The Effect of Mounting Parameters on the Performance of Bifacial Solar Modules

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Abstract

This study investigates the performance of a bifacial solar module configuration in an equatorial zone using Chiromo Campus (1.2732° S, 36.8049° E), University of Nairobi, Kenya. Two 60 W polycrystalline solar modules were mounted back-to-back on a fabricated rack to emulate a bifacial configuration, with one facing the sky (front side) and the other facing the ground (back side). Three parameters were optimized: ground elevation, tilt angle, and reflective background surface. Current-voltage (I-V) measurements were taken using an HT I-V analyzer at various elevations and tilt angles. Three reflective materials were evaluated: metallized polyethylene terephthalate (MPET), Mylar windshield sunshade, and iron sheet. The study established that optimal performance was achieved at a ground elevation of approximately 1.2 m and a tilt angle of approximately 30°. Among the reflectors, MPET produced the highest irradiance increase on the back side (84.6%), followed by Mylar (77.2%) and iron sheet (22.9%), with corresponding power increases of approximately 13.7%, 5.2%, and 1.9%, respectively. These findings provide practical guidance for bifacial solar module installation in equatorial regions with similar climatic conditions.

Keywords: bifacial module, optimization, reflective background, irradiance, ground elevation, tilt angle

1. Introduction

The rising demand for energy, along with concerns about the environmental impact of fossil fuels, has fostered interest in alternative energy sources. As traditional fossil fuel supplies decline, there is growing pressure to develop energy sources that are both sustainable and environmentally friendly. Renewable energy sources offer a viable alternative, being abundant, sustainable, and producing minimal air pollution and greenhouse gas emissions.

Photovoltaic (PV) technology has been extensively researched and developed over the past few decades due to its potential to contribute significantly to the transition to a sustainable energy system. It is a clean and renewable energy source that can generate electricity in a decentralized manner, reducing the carbon footprint of energy production (Chen et al., 2019). At present, the most common PV technology is silicon-based, historically comprising mainly monofacial modules that generate electricity from one surface only. However, bifacial modules, which have solar cells on both the front and back surfaces, can collect both direct and reflected (albedo) irradiance (Guerrero-Lemus et al., 2016; Salloom et al., 2018).

Commercial and academic interest has shifted markedly from monofacial to bifacial technology. According to the International Technology Roadmap for Photovoltaic (ITRPV, 2024), bifacial modules now account for over 80% of global PV module production, having grown from less than 20% in 2019. This rapid adoption underscores the importance of understanding bifacial module performance under diverse climatic and installation conditions.

The first bifacial laboratory solar cell was demonstrated in 1977 (Guerrero-Lemus et al., 2016). Since then, extensive research has been conducted, and today commercial bifacial modules are widely available. Chen et al. (2019) developed a model to examine the energy generation capability of bifacial solar modules by varying the ground reflection (albedo). They established that the optimal tilt angle of the modules increased as the distance between the modules and the ground decreased, since the ideal tilt angle is strongly related to the albedo coefficient. Wei et al. (2016) demonstrated that bifacial solar modules can produce significant bifacial gains when mounted on surfaces such as grass (7.6%), sand (15.4%), and snow (29.2%).

Reflectors have been studied as a means of boosting power generation, since the bifacial gain depends on the amount of irradiance reaching the back side. Various factors, including the spacing between the back side and

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the reflector, the elevation, the tilt angle, and the reflectivity of the reflector material, are critical determinants. A number of works have explored various reflector designs for increasing the power output of bifacial modules. These range from simple approaches such as mirrors (Chin et al., 2013) and paints to more sophisticated designs incorporating light-scattering materials such as beads or powders, as well as variable mirror arrays and pyramids (Rueter et al., 2021). Studies have confirmed that the incorporation of reflectors improves the power output of bifacial solar modules (Chin et al., 2013; Riedel-Lyngskær et al., 2020; Rueter et al., 2021; Martin and Tamizhmani, 2019).

While several reflector materials have been studied and have demonstrated the ability to enhance power generation in bifacial modules, further research is needed to evaluate a more diverse range of reflective surfaces, particularly in tropical and equatorial regions where solar irradiance conditions differ from those in temperate climates. To the best of our knowledge, no comprehensive optimization study of bifacial module mounting parameters has been conducted specifically for Nairobi or the broader East African region. This study therefore aims to: (1) determine the optimum ground elevation for the module, (2) determine the best tilt angle, and (3) evaluate the effect of three reflective background materials — iron sheet, Mylar windshield sunshade, and metallized polyethylene terephthalate (MPET) — on the power output of a bifacial solar module configuration in a high-albedo equatorial area.

