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Investigating the Performance of Bifacial PV Module at Different Heights Using Exergy and Energy Analysis

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Abstract
Bifacial photovoltaic technology has attracted attention due to its capacity to produce energy from the front and back sides. This study investigates the impact of mounting heights on the performance of bifacial Photovoltaic solar modules using a realistic model of energy and exergy analysis in the QASSIM university campus in Buraydah City Saudi Arabia. The experiment involves installing bifacial modules with a tilt angle of 26.3^o at various heights above the ground (0.5 m, 1.0 m, and 1.5 m) with an evaluation of the module's efficiency, energy yield, and exergy yield was recorded before noon in two periods; P1 (8:30 am - 10 am), and P2 (11 am - 12:30 pm). The performance of a bifacial photovoltaic module is analyzed by the measurement of the I-V characteristics where the solar cell is connected to a variable resistive load. This load varies from the short circuit condition to the open circuit condition while both the voltage in the output terminals of the PV cell and the output current are measured.The results show that the bifacial module with a height of 1.5 meters is the most efficient and productive option than the lower heights. The bifacial module at 1.5 m height is efficiently high during P2 the Exergy output is 229 W/m^2withan efficacy of 24.5% and Elec. 205 $W/m^2$with an efficacy of 20.5 %. The bifacial module with a height of 1.5 meters displays a short-circuit current I_{sc} of 12.9 A with an open-circuit voltage V_{oc} of 45.3 V giving an output power reached at 205 W/m² in the period of P2.These results help to optimize the system design and installation of solar farms on a large scale where photovoltaic module height is variable.

Keywords: Bifacial Photovoltaic Module, Energy Analysis, Exergy Analysis, Energy efficiency, Exergy efficiency.

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I. Introduction

Solar energy is a promising alternative to renewable energy resources to increase the demand for clean energy because it is cheap and abundantly available. Integration of solar energy with various types of other energy systems plays an important role in the reinforcement of sustainable development [1].Solar energy can be used to generate electricity, desalinate water generate heat, etc.Solar cells are devices that convert sunlight directly into electricity; typical semiconductor materials are utilized to form a PV solar cell device. These materials' characteristics are based on atoms with four electrons in their outer orbit or shell. Semiconductor materials are from the periodic table's group 'IV' or a mixture of groups 'IV' and 'II', the latter known as 'II–VI' semi-conductors[2]. Solar photovoltaics (PV) is developed as a transformative technology in the clean energy transition because it converts the absorbed solar energy into electrical and thermal energy. When solar radiation incident on the panel then 75-80% of the absorbed radiation generates electricity and is dissipated in the form of heat to the surrounding after photovoltaic conversion [3, 4]. Both heat and electricity are obtained from the integration of solar thermal components with solar photovoltaic (PV) cells to form a hybrid unit [5]. These energy systems are also suffering from low conversion efficiency, high initial investment costs, long payback periods, and unavailability of skilled manpower. Therefore, hybrid energy systems in our real-life applications require special attention for their fast and sustainable development [6].

The advancement of bifacial photovoltaic solar modules in photovoltaic technology shows great promise. According to the ITRPV 2023 report, bifacial modules are popular and are expected to capture the largest share of the photovoltaic market [7]. Bifacial photovoltaic cells capture photons on both cell faces from the front and from the rear to improve their efficiency[8].This system includes rooftops, balconies, curtains, sunshades, and wall types to generate power from direct sunlight, reflected sunlight, and diffusion irradiation. These systems provide buildings with the ability to perform two tasks firstly, they should meet the standards of traditional building envelope materials, including acceptable structural strength, thermal insulation, weather protection, and noise protection[9, 10]. A transparent back cover integrates bifacial cells into a panel based on glass or transparent foil to produce higher energy output due to the additional energy generated by rear irradiation [11].

