Effects of Controlled Stationary Back Reflectors on Bifacial Photovoltaic Modules

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Effects of Controlled Stationary Back Reflectors on Bifacial Photovoltaic Modules

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Abstract — To meet increasing demand for sustainable and reliable energy solutions, the bifacial solar photovoltaics (PV) technology has the capacity to provide additional energy generation for installed power systems due to its ability to utilize both front irradiance and ground reflected light. Back reflectors have been designed to increase the power of the cell found on the rear side of the module by utilizing the intercell light passing through the module to increase the incident irradiance. The effect of back reflectors on the overall energy output of bifacial PV modules using six different profiles placed at varied distances from the plane of array (POA) is examined. This work demonstrates that a significant energy gain and cost reduction in the array structures can be achieved using back reflectors compared to conventional bifacial arrays.

Index Terms - Bifacial, Back Reflectors, Optimization

I. INTRODUCTION

Solar photovoltaic (PV) technology has seen a significant increase in demand in recent years. This has led to the increase in research to find innovative designs to maximize the efficiency of modules and installed power systems to reduce the levelized cost of energy (LCOE). Newly introduced solar bifacial PV modules, with the capacity to increase the overall energy output using the diffuse ground reflected light, has shown potential of providing significant additional energy of about 20% more compared to monofacial PV modules. However, the efficiency of bifacial modules is dependent of the bifaciality gain (BGf) [1]. The ratio of the power output of the front side to the power output of the rear side is defined as the bifaciality gain. It is defined by:

$$BGf = \frac{(3\theta + 115h + 1.34\alpha)}{10}$$

where $\theta$ is the tilt angle of the modules (degree), $h$ is the height above the ground of the lowest point on the module (in m), and $\alpha$ is the albedo of the ground surface (%) and the result is $BGf$ in % (for module heights that range from 0.15m to 0.8m and for tilt angles less than 35°).

The rear side irradiance is huge affected by external factors such as the incident irradiance on the ground surface (which then reflects on to the solar cells on the rear side), shading from the racking system and modules, height of the module installation, spacing of cells in the module, and albedo. The efficiency of the bifacial can be increased by improving the relectivity of the surface of the ground or back reflected area [1-2]. A significant boost of up to 25% has been reported by SolarWorld [2] and Sandia National Laboratory in collaboration with University of Iowa [1].

This work aims to increase the energy production of bifacial modules further using back reflectors. These back reflectors increase the incident irradiance on the rear side of the bifacial PV module to increase the overall power of the module. These reflectors are mounted behind bifacial modules to effectively increase the back reflection [3]. This work is a continuation of our previous work based on bifacial modules with sparsely spaced cells [4]. To improve the reflected light uniformity on the backside of the sparsely spaced bifacial cells, this work has attempted to optimize the back reflectors by adjusting the reflector profiles and the distance between module and reflector.

Bifacial PV modules are usually positioned in the Plane of Array (POA) to enable the front side to capture the front light from the sun while the ground reflected light is utilized by the rear side. As shown in Fig. 1, the diffuse reflectors tend to have higher performance compared to specular reflectors due to improved uniformity over the rear side solar cells [3]. Reflective surfaces have been investigated to highlight the nature of reflective material needed to provide optimum boost in the overall energy generation of bifacial modules. The following types of reflective characteristics have been investigated for various bifacial PV panel applications: mirror type (total reflection of incident light), diffuse type (scattering of incident light), and semitransparent reflection, which exhibits both spectral and diffuse properties [3].

![Fig. 1. Bifacial PV panel integrated with (a); mirror type reflector (b); semi mirror type reflector and (c) diffuse type reflector [3]](image)

This paper presents the effects of reflectors with different profiles placed at varied distance from the module on the overall energy output. Key amongst the objectives are:

- To study the performance of bifacial photovoltaic modules and its dependence on various profiles of stationary reflectors
- To determine the optimum reflector placement distance from the back of the modules.
- To optimize the diffuse reflector surface profile yielding the best PV module performance
- To investigate the effect of reflectors on array row spacing for bifacial installation configuration.
II. METHODOLOGY

As shown in Table 1, this research was conducted on a set of five new modules consisting of four identical 48-cell bifacial modules and a 60-cell bifacial module. These modules were mounted on a rack above the ground.

