPVM and both sides of the BPVM.

3.1.4. Case 4

For case 4, various shading patterns are created with different shading ratios on the front and rear sides of the BPVM, as shown in Fig. 8 (ca - cn). Here, the shading patterns on the front side of polycrystalline and BPVMs are identical and the rear side of the BPVM are different.

3.2. Performance parameters

This section describes the performance assessment of a polycrystalline and BPVM that offers superior performance under partial shading conditions. The performance of the modules is analyzed in terms of the percentage of power extraction, percentage power loss and power extraction per meter square. The performance parameters can be expressed as follows [21].

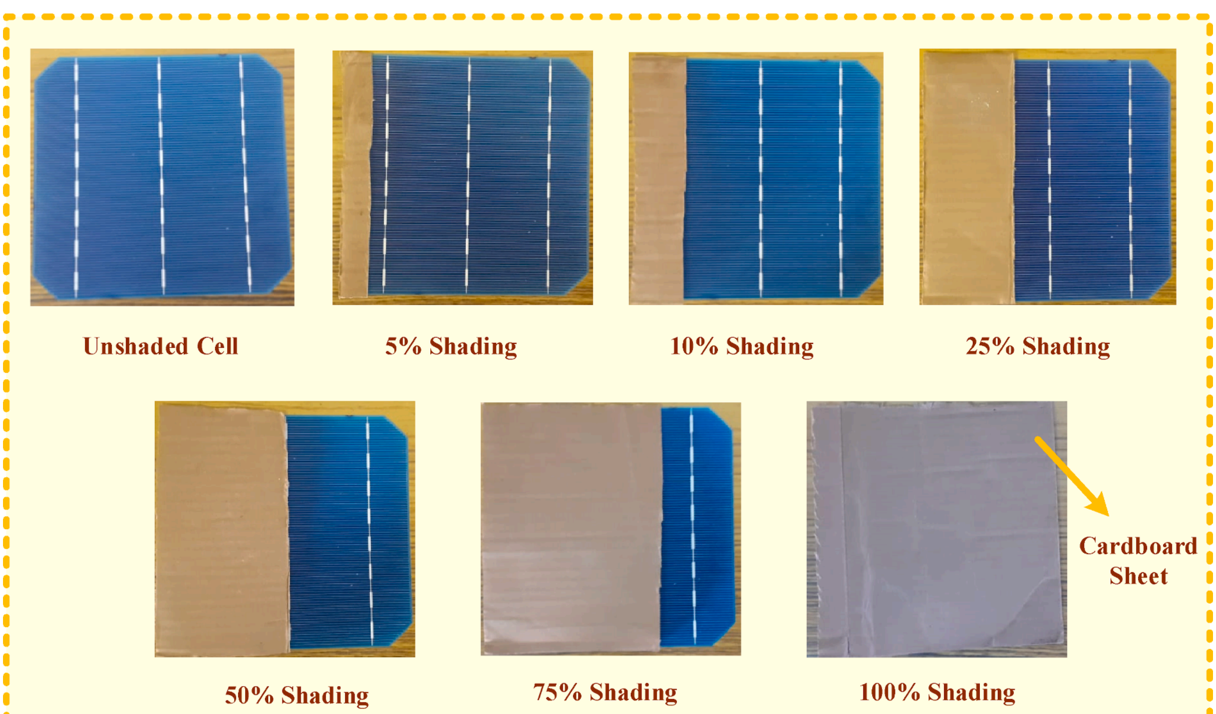


Fig. 3. Implementation of partial shading scenario in solar PV cell.

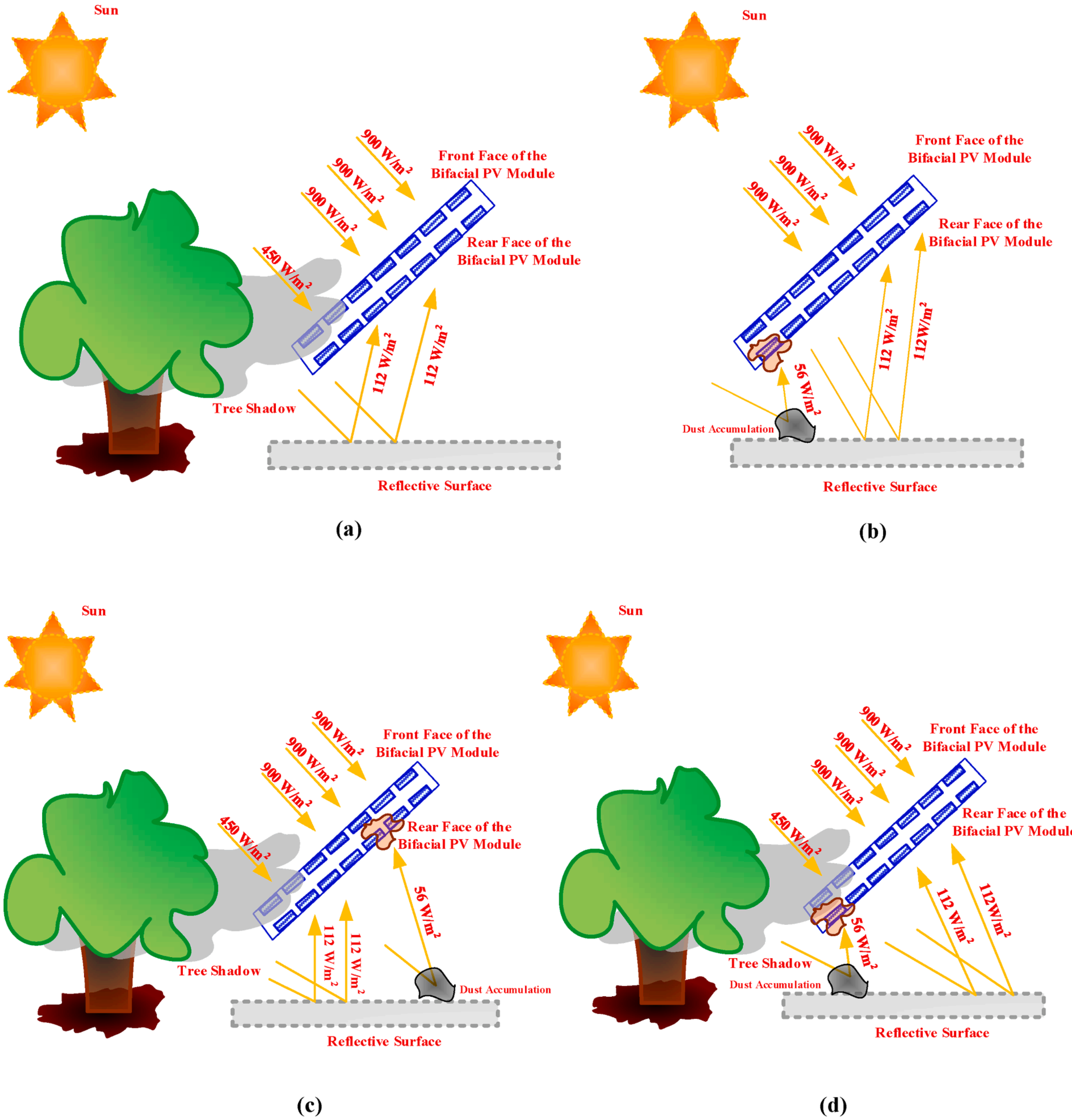


Fig. 4. Possibility of the partial shading scenario in the real time. (a) Front side shading only, (b) Rear side shading only, (c) Both front side and rear side shading in different places & (d) Both front side and rear side shading in the same place.