Thus, it attracts researchers for its use in various theoretical and experimental studies. Hasan and Dincer [12]have studied the bifacial PV solar panel modules for offshore power production under various operating and design parameters including the location of the sun throughout the day, solar irradiance intensity, as well as wavy and still water conditions and orientation of the module[12]. Although, Alaa et al [13]investigated thebifacial solar cell module fixed on an adjustable ground-mounted frame and the tilt angle was varied to be (30º, 45º, 60º, and 90º). For each angle, temperature and irradiance were monitored on a sunny day at noon in the middle of July in Baghdad city [13]. This study has shown that environmental conditions such as irradiance intensity, and ground albedo can dictate the energy and exergy efficiency of bifacial solar modules Ahmed et al.[14]evaluated theexergy, energy, and power conversion efficiencies for the two days based on measured parameters such as solar intensity, ambient temperature and module temperatureinstalled at Poornima University, Jaipur. The exergy efficiency varies between 4.5 and 8.93%, the energy efficiency varies between 11.08 and 14.50% and the power conversion efficiency varies between 7.98 and 10.49% throughout the day in the clear sky [14]. Furthermore, Aoun et al. [15] have also experimentally studied the energy and exergy performance of a mono-crystalline PV panel in terms of energy, exergy, and power energy efficiencies. On cloudy days, energy efficiency (22.3%), exergy efficiency (12.0%), and power energy efficiency (16.0%) were obtained [15].

Energy and Exergy analysis is based on the first and secondlaws of thermodynamics. In energy analysis, only aquantitative evaluation is performed, while in exergy analysisa qualitative evaluation is performed [16].Energy analysis can be expressed as the ratio of the amount of energy at the system output to the amount of energy input whereas exergy analysis helps to find the fraction of available energy that is converted into actual work[17].Exergy analysis evaluates the efficient usage of energy by calculating the magnitude of irreversibility and therefore, this analysis improves the system performance[18]. Solar radiation incident on the photovoltaic module surface will be converted into electrical and thermal energy. The thermal energy is dissipated to the surroundings as heat or thermal loss causing exergy destruction, while the electrical energy is utilized[19].The solar cell is connected to an electrical circuit is the ratio of output electric power to the incident solar radiation on the solar cell surface. The electrical power output of a photovoltaic cell depends on the surface temperature and quantity of incident solar radiation[20].

Hence, in this study, a realistic model of energy and exergy analysis was used for predicting the performance of bifacial photovoltaic modules at different heights installed in the QASSIM university campus in Buraydah City Saudi Arabia. The performance of a bifacial photovoltaic module is analyzed by the measurement of the current and voltage characteristics. In this method, a solar irradiance is applied to the solar cell connected to a variable resistive load. This load varies from the short circuit condition to the open circuit condition while both the voltage in the output terminals of the PV cell and the output current are measured [21].

II. Research Methodology and Materials

2.1 Energy and Exergy Efficiency of Solar Panel

Energy efficiency gives the quantity of energy interaction during a process whereas exergy efficiency gives the quality of energy available for converting to useful work when the system reaches a steady state.Overall, the exergy analysis evaluates the efficient use of PV modules and provides the actual performance. Mathematically the exergy balance relation for a PV module is given by Equation (1).

$$\text{Exergy Input} = \text{Exergy Output} + \text{Exergy Loss} + \text{Irreversibility}$$

$$Ex_{in} = Ex_{out} + Ex_{loss} + I_r \qquad (1)$$

where Ex_{in} is the exergy input represented in Watt; Ex_{out} is the exergy output represented in Watt; Ex_{loss} is the exergy loss represented in Watt; Ir is the irreversibility.

The exergy input Ex_{in}, can be calculated using Patela's mathematical model, see in Equation (2). According to Patela's relation, the input exergy is defined as the amount of power received by the PV module [22], [23].

$$Ex_{in} = AG\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{2}$$

where A is the area of the PV module in m^2; G is solar radiation intensity measured in w/m^2; T_a and T_s are the ambient and sun temperatures in K.

The exergy output Ex_{out} of any electricity generation device can be represented numerically, considering the electrical outputs from the device and thermal energy gained by the device. In solar PV applications, the gained thermal energy is dissipated into the local surroundings from the surface of the PV module. Here, the available thermal gains are left unused, which is generally considered as thermal loss in the PV module. Hence, the exergy output from the PV module can be expressed as per Equation (3) [22], [23].

$$Ex_{out} = Ex_{elec} + Ex_{thermal} \tag{3}$$

where $Ex_{ele}$is the exergy electrical represented in Watt; $Ex_{thermal}$is the exergy thermal represented in Watt. The exergy electrical Ex_{ele} is the amount of electricity generated by the PV module in Watt and given by the relation shown in Equation (4) [22], [23].

