OPTIMISATION OF BIFACIAL PHOTOVOLTICS MODULE WITH REFLECTIVE LAYER IN OUTDOOR PERFORMANCE

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ABSTRACT: While the improvements of STC maximum power point (Pmpp) and current from inserting reflective layers in the inter-cell gap of bifacial modules have been reported, there are many additional factors that contribute to the module outdoor performance in addition to the module STC performance. This paper presents the analysis and optimisation of bifacial PV modules with reflective layer at the inter-cell gap for outdoor performance. Bifacial module with reflective layer was studied where the reflective surfaces are inserted behind the rear glass. Normal glass/glass bifacial modules were compared to the proposed bifacial modules with reflective layers that were fabricated with the same cell type. A numerical model was created to simulate the current gain from each configuration with varying outdoor conditions. The numerical model was verified with an outdoor performance set-up that was experimentally constructed.
Keywords: Bifacial, PV Module, Ray Tracing

1 INTRODUCTION

Demand of energy has always been in tandem with the progression of mankind since the first industrial revolution. Singapore's energy demands increased year on year since 1965 and in year 2017 to 2018 consumed 49,643GWh of electricity. Its consumption is projected to increase to 62,700GWh by 2030 [1]. For a sustainable future, renewable sources such as solar, wind, geothermal, hydropower, and biomass could provide the energy demand in place of non-renewable sources. Solar energy from the sun is ubiquitous and a dependable source of energy which is also in abundance. Furthermore, solar energy sources are not geologically limited like wind, geothermal or hydropower and hence is suitable for application in Singapore. However, in Singapore, there are only approximately 114.8MWac of grid-connected installations, which is 0.8% of its total energy generation. Bifacial photovoltaic modules could be the economical solution to reach the target of 350MWp of photovoltaics installation by year 2020 in the land scarce Singapore. While the monofacial modules in Singapore are commonly mounted at 10 degree South facing, bifacial modules could be mounted in similar set up or 90 degree East-West facing [2]. The additional factor of ground albedo and elevation complicates the energy yield optimisation, as compared to conventional monofacial modules. Performance gain of 10% was reported for bifacial modules installed in Singapore on roof with less than 20% albedo [3]. A simulation of bifacial modules in Singapore illustrates additional bifacial energy gain with higher ground albedo [4]. It was also seens that increasing module elevation height reduces self-shading and improves rear illumination inhomogeneity [5][6].

With the recent developments of modules with reflective layer, different approaches in the mounting optimisation for different configurations have emerged, as compared to the Type 0 normal glass/glass bifacial module, as shown in Figure 1. The varying location of the reflective layer results in the differing ray path from the reflected irradiance in the module internally. As shown in Figure 2, a Type 1 module was reported previously with the highest current gain for STC front side flash at 3.4%. With 1 sun on front and rear illumination, the current gain for Type 1 was reduced to 1.7% [7]. In an outdoor setting the illumination for both front and rear would unlikely be 1 sun simultaneously for both front and rear. Hence, a ray tracing model would be required to incorporate the reflected ground and global irradiance in an outdoor performance test to study the optimal module configuration and mounting arrangement.

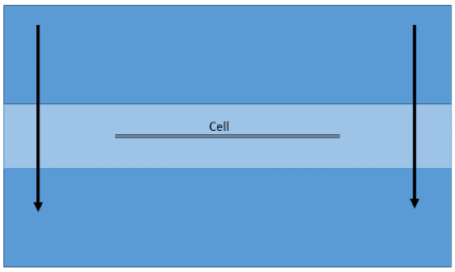

Figure 1: Bifacial modules Type 0

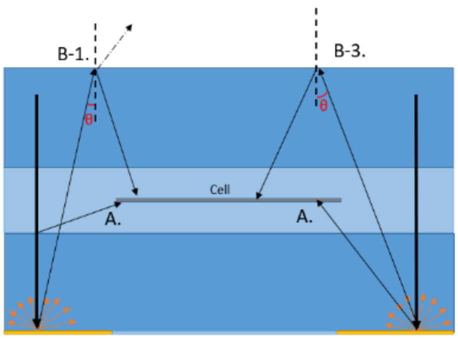

Figure 2: Bifacial module Type 1

In this paper, the current gain with Type 1 reflective layer configuration was first analysed and physical measurements were performed on both the module and ground conditions for inputs to the model. Next, the different mounting set-ups of the two configurations were then modelled to evaluate the module configuration current gain from the reflected ground irradiance across the day. Lastly, the outdoor set-up was constructed experimentally to validate the results from the model.

The paper is organised as follows: Section 2 provides the update for the ray tracing numerical model and the experimental set-up. Section 3 discusses the results from the simulations on the different tilt angles effect on the bifacial modules and the experimental results from outdoor comparison between Type 0 glass/glass and Type 1 glass/glass/reflective layer at the inter cell gap bifacial modules. Conclusions are then presented in Section 4.