3.2.1. Percentage of power extraction

The percentage of power extraction is defined as the percentage ratio of the maximum power to the partial shading condition to the maximum power at the standard test condition.

$$\text{Percentage power extraction} = \frac{G(\text{Partial shading condition})}{G(\text{Standard test condition})} \times 100 \tag{4}$$

3.2.2. Percentage power loss

Percentage Power Loss is defined as the percentage ratio of the difference between the maximum power at the standard test condition and the maximum power at the partial shading condition to the maximum power at the standard test condition.

$$\text{Percentage power loss} = \frac{G(\text{Standard test condition}) - G(\text{Partial shading condition})}{G(\text{Standard test condition})} \times 100 \tag{5}$$

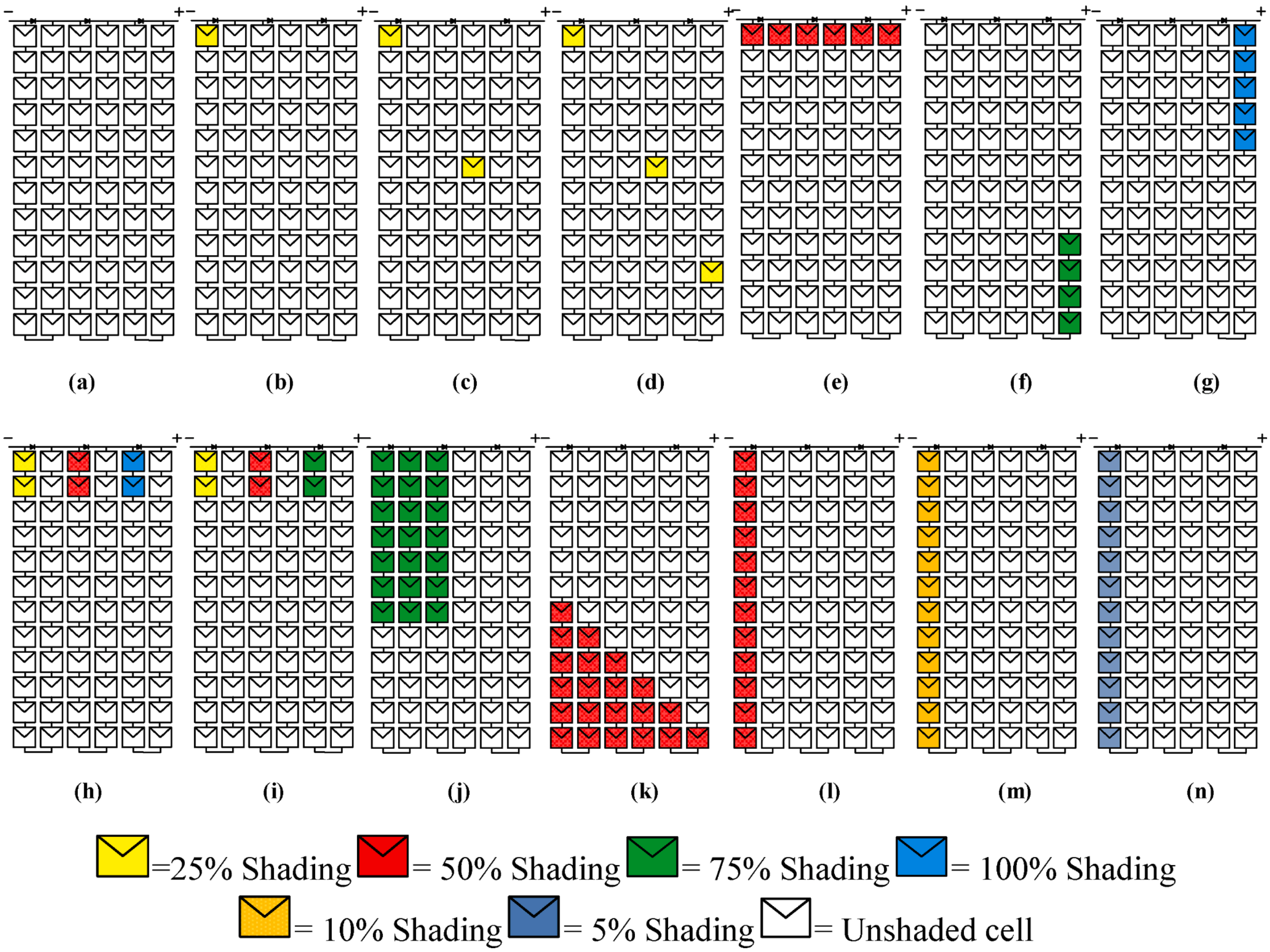


Fig. 5. Shading pattern on the PPVM and the front side of the BPVM: (ca) PV modules under uniform irradiation condition, (cb – cd) single module distributed shading condition type – I, II, and III, (ce) row shading, (cf & cg) short column shading type – I and II, (ch – ck) distributed short column shading – I, II, III and IV, (cl – cn) column shading type – I, II and III.

3.2.3. Power extraction per meter square

Power extraction per meter square is defined as the ratio of the maximum power to partial shading conditions to the area of one cell of the module.

$$\text{Power extraction per meter square} = \frac{G(\text{Partial shading condition})}{A} \quad (6)$$

where,

G (Standard test condition) be the irradiation level at standard test condition.

G (Partial shading condition) be the irradiation level at partial shading condition.

A be the area of one cell of the module.

4. Results and discussion

Performance analyses of PPVM and BPVMs with different shading patterns and shading ratios were performed. The results are presented in the form of a percentage of power extraction, percentage power loss and power extraction per meter square.

4.1. Case 1

In case 1, the shade is assumed to occur only on the front side of the PPVM and BPVM, as shown in Fig. 5. The rear side of the BPVM is considered to be unshaded. Fig. 9 shows the comparison of performance parameters and their results are shown in the Table 2.

4.1.1. Uniform irradiation condition

In solar photovoltaic module, the 100% power extraction is possible only when the module receives 1000 W/m^2 irradiation level. Here the irradiation level is 900 W/m^2. Therefore, the percentage of power extraction from the PV module is 90. For the uniform irradiation condition, the BPVM produces a power of 357 W compared to the PPVM of 288 W. Both the modules has the power extraction and power loss of 90% and 10% respectively. The BPVM has a higher power extraction of 208 W/m^2 compared to the PPVM of 167 W/m^2. During the full irradiation condition, the BPVM yielded better results because of the increase in the area of power extraction by the albedo on the rear side of the module.

4.1.2. Single module distributed shading

In the single module distributed shading type – I, PV cell 1 is shaded with a shading ratio of 25% as shown in Fig. 5(b). Table 2 represents the results for the front side shade on both the modules. The BPVM and PPVM produces a maximum power of 238 W and 192 W and also has the similar power extraction and power loss of 60% and 40%. The BPVM has a higher power extraction of 138 W/m^2 because of the unshaded rear side compared to the PPVM of 112 W/m^2.

For the type- II shading PV cells 1 and 43 were shaded with a shading ratio of 25% as shown in Fig. 5(c). The maximum power of 119 W and