$$Ex_{elec} = V_{oc} \times I_{sc}\ x\ FF \tag{4}$$

where $V_{oc}$is the open-circuit voltage in Volts; $I_{sc}$is the short-circuit current in Amps; and FFis the fill factor. The fill factor will vary depending on the PV technology and the local operating conditions. The exergy thermal $Ex_{thermal}$ is the amount of energy lost to the local surrounding areas from the PV module in the form of heat. Generally, the PV module experiences heat gain, and this can be understood based on the rise in PV cell temperature. The exergy thermal of a PV module can be calculated using Equation (5) [22], [23].

$$Ex_{thermal} = (h_{conv} + h_{rad}) \times A\,(T_m - T_a) \times \left[1 - \frac{T_a}{T_m}\right] \tag{5}$$

where the $h_{conv}$is the convective heat loss or transfer co-efficient and h_{rad} is the radiative heat loss or transfer co-efficient which is given by the relations as shown in equations (6) and (7)

$$h_{conv} = 2.8 + 3V_w \tag{6}$$

$$h_{rad} = \varepsilon\sigma\left(T_{sky} + T_m\right)\left(T_{sky}^2 + T_m^2\right) \tag{7}$$

$T_m$is the module temperature given in K and $T_{sky}$is the sky's effective temperature given by the relation,

$$T_{sky} = T_a - 6 \tag{8}$$

Module temperature based on NOCT can be calculated as.

$$T_m = T_a + (NOCT - 20)\frac{G}{800}. \tag{9}$$

Electrical exergy in the output power of solar photovoltaic module:

$$Ex_{elec} = V_{oc} \times I_{sc} \times FF \tag{10}$$

Energy efficiency is the ratio of the power output of a solar cell to the solar energy delivered to the solar panel[24]. The following equation gives the energy conversion efficiency of the solar photovoltaic

$$\eta_{en} = \frac{E_{out}}{E_{in}} \tag{11}$$

$$\eta_{en} = \frac{Voc\ x\ Isc\ x\ FF}{AxG} \tag{12}$$

The I-V characteristics i.e. current-voltage characteristics of the solar cell can be given by the following equation:

$$I = I_1 - I_0 \times \exp^{\left[\frac{q \times (V - IR_S)}{A \times K \times T}\right]} \tag{13}$$

The output electrical power of solar photovoltaic is given by:

$$P_{el} = IxV \tag{14}$$

Moreover, the maximum electrical output power is given by:

$$P_{max} = V_{oc}\ x\ I_{sc}\ x\ FF \tag{15}$$

$$P_{max} = V_{mp}\ x\ I_{mp} \tag{16}$$

2.2 Experimental Setup

The south-facing bifacial PV module is installed at the QASSIM university campus in Buraydah City Saudi Arabia (26.34 N, 43.76 E)and its specification is stated in Table 1. Bifacial PV module performance was investigated at different elevations of 0.5 m, 1.0 m, and 1.5 m with a tilt angle of 26.3° as shown in Fig.1. The recorded readings of PV module are solar irradiance, ambient temperature, and PV module temperature with the operational characteristic quantities of the modules such as V_{oc}, I_{sc}, V_m, I_m, P_m, FF, IV, and PV curves and were recorded before noon during two periods; P1 (8:30 am - 10 am), and P2 (11 am - 12:30 pm). A PV200 instrument is used to measure these readings and its manufacturer's data sheet is shown in Table 2.

Table1. Bi-facial PV module specifications

Characteristics	**Bi-facial Module**
Technology	Bifacial PERC Half -cut
Dimensions (mm)	2094x1038x35mm
Number of cells	144
Maximum Power (W)	339.8
Maximum Current (A)	8.76
Maximum Voltage (V)	38.8
Open Circuit Voltage (V)	46.6
Short Circuit Current (A)	9.41
Module Efficiency (%)	20.9

Figure 1. Installation of the bifacial module at different elevations

Table 2. Manufacturer's data sheet of PV200

PV200 Specifications	
Weight	1.04kg / 2.3lb
Dimensions	26.4 x 10.7 x 5.8cm / 10.4 x 4.2 x 2.3”
Open Circuit Voltage	
Display Range	0.0VDC - 1000VDC
Measuring Range	5.0VDC - 1000VDC
Resolution	0.1VDC maximum
Accuracy	± (0.5 % + 2 digits)
Short Circuit Current	
Display Range	0.00ADC - 15.00ADC
Measuring Range	0.50ADC - 15.00ADC
Maximum power	10kW
Resolution	0.01ADC maximum
Accuracy	± (1% + 2 digits)