<table>
<thead>
<tr>
<th>Module No.</th>
<th>Configuration</th>
<th>PV Technology</th>
<th>Pmax (W)</th>
<th>Vmp (V)</th>
<th>Imp (A)</th>
<th>Voc (V)</th>
<th>Isc (A)</th>
<th>PmaxB (W)</th>
<th>VmpB (V)</th>
<th>ImpB (A)</th>
<th>VocB (V)</th>
<th>IscB (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60-cell</td>
<td>Bifacial</td>
<td>290</td>
<td>32.4</td>
<td>8.95</td>
<td>40.2</td>
<td>9.48</td>
<td>368</td>
<td>12.4</td>
<td>8.95</td>
<td>40.2</td>
<td>9.48</td>
</tr>
<tr>
<td>2</td>
<td>48-cell</td>
<td>Bifacial</td>
<td>230</td>
<td>25.9</td>
<td>8.87</td>
<td>32.2</td>
<td>9.39</td>
<td>292</td>
<td>11.9</td>
<td>8.87</td>
<td>32.2</td>
<td>9.39</td>
</tr>
<tr>
<td>3</td>
<td>48-cell with inverted U reflector</td>
<td>Bifacial</td>
<td>230</td>
<td>25.9</td>
<td>8.87</td>
<td>32.2</td>
<td>9.39</td>
<td>292</td>
<td>11.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>48-cell with inverted V reflector</td>
<td>Bifacial</td>
<td>230</td>
<td>25.9</td>
<td>8.87</td>
<td>32.2</td>
<td>9.39</td>
<td>292</td>
<td>11.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>48-cell with flat reflector</td>
<td>Bifacial</td>
<td>230</td>
<td>25.9</td>
<td>8.87</td>
<td>32.2</td>
<td>9.39</td>
<td>292</td>
<td>11.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The modules were first tested with non-destructive performance characterization techniques including outdoor IV curve tracing, IR imaging and UV fluorescence (UVF) imaging to achieve a baseline performance profile for these modules. Four types of experiments were executed as shown in Table 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>60-cell module</th>
<th>48-cell module</th>
<th>48-cell module</th>
<th>48-cell module</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>2</td>
<td>NR</td>
<td>NR</td>
<td>UR-3cm</td>
<td>VR-3cm</td>
</tr>
<tr>
<td>3</td>
<td>NR</td>
<td>NR</td>
<td>UR-6cm</td>
<td>VR-6cm</td>
</tr>
<tr>
<td>4</td>
<td>NR</td>
<td>NR</td>
<td>UR-9cm</td>
<td>VR-9cm</td>
</tr>
</tbody>
</table>

UR - Inverted U reflector  
VR - Inverted V reflector  
FR - Flat Reflector  
NR - No Reflector

The modules were then mounted with reflectors of different profiles at varied distances as shown in Fig. 2. Reflectors made of inverted cones of various heights were placed at the back of the 48-cell the modules. The reflectors were designed such that the incident light passing through the space in between the sparsely arranged cells falls directly unto the cone surface. All modules are installed at 33° latitude tilt for Phoenix, AZ [4]. The 48-cell and 60-cell modules with no reflectors utilizing the natural ground reflection serve as a benchmark to ensure comparative analysis of energy gains of the modules with back reflectors of different profiles. Performance measurements techniques were then employed to establish the effects of these reflectors on the overall energy generation on the bifacial modules. These measurements were performed under natural sunlight on clear sunny days for all the five test modules simultaneously. The results simultaneously collected using a multi-curve I-V tracer at an identical irradiance, spectrum and ambient temperature conditions. This process allowed for direct relative comparison of the performance of the test modules without the use of any translation models for performance normalization and comparison.