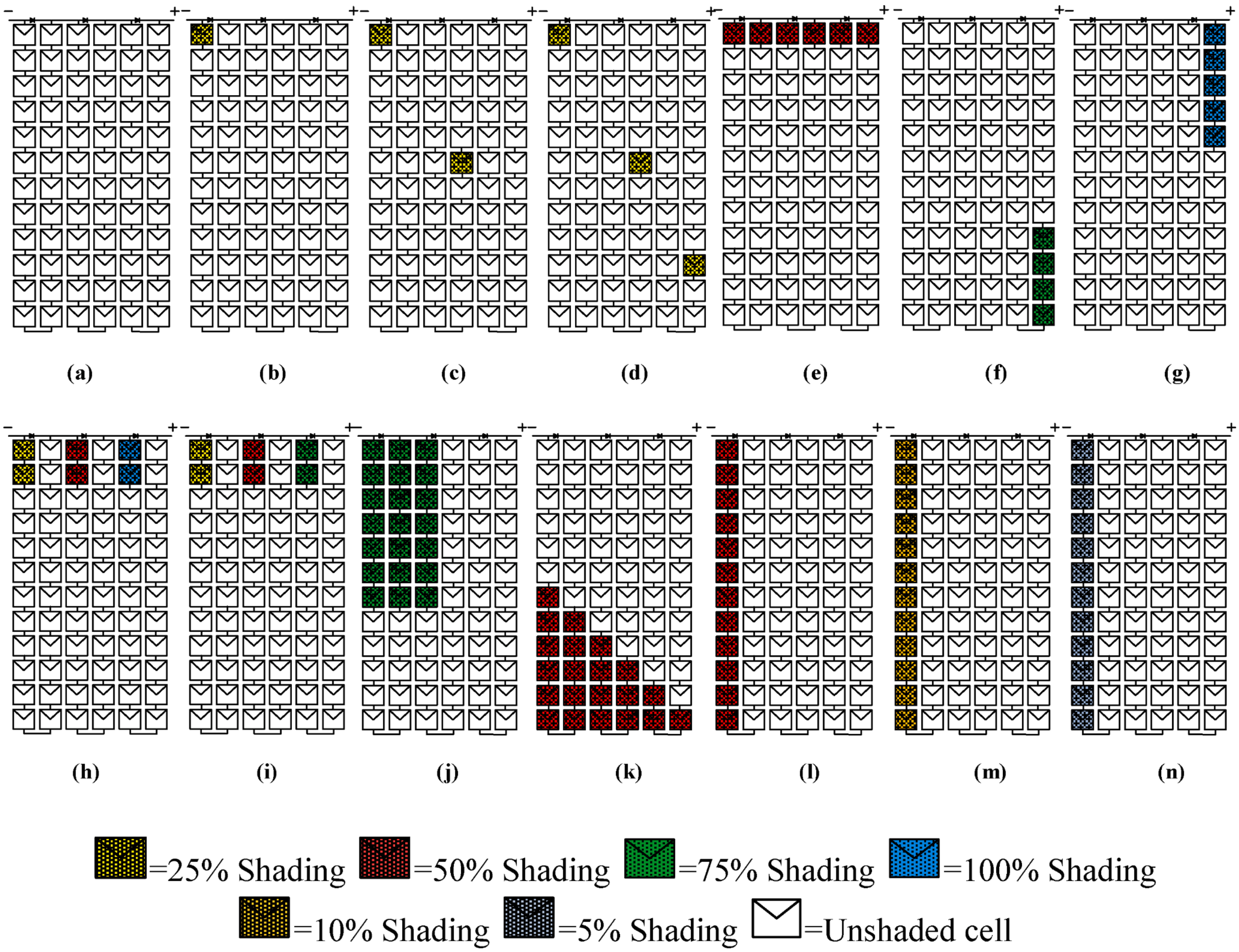


Fig. 6. Shading pattern on rear side of BPVM: (ca) PV modules under uniform irradiation condition, (cb – cd) single module distributed shading condition type – I, II, and III, (ce) row shading, (cf & cg) short column shading type – I and II, (ch – ck) distributed short column shading – I, II, III and IV, (cl – cn) column shading type – I, II and III.

96 W is produced by the BPVM and PPVM. The power extraction and power loss of 30% and 70% is produced by both the modules. The BPVM has a power extraction of 69 W/m^2 compared to the PPVM of 56 W/m^2.

Under the single module distributed shading type – III, PV cells 1, 43 and 63 are shaded with a shading ratio of 25% as shown in Fig. 5(d). The BPVM generates a maximum power of 277 W, followed by the PPVM of 216 W. The BPVM had percentage power extraction and percentage power loss of 70% and 30% followed by the PPVM by 68% and 33%. The BPVM has a power extraction of 161 W/m^2 compared to the PPVM of 126 W/m^2.

For the single module distributed shading types, the number of cells which are shaded varies in each shading type. If one cell in all strings is shaded, more output power is generated compared to one cell shaded in each string.

4.1.3. *Row shading*

In row shading type – I, the PV cells 1, 24, 25, 48, 49 and 72 connected in the first row are subjected to shade with a shading ratio of 50% as shown in Fig. 5(e). The BPVM generates a maximum power of 196 W compared to PPVM by 144 W. The BPVM has improved the power extraction to 50% and reduce the power loss by 50%. Also, the BPVM has enhanced the power extraction to 114 W/m^2.

4.1.4. *Short column shading*

In the short column shading type – I, the PV cells 61, 62, 63 and 64 in the third string is subjected to shade with a shading ratio of 75% Fig. 5 (f). The BPVM produces a maximum power of 238 W in comparison with PPVM by 192 W. Because of the occurrence of similar shading pattern on the front surface of both the modules, the percentage power extraction and percentage power loss is obtained as 60% and 40% respectively. The BPVM has a maximum power extraction per meter square of 138 W/m^2 because of the power generation by the rear side.

For the short column shading type – II, the PV cells 69, 70, 71 and 72 in the third string is subjected to shade with a shading ratio of 100% as shown in Fig. 5(g). The power developed from the BPVM is 238 W followed by the PPVM of 192 W. The percentage power extraction and percentage power loss of both the modules is 60% and 40% respectively. The BPVM has a power extraction per meter square of 138 W/m^2 compared to the PPVM of 112 W/m^2.

Here, the shading pattern on both modules are identical with a different shading ratio. Both the module has generated a similar maximum power and the variation in the shading ratio does not impact on the output power.

4.1.5. *Distributed short column shading*

In the distributed short column shading type – I and II, the PV cells 1 & 2 in string 1, 25 & 26 in string 2 and 49 & 50 in the string 3 is subjected to shade with shading ratio of 25%, 50%, 75% and 100% Fig. 5(h, i). The BPVM and PPVM produces a maximum power of 92 W and 72 W. The BBPVM and PPVM modules has a similar power extraction of 23% and

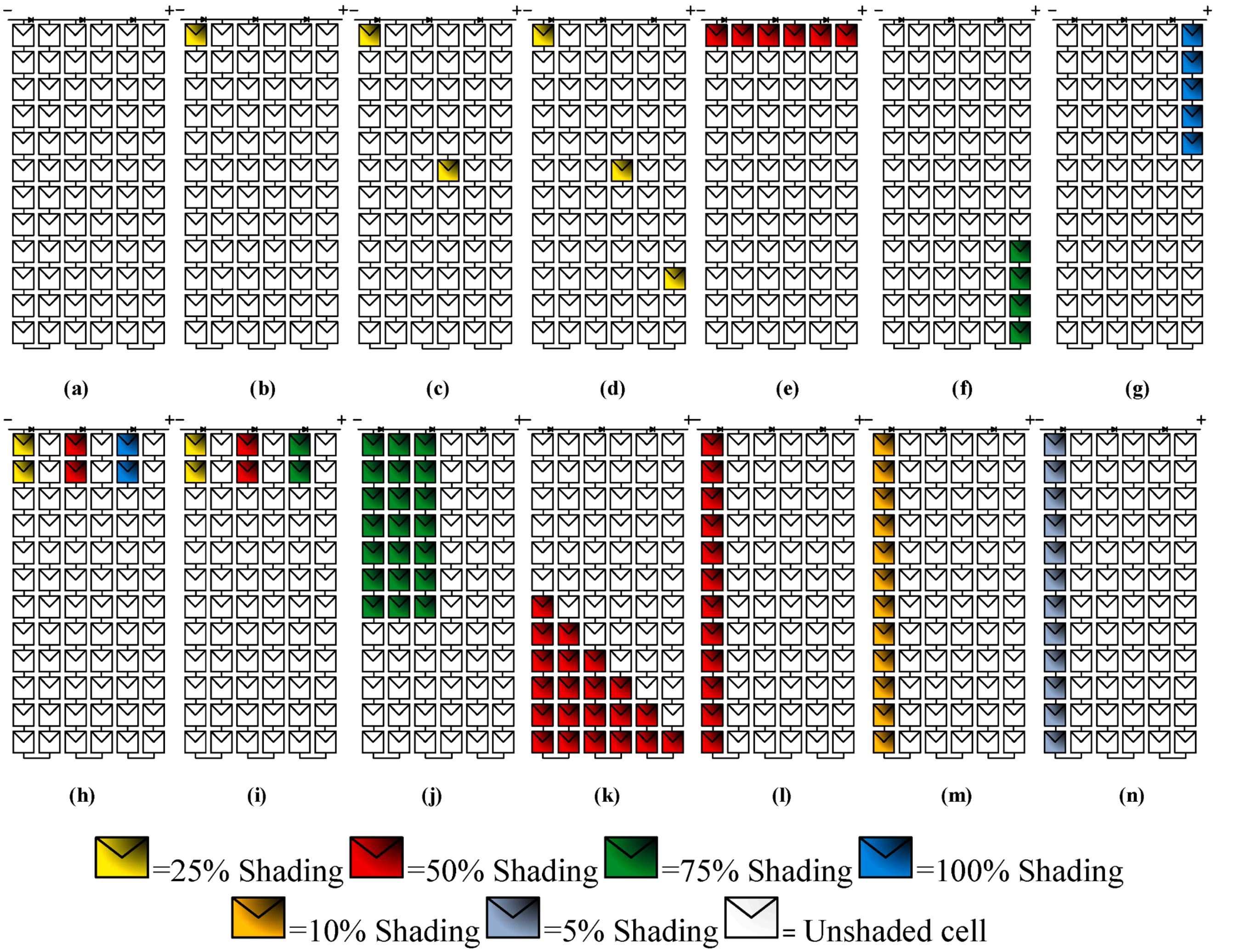


Fig. 7. Shading pattern on PPVM and both sides of BPVM: (ca) PV modules under uniform irradiation condition, (cb – cd) single module distributed shading condition type – I, II, and III, (ce) row shading, (cf & cg) short column shading type – I and II, (ch – ck) distributed short column shading – I, II, III and IV, (cl – cn) column shading type – I, II and III.

the power loss of 77% and 78% respectively. Also, the power extraction of BPVM is 53 W/m^2 compared to the PPVM of 42 W/m^2. With the similar pattern and the variation in shading intensity does not has an impact on the output power of the modules.

