Experimental Investigation of 4E Performance of A Vertical Bifacial Solar Module During Summer and Winter

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Abstract

The proposed research work presents the performance analysis of vertically mounted bifacial module (VBFM) with and without tracking during summer and winter season. Also various parameters like Energy Efficiency, Electrical Efficiency, Electrical Exergy, Thermal Exergy, Exergy Efficiency, Environmental analysis, Economic analysis, Exergo-Economic analysis, Enviro-Economic analysis and Exergo-Enviro-Economic analysis of VBFM were studied and presented. The comparative analysis was carried out between two Bifacial solar modules installed in two different orientations (East-West and South – North). The experiments were conducted in the real climatic condition of Minjur, Tamilnadu, India. Under the summer and winter climatic condition, when the life time period of 10, 15 and 20 years are considered higher Energy production factor and higher Life cycle conversion efficiency was obtained from VBFM-EW with tracking during summer and VBFM-SN module without tracking during winter season. Exergetic cost was calculated by considering 15, 20, 25 and 30 years of the system with 2 %, 5% and 10% Interest rate. The maximum exergetic cost was obtained from 30 years of the system under 2 % Interest rate. The Enviro-economic and Exergo-Enviro-Economic analysis provides the carbon credits earned from E-W module was maximum with Rs. 11036.18 during summer season & Rs. 12413.48 from VBFM-SN module during winter season considering the life of the system as 15 years.

Introduction

The mass production of electricity in India is through a thermal power station. The major problem involved in a coal-based generation is the waste that comes out by the end of the processing of coal. It causes both water and air pollution. Air pollutants through chimneys reach a large area of livelihood and after the air purity. The same is applicable for water resources around the thermal power station. It is very essential that the present generation people understand that the future generation needs to enjoy all the natural resources. In order to reduce the pollution, every citizen must feel responsible and start adopting clean green energy based electricity generation in every home. This paper aims at the way of promoting the usage of solar energy especially at rural area in order to reduce the transmission problems. In view of that it is important to showcase the exclusive advantages of Bifacial solar module integrated with building may increase the usage of solar energy. This Bifacial modules has the capability to generate power from both front and rear side of the module. Therefore this technology yields higher yield when compared to monofacial module. Also when Bifacial technology is integrated with building may be able to utilize the light inside the building during night time.

(Castillo-aguilella & Hauser, 2016) optimized the variable parameters of the Bifacial Photo-Voltaic Module (BPVM). The results reported that the BPVM height should be 0.15 to 0.8 m, tilt angle should be 7.5 to 35 ° and albedo should be 10 to 90%. (Yu et al., 2016) experimentally tested the energy output between BPVM and Bifacial Photo-Voltaic Module (MPVM). It was reported that annual average energy output of the BPVM was 89.05 Kwh/Kwp and from the MPVM was 86.22 Kwh/Kwp. Also it was found that daily output produced from the BPVM was 3.2% higher than the MPVM. (Siddique, 2015) enhanced the back side efficiency of the BPVM by about 35% using stable sea shell concentrator. (Poulek et al., 2015) introduced BPVM with novel pseudo parabolic concentrator. This system produced 167% higher daily energy output than the conventional BPVM. (Lo et al., 2015) used simulation tool for predict the performance of the BPVM with reflectors. It was reported that BPVM with reflectors produced 26% higher annual yield as compared to the conventional BPVM. (Lim et al., 2014) experimentally studied the performance of the BPVM using different concentrators (transparent glitter powder, silver glitter powder, rhinestone, reflective bead, thumb tack and luminescent solar concentrator plate) and reflectors (adjustable plane mirror). Among the tested concentrators and reflectors it was reported that mirror positively improves the power production whereas concentrators decreased the power production. (Obara et al., 2014) modeled the vertical BPVM using 3D-CAD and reported that maximum output from the BPVM was generated during morning and evening whereas MPVM was produced during noon hours.