2. Materials and Methods

Two polycrystalline solar modules, each rated at 60 W, were sourced locally from Chloride Exide (K) Ltd (Industrial Area, Nairobi), while the galvanized iron sheet was obtained from a local hardware store. The reflective Mylar windshield sunshade was purchased from a local supermarket, and the MPET material was obtained from Heliac Solar Cooker Company, a local supplier and designer of solar cooking technology products. The Solar Laboratory at the Department of Physics, Chiromo Campus, University of Nairobi, provided the solar I-V analyzer (HT), multimeter, and an HT304N reference solar cell. An adjustable solar mounting rack with a calibrated angle scale was fabricated in a workshop on the campus. The mounting rack had a maximum ground elevation of 1.5 m, and the module tilt angle was adjustable from 0° to 90° in 30° increments. The electrical parameters of the modules are presented in Table 1.

Table 1: Electrical parameters of the 60 W polycrystalline solar module used in this study.

Parameter	Rating
Maximum power, Pmax	60 W
Maximum current at power point, Imp	3.2 A
Maximum voltage at power point, Vmp	18 V
Open circuit voltage, Voc	22.9 V
Short circuit current, Isc	3.4 A
Power tolerance	± 5%

2.1 Experimental setup and procedure

The experiment was carried out in three phases: first, ground-level elevation optimization; second, tilt angle optimization; and third, incorporation of reflective surfaces. To form a bifacial configuration, the two 60 W polycrystalline solar modules were mounted back-to-back, with the one facing upwards designated the front side and the one facing downwards designated the back side. Solar irradiance was measured using an HT304N reference cell, which has two output ports for Si multi-crystalline and Si monocrystalline cells. The reference cell was firmly affixed parallel to the solar module to maintain the same orientation and tilt. The power output of the solar module and reference cell was measured by recording the current and voltage from the I-V analyzer, which was connected to a computer. Each side was first characterized by taking its I-V data as shown in Figure 1.

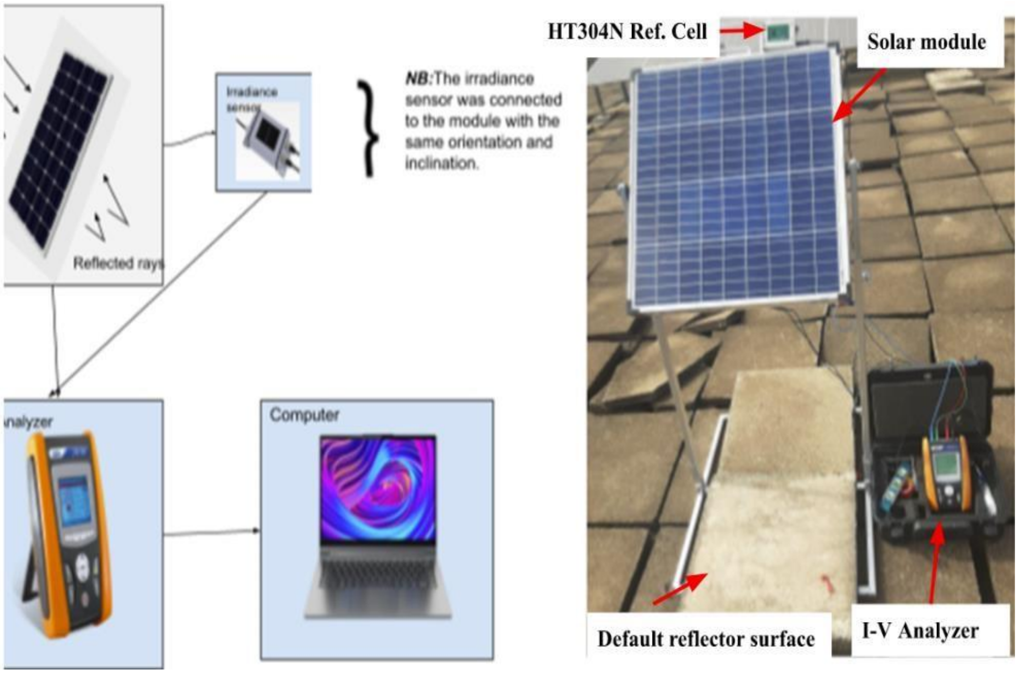


Figure 1: Layout of the equipment interconnection (a) and the actual experimental setup (b).