III. Results and Discussion

The experimental data of the Bifacial PV module temperature T_m at different heights, 0.5 m, 1.0 m, and 1.5 m are reported in Figures 2 to 4.These results show that thephotovoltaic cell temperature T_m reaches its highest value in the second period where the ambient temperature and solar radiation are at maximum value. The Bifacial module temperatures are higher than the ambient temperature since the solar irradiation warms up the PV modules. The photovoltaic cell temperature $T_m$reaches51.6, 53.6, and 56 °C for the heights of 0.5 m, 1.0 m, and 1.5 m respectively. Among them, the photovoltaic cell temperature T_m of 1.5 m height is high because the module receives an extra amount of solar irradiance from its backside causing itsinterior temperature to increase.

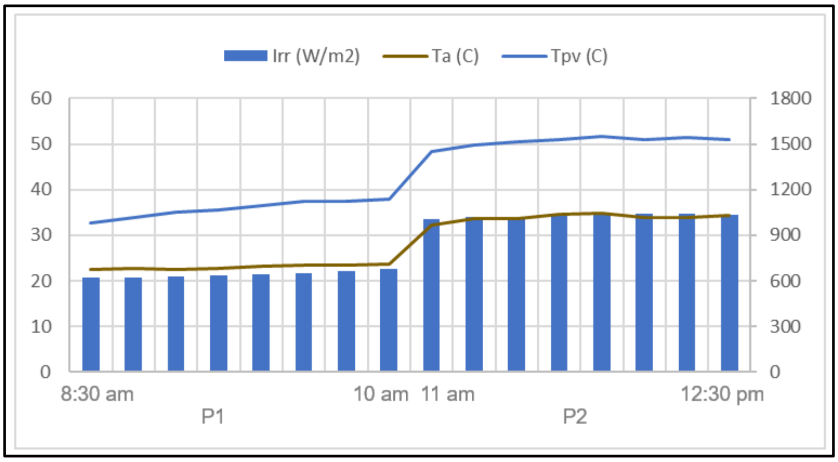

Figure 2. Variation of module temperature with ambient temperature and solar irradiance for 0.5 m height

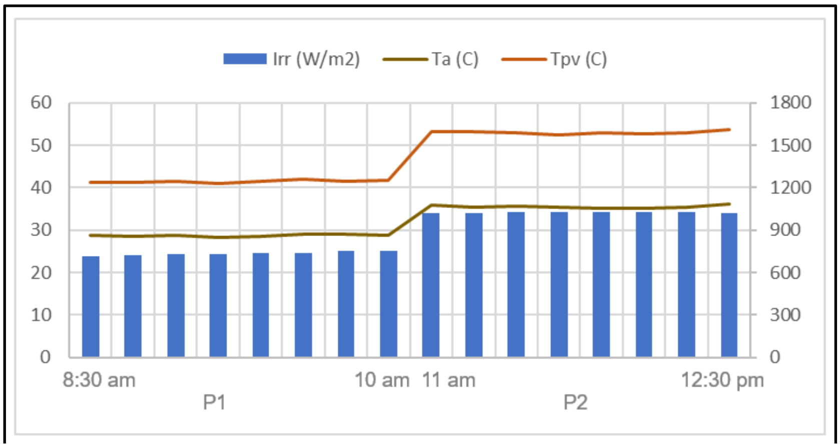

Figure 3. Variation of module temperature with ambient temperature and solar irradiance for 1.0 m height