(Alper et al., 2014) simulated the South faced BPVM. The results show that BPVM produced 30% higher annual energy yield than the MPVM. (João et al., 2013) designed asymmetric and symmetric concentrating collector for indoor testing of the BPVM. It was found that efficiency of the BPVM with symmetric concentrator (10.3%) was lower than the asymmetric concentrator (11.5%). (Moehlecke et al., 2013) studied the performance of the BPVM using aluminum reflector. The output from the BPVM can be improved up to 29% by using aluminum reflector. Also it was mentioned that dust particles on the panel surface reduces the power output by maximum of 4%. (Hemandel & Benitez, n.d.) 2002 published BPVM with concentrator for facades application. (Krein et al., 2010) studied the performance of the BPVM by varying elevation of the panel and it was reported that when the BPVM was installed at minimum

elevation it received solar intensity between 66–328 W/m² whereas when installed at elevation of 58 cm it received solar intensity between of 360–390 W/m². (Edmonds, 1992) reported that BPVM fixed in compound parabolic concentrator and prism shaped dielectric medium as receiver. This system produced 3 times higher power output than the conventional BPVM. In another study (It, 1990) mentioned that BPVM produced 50% higher power output than the MPVM also he reported that BPVM integrated with fixed concentrators produced 7 times higher annual power production than the MPVM. (Enxlonos & Ctlan, 1987) researched the performance of the BPVM placed on liquid (oil and water) filled concentrators. It was concluded that oil filled concentrator produced higher output than the water filled concentrator. Some scientists mentioned that operating temperature of the BPVM was higher than the MPVM (F & Energy, 2005)(King et al., 2004)(B. Li et al., 2011)(Maturi et al., 2014)(Yusufoglu et al., 2015) whereas some scientists reported that operating temperature of the MPVM was higher than the BPVM (Yang et al., 2011)(Appelbaum, 2016) (Guerrero-lemus et al., 2016)(C. T. Li, 2016)(Ganilha, 2017)(Lamers et al., 2018). Also some scientists reported that both BPVM and MPVM have same operating temperatures (Milan, 2007)(Soria et al., 2015)(Molin et al., 2018). A simulation study on BPVM in different country was studied by different authors (Janssen et al., 2015)(Berrian et al., 2019)(Yusufoglu et al., 2015)(No Title, n.d.) (Kuo et al., 2017) (Chudinow et al., 2019). Experimental (Shoukry et al., 2016) (Pelaez, Deline, Macalpine, et al., 2019)works on the BPVM was done in the country such as Germany (Shoukry et al., 2016), Saudiarabia (Katsaounis et al., 2019), USA (Pelaez, Deline, Macalpine, et al., 2019)(Stein et al., n.d.)(Stein et al., n.d.)(Burnham et al., 2019)(Pelaez, Deline, Greenberg, et al., 2019), South Korea (Seo et al., 2019) and Japan.

On reviewing the above papers, there are so far very less papers reported on the experimental studies of vertically oriented Bifacial solar module (VBFM) for the climatic condition of India. As the main application of bifacial solar modules lies integrated with buildings, it is important to focus on the VBFM on the specific site to analyse the potential available from the system. Basically tracking of the solar panel will yield higher output when compared to non-tracked solar panel. The core idea behind this research work is to analyse the performance of VBFM during summer and winter season. This is because, Sun which is the primary input source for the solar panel does not travel in the same path for all the seasons, this leads a spark to analyse during various seasons. This paper not only gives an insight on the performance of VBFM however has also focused on the effect of tracking on VBFM which would pave an way for the installation of Bifacial solar module integrated as doors or window in the building. So far not many papers were reported about the one time tracking on VBFM facing direct directions and different seasons.

This manuscript is presented as follow: Sect. 1 presents detailed explanation of Bifacial technology, literature survey, investigation gap and involvement. Section 2 defines about the experimental structure, objective and novelty which include the system configuration. Section 3 explains the Results and discussions. Finally, Sect. 4 gives the conclusion of this manuscript.