The experimental configuration uses the front side of a second monofacial module to emulate the back side of a bifacial module. In commercial bifacial modules, the rear-side efficiency is characterized by the bifaciality factor, which is typically approximately 70% for PERC cells, approximately 80% for TOP Con cells, and approximately 90% for HIT cells (Guerrero-Lemus et al., 2016). The configuration used in this study effectively assumes a bifaciality factor of 100%, which represents an idealized scenario. The actual power contribution from the rear side of a commercial bifacial module would therefore be lower than the values reported here, and this limitation should be considered when interpreting the results.

2.2 Optimization of ground elevation

To optimize the ground elevation, the module was kept horizontal (defined as 0° tilt). The ground-to-module distance was then varied while collecting I-V data at 30-minute intervals from 10:00 to 15:00 East African Time (EAT). This procedure was repeated over several days.

2.3 Optimization of tilt angle

The module tilt angle was optimized by maintaining the ground elevation at the optimal height obtained in Section 2.2 and adjusting the tilt angle from 0° to 90°. I-V data at each tilt angle were collected at 30-minute intervals between 10:00 and 15:00 EAT. This procedure was repeated twice for each angle.

2.4 Effect of reflective surfaces

The module was installed at the optimized elevation and tilt angle, and the reflective surfaces were placed on the ground beneath the module in alternation. The study was conducted around solar noon on clear, sunny days. Data were collected at 2-minute intervals 10:00–15:00 EAT, which captures peak solar hours but does not represent full daily behavior. This window was selected because it encompasses the period of highest and most stable irradiance; however, early morning and late afternoon performance, when lower sun angles may alter the relative front-to-back irradiance ratio, is not captured. This limitation means that the daily energy yield estimates derived from these measurements may not be directly generalizable to full-day performance. Figure 2 shows the reflective surface setup with a tilt angle of 30° and an elevation of 1.2 m.

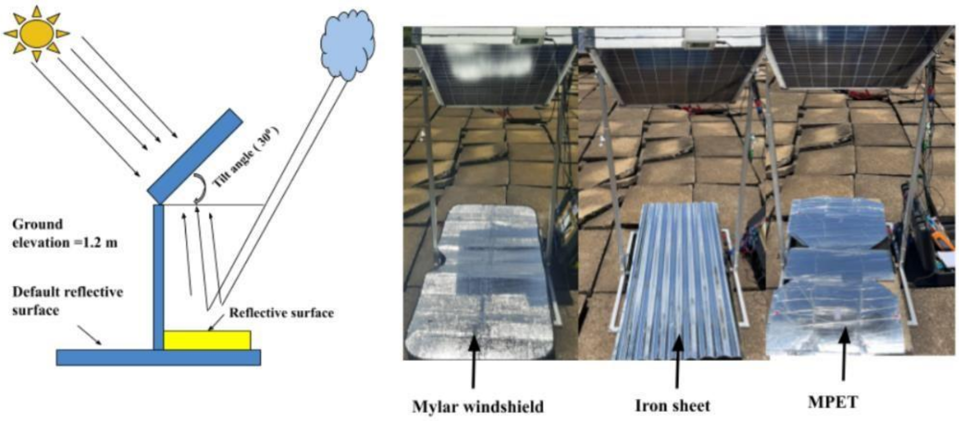


Figure 2: Schematic design of the experimental setup (a) and the actual experimental arrangement (b) with reflecting surfaces positioned beneath the module.

The natural ground surface at the experimental site was a combination of grass and compacted soil, with an estimated albedo of approximately 0.20–0.25. The reflective materials used in this study have substantially higher reflectance values: MPET has a reflectance of approximately 0.85–0.95, Mylar sunshade approximately 0.75–0.85, and galvanized iron sheet approximately 0.35–0.60, depending on surface condition and angle of incidence. Measurements were conducted on clear days with stable irradiance conditions to minimize variability. Temperature and irradiance were recorded simultaneously with each I-V measurement. Nevertheless, some variation in atmospheric conditions was unavoidable over the measurement period, and this contributes to the scatter observed in the data.

3. Results and Discussion

3.1 Module measured parameters

The measured values for front and back sides, together with the manufacturer's ratings under Standard Test Conditions (STC: 1000 W/m^2, 25 °C), are shown in Table 2.

Table 2: Module STC ratings and measured values at an elevation of 1.2 m and a tilt angle of 30°.