2 EXPERIMENTAL PROCEDURES

2.1 Methodology of simulation

Unlike indoor Standard Test Conditions where the modules are perpendicular to the illumination source, outdoor conditions modules are mounted at an angle that is approximate to the location latitude. Other than mounting angle, the module mounting height and ground reflectance also impact its outdoor performance. In this paper, the previously reported numerical model that considered absorption loss is used to simulate the current gain from each configuration, with varying inter-cell spacing [7], to study effects from varying mounting tilt angles.

Firstly, as per the previously reported work, some assumptions of the material properties of air, glass, and encapsulants were made for the simulation. The glass and encapsulants were assumed to be the same and the optical losses between them are at a minimal. The glass and encapsulant refractive index are assumed to be 1.5 while air to be 1 [7][8]. Secondly, the ground coating results in a totally diffused reflected irradiance from the incoming irradiance. The reflected unpolarized rays are scattered uniformly into 3600 rays in both the azimuth and polar direction at 3 degrees and 6 degrees respectively. Lastly, all rays were assumed to consist of parallel and perpendicular components.

Additional assumptions were made for this new proposed model are firstly, the modules only tilt on a single axis centered on the middle of the middle cell in the polar direction. Secondary, irradiance that were transmitted out from the rear glass would not have the probability to be reflected onto the cell. Lastly, tilt angle of full vertical 90° could not be simulated with this model as there is zero direct irradiance on the cell and Type 0 bifacial modules has no current gain from the absence of reflect layer in the inter cell gap or additional influence of tilt angle on the current gain.

Mounting tilt angle with respect to the bifacial module configuration was simulated via the calculation of minimum and maximum polar angles that reflected light rays for the spot could be reflected onto the cell. For rays that were reflected to the rear and front respectively, they were calculated using Equation (1) and Equation (2).

$$\theta_{min} = \arccos\left[\frac{x_{ray} \cdot x_{min}}{|x_{ray}||x_{min}|} \times \cos(\theta_{tilt})\right] \quad (1)$$

$$\theta_{max} = arcos\left[\frac{x_{ray} \cdot x_{max}}{|x_{ray}||x_{max}|} \times \cos(\theta_{tilt})\right] \quad (2)$$

where x_{ray} is the coordinate of the incoming ray and θ_{tilt} is the tile angle illustrated in Figure 3 and Figure 4 for rays that are reflected to the rear and front respectively. To compute the minimum, θ_{min}, and maximum, θ_{max}, which provide the range of angles of rays that were reflected to the rear of the cell, x_{min} and x_{max} are the distance between the reflected ray coordinates to the nearest and furthest point of the cell with respect to the ray initial position. For the front rays, x_{min} and x_{max} are the nearest and furthest position on the front glass where rays reach the front side of the cell respectively.

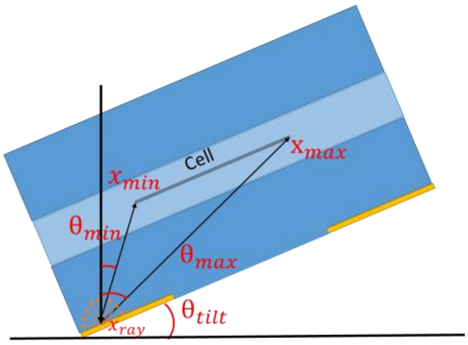

Figure 3: Rear rays' path of Type 1 module with tilt

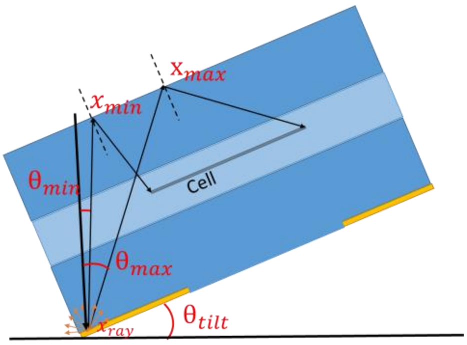

Figure 4: Front rays' path of Type 1 module with tilt

For computing the total additional radiant power reflected onto the cell, additional checks for the minimum and maximum polar angles were updated to the previous reported model binary output equation. Additional functions $T1\,(x2, y2, \theta_1)$ and $T1\,(x3, y3, \theta_2)$ are checked if the light rays final positions are on the cell and within the minimum and maximum angles, which are shown in Equation (3) and Equation (4) for the summation of rays that contributes to the rear and front power respectively. Following which, the additonal rear and front current contributions of the inter cell gap reflective area were compared with the cell intristic generated current to compute the current gain, as per the previously proposed model [7].

