Investigating the effect of orientation and tilt angle on bifacial PV modules on vertical east-west and tilted north-south modules

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Abstract
Photovoltaic (PV) technology is an attractive renewable source for regions with many hours of sunlight. Bifacial PV modules are an evolution of PV module structure to improve the efficiency of converting solar irradiance from the back surface as well as the front surface into electricity. In a non-tracking system, bifacial modules can be mounted vertically in an east-west orientation or tilted in a north-south orientation. Modules installed vertically produce two peaks in power generated throughout the day, while the tilted modules peak around noon when irradiation intensity is at maximum. In this research, a Bifacial PV system of each configuration is to be installed at the Outdoor Research Facility at Nelson Mandela University, Gqeberha, South Africa. The performance of the system was simulated. The results obtained from the simulation show that the tilted configuration produces more electrical energy than the vertical configuration, and between April and August a single tilted module produces has higher output than two vertical modules. The vertical configuration spreads the generation over a longer period, with two peaks in a day. The results show the vertical system would best fit a grid-tied system because the generation peak is closer to times of high demand. The tilted installation would have the highest daily average energy generation making it more useful for a standalone system.

Keywords: Bifacial PV modules, vertical / tilted bifacial modules.

1. Introduction

This paper is based on a simulation of bifacial modules installed in two configurations, with one module installed at 34° facing north and two modules installed vertically in opposite directions with east-west orientation using default parameters, and an albedo of 0.2. The actual system is being set up at Nelson Mandela University and is not yet ready to analyse its performance. Similar experiments testing on bifacial photovoltaic (bPV) modules under outdoor conditions have been performed before, for example (Guo, Walsh and Peters, 2013; Gu et al., 2021; Lorenzo, 2021), and different models exist to analyse the performance of such systems (Gu, Ma, Li, et al., 2020).

Monofacial photovoltaic (mPV) modules only absorb irradiance in their plane of array (POA) to generate electricity through the photoelectric effect (Hersch and Zweibel, 1981). Bifacial photovoltaic (bPV) modules not only absorb irradiance on the front face, but also on the rear face as well for electrical energy generation (Guo, Walsh and Peters, 2013; Gu, Ma, Ahmed, et al., 2020; Gu, Ma, Li, et al., 2020; Gu et al., 2021; Lorenzo, 2021). This is because bPV modules are constructed with a near-symmetric cross-section from the front surface to the rear surface, and bifacial cells/modules have the following layers: an anti-reflecting coating layer (ARC), front electric contacts, n-type semiconductor (emitter), depletion layer (middle layer), p-type semiconductor (substrate), ARC and back electric contacts. The back contacts in an mPV module cover the whole cell surface area instead, there is a back surface field, which is not transparent to light (Gu, Ma, Ahmed, *et al.*, 2020; Gu, Ma, Li, *et al.*, 2020). This means bPV modules have similar-looking front and rear faces, the difference coming from the amount of ARC applied on the two faces; the rear faces appear lighter than the front faces because less ARC is applied to them (Gu, Ma, Ahmed, et al., 2020).

1.1. Electrical characterisation of bifacial modules

The performance of a bPV can be tested using either a single light source to illuminate one face at a time, or by using two light sources to illuminate both faces simultaneously, as described in the IEC testing standard 60904-1-2. To determine the performance of each face, a single light source is illuminated on the face that is being tested. The following parameters are then measured: open circuit voltage V_{OC}, short circuit current I_{SC}, maximum power P_{max} (of each face when using single face illumination), voltage at maximum power V_{mp} and current at maximum power I_{mp}. The $I_{SC,bPV}$ and $V_{OC,bPV}$ of a bPV module are given in terms of the $I_{SC,R/F}$ and $V_{OC,R/F}$ of the front and rear faces by the following equations:

$$I_{SC,bPV} = I_{SC,R} + I_{SC,F} \qquad (1)$$

$$V_{OC,bPV} = V_{OC,F} + \frac{\left(V_{OC,R} - V_{OC,F} \cdot ln\left({I_{SC,R} + I_{SC,F}}/{I_{SC,F}}\right)\right)}{ln\left({I_{SC,R}}/{I_{SC,F}}\right)} \qquad (2)$$