Parameter	STC (1000 W/m^2, 25 °C)	Front side (1060 W/m^2, 42 °C)	Back side (97 W/m^2, 38 °C)
Power output, Pmax (W)	60.0	53.9	4.6
Max. current, IM (A)	3.2	3.6	0.3
Max. voltage, VM (V)	18.0	14.8	13.3
Short circuit current, ISC (A)	3.4	3.8	0.4
Open circuit voltage, VOC (V)	22.2	20.5	17.5
Fill factor, FF	0.7	0.7	0.7
Module efficiency, η (%)	14.9	14.6	14.0

The measured short-circuit and maximum-power-point currents for the front side were slightly greater than the manufacturer's values, which is attributed to the higher irradiance at the site (1060 W/m^2) compared to STC (1000 W/m^2). Conversely, the measured voltages were lower than the manufacturer's ratings, which can be explained by the higher module temperature at the site (42 °C) compared to STC (25 °C), since elevated temperatures reduce the open-circuit voltage of silicon solar cells. The back-side values follow a similar pattern. The total power output was 53.9 W (front) plus 4.6 W (back), totaling 58.5 W, with the back side contributing an additional 8.6%. The measured I-V data were not corrected to STC, as the primary objective of this study was to evaluate relative performance trends under field conditions rather than to provide absolute STC-referenced values. Direct comparison of absolute power values between measurement sessions conducted under different irradiance and temperature conditions should therefore be interpreted with caution. Future work could incorporate STC correction using established methods (e.g., IEC 60891) to enable more rigorous comparisons with manufacturer specifications.

3.2 Ground elevation optimization

Figure 3 illustrates how the ground elevation varied with power output for both the front and back sides of the module.

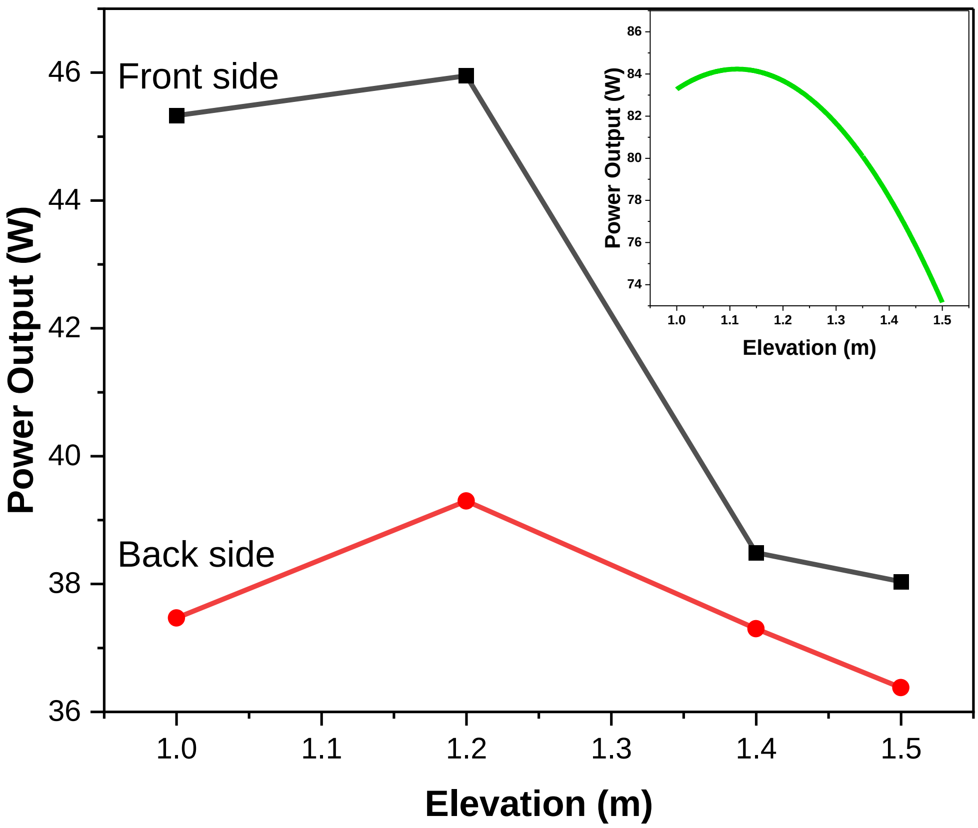


Figure 3: Power output versus ground elevation for the front and back sides (main graph) and the total combined variation (inset) at a 30° tilt angle. Front-side irradiance: 1016 W/m²; back-side irradiance: 97 W/m².