For the distributed short column shading type – III, the PV cells 1 to 7 in the string 1, 18 to 24 in string 2 and 25 to 31 in the string 3 are shaded with a shading ratio of 75% as shown in Fig. 5(j). The BPVM produces a maximum power of 119 W and PPVM of 96 W. Both the modules has percentage power extraction and percentage power loss of 30% and 70% respectively. Because of the ability to generate power on the rear side, the BPVM has a higher power extraction per meter square of 69 W/m^2. Here, the output power decreases with an increase in the number of series-connected PV cells.

In distributed short column shading type – IV, the PV cells connected in the bottom diagonal are shaded with a shading ratio of 50% as Fig. 5 (k). The BPVM and PPVM produces a maximum power of 196 W and 144 W. The BPVM has the highest power extraction of 50% and lowest power loss of 55%. The BPVM has a power extraction per meter square of 114 W/m^2 compared to the PPVM of 84 W/m^2. Here, the output power of both the PV modules is increased compared to the distributed short column shading type- III because the number of series-connected PV cells varies with strings. Here, the number of shaded series cells is less compared to distributed short column shading type – III and therefore it produces more output power.

4.1.6. Column shading

In column shading type – I, the series-connected PV cells 1 to 12 connected in the first column is shaded with a shading ratio of 50% as shown in Fig. 5(l). The BPVM produced a maximum power of 238 W, followed by the PPVM of 192 W. Both the modules have percentage power extraction and percentage power loss of 60% and 40% respectively. The BPVM has a power extraction of 138 W/m^2 compared to the PPVM of 112 W/m^2.

In column shading type – II, the PV cells 1 to 12 connected in the first column are shaded with a shading ratio of 10% as shown in Fig. 5(m). The BPVM produced a maximum power of 324 W, followed by the PPVM of 173 W. The BPVM had percentage power extraction and percentage power loss of 82% and 18% followed by the PPVM of 54% and 46% respectively. The BPVM had a power extraction per meter square of 188 W/m^2 compared to the PPVM of 101 W/m^2. The output power decreases with the shading ratio of the series-connected PV cells in string 1.

In column shading type – III, the PV cells 1 to 12 connected in the first column are shaded with a shading ratio of 5% as shown in Fig. 5(n). The BPVM produced a maximum power of 340 W followed by the PPVM of 182 W. The BPVM has generated 32% more power than the PPVM. The BPVM has a percentage power extraction of 86% and the power loss is reduced by 14%. The BPVM has extracted power per meter square of 95%.

For the column shading conditions, cells 1 to 12 are shaded with

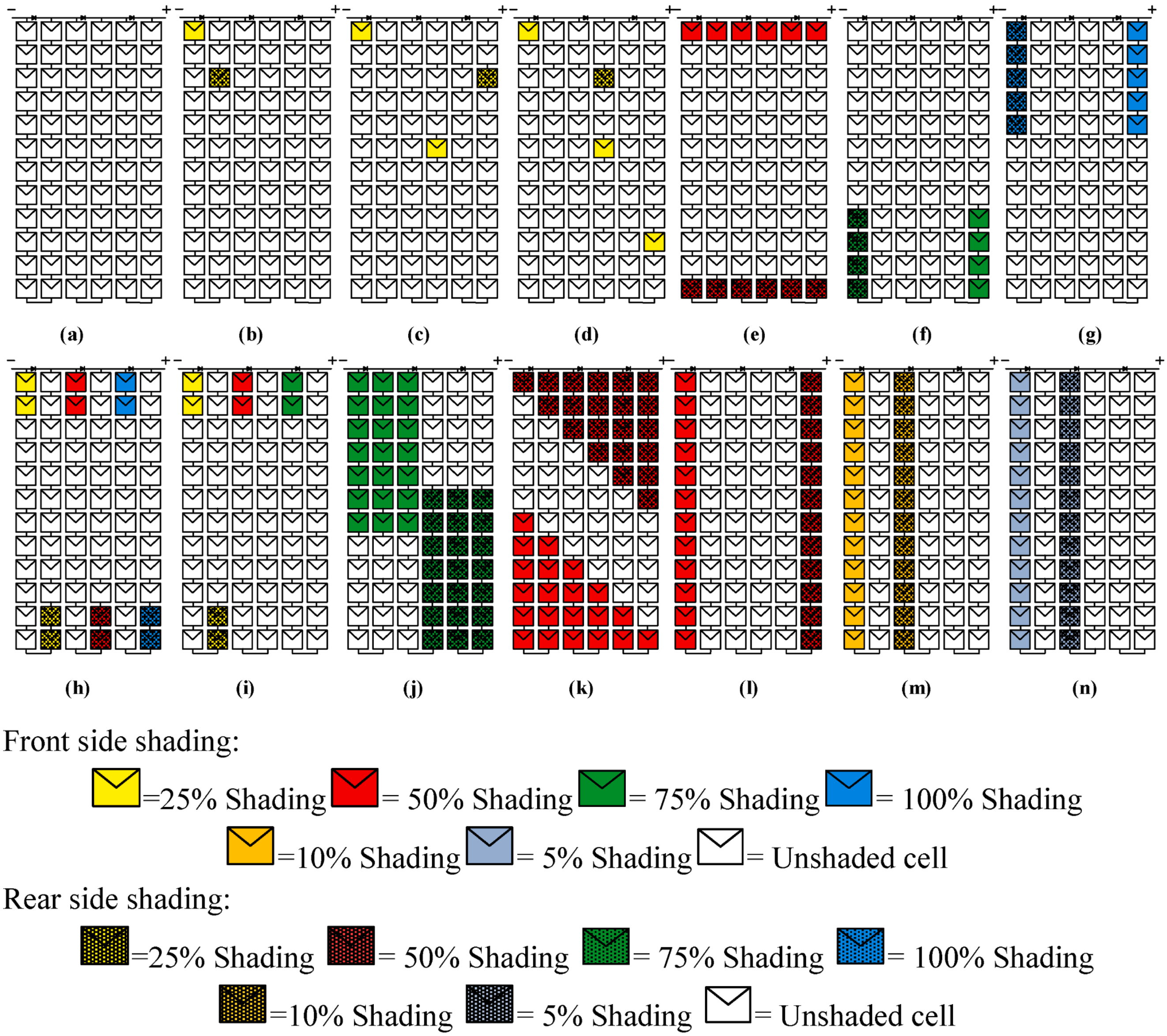


Fig. 8. Identical shading pattern on the front side of polycrystalline and BPVM with different shading patterns on the rear side of BPVM: (ca) PV modules under uniform irradiation condition, (cb – cd) single module distributed shading condition type – I, II, and III, (ce) row shading, (cf & cg) short column shading type – I and II, (ch – ck) distributed short column shading – I, II, III and IV, (cl – cn) column shading type – I, II and III.

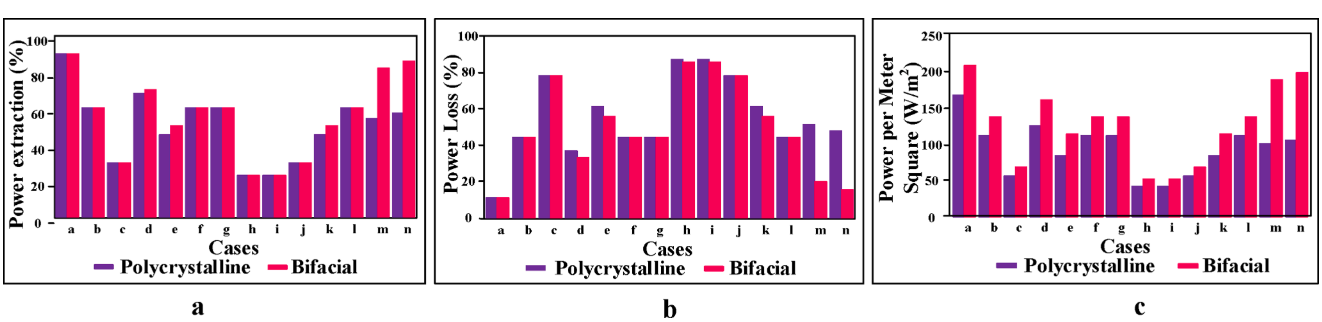


Fig. 9. Comparison of (a) percentage of power extraction (b) percentage of power loss (c) power per meter square for case 1.

Table 2
Results for the shading pattern on the front side of the polycrystalline and BPVM for case 1.