Experimental Procedure

2.1 System description

Under the experimental system, Fig. 1 shows two BPVM (i) VBFM facing South direction and (ii) VBFM facing East direction. The same two modules are installed and performance was compared. Different measuring equipment are involved to acquire the system input and output parameters and environmental weather data.

2.2 Experimental Apparatus

Two Mono crystalline Bifacial modules with same capacity of 416 watts with front and rear power are 300 W and 96 W respectively were chosen for the experimentation. Specification of BPVM is given in Table 1.

Table I Key parameters of the BPVM in the experiment

Specification	BPVM	
Testing condition	Front side	Rear side
Open-Circuit Voltage at STC ($V_{oc,ref}$)	45.25 V	45.25 V
Short-circuit current at STC ($I_{sc,ref}$)	9.10 A	2.73 A
Voltage at Maximum power at STC ($V_{mp,ref}$)	37.20 V	37.20 V
Current at Maximum power at STC ($I_{mp,ref}$)	8.61 A	2.58 A
Maximum Power at STC ($P_{max,ref}$)	320 W	96 W
Module Efficiency at STC (η)	16 %	4.8 %
Number of cells in a module	72 cells	
Dimension of the solar cell	178.50 mm x 178.50 mm	
Temperature Coefficient of $I_{sc,ref}$ (α)	0.05 %/ $^{\circ}$ C	
Temperature Coefficient of $V_{oc,ref}$ (β)	-0.36 %/ $^{\circ}$ C	
Temperature Coefficient of $P_{max,ref}$ (γ)	-0.43 %/ $^{\circ}$ C	

The installation of the modules was done on the roof top in the latitude and longitude of 13.27° N, 80.26° E at an altitude of 11 metre. The modules are frameless therefore the fabrication was done with incorporating a rubber beading in between the iron and the module corners. To make the module movable, the four legs of the module are fastened using the cement packed in the bucket. Since the module weights around 34 kg each, the cement packing consists of pebbles to increase the strength of the packing. The module is fabricated such that manual tracking over 360° is possible. The module height from the ground clearance is maintained at 100 cm (Baloch et al., 2020) (Gu et al., 2020). The modules are connected to the resistive load of 3.32 ohms individually.

The first module is directed towards South/North direction and second module is facing East/West which is shown in Fig. 1. For tracking purpose, the module was cambered by adjusting the nuts and bolts.

For the site chosen, the ambient temperature fluctuates between 14 and 45° C. During experimentation, parameters such as solar irradiation, V_p , I_p wind speed, Ambient temperature, module temperature were measured between 6.00 AM to 18.00 PM at an interval of one hour. Digital panel meter was used to measure voltage and current. Wind speed and incident solar irradiation are measured by anemometer and MECO make Solar Meter Model: 936. The ambient temperature and module temperature is measured using MECO digital multimeter.

2.3 Experimental setup

Generally rooftop solar modules are installed facing South direction and fixed in the tilt angle equal to the latitude. However, Bifacial solar modules are designed to integrate with buildings and serve the purpose to generate electrical energy. Considering the building integrated application the modules can be fixed by replacing the door, window, Sunshade, or balcony handrail. For the mentioned applications the module needs to be oriented in a vertical orientation so this paper focuses on the vertical oriented bifacial module with and without tracking.

Vertical orientation was chosen as the application of Bifacial module generally lies in the Building Integrated system. In order to analyse the performance of the Bifacial module in the specific site, same set of experimentation was carried out in summer and winter season and their results were compared and analysed.

Experimentation set I - without tracking: Module (i) fixed in Vertical orientation front side facing South Direction and Module (ii) placed in Vertical orientation front side facing East direction.

Experimentation set II with tracking: Module (i) fixed in Vertical orientation front side facing South Direction and Module (ii) placed in Vertical orientation front side facing East direction underwent one time manual tracking at 12.00 PM.