As shown in Figure 3, elevating the module from the ground level led to an increase in power output up to approximately 1.2 m, after which the power output decreased. The increase in back-side power with elevation is attributed to increased irradiance reaching the back side as the distance from the ground increases, allowing a larger view factor for reflected irradiance. Beyond the optimal elevation, the declining power output from the back side is due to the reduced solid angle subtended by the reflective ground surface, resulting in less reflected irradiance reaching the rear module.

The observed slight decrease in front-side power at higher elevations is likely attributable to variations in ambient conditions (irradiance and temperature) during the measurement period rather than a direct effect of elevation on front-side performance. Module temperatures during these measurements ranged from 38 °C to 44 °C. Without STC correction, small differences in irradiance and temperature between measurement sessions can produce apparent power variations that are not attributable to the parameter being investigated. Consequently, a ground elevation of approximately 1.2 m was identified as optimal, yielding the highest combined power output from both sides.

3.3 Tilt angle optimization

The relationship between tilt angle and power output is depicted in Figure 4. The trend for both sides shows an initial increase to a maximum at approximately 30°, followed by a decline at higher angles. At the optimum angle (30°), the front side produced more power (43 W) than the back side (36 W), as expected, since the front side receives direct irradiance from the sky.

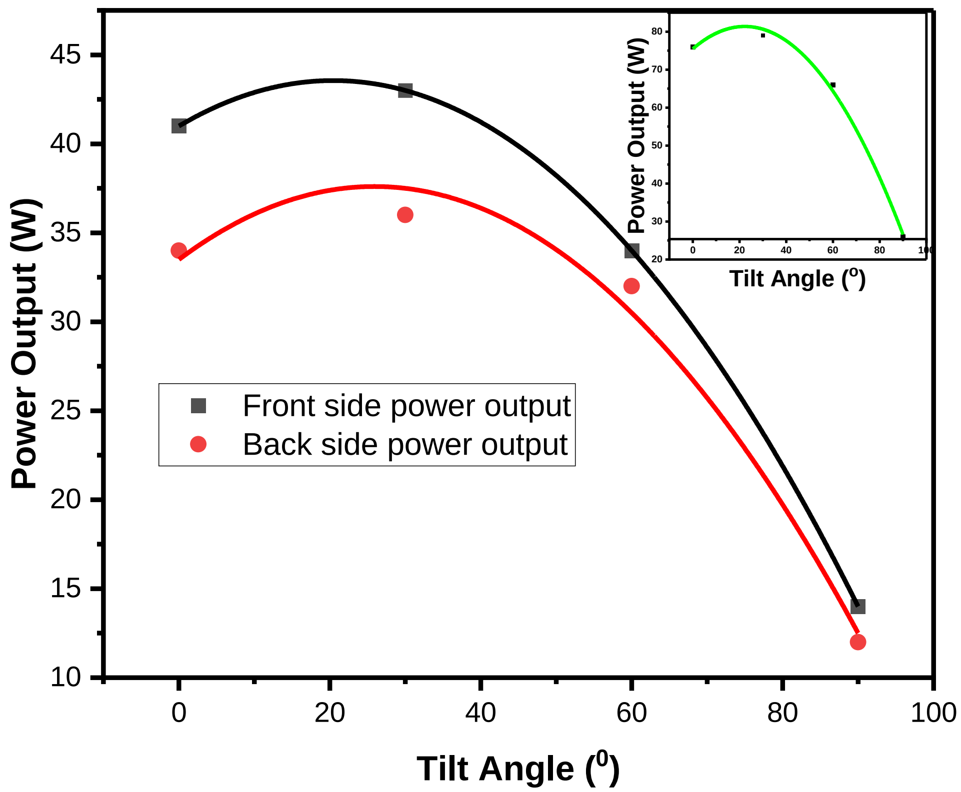
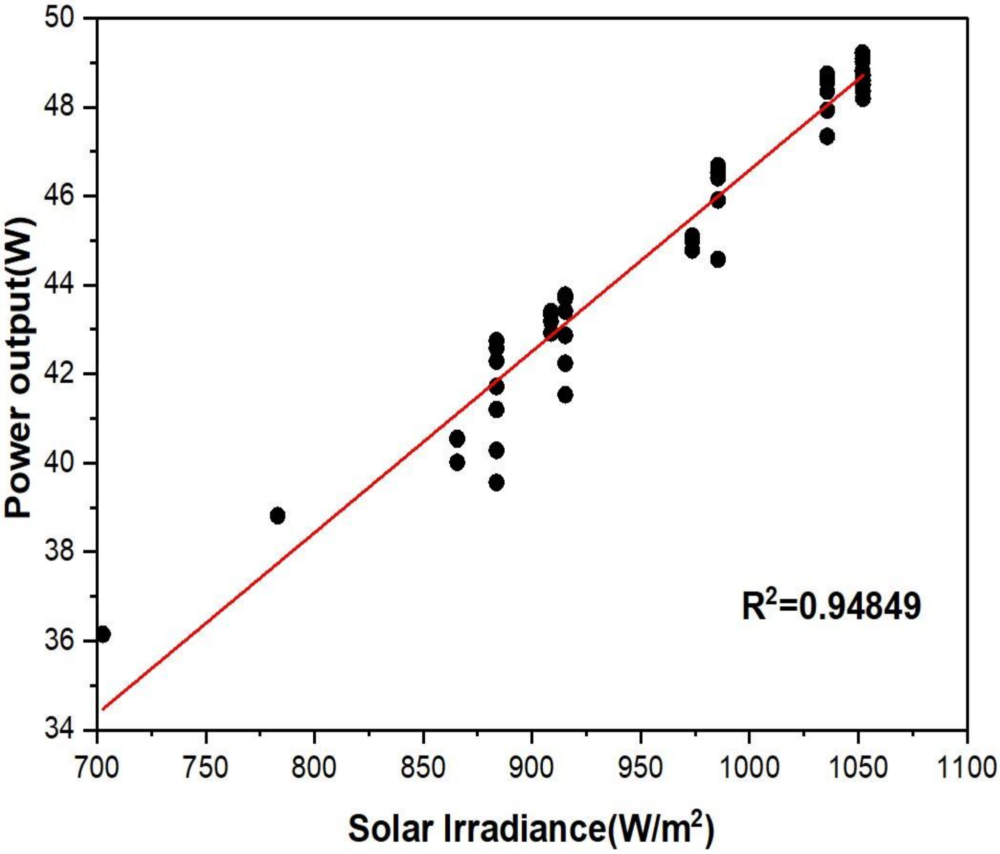