Case 1	PPVM						BPVM with shading on the front side					
	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction /m^2 (W)	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction /m^2 (W)
ca	36.58	7.88	288	90	10	167	38.3	9.32	357	90	10	208
cb	24.38	7.88	192	60	40	112	25.53	9.32	238	60	40	138
cc	12.19	7.88	96	30	70	56	12.76	9.32	119	30	70	69
cd	36.58	5.91	216	68	33	126	38.3	7.22	277	70	30	161
ce	36.58	3.94	144	45	55	84	38.3	5.13	196	50	50	114
cf	24.38	7.88	192	60	40	112	25.53	9.32	238	60	40	138
cg	24.38	7.88	192	60	40	112	25.53	9.32	238	60	40	138
ch	12.19	5.91	72	23	78	42	12.76	7.22	92	23	77	53
ci	12.19	5.91	72	23	78	42	12.76	7.22	92	23	77	53
cj	12.19	7.88	96	30	70	56	12.76	9.32	119	30	70	69
ck	36.58	3.94	144	45	55	84	38.3	5.13	196	50	50	114
cl	24.38	7.88	192	60	40	112	25.53	9.32	238	60	40	138
cm	24.38	7.09	173	54	46	101	38.3	8.47	324	82	18	188
cn	24.38	7.48	182	57	43	106	38.3	8.89	340	86	14	198

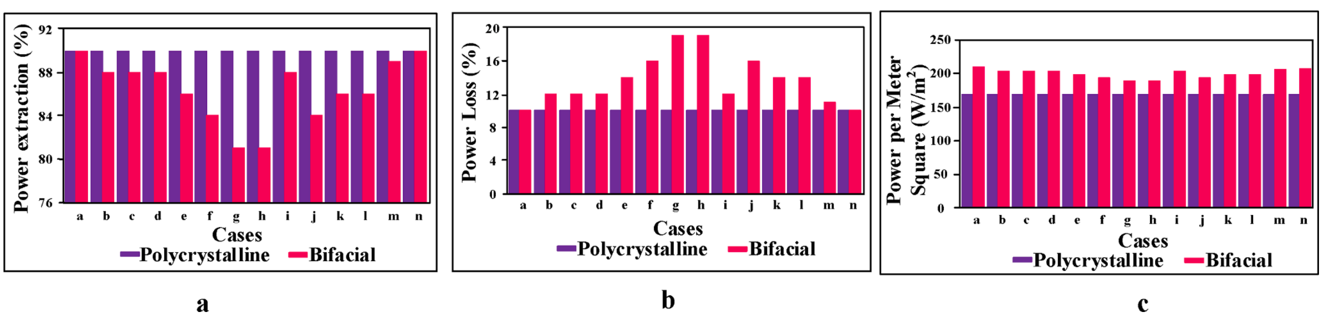


Fig. 10. Comparison of (a) percentage of power extraction (b) percentage of power loss (c) power per meter square for case 2.

Table 3
Results for the shading pattern on the PPVM and rear side of a BPVM for case 2.

Case 2	PPVM						BPVM with shading on the rear side					
	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction /m^2 (W)	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction /m^2 (W)
ca	36.58	7.88	288	90	10	167	38.3	9.32	357	90	10	208
cb	36.58	7.88	288	90	10	167	38.3	9.09	348	88	12	202
cc	36.58	7.88	288	90	10	167	38.3	9.09	348	88	12	202
cd	36.58	7.88	288	90	10	167	38.3	9.09	348	88	12	202
ce	36.58	7.88	288	90	10	167	38.3	8.84	339	86	14	197
cf	36.58	7.88	288	90	10	167	38.3	8.61	330	84	16	192
cg	36.58	7.88	288	90	10	167	38.3	8.38	321	81	19	187
ch	36.58	7.88	288	90	10	167	38.3	8.38	321	81	19	187
ci	36.58	7.88	288	90	10	167	38.3	9.09	348	88	12	202
cj	36.58	7.88	288	90	10	167	38.3	8.61	330	84	16	192
ck	36.58	7.88	288	90	10	167	38.3	8.84	339	86	14	197
cl	36.58	7.88	288	90	10	167	38.3	8.84	339	86	14	197
cm	36.58	7.88	288	90	10	167	38.3	9.22	353	89	11	205
cn	36.58	7.88	288	90	10	167	38.3	9.27	355	90	10	206

different shading ratios, the output power increases with a reduction in the shading ratio.

4.2. Case 2

In case 2, the shade is assumed to occur only on the rear sides of the BPVM and the front side of both the modules is unshaded as shown in Fig. 6. Since the front side of the PPVM is unshaded it produces the maximum power, percentage power extraction and power loss of 288 W, 90% and 10% for all the shading conditions. Fig. 10 shows the comparison of performance parameters and their results are recorded in the Table 3.

4.2.1. Uniform irradiation condition

For the uniform irradiation condition, the both the module produces its maximum power of 357 W and 288 W as shown in Fig. 6(a). Also, obtained a similar power extraction and power loss of 90% and 10% respectively. The BPVM has a higher power extraction per meter square of 208 W/m^2 compared to the PPVM of 167 W/m^2. The increase in power extraction is because of the increase in the area of power extraction by the albedo on the rear side of the module.

4.2.2. Single module distributed shading

Under the single module distributed shading, type I - PV cell 1 is shaded, for type II – PV cells 1 and 43 is shaded, for type III - PV cells 1, 43 and 63 are shaded with a shading ratio of 25% as shown in Fig. 6(b -

d). For the above three cases, the BPVM produced power of 348 W. The PPVM has obtained highest power extraction of 90% and lowest power loss of 10%. The BPVM has a power extraction of 202 W/m^2 compared to the PPVM of 167 W/m^2. The increase in the number of shaded cells on the rear side have a significant impact on the output power.

4.2.3. Row shading

In row shading type – I, the PV cells 1, 24, 25, 48, 49 and 72 connected in the first row is subjected to shade with a shading ratio of 25% as shown in Fig. 6(e). The BPVM produces a maximum power of 339 W and PPVM by 288 W. The PPVM has improves the power extraction to 90% and reduces the power loss by 10%. The BPVM has the power extraction of 197 W/m^2.

4.2.4. Short column shading

For the short column shading type – I, the PV cells 61, 62, 63 and 64 is shaded with a shading ratio of 75% and for the short column shading type – II the PV cells 69, 70, 71 and 72 is shaded with a shading ratio of 100% as shown in Fig. 6(f, g). For both the cases the BPVM produces the output power of 330 W and 321 W. The reduction in the output power is because of the increase in the shading ratio. The PPVM has obtained highest power extraction and lowest power loss of 90% and 10% respectively. The BPVM has high power extraction of 192 W/m^2 compared with the PPVM by 167 W/m^2.

4.2.5. Distributed short column shading

For the distributed short column shading type – I & II, the PV cells 1 & 2, 25 & 26 and 49 & 50 is subjected to shading ratio of 25%, 50%, 75% and 100% (Fig. 6(h, i)). The BPVM produced a power of 321 W and 348 W. The distributed short column shading type – II has higher power extraction of 202 W/m^2 compared to distributed short column shading type – I by 53 W/m^2 followed by the PPVM by 42 W/m^2.

In distributed short column shading type – III, the PV cells 1 to 7, 18 to 24 and 25 to 31 is shaded with a shading ratio of 75% Fig. 6(j). The BPVM produces a maximum power of 330 W and has power extraction and power loss of 84% and 16% compared to PPVM by 90% and 10% respectively. The BPVM had a power extraction of 192 W/m^2 compared with the PPVM by 167 W/m^2.

Under the distributed short column shading type – IV, the PV cells connected in the bottom diagonal is shaded with a shading ratio of 50% Fig. 6(k). The BPVM produced a maximum power of 339 W. Here, the output power of BPVM drops by 54%. The PPVM has obtained power extraction and power loss of 90% and 10% respectively. The BPVM has a power extraction of 197 W/m^2 compared to the PPVM by 167 W/m^2. Here, the output power of the module is increased compared to the distributed short column shading type- III because the reduction in the number of series-connected PV cells varies with strings.

4.2.6. Column shading

The PV cells 1 to 12 in the first string is shaded of 50% for the column shading type I followed by the column shading type – II and III by 10% and 5% Fig. 6(l – n). The BPVM produces a maximum power of 339 W, 353 W and 355 W for the cases I, II and III. The PPVM has superior percentage power extraction and power loss of 90% and 10%. However, the power extraction per meter square of increases with the reduction in the intensity of the shade.