$$P_r = \int_{q1}^{q2}\int_{p1}^{p2}\int_{0}^{\pi}\int_{\alpha}^{\frac{\pi}{2}} S\,(\theta).\,T1\,(x2, y2, \theta_1) d\theta\, d\varphi\, dx\, dy \quad (3)$$

$$P_f = \int_{q1}^{q2}\int_{p1}^{p2}\int_{0}^{\pi}\int_{0}^{\alpha} S\,(\theta)\,.\,T1\,(x3, y3, \theta_2) d\theta d\phi dx dy \quad (4)$$

2.2 Experimental setup

An N-type 60-cells bifacial module with 90% bifacial ratio of Type 0 glass/glass configuration was mounted on a movable and tiltable rack at 1m above the ground in an East-West facing direction. The set-up was positioned in existing solar test bed in Singapore with other solar module arrays with minimal shading with a mesured ground reflectance of approximately 10% to 15%. The experiment module was connected to a Tristar MPPT solar charge controller with the energy storage in a lead acid battery with discharge load, as shown in Figure 5

Figure 5: Outdoor site

Two silicon-cell pyranometer were used to log the real time solar irradiance and reflected ground irradiance separately. The modules have an area of 1.6m^2 with both configurations having a cell to cell gap of 2mm. With irradiance sensors mounted on the module frame, a comparison could be done on energy conversion efficiency of the module for different tilt angles with real time recording of irradiance and ground reflectance across a day, as illustrated in Figure 6.

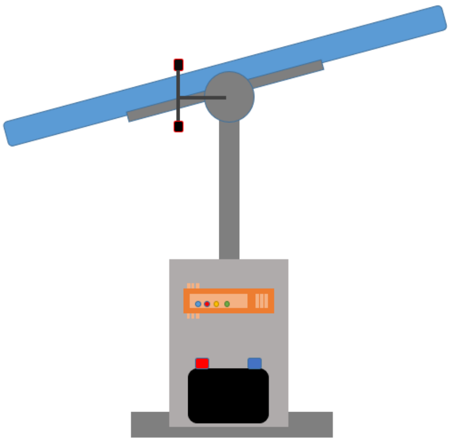

Figure 6: Outdoor monitoring set-up

3 RESULTS AND DISCUSSIONS

Using the ray tracing model presented above, tilt angles of 0°, 22.5°, 45°, and 67.5° were chosen to represent influence of tilt angle on Type 1 bifacial module in the outdoor site. From the simulation, Type 1 bifacial module current gain increases as the module tilts towards 45° giving a maximum increase of 79% in current gain as compared to 0°. This increase in current gain reduces as the tilt angle goes beyond 45° towards 67.5°, as plotted in Figure 7. A full vertical module of 90° could not be simulated in the model. Hence, the postulation of reducing current gain in Type 1 bifacial module beyond 45° towards 67.5° could be extrapolated to 90° which has 0% current gain from the assumption discussed in Section 2.1.

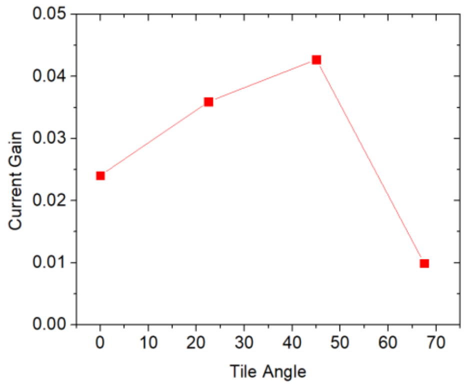

Figure 7: Type 1 module current gain with tilt angle

Previously reported work has shown that a significant amount of current gain is contributed by rays reflected to the rear of the cell from reflective layers next to the cell. It was also reported that the current gain reduces exponentially with the increase inter cell gap [7]. As illustrated in Figure 3, the increase in tilt angle from 0° to 45° increases the number of rays that could be reflected toward the rear of the cell rather than towards the front glass which could result in front transmission losses, Hence, the increase in current gain comes with the increase of tilt angle is the result of the increase of rays reflected onto the rear of the bifacial cell.

In addition, the decrease in current gain beyond 45° shows a self-shading effect where the cell shades the incoming irradiance from reaching the reflective layer at the inter cell gap. Thus, even with the increase in ray being reflected to the rear of the cells, the shaded inactive reflective layer at the inter cell gap reduces the net current gain of Type 1 bifacial module. With the increase of tilt angle beyond 45°, the distance of active reflective layer from the cell increase. The magnitude of self-shading effect is the function of the encapsulant material thickness which changed the distance of the reflective layer position to the rear of the cell, as illustrated in Figure 8 dotted line, with the vertical line that illustrates incoming rays that is perpendicular to the ground.