Figure 4: Power output variation with tilt angle for the front side, back side, and total power output (inset) at 1.2 m ground elevation. Front-side irradiance: 1016 W/m²; back-side irradiance: 97 W/m². Module temperature: 40–44 °C.

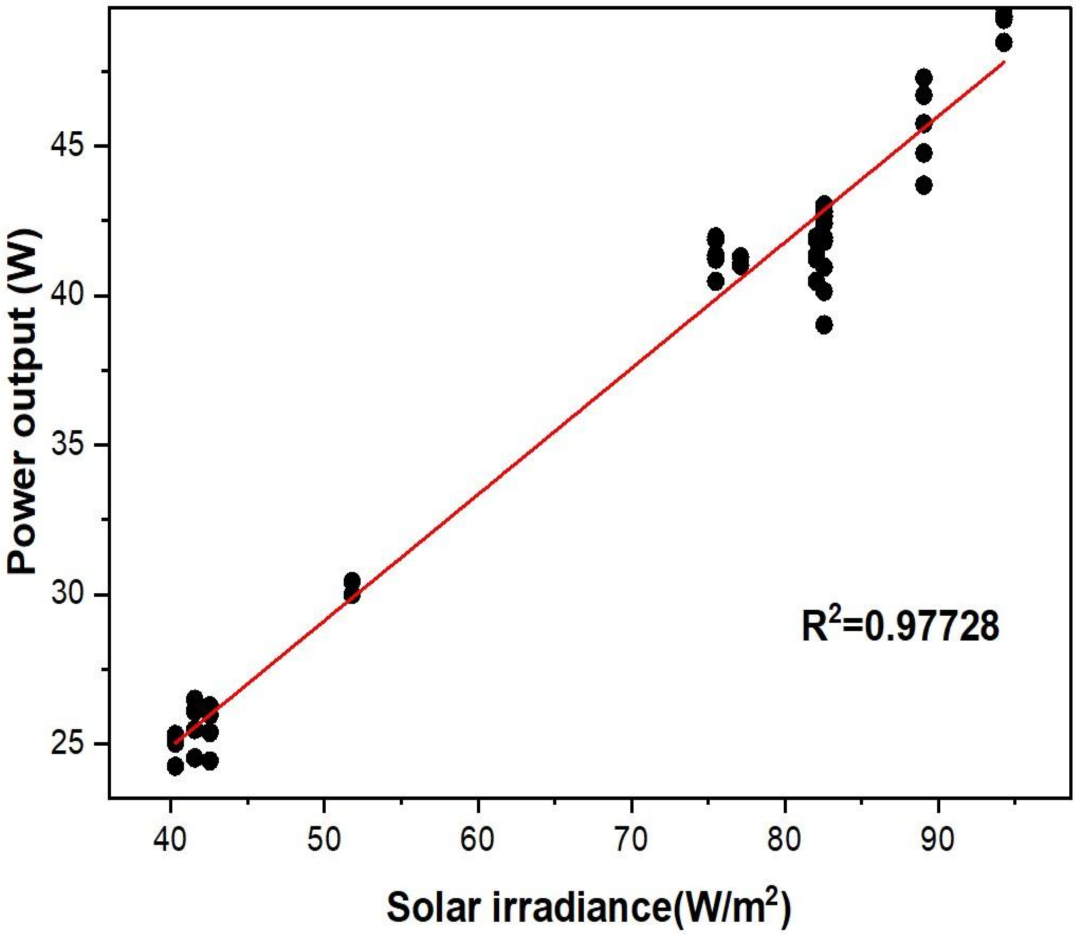
The combined power output (inset) follows the same trend. At lower and higher tilt angles, the irradiance on both sides was reduced, leading to lower power output. The optimal tilt angle of approximately 30° is consistent with the site latitude (1.27° S), as tilt angles near the latitude generally maximize annual energy capture for fixed installations. It should be noted that irradiance and temperature conditions varied slightly between measurement sessions for different tilt angles; the values reported represent typical conditions during the measurement period.

3.4 Power versus irradiance

Figure 5 shows the relationship between power output and solar irradiance, which exhibits a direct linear correlation as expected, since higher irradiance produces greater photocurrent and thus more power. The linear fit yields a coefficient of determination (R^2) of 0.95 for the front side and 0.98 for the back side.


Power output(W)
50
48
46
44
42
40
38
36
34
700
750
800
850
900
950
1000
1050
1100
Solar Irradiance(W/m2)
R2=0.94849

(a)



(b)

Figure 5: Power output versus solar irradiance for the front side (a) and back side (b) at 1.2 m elevation and 30° tilt angle.

The highest power output for the front side was 53.87 W at an irradiance of 1060 W/m^2, while the lowest was 34.3 W at 718 W/m^2. For the back side, the maximum power was 4.82 W at 94.5 W/m^2 and the minimum was 1.56 W at 40 W/m^2.

3.5 Effect of reflective surfaces on power output

The solar irradiance reaching the back side increased substantially with the introduction of reflective materials. The MPET reflector produced the highest percentage increase in irradiance (84.6%), while the iron sheet produced the lowest (22.9%). Figure 6 summarizes the performance of the three reflectors across multiple measurement attempts.