4.3. Case 3

For case 3, a similar shading pattern is assumed to occur on the PPVM and both the sides of the BPVM, as shown in Fig. 7. Fig. 11 shows the comparison of performance parameter and its results are tabulated in the Table 4.

4.3.1. Uniform irradiation condition

For the uniform irradiation condition, the BPVM produced a power of 324 W compared to the PPVM of 288 W (Fig. 7(a)). The BPVM had percentage power extraction and percentage power loss of 82 and 18 followed by the PPVM of 90% and 10% respectively. The BPVM has a higher power extraction per meter square of 188 W/m^2 compared to the PPVM of 167 W/m^2.

During the full irradiation condition, the BPVM yielded better results because of the increase in the area of power extraction by the albedo on the rear side of the module.

4.3.2. Single module distributed shading

In the single module distributed shading type PV cells 1, 43 and 63 is shaded with the shading ratio of 25% as shown in Fig. 7(b-d). The BPVM produces output power of 211 W, 105 W and 243 W for the single module distributed shading type I, II and III. The reduction in power extraction and increase in power loss depends on the cells shaded. The BPVM of type- I has obtained power extraction of 123 W/m^2 followed by the type- II and III by 61 W/m^2 and 141 W/m^2.

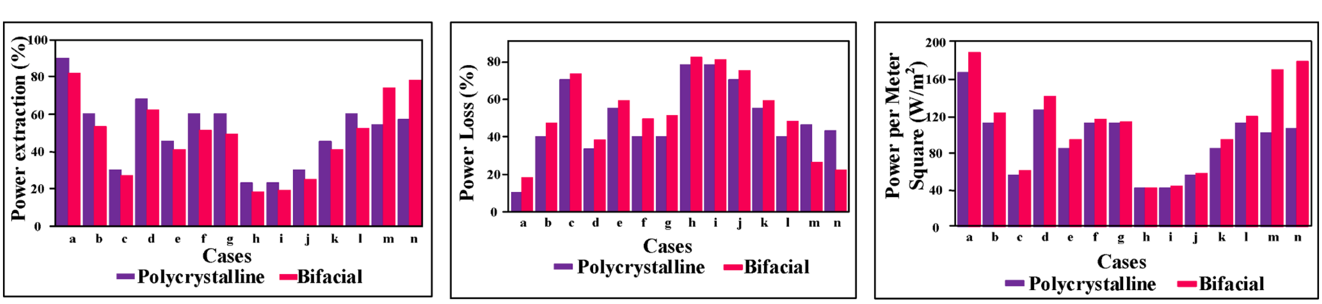
For the single module distributed shading types, the number of cells shaded varies in each case. If one cell in all strings is shaded, more output power is generated compared to one cell shaded in string 1, string 1 and string 2.

4.3.3. Row shading

For the row shading type – I, the PV cells 1, 24, 25, 48, 49 and 72 connected in the first row is subjected to shade with a shading ratio of 25% (Fig. 7(e)). The BPVM produced a maximum power of 162 W, followed by the PPVM by 144 W. The BPVM has lowest power extraction of 41 and higher power loss of 59 because of the occurrence of shade on both modules. The BPVM has higher power extraction per meter square of 94 W/m^2 compared to the PPVM of 84 W/m^2.

4.3.4. Short column shading

In the short column shading type – I, the PV cells 61, 62, 63 and 64 is subjected to shade with a shading ratio of 50% as shown in Fig. 7(f). The BPVM produces a maximum power of 200 W followed and PPVM by 192 W. The BPVM has power extraction of 51% and power loss of 49%



a b c

Fig. 11. Comparison of (a) percentage of power extraction (b) percentage of power loss (c) power per meter square for case 3.

Table 4
Results for the identical shading pattern on PPVM and both sides of BPVM of case 3.

Case 3	PPVM						BPVM with identical shading pattern on both sides					
	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction / m^2 (W)	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction / m^2 (W)
ca	36.58	7.88	288	90	10	167	38.3	9.32	324	82	18	188
cb	24.38	7.88	192	60	40	112	25.53	9.09	211	53	47	123
cc	12.19	7.88	96	30	70	56	12.76	9.09	105	27	73	61
cd	36.58	5.91	216	68	33	126	38.3	6.99	243	62	38	141
ce	36.58	3.94	144	45	55	84	38.3	4.65	162	41	59	94
cf	24.38	7.88	192	60	40	112	25.53	8.61	200	51	49	116
cg	24.38	7.88	192	60	40	112	25.53	8.38	195	49	51	113
ch	12.19	5.91	72	23	78	42	12.76	6.28	73	18	82	42
ci	12.19	5.91	72	23	78	42	12.76	6.51	76	19	81	44
cj	12.19	7.88	96	30	70	56	12.76	8.61	100	25	75	58
ck	36.58	3.94	144	45	55	84	38.3	4.65	162	41	59	94
cl	24.38	7.88	192	60	40	112	25.53	8.84	205	52	48	119
cm	24.38	7.09	173	54	46	101	38.3	8.38	292	74	26	170
cn	24.38	7.48	182	57	43	106	38.3	8.84	308	78	22	179

followed by the PPVM of 60% and 40% respectively. The BPVM has a power extraction per meter square of 116 W/m^2 compared to the PPVM of 112 W/m^2.

In short column shading type – II, the PV cells 69, 70, 71 and 72 is shaded with a shading ratio of 75% as shown in Fig. 7(g). The BPVM produces a maximum power of 195 W and PPVM of 192 W. The BPVM has power extraction and percentage power loss of 49% and 51% followed by the PPVM of 60 and 40, respectively. The BPVM has a power extraction per meter square of 113 W/m^2 compared to the PPVM of 112 W/m^2.

The performance of both the modules for the short column shading type pattern – I and II are almost similar. The variation in the shading ratio in the PV cells connected in the column has almost similar impacts on the output power of both the modules.

4.3.5. *Distributed short column shading*

In distributed short column shading type – I and II, the PV cells 1 & 2, 25 & 26 and 49 & 50 is subjected to shade with shading ratios of 25%, 50%, 75% and 100% as shown in Fig. 7(h,i). The performance of PPVM is found to be superior because of the improved power extraction and reduction in power loss compared to BPVM. The power extraction per meter increases with the reduction in shading intensity.

For the distributed short column shading type – III, the PV cells 1 to 7, 18 to 24 and 25 to 31 is shaded with a shading ratio of 75% as shown in Fig. 7(j). The BPVM and PPVM produces a maximum power of 100 W and 96 W. The PPVM has power extraction and power loss of 30% and 70%, followed by the BPVM by 25% and 75% respectively. The PPVM has enhanced the power extraction of 70 W/m^2 compared to the BPVM by 58 W/m^2.

In distributed short column shading type – IV, the PV cells connected to the bottom side of the diagonal are shaded with a shading ratio of 50% as shown in Fig. 7(k). The BPVM produces a maximum power of 162 W and PPVM produces 144 W. The PPVM improves power extraction and reduces by 45% and 55% followed by the BPVM by 41% and 59%. With the higher power extraction of 94 W/m^2 obtained by the BPVM compared to PPVM by 84 W/m^2. The BPVM has the higher power loss.

4.3.6. *Column shading*

In column shading type – I, II & III the PV cells 1 to 12 with a shading ratio of 5, 10 % and 50% as shown in Fig. 7(l-n). The BPVM produced a maximum power of 205 W for the column shading type- I, followed by the column shading type II & III by 292 W and 308 W. The power extraction and power loss depend on the shading ratio. The BPVM has the higher power extraction of 179 W/m^2 followed by the type II, I by 170 W/m^2 and 119 W/m^2. For the column shading conditions, cells 1 to 12 are shaded with different shading ratios, the output power increases with a reduction in the shading ratio.

4.4. *Case 4*

In case 4, the identical shading pattern is assumed to occur on the PPVM and front side of the BPVM and a different shading pattern on the rear side of the BPVM as shown in Fig. 8. A comparison of the performance parameters is illustrated in Fig. 12 and the results are recorded in the Table 5.

4.4.1. *Uniform irradiation condition*

For the uniform irradiation condition, the BPVM produces maximum power of 324 W compared to the PPVM of 288 W Fig. 8(a). The PPVM has power extraction and power loss of 90% and 10% followed by the BPVM by 82% and 18% respectively. The BPVM has a higher power extraction per meter square of 188 W/m^2 compared to the PPVM of 167 W/m^2.