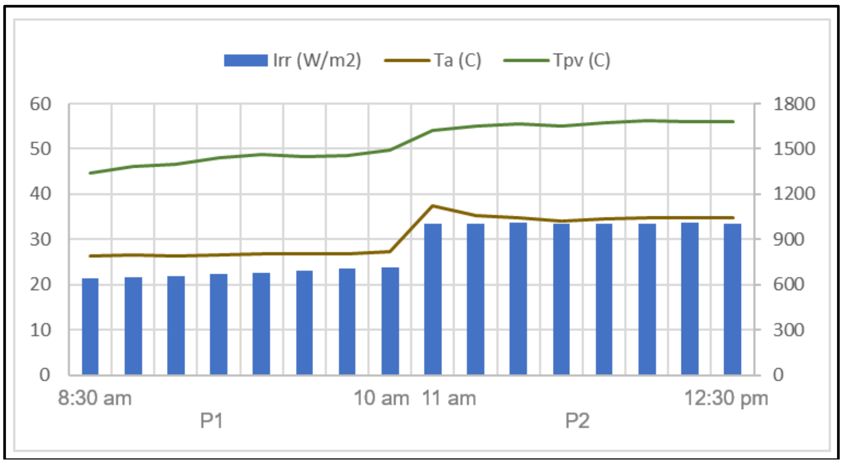

Figure 4. Variation of module temperature with ambient temperature and solar irradiance for 1.5 m height

The Exergy analysis for Bifacial PV modules at different heights, 0.5 m, 1.0 m, and 1.5 m are shown in Figures 5, 6, and 7respectively. It includessolar irradiance incident, input exergy, electrical exergy, thermal energy, output exergy, and lost exergy were obtained from recorded readings using equations from 1 to 13.