V_{OC} is negatively affected by high temperatures, on the information sheet of a module the manufacturer gives temperature ratings of the module, including temperature coefficients of V_{OC} ($\alpha_{V_{OC}}$) and of P_{max} ($\alpha_{P_{max}}$). For example, a LONGI LR4-72HBD-435M has $\alpha_{V_{OC}} = -0.300\,\%/℃$ and $\alpha_{P_{max}} = -0.370\,\%/℃$: for 1°C increase in temperature, V_{OC} and P_{max} will drop by 0.30% and 0.37% respectively.

The bifaciality coefficients of a bPV module include the bifaciality coefficient of maximum power $\varphi_{P_{max}}$, the bifaciality coefficient of short-circuit current $\varphi_{I_{SC}}$, and the bifaciality coefficient of open circuit voltage $\varphi_{V_{OC}}$ and are given by equations 3, 4 and 5 respectively:

$$\varphi_{P_{max}} = \frac{P_{max,R}}{P_{max,F}} \times 100\% \qquad (3)$$

$$\varphi_{I_{SC}} = \frac{I_{SC,R}}{I_{SC,F}} \times 100\% \qquad (4)$$

$$\varphi_{V_{OC}} = \frac{V_{OC,R}}{V_{OC,F}} \times 100\% \qquad (5)$$

$\varphi_{P_{max}}$ and $\varphi_{I_{SC}}$ are useful quantities in characterising bPV modules and for a bPV, the higher these coefficients are the higher the power output of a bPV under the same conditions (Gu, Ma, Ahmed, et al., 2020). For a monocrystalline PERC bPV module the expected yield of a bPV module, Y_{bPV}, is compared to the yield of an mPV, Y_{mPV}, with a quantity called the rear irradiance-driven power gain G_{bPV}:

$$G_{bPV} = \frac{Y_{bPV} - Y_{mPV}}{Y_{mPV}} \times 100\% \qquad (6)$$

2. Proposed method

This paper is based on a simulation of a bPV system that is being constructed at the Outdoor Research Facility at the Nelson Mandela University's South Campus in Gqeberha. The simulations were performed using PV*Sol premium 2022 software (Valentin Software, 2022) and PVSyst 7.2 software (PVSyst Photovoltaic Software, 2022). The modules selected for this research are the LONGI LR4-72HPH-440M, and the same module was selected in the simulation. Figure 1 shows the system configuration. Each module has a separate maximum power point tracker coupled to the system's inverter. This is so each module can be monitored individually.

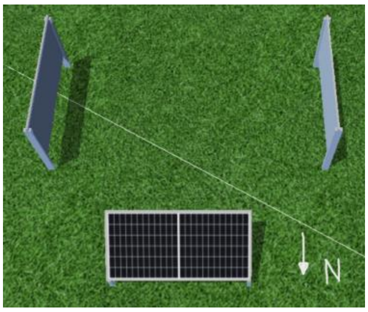

Figure 1: An image of the bifacial system this paper is based on. The two vertical modules are facing east and west, and the bottom module is tilted at 34° and is facing north.

The electrical power of the two configurations is then contrasted with a profile of the average electricity consumption of an urban South African household (Hughes and Larmour, 2021) to see which configuration would be preferable depending on the needs of the consumer.

3. Research Methodology

There are installations of bPV modules as shown in figure 1. The system performance is to be monitored for one year, by measuring the voltage, current and electrical power from each of the three modules and relating these measurements to the irradiance incident on the modules and temperature. In this paper, the same system was simulated on the PV*Sol premium 2022 software (Valentin Software, 2022) and PVSyst 7.2 software (PVSyst Photovoltaic Software, 2022).

4. Results and discussion

The results of the simulation of the bifacial system at ORF, show that tilted north-facing bifacial modules always generate more electricity than east/west facing modules.