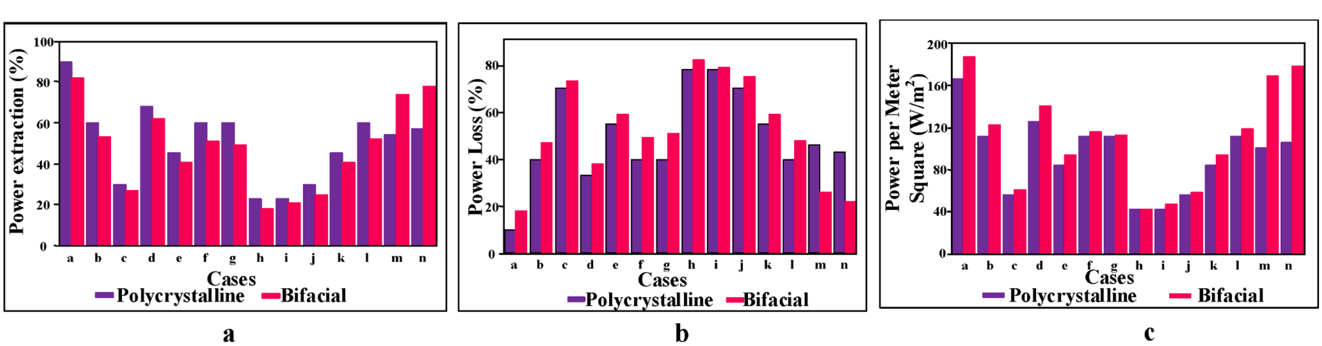


Fig. 12. Comparison of (a) percentage of power extraction (b) percentage of power loss (c) power per meter square for case 4.

Table 5
Results for the identical shading pattern on PPVM & front side of BPVM and different shading pattern and shading ratio on the rear side for case4.

Case 4	PPVM						BPVM with different shading patterns on the front and rear side					
	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction / m^2 (W)	V_m (V)	I_m (A)	P_m (W)	% Power Extraction (%)	% Power Loss (%)	Power Extraction / m^2 (W)
ca	36.58	7.88	288	90	10	167	38.3	9.32	324	82	18	188
cb	24.38	7.88	192	60	40	112	25.53	9.09	211	53	47	123
cc	12.19	7.88	96	30	70	56	12.76	9.09	105	27	73	61
cd	36.58	5.91	216	68	33	126	38.3	6.99	243	62	38	141
ce	36.58	3.94	144	45	55	84	38.3	4.65	162	41	59	94
cf	24.38	7.88	192	60	40	112	25.53	8.61	200	51	49	116
cg	24.38	7.88	192	60	40	112	25.53	8.38	195	49	51	113
ch	12.19	5.91	72	23	78	42	12.76	6.28	73	18	82	42
ci	12.19	5.91	72	23	78	42	12.76	6.99	81	21	79	47
cj	12.19	7.88	96	30	70	56	12.76	8.61	100	25	75	58
ck	36.58	3.94	144	45	55	84	38.3	4.65	162	41	59	94
cl	24.38	7.88	192	60	40	112	25.53	8.84	205	52	48	119
cm	24.38	7.09	173	54	46	101	38.3	8.38	292	74	26	170
cn	24.38	7.48	182	57	43	106	38.3	8.84	308	78	22	179

4.4.2. Single module distributed shading

For the single module distributed shading type – I PV cell 1 is shaded on the front side and PV cell 22 is shaded on the rear side with a shading ratio of 25% Fig. 8(b). The BPVM produces a maximum power of 211 W and PPVM of 192 W. The BPVM has superior power extraction and lower of 60% and 40% compared to BPVM. The BPVM has a higher power extraction BPVM is 123 W/m^2 compared to the PPVM by 112 W/m^2.

In the single module distributed shading type – II, PV cells 1 and 43 is shaded on the front side and PV cell 70 is shaded on the rear side with a shading ratio of 25% (Fig. 8(c)). The BPVM and PPVM produces maximum power of 105 W and 96 W. The PPVM has power extraction and power loss of 30% and 70% compared to 27% and 73% for BPVM. The BPVM has a power extraction of 61 W/m^2 compared to the PPVM of 56 W/m^2.

Under the single module distributed shading type – III, PV cells 1, 43 and 63 is subjected shade on the front side and PV cell 46 is shaded on the rear side with a shading ratio of 25% (Fig. 8(d)). The BPVM and PPVM produces a maximum power of 243 W and 216 W. The PPVM has power extraction and power loss of 68% and 33% followed by the BPVM by 68% and 33% respectively. The BPVM has a power extraction of 141 W/m^2 compared to the PPVM by 126 W/m^2. For the single module distributed shading types, the performance of both the modules in cases 3 and 4 is similar.

4.4.3. Row shading

Under the row shading, the PV cells 1, 24, 25, 48, 49 and 72 is shaded on the front side and PV cells 12, 13, 36, 37, 60 and 61 is shaded on the rear side with a shading ratio of 50% (Fig. 8(e)). The BPVM and PPVM produces a maximum power of 162 W and 144 W. The PPVM has highest power extraction and lower power loss of 45% and 55% followed by the BPVM by 41 and 59 respectively. The BPVM has a power extraction per meter square of 94 W/m^2 compared to the PPVM of 84 W/m^2.

4.4.4. Short column shading

In the short column shading type – I, the series-connected PV cells 9 to 12 is subjected shade on the front side and the PV cells 61 to 64 is shaded with a shading ratio of 75% ((Fig. 8(f)). The BPVM produced a maximum power of 200 W and PPVM of 192 W. The BPVM has higher power extraction of 51% and power loss of 49%. The BPVM has a power extraction per meter square of 116 W/m^2 compared to the PPVM of 112 W/m^2.

For the short column shading type – II, the series-connected PV cells 1 to 4 is shaded on the front side and PV cells 69 to 72 is shaded with a shading ratio of 100% (Fig. 8(g)). The BPVM and PPVM produces a maximum power of 195 W and 192 W. The PPVM has superior power extraction of 60% and power loss of 40%. The power extraction per meter square of both the modules is almost similar. The performance of both the modules for the short column shading type pattern – I and II is almost similar to case 3.

4.4.5. Distributed short column shading

In distributed short column shading type – I, the PV cells 1, 2, 25, 26, 49 and 50 are shaded on the front side and PV cells 13, 14, 7, 38, 61 and 62 are shaded on the rear side with shading ratios of 25%, 50% and 100% (Fig. 8(h)). The BPVM and PPVM produces a similar maximum power of 73 W and 72 W. The BPVM has power extraction and power loss of 18 % and 82%, followed by the PPVM by 23% and 78% respectively. The BPVM has a power extraction of 42 W/m^2 compared to the PPVM by 78 W/m^2.

Under the distributed short column shading type – II, the PV cells 1, 2, 25, 26, 49 and 50 is shaded on the front side with a shading ratio of 25%, 50% and 75% (Fig. 8(i)). The PV cells 13 and 14 is shaded on the rear side with a shading ratio of 25%. The BPVM produced a maximum power of 76 W, and PPVM produces power of 72 W. The PPVM has power extraction and power loss of 23% and 78% compared to PPVM by 19% and 81%. The BPVM has a power extraction per meter square of 44 W/m^2 compared to the PPVM of 42 W/m^2.

In the distributed short column shading type – III, the PV cells 1 to 7, 18 to 24 and 25 to 31 are shaded on the front side and PV cells 37 to 43, 54 to 60 and 61 to 67 are shaded on the rear side with a shading ratio of 75% (Fig. 8(j)). The maximum power of 100 W and 96 W is produced BPVM and PPVM respectively. The PPVM has power extraction and power loss of 30% and 70% compared BPVM by 25% and 75%. The PPVM has a power extraction of 70 W/m^2 compared to the BPVM by 58 W/m^2.

Under the distributed short column shading type – IV, the PV cells connected in the bottom side of the diagonal is shaded on the front and PV cells on the top side of the diagonal is shaded on the rear side with a shading ratio of 50% (Fig. 8(k)). The BPVM and PPVM produces a maximum power of 162 W and 144 W. The PPVM has superior power extraction of 45% and lesser power loss of 55%. The BPVM has a power extraction per meter square of 94 W/m^2 compared to the PPVM of 84 W/m^2. The output power of both the PV modules is higher than to the distributed short column shading type- III because the number of series-connected PV cells varies with strings.

4.4.6. Column shading

For the column shading type – I, the series-connected PV cells 1 to 12 is shaded on the front side and PV cells 61 to 72 is shaded on the rear side with a shading ratio of 50% (Fig. 8 (l)). The BPVM produces a maximum power of 205 W and PPVM by 192 W. The BPVM has a power extraction and power loss of 60% and 40% followed by the PPVM by 52% and 48% respectively. The BPVM has a high power extraction of 119 W/m^2 compared to the PPVM by 112 W/m^2.