Using the data obtained from the experimental investigation, the effect of stationary reflectors on array height and array row spacing for bifacial power plants was examined by comparing the standard 60 cell benchmark module and 48-cell bifacial panels fitted with stationary reflectors at optimum heights. Simulations were done utilizing libraries from System Advisor Model (SAM) to investigate the annual power and energy production, and LCOE. Theoretical investigations with analytical methods and modelling were developed to predict the optimum reflector profile and placement distance from the module. After evaluating the results of these two investigations, conclusions were made about the validity of the experimental findings, and then verified by analytical results. The details are presented elsewhere [5].

![Figure 2](image1.png)

Fig. 2. Sample configuration of inverted U reflector placed at 50cm from the module.

Three of the four identical modules were then mounted with reflectors of different profiles at varied distances as shown in Fig. 2. Reflectors made of inverted cones of various heights were placed at the back of the 48-cell the modules. The reflectors were designed such that the incident light passing through the space in between the sparsely arranged cells falls directly unto the cone surface. All modules are installed at 33° latitude tilt for Phoenix, AZ [4]. The 48-cell and 60-cell modules with no reflectors utilizing the natural ground reflection serve as a benchmark to ensure comparative analysis of energy gains of the modules with back reflectors of different profiles. Performance measurements techniques were then employed to establish the effects of these reflectors on the overall energy generation on the bifacial modules. These measurements were performed under natural sunlight on clear sunny days for all the five test modules simultaneously. The results simultaneously collected using a multi-curve I-V tracer at an identical irradiance, spectrum and ambient temperature conditions. This process allowed for direct relative comparison of the performance of the test modules without the use of any translation models for performance normalization and comparison.

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![Figure 3A](image2.png)

Fig. 3A. Row to row spacing configuration for bifacial modules without reflectors. (Source: PVsyst)

![Figure 3B](image3.png)

Fig. 3B. Row to row spacing configuration for bifacial modules with reflectors (Source: PVsyst)

The ground height clearance also plays a role in the row to row spacing for bifacial modules. Hence, its effects on bifacial modules with or without reflectors was duly investigated with models shown in Figures 3A and 3B.
III. RESULTS AND DISCUSSION

A. I-V Measurements

The baseline current-voltage (I-V) characteristics of the modules were traced to establish the identically of the four 48-cell modules. In Figure 4(a and c), the I-V traces of the full module (exposed front and back) indicated an approximately equal performance of the four 48-cell modules; the steps in the horizontal parts of the curves are attributed to the non-uniformity of incident irradiance on the rear side of the module as shown in Fig. 4(b and d) which were obtained by completely blocking the front side irradiance and allowing only the back side irradiance.

From the graphs above, the 60-cell reference module indicated a higher Voc value due to the presence of 12 additional cells compared to 48-cell modules. This tracing technique established the relatively low contribution of the rear cells to the performance of the bifacial module, indicating about 12.5% of total performance. The performance of 48-cell modules used in this study are not perfectly identical due to variation in the rear side irradiance depending on the module shades on the ground and type of ground surface behind modules. To account for any variation in power output in relation to these factors using the baseline I-V curves taken for each of the five modules without any reflectors for multiple sunny days. The power output of 48-cell benchmark module was used to determine correction coefficients which could be used to correct the power output of the other modules, ensuring normalization to the output as presented in the following equation:

\[
\text{Correction Factor (CF)} = \frac{P_{mp}(\text{48-cell module without reflector})}{P_{mp}(\text{module x})}
\]

where CF is the correction coefficient, and P_{mp}(module x) is the average power output of the other 48 and 60 cell modules (namely, 1, 3, 4, or 5). The correction coefficient was evaluated for each module for all readings throughout the solar window.