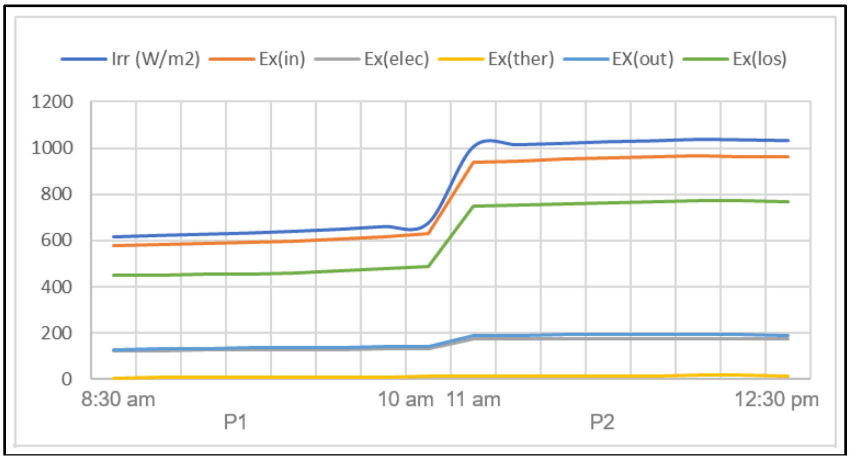

Figure 5. Bifacial module exergy analysis at height 0.5 m

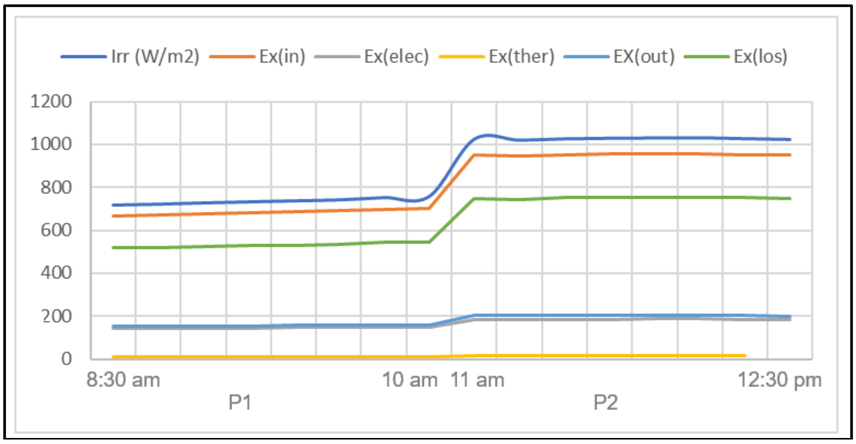

Figure 6. Bifacial module exergy analysis at height 1.0 m

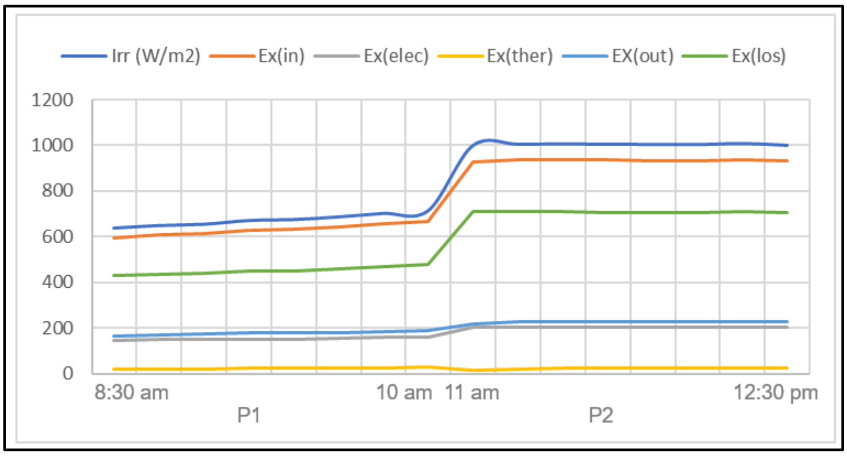

Figure 7. Bifacial module exergy analysis at a height of 1.5 m

Exergy component breakdown percentages for solar PV modules at different heights for both periods are shown in Figure 8. The solar input exergy is 93% incident on PV modules while 7% is reflecteddue to non-absorption energy and the remaining exergy is either utilized as output exergy or lost due to exergy destruction within the process. In Figure 8, the output exergy from the solar photovoltaic module is much less, because exergy loss is high as a result of irreversibility.

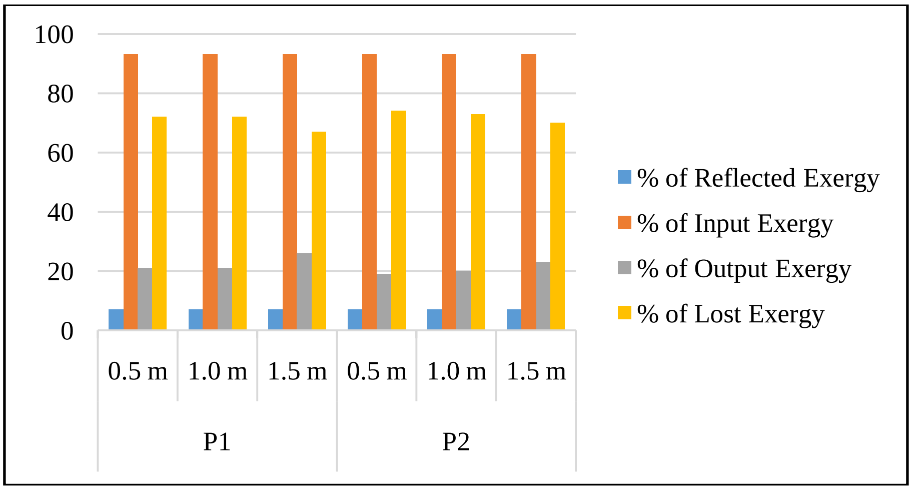

Figure 8. Exergy components breakdown percentage

Peak values of exergy output efficiency and electrical output efficiency for different heights 0.5 m, 1.0 m, and 1.5 m were compared and are graphically represented in Figure 9.Among them the 1.5 m height is efficiently high during P1 the Exergy output is 188W/m^2 at 28.4% and Elec is 160 W/m^2 at 23 % and in P2 the Exergy output is 229 W/m^2 at 24.5% and Elec. 205 W/m^2 at 20.5 %.

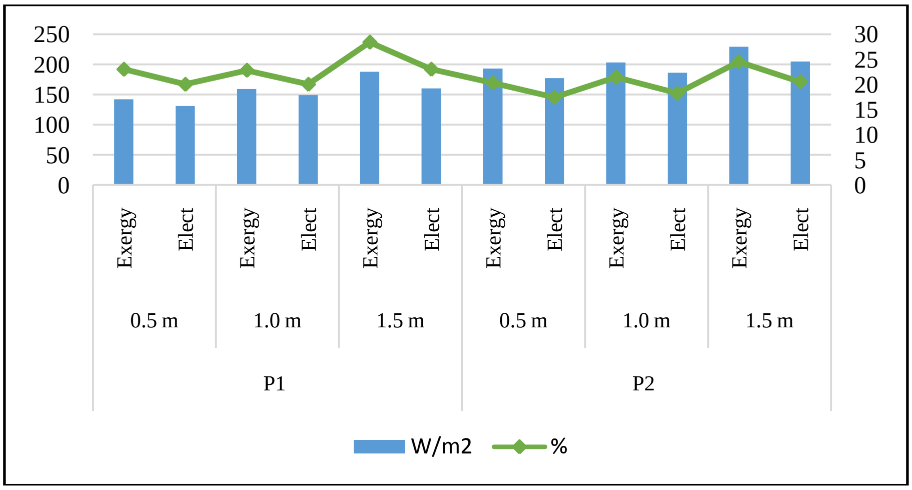

Figure 9. Comparing the peak values of Exergy and Energy outputs and efficiencies