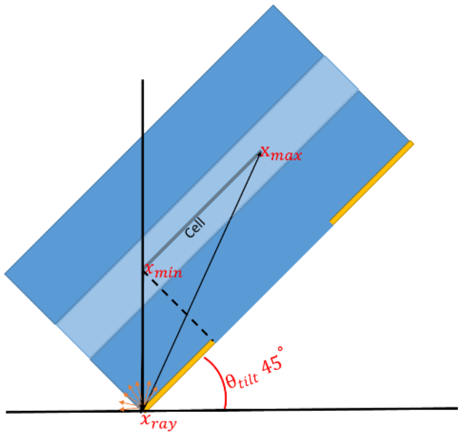

Figure 8 Type 1 tilt more than 45°

Going on to the results from the outdoor experimental setup, the conversion efficiency of Type 0 and Type 1 bifacial module in 0° , 45° , and 90° tilt angles was compared in Figure 9 and Figure 10. The exact bifacial module was used for comparison between Type 0, Type 1 and monofacial by physically attaching reflective back sheet at the rear of Type 0 bifacial module. The calculation of conversion efficiency was done by taking the module output energy at the MPPT divided by the sum of energy input that was measured by the two mounted irradiance sensors.

As discussed in the previous Section, Type 0 Bifacial module would not see a rise in conversion efficiency when tilt angle was increased at 45°, this phenomenon is shown again with the experimental data. However, when mounted in full vertical 90° tilt angle, the conversion efficiency increased by 1.64% as compared to 0°. This shows the versatility of Type 0 bifacial modules in mounting conditions in the test site for locations, which are near the equator.

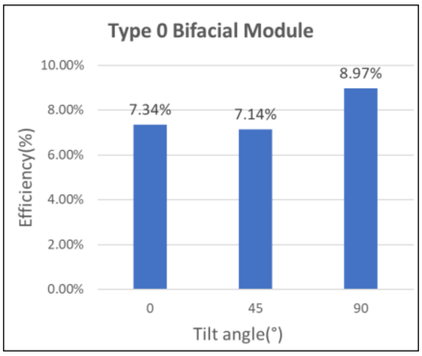

Figure 9 Module energy yield efficiency Type 0 module

While Type 1 bifacial module do show an improvement in conversion efficiency when the tilt angle increases from 0° to 45°, it was significantly lesser, as compared to the model. Across all three different tilt angles, Type 0 bifacial module has an average of 1.55% additional conversion efficiency, as compared to Type 1 bifacial modules with reflective layers.

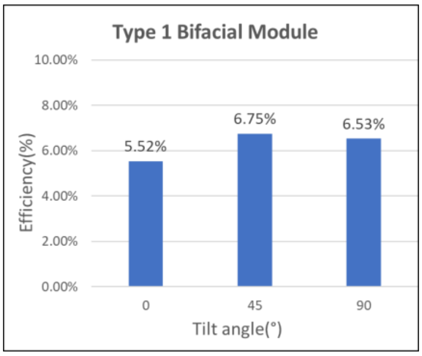

Figure 10 Module energy yield efficiency Type 1 module

Although bifacial modules with reflective layer at the inter cell gap has a significant current gain from reported simulations and indoor flash test [7][9][10], this is reduced due to the front transmission losses. As compared to monofacial modules, it is shown that different mounting conditions and module design would result in varying performance during outdoor energy yield.

4 CONCLUSIONS

In this paper, two bifacial module configurations were discussed. They were Type 0 normal glass/glass bifacial module and Type 1 bifacial module with inter-cell gap reflective layers at the rear of the module glass. An optical ray trace model for the two configurations was created with inputs from physical measurements. Ray tracing modelling method for quantifying the contribution of internal reflection from the reflective layer in the bifacial module inter-cell gap during indoor flash test was further developed to estimate the bifacial module configurations current gain with respect to the outdoor mounting tilt conditions. Type 1 bifacial modules were fabricated for outdoor monitoring energy yield experiment on variable tilt angles and compared with the results from the model.

The simulation showed an increase of current gain for Type 1 bifacial module with the increase of tilt angle from 0° to 45° due to the additional rays being reflected to the rear of the cell. Beyond 45° tilt, the self-shading effect reduced the current gain from in-active reflective layers in the inter cell gap. While the model for Type 1 bifacial module indicated a 79% increase in current gain from 0° to 45°, the field data has shown a lesser increase of around 22% with increased tilt angle. It is also shown that Type 0 bifacial module outperforms Type 1 module during outdoor energy conversion efficiency across all tilt angles.

Further improvements of the ray tracing model would include rays reflected from the ground and its interaction to the module inter-cell gap reflective layer configuration type to improve the accuracy of this model for module design optimization for both indoor flash test and outdoor energy yield scenarios.

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