<table>
<thead>
<tr>
<th>Module</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-cell benchmark (module 1)</td>
<td>None</td>
</tr>
<tr>
<td>48-cell module with inverted U</td>
<td>0.996</td>
</tr>
<tr>
<td>48-cell module with inverted V</td>
<td>0.998</td>
</tr>
<tr>
<td>48-cell module with flat reflector</td>
<td>0.998</td>
</tr>
</tbody>
</table>

It can be seen from figures 5(a), 5(b), 5(c) and 5(d), a significant rise in Isc values for the modules with reflectors whereas no significant change was seen the Voc of such modules.

This is a direct effect of high increase in the incident irradiation on the rear side of the module. This also accounted stepwise nature of curves obtained since the diffuse reflection disperses reflected light on the surface of cells found on the rear side of the module. This effect may result in higher concentration of light at some areas of the modules when the reflector is placed closer to the module. This phenomenon gradually diminishes as the distance between the reflector and the module increases as shown in Figures 5(a) and 5(b). The increase in Isc values for modules with reflectors and gradually smoothing of curves with increased uniformity was evident in all I-V graphs for all reflector types.

To optimize the reflector placement distance, it can be seen from Figure 6 that the inverted U reflector of height 3cm produces more additional power as it provides high gain in the short circuit current of the bifacial module. This is as a result of its high uniformity in reflected light incident on the rear cells of the modules and the effective distribution of reflected light on the rear side of the module.
C. Overall Energy Performance

The boost in performance with a reflector in producing additional energy is highly significant as it could offer opportunities in improving the LCOE for bifacial PV systems leading to a rise in the current usage of the bifacial technology. A better understanding of how the energy generation is affected by the introduction of each reflector is the estimation of the total energy production boost of the 60-cell reference/benchmark module (densely spaced cells) and 48-cell modules (sparsely spaced cells) with reflectors as a function of gain with respect to the 48-cell reference module (sparsely spaced cells). The percentage energy gain is mathematically defined by the following equations:

\[
\text{Energy Gain} = \left( \frac{(48 - \text{cell module with reflector} - 48 - \text{cell reflector without reflector})}{48 - \text{cell module without reflector}} \right) \times 100\%
\]

or

\[
\left( \frac{(60 - \text{cell module with reflector} - 48 - \text{cell reflector without reflector})}{48 - \text{cell module without reflector}} \right) \times 100\%
\]

As shown in Fig. 8, 9 and 10, the performance of modules with reflectors generally increased with higher energy gain as the distance between the module and the reflector increases. This is a direct result of increased incident irradiance on the rear side of the module, uniformity of reflected light, reflectivity of reflector materials and dispersion of reflected light over large cell areas. The boost in performance with a reflector in producing additional energy is highly significant as it could offer opportunities in improving the LCOE for bifacial PV systems leading to a rise in the current usage of the bifacial technology.
Both the inverted U and V profiles performed poorly for the 6cm cone height. The flat reflector, however, in this instance, had a higher additional energy as compared to the later and a nearly half gain in additional energy produced by 60-cell reference module. Paramount amongst the reasons for this occurrence, is the high incidence angle on the reflector surfaces leading to an increase in the non-uniformity of reflected incident on the rear side of the bifacial module.

As shown above, the inverted U reflector has a higher energy gain compared to the flat and inverted V reflector for both the 3cm and 9cm profile reflectors. This is as a result of reduced incident angle on the reflectors. Significant gain could be seen when the reflector is placed at a higher distance from the module. However, the flat reflector shows increased energy gain compared to the 6cm profile reflectors for both inverted V- and U- reflectors. As the distance between the modules increased, the inverted U reflector showed significant gains. The inverted V reflector has potential for greater energy gain for the 9cm reflector profile at farther distances from the module.

**D. Plant Modelling**

One key component of initial cost and investments made into PV installations is as a result of land siting and sizing. With the use of back reflectors for bifacial PV modules, the constraints imposed by ground height clearance will be significantly addressed leading to reduced structural cost and land area. Bifacial modules are mounted at height to ensure effective collection of ground reflected light. Utilizing models from System Advisor Model (SAM), and PVsyst, the effect of ground height clearance on the annual energy output, ground cover ratio and optimal row to row spacing of a bifacial system with a back reflector was investigated.