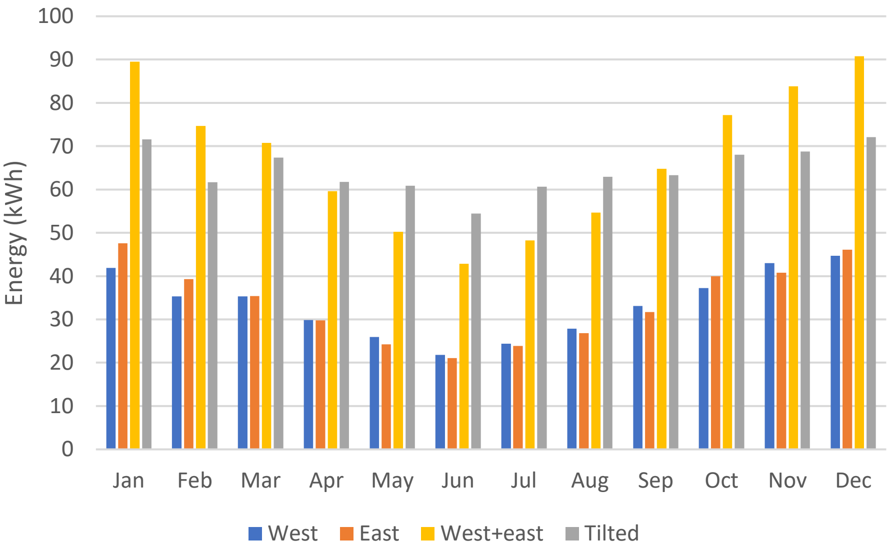

Figure 2: The electrical energy, simulated on PVSyst, generated by the bPV modules mounted at different orientations: bPV mounted vertically with the front facing west, east and the tilted module is mounted at 34° and faces north.

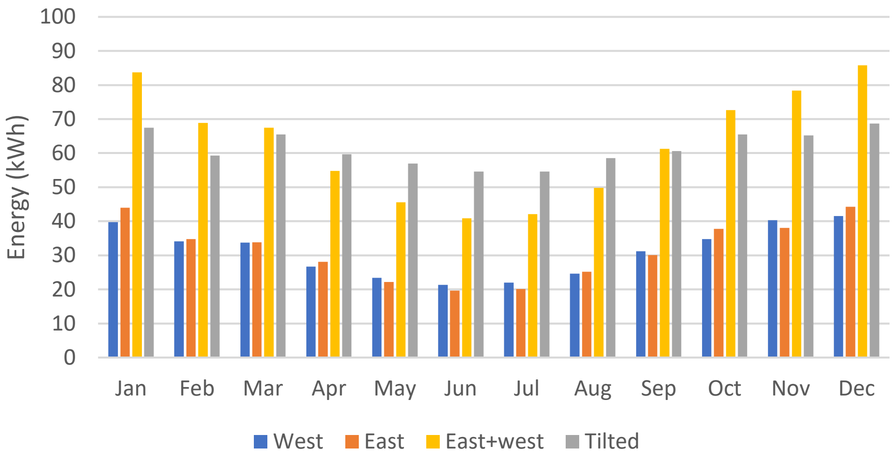

Figure 3: The electrical energy output of the system simulated on PV*SOL software.

The results of the system simulated on PV*SOL show a noticeably similar trend; a tilted module far outperforms the individual vertically installed modules.

Looking at single-day performance of a PV module, the power output only peaks when the sun is illuminating a module face directly. For a vertically installed bPV module, the sun illuminates both faces at different times of the day, in the morning for an east-facing module and afternoon for a west-facing module. In a system of two vertical bPV module facing in opposite directions, the peaks at either side of noon are observable on a clear day. Figure 4 shows the power output for the day with the highest power electrical power output (1 Dec) using the climate data of 1990 for the two different installations. The two vertical modules combined generated total daily energy of 3.780 kWh and the tilted module generated a total of 2.923 kWh.