Under the column shading type – II and III, the series-connected PV cells 1 to 12 is shaded on the front side and PV cells 25 to 36 are shaded on the rear side with a shading ratio of 5% and 10% (Fig. 8(m,n)) respectively. For the column shading type- II, the BPVM and PPVM produces a maximum power of 292 W and 173 W. And, for the column shading type –III, the maximum power of 308 W and 182 W is produced by the BBVM and PPVM. The power extraction and power loss of both the modules are almost similar.

In this study, the experimental results are validated with the simulated results by the equivalent circuits in the MATLAB/ SIMULINK platform.

4.5. Comparison of the performance of polycrystalline and BPVM under different partial shading patterns

For the case 1, the occurrence of shade only on the front side of both the modules. The BPVM performs superior compared to PPVM higher power extraction and lower power loss. In the case 2, the occurrence of shade was only on the rear side of the BPVM. The PPVM produced the same maximum power for all shading patterns. Here, the PPVM gives better performance compared to BPVM. The BPVM has lost its advantage of higher power generation in this case.

In case 3, the occurrence of a similar shade pattern was present on the front of the PPVM and both sides of the BPVM. The performance of the BPVM drops significantly compared to PPVM and also BPVM lost its advantages of rear-side generating power. For the case 4, the occurrence of a similar shading pattern on the front of the polycrystalline and BPVMs and a different shading pattern on the rear side of the BPVM. The performance of both the modules is identical to that of case 3.

From the experimental results, it is observed that the BPVM yields superior performance under the shading conditions. However, if the shade occurs on the rear-side of the BPVM, its performance drops slightly. Meanwhile, if the shade occurs on both sides of the BPVM, it loses the advantage of delivering superior performance and behaves like a PPVM. Hence, care should be taken during the PV installation to avoid the occurrence of shade on the rear side. Attention can be given in the installation parameters such as the junction box on the rear side, mounting frame and bracket.

5. Conclusion

This research investigates the impact of partial shading on the performances of PPVM and BPVM. It is possible for both PPVM and BPVM to exhibit partial shading on the front side, whereas BPVM can exhibit partial shading on the rear side as well. By comparing the average values for each type of shading it is identified that BPVM extracts 26% more power in the front side partial shading, 16% in rear side shading and 15% in both side partial shading when compared to polycrystalline. For the different partial shading cases BPVM generates higher power because of the arrangements to grab reflected solar energy on the rear side. There is almost no difference in performance between the PPVM and the bifacial under partial shading conditions when the rear side is partially shaded. For the front and rear side partial shading conditions, the BPVM losses its advantage of yielding more power compared to the PPVM.

- During the front side shading effect, the BPVM extracts more power than the PPVM. The BPVM extracts maximum power of 208 W per meter square area for case ca, whereas the PPVM extracts only 167 W.
- During the rear side shading effect, BPVM's power extraction is greatly reduced for high rear side partial shading whereas it is lesser for low partial shading.
- During combined shading effect with identical shading location, the BPVM extracts maximum power of 179 W per meter square area for case cn, whereas the PPVM extracts only 106 W.
- During combined shading effect with different shading location, the BPVM extracts maximum power of 170 W per meter square area for case cm, whereas the PPVM extracts only 101 W.

Further this study can be extended for various geographical locations, fast changing environmental conditions, various tilt angle, and also with various heights. The bifacial modules can deliver better performance in higher latitude locations even during partial shading conditions. The partial shading performance assessment of bifacial PV modules can be analysed for medium sized and large sized power plants with the different interconnection patters such as Series-Parallel, Bridge Link, Honey Comb, and Total Cross Tied.

CRediT authorship contribution statement

T. Hariharasudhan: Writing – original draft, Writing – review & editing. **D. Prince Winston:** Supervision, Validation. **M. Palpandian:** Visualization, Methodology. **M. Pravin:** Conceptualization, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] IEEE Staff and IEEE Staff, 2011 IEEE Energy Conversion Congress and Exposition.
[2] Allouhi A, Saadani R, Buker MS, Kousksou T, Jamil A, Rahmoune M. Energetic, economic and environmental (3E) analyses and LCOE estimation of three technologies of PV grid-connected systems under different climates. Sol Energy 2019;178:25–36. https://doi.org/10.1016/j.solener.2018.11.060.
[3] Lopez-Garcia J, Casado A, Sample T. Electrical performance of bifacial silicon PV modules under different indoor mounting configurations affecting the rear reflected irradiance. Sol Energy 2019;177:471–82. https://doi.org/10.1016/j.solener.2018.11.051.
[4] 2018 SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS. 2018. [Online]. Available from: https://www.researchgate.net/publication/324703156.
[5] Photos in the report©Shutterstock. 2016. [Online]. Available from: www.irena.org.
[6] Metz A, Fischer M, Trube J. International Technology Roadmap for Photovoltaics (ITRPV) 8 th edition: Crystalline Silicon Technology - Current Status and Outlook; 2017. [Online]. Available from: www.siemens.com/presse.
[7] Liang TS, Pravettoni M, Deline C, Stein JS, Kopecek R, Singh JP, et al. A review of crystalline silicon bifacial photovoltaic performance characterisation and simulation. Energy Environ Sci 2019;12(1):116–48.
[8] Luque A, Lorenzo E, Sala G, López-Romero S. Diffusing reflectors for bifacial photovoltaic panels. Solar Cells 1985;13(3):277–92.
[9] IEEE Electron Devices Society, IEEE Photonics Society, Institute of Electrical and Electronics Engineers, H. IEEE Photovoltaic Specialists Conference (45th : 2018 : Waikoloa, H. Kōki Denryoku Kōka no Kiso to Ōyō ni kansuru Shinpojūmu (28th : 2018 : Waikoloa, and H. European Photovoltaic Solar Energy Conference (34th : 2018 : Waikoloa. In: 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC): 10-15 June 2018.
[10] 2019 8th International Conference on Power Systems (ICPS). IEEE.
[11] Lamers MWPE, Özkalay E, Gali RSR, Janssen GJM, Weeber AW, Romijn IG, et al. Temperature effects of bifacial modules: hotter or cooler? Sol Energy Mater Sol Cells 2018;185:192–7.
[12] Padhy A, Vishal B, Verma P, Dwivedi G, Behura AK. Fabrication of parabolic trough hybrid solar PV-T collector using a-Si thin film solar cells in Indian perspective. Mater Today: Proc 2020;38:56–62. https://doi.org/10.1016/j.matpr.2020.05.652.
[13] Marion B. et al., A Practical Irradiance Model for Bifacial PV Modules Preprint A Practical Irradiance Model for Bifacial PV Modules. [Online]. Available from: http:/www.osti.gov/scitech.
[14] Hubner A, Aberle AG, Hezel R. Temperature behavior of monofacial and bifacial silicon solar cells.
[15] de Groot KM, van Aken BB. Near-field partial shading on rear side of bifacial modules. Energy Procedia 2017;124:532–9. https://doi.org/10.1016/j.egypro.2017.09.254.
[16] Raina G, Sinha S. A comprehensive assessment of electrical performance and mismatch losses in bifacial PV module under different front and rear side shading scenarios. Energy Convers Manage 2022;261:115668.
[17] Zhao C, Xiao J, Yu Y, Jaubert J-N. Accurate shading factor and mismatch loss analysis of bifacial HSAT systems through ray-tracing modeling. Solar Energy Adv 2021;1:100004. https://doi.org/10.1016/j.seja.2021.100004.

[18] Zhang Y, Yu Y, Meng F, Liu Z. Experimental investigation of the shading and mismatch effects on the performance of bifacial photovoltaic modules. IEEE J Photovoltaics 2020;10(1):296–305. https://doi.org/10.1109/JPHOTOV.2019.2949766.

[19] Bhang BG, Lee W, Kim GG, Choi JH, Park SY, Ahn HK. Power performance of bifacial c-Si PV modules with different shading ratios. IEEE J Photovoltaics 2019;9(5):1413–20. https://doi.org/10.1109/JPHOTOV.2019.2928461.

[20] Shoukry I, Libal J, Kopecek R, Wefringhaus E, Werner J. Modelling of bifacial gain for stand-alone and in-field installed bifacial PV modules. Energy Procedia 2016;92:600–8. https://doi.org/10.1016/j.egypro.2016.07.025.

[21] Prince Winston D, Karthikeyan G, Pravin M, JebaSingh O, Akash AG, Nithish S, et al. Parallel power extraction technique for maximizing the output of solar PV array. Sol Energy 2021;213:102–17.