From Figure 11, increasing ground height clearance increases the annual energy output and the bifacial irradiance gain. More land size will be needed to put up a design bifacial system since the row to row spacing increases with increasing ground height clearance as shown in Figure 12.

**Fig. 9.** Energy gain for 6cm reflector profile at various distances.

**Fig. 10.** Energy gain for 9cm reflector profile at various distances.

**Fig. 11.** Effect of Ground Height Clearance on Performance of Bifacial Modules (Based on calculation done by ASU-PRL using SAM software of NREL).

**Fig. 12.** Row spacing for bifacial modules without reflectors (Based on calculation done by ASU-PRL using MATLAB developed code).

Although the bifacial irradiance gains increased with an increase in the ground clearance height, more land size will be
needed to put up a design bifacial system since the row to row spacing increases with increasing ground height. This largely affects the initial invested capital and the levelized cost of energy. The increase in the row spacing is due to the self-shading cast on other arrays. However, the use of the back reflectors largely reduces the both ground height clearance and the row to row spacing shown in Figure 12. The minimum ground height clearance is calculated for each displacement configuration of reflectors from the module. The maximum height clearance of 1.62m above ground occurs when the back reflector is placed 1m away from the module. The use of the back reflectors largely reduces the both ground height clearance and the row to row spacing as shown Figure 13.

![Minimum Ground Clearance Height vs Row to Row Spacing](image)

Fig. 13. Row spacing for bifacial modules with reflectors (Based on calculation done by ASU-PRL using MATLAB developed code).

### TABLE IV: SUMMARIZED FINDINGS

<table>
<thead>
<tr>
<th></th>
<th>60-cell bifacial</th>
<th>48-cell bifacial with Inverted U Reflector placed 100cm from the module</th>
<th>Takeaway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Gain (%)</td>
<td>19.0</td>
<td>13.67</td>
<td>Generation of half of additional energy with 50% less additional cells</td>
</tr>
<tr>
<td>Cell Temperature Gradient (°C)</td>
<td>0.5</td>
<td>0.45</td>
<td>No significant rise in NMOT</td>
</tr>
<tr>
<td>Ground Clearance Height (m)</td>
<td>3.0</td>
<td>1.67</td>
<td>Reduction of column height by nearly half leading to material cost savings</td>
</tr>
<tr>
<td>Land Size - Row to Row spacing (m)</td>
<td>11.9</td>
<td>7.00</td>
<td>40% reduction in land size required.</td>
</tr>
</tbody>
</table>

From Table 4, it can be inferred that the bifacial system with back reflectors has shown potential for effective land utilization and reduction of material cost close to half for the bifacial systems with reflectors. This is an indicator of the potential for bifacial PV modules with back reflectors to improve the LCOE of the solar technology and increase the use of bifacial modules instead of mono-facial modules.

### IV. CONCLUSIONS

Bifacial modules have the capacity to produce additional energy with the use of effective stationary back reflectors. The bifacial technology with back reflectors represents a paradigm shift in reducing the levelized cost of energy (LCOE) of solar installations. The most suitable reflector profile is determined to be the diffuse inverted U reflector. This reflector type produces higher energy gain when placed at farther distances from the module. It performed the best out of all current construction geometries, generating nearly a half of the additional energy produced by a densely spaced 60-cell benchmark module compared to a sparsely-spaced 48-cell benchmark module. With a gain of 11-14% of additional energy with back reflector over a 48-cell reference module with ground reflection (16-19% for 60-cell bifacial module with ground reflection) producing more than half of the additional energy of the 60-cell module. Not only does a reflector increase energy output of the bifacial modules, the structural and land costs involved in setting up bifacial systems are largely reduced. Structural and land cost can be potentially reduced up to 50% with use of back reflectors.

### REFERENCES