Figures 10 and 11 illustrate how the exergy and energy efficiencies of a bifacial module vary with its height during periods 1 and 2. The bifacial module with a height of 1.5 meters outperforms the others in both exergy and energy efficiency. Specifically, the bifacial module with a height of1.5 meters exhibits approximately 5% higher exergy efficiency in period 1 and 4% higher exergy efficiency in period 2. However, these differences are not directly reflected in the energy efficiency percentages. This is because the module temperature is higher in the case of the 1.5 meter module compared to the others. The gap between exergy efficiency and energy efficiency, which reaches 5% for the 1.5 meter module and is lower for the other modules, represents the amount of exergy lost by the module as heat.

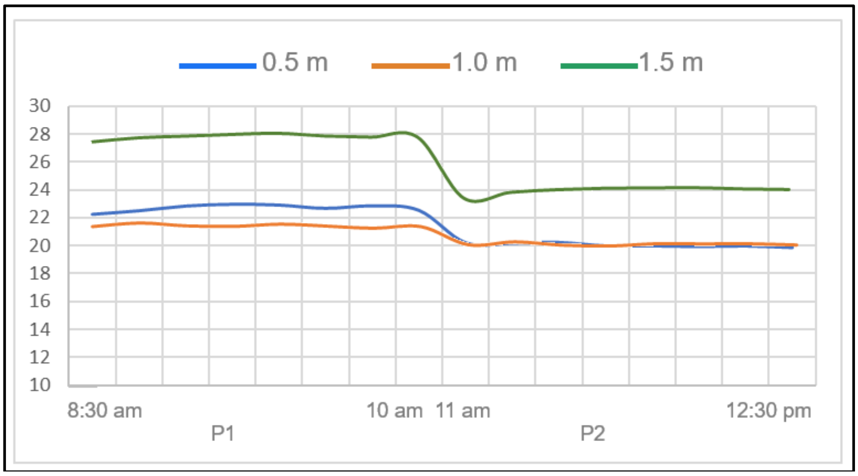

Figure 10. Variation of Exergy Efficiency

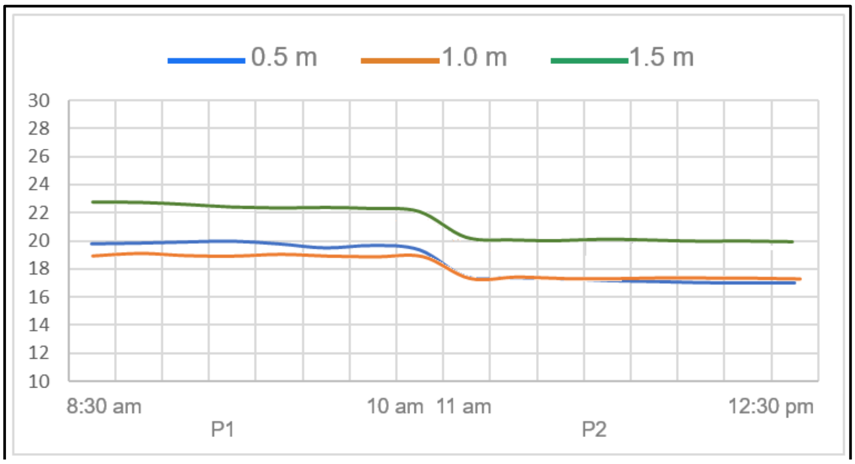

Figure 11. Variation of Energy Efficiency

The electrical performance of bifacial modules with different heights was evaluated through a PV200 instrument to record the I-V and P-V curves during two different periods (P1 and P2) and a comparison between the two periods is graphically represented in Figures 12 and 13. The bifacial module with a height of 1.5 meters displayed a short-circuit current (I_{sc}) of 12.9 A with an open-circuit voltage (V_{oc}) of 45.3 V with anoutput power reached at 205 W/m² in the peak period of P2 whereas the module's height 0.5 meters showed an I_{sc} of 12.3 A, a V_{oc} of 45.1 V, and an output power of 177 W/m². The performance of the module with a height of 1.0 meters is lower than the module with a height of 1.5 as shown in Fig.12 and 13.