For the months from April to August, the combined output of the two vertical modules is less than the output of the tilted module due to fewer hours of sunshine per day. In March the two vertical modules generated not more than 3.5 kWh (3.43 kWh on PVSyst, and 2 kWh PV*SOL) more than the tilted module. In September, this difference is even less, not more than 1.5 kWh.

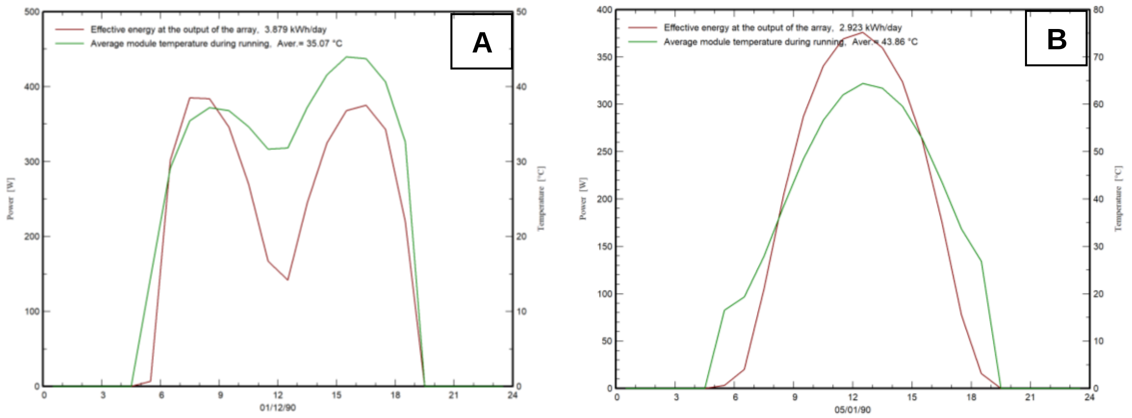

Figure 4: Electrical power output and temperature curves for bPV modules for a 24-hour period: (A) Power output of two bPV modules installed vertically with one oriented east and the other oriented west with an output of 3.879 kWh/day. (B) The output of the single tilted bPV module with an output of 2.923 kWh/day.

Vertical installation of bPV distributes electricity generated over a wider time period than a tilted installation which has a narrow but high peak. This can remove the need to store the generated electricity since the electricity is generated close to when it is needed, which would require the purchase of more components for the system. If batteries are installed in a system with vertical modules, the batteries will likely not be needed to be fully discharged because the PV system will still be generating electricity during peak use, extending the life cycle of the batteries or decreasing the installed storage capacity.

As mentioned earlier, the tilted bPV module always generates more electricity than a single vertically installed module, and outside of summer months, a tilted module generates more electricity two modules facing east and west. The performance of bPV can be improved further by increasing the albedo of the area where the modules are installed.

Looking at the graphs in Figure 4, the vertical modules experience a lower average temperature of 35.07°C and do not reach above 45°C. The tilted module recorded an average temperature of 43.86°C and a maximum temperature of 76°C.

5. Conclusions and recommendations

Vertically installed bPV modules extend the peak productivity of the PV system over a wider time period, and tilted bPV have a narrower peak. Tilted north-facing bPV modules generate more electricity than vertical bPV modules, but in some cases it would be preferable to install the modules vertical than tilted. A tilted north facing system would best suit an off-grid PV system with high battery capacity.

The advantages of a vertical installation include the following, the electricity generation is spread out more, and this may reduce the need to store the generated electricity because it can be used as it is being generated. This will reduce the cost of installing PV and give a low levelized cost of energy (LCOE). Vertical installation reduces the average temperature of the modules because the modules receive direct sunlight at low irradiance intensity than the tilted modules. High temperatures lower the electrical output of PV modules and can also speed up the degradation of the modules. Vertical installation of east-west bPV, like in agriculture, allow for dual use of land because such modules will not shade the crops.

Once data from the system at Nelson Mandela University is available, it will be compared to the electricity consumption of a household, and other energy consumers to determine which of the two configurations can meet their needs.

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