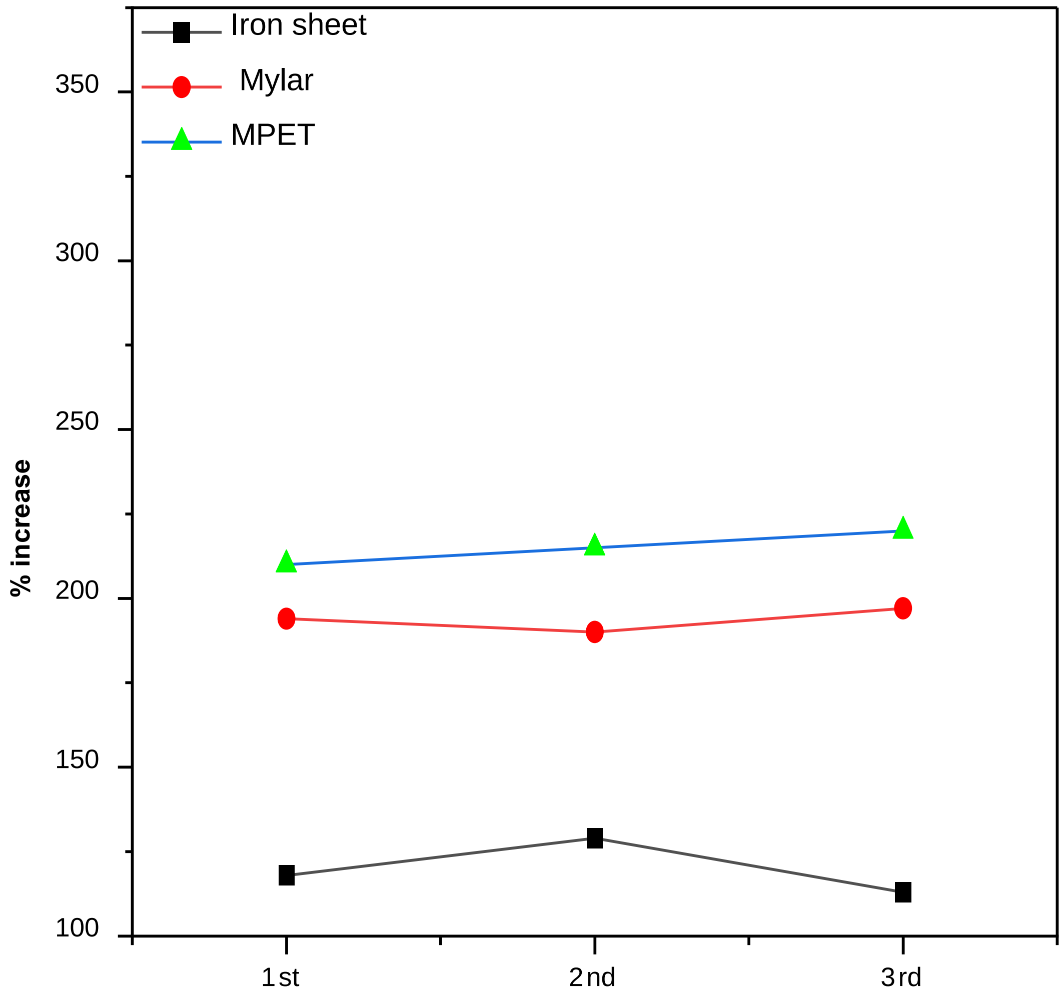


Figure 6: Percentage increase in irradiance versus the number of measurement attempts for the three reflectors.

The amount of reflected irradiance on the module back side had a direct correlation to the power generated. Without any reflector, the combined power output was 57.4 W. With reflectors, the power outputs were: MPET 65.3 W (13.7% increase), Mylar 60.4 W (5.2% increase), and iron sheet 58.6 W (1.9% increase). These results are consistent with the findings of Martin and Tamizhmani (2019), who reported comparable improvements using back-surface reflectors. Caixia et al. (2023) also found that reflectors increase bifacial module power output under various reflection conditions. The superior performance of MPET is attributed to its high specular reflectivity, which is characteristic of the metallized polymer films used in solar cooker applications. If a 60 W module with an active area of approximately 0.25 × 0.23 m achieved a power increase of approximately 13.7%, it is reasonable to expect that larger panels and arrays would yield correspondingly significant absolute power increases.

4. Conclusion

A study on bifacial solar module performance within the tropics has been carried out using Chiromo Campus, University of Nairobi, Kenya, as the case study site. The study established that the best performance was achieved at a ground elevation of approximately 1.2 m and a tilt angle of approximately 30°. The three reflective surfaces enhanced irradiance reaching the back side with the following percentage increases: MPET (84.6%), Mylar (77.2%), and iron sheet (22.9%). The corresponding power increases were approximately 13.7% (MPET), 5.2% (Mylar), and 1.9% (iron sheet). MPET would therefore be the most effective background reflector material among the three tested. These results demonstrate that, to fully benefit from bifacial modules, their installation must account for ground elevation and background type, unlike conventional monofacial installations.

Several limitations of this study should be acknowledged. First, the experimental configuration used two monofacial modules mounted back-to-back, which assumes a bifaciality factor of 100% and likely overestimates the actual rear-side power contribution compared to commercial bifacial modules. Second, measurements were restricted to the 10:00–15:00 time window and were not corrected to STC, which limits direct comparability across sessions and with manufacturer specifications. Third, the measurement campaign spanned approximately two and a half months, and longer-term seasonal variations were not captured. Future work should employ commercial bifacial modules, incorporate STC correction of I-V data, extend measurements to cover full daily profiles and seasonal variations, and include additional reflector materials and ground surface types relevant to the East African region.

5. Acknowledgments

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