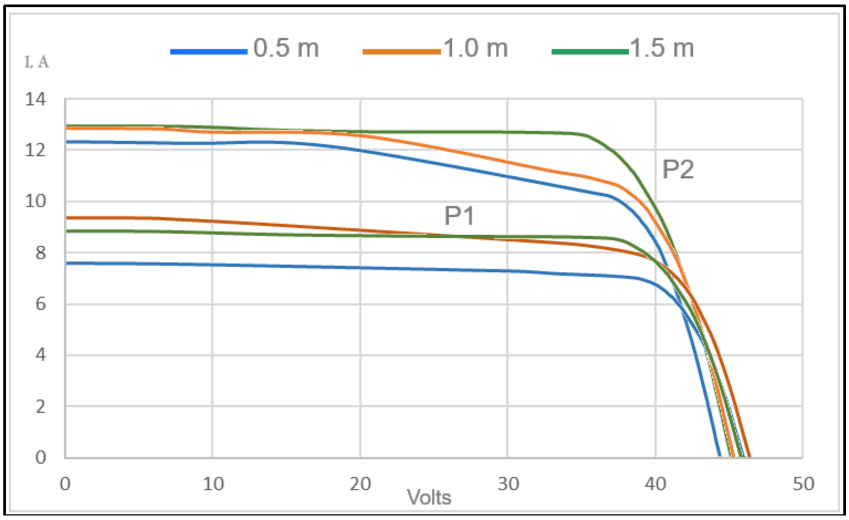

Figure 12. I-V curves at different heights for both periods

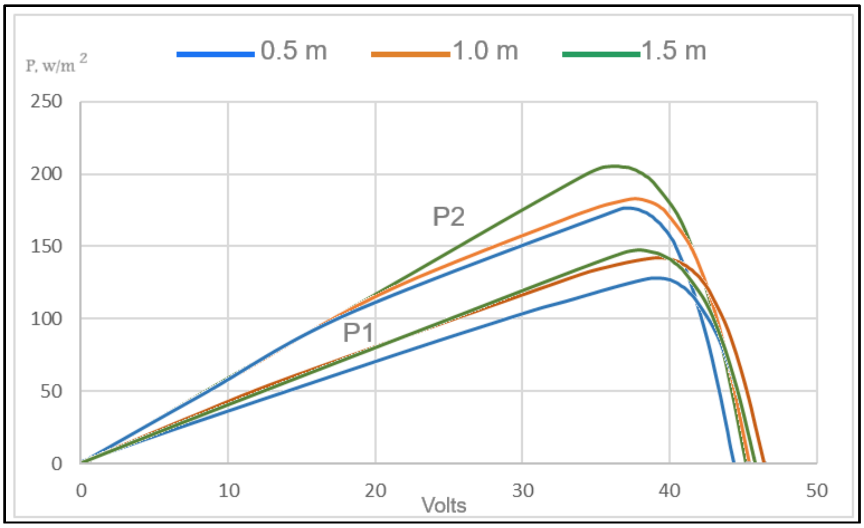

Figure 13. P-V curves at different heights for both periods

IV. Conclusion

In conclusion, the effect of changing the elevation from the ground on the performance of bifacial modules on a sunny day was investigated. The experiments were conducted in sunny day, multiple readings were recorded during the day for different elevations (0.5 m, 1.0 m, 1.5 m). The recorded readings are solar irradiance, ambient temperature, and PV module temperature in addition to the operational characteristic quantities of the modules such as Voc, Isc, Vm, Im, Pm, FF, and the IV curves. The results of investigation show that the bifacial module with a height of 1.5 meters is the most efficient and productive option among the modules with lower heights. Overall, the results demonstrate that the performance of bifacial modules improves as the elevation from the ground increase. This is evident from the higher short-circuit current, open-circuit voltage, and maximum power output of the bifacial module. These results demonstrate the potential advantages of using bifacial modules in real-world applications, where varying irradiance conditions are common.

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Competing Interests

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.

Availability of data and materials
The datasets generated during and/or analyzed during the current study are included in the manuscript

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