The above mentioned experimentations were carried out both in the month of January and May as follows:

Experimentation set I was carried out on 22nd May 2020 without tracking the East facing panel. Similarly on 25th May 2020 experimentation set II was carried out with tracking. Generally the front side of the module which was facing East was receiving the direct radiation from Sun from 6 AM TO 11 AM. After 12 PM, the direct Sun radiation on the module was not possible as the modules are oriented vertically. After 1 PM, the rear side starts receiving direct irradiation. In order to make the front side (maximum power production capability) to receive direct Sun illumination even after 2 PM, the module is rotated once in a day manually. Now the rear side of the module which has minimum power capacity is made to face East direction and front side to face West direction. Tracking was also carried out in the VBFM-SN module. Similarly experimentation set I & II was carried out on 27th January 2021 and 26th January 2021.

2.4 THEORETICAL ANALYSIS

Table II. Theoretical analysis

TERM	FORMULA	EXPLANATION
ENERGY EFFICIENCY		
power output from the PV module (Taylor et al., 2014)	$P_{out} = V_{oc} \times I_{sc}$	V_{oc} - Open circuit voltage I_{sc} - short circuit current FF - Fill factor.
Fill factor	$FF = \frac{V_{mp}}{V_{oc}} \times \frac{I_{mp}}{I_{sc}}$	V_p - Voltage obtained from the PV module I_p - Current obtained from the PV module.
Energy efficiency	$\eta_m = \frac{V_{oc} I_{sc}}{S \times A}$	S - Solar irradiation received by the PV module
ELECTRICAL EFFICIENCY	$E_{p,dist} = V_p I_p$ (or) $E_{p,dist} = V_{oc} I_{sc} FF$ (Taylor et al., 2014)	
THERMAL ENERGY	$B_{thermal} = \left(1 - \frac{T_{amb}}{T_{module}}\right) Q$ $Q = h_{tot} A (T_{panel} - T_{amb})$ $h_{tot} = 5.7 + 5.8 v$	T_{amb} - ambient temperature in kelvin T_{module} - module temperature in kelvin Q - heat emitted to the surrounding in watts h_{tot} - Heat transfer coefficient (W/m ² K) v is the wind velocity (m/s)
ENERGY EFFICIENCY	Input energy $E_{in} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) A S_{max}$ Output energy, $E_{out} = V_p I_p - \left[1 - \frac{T_{amb}}{T_{module}}\right] h_{tot} A (T_{module} - T_{amb})$ $\eta_{heat} = \frac{V_p I_p - \left[1 - \frac{T_{amb}}{T_{module}}\right] h_{tot} A (T_{module} - T_{amb})}{\left[1 - \frac{T_{amb}}{T_{sun}}\right] A S_{max}}$	T_{sun} - Temperature of clear Sun which is considered as 5777 K. A - area of the module (m ²) S_{max} - Solar irradiation received by the PV module
Embodied Energy - 2525.04 (kWh)		
ENERGY MATRICES - The enhanced performance of the system over the lifespan can be analysed through three parameters such as Energy payback time, Energy production factor and Life cycle conversion efficiency (Tripathi & Tiwari, 2019)		
Energy production factor (EPF)	$EPF = \frac{E_p \times T}{N}$	T - life time period
Life cycle conversion efficiency (LCCE)	$\eta_{LCC} = \frac{(E_p \times T) - E_{emb}}{S_{annual} \times T}$	S_{annual} - Annual solar irradiation energy received from Sun.
Exergoeconomic analysis (or) Exergoeconomic analysis	$R_{exergoe} = \frac{I_{ex,annual,system}}{UYC}$ $UYC = (P_c \times F_{CRF}) + (M_c \times F_{CRF}) - (S_c \times F_{DRF})$ $F_{CRF} = \frac{ROI \times (1 + ROI)^N}{(1 + ROI)^N - 1}$ $F_{DRF} = \frac{ROI}{(1 + ROI)^N - 1}$	$I_{ex,annual,system}$ - Annual overall energy gain UYC - Uniform end of annual cost P_c - net present cost = Cost of PV modules + Fabrication cost S_c - salvage value M_c - maintenance cost F_{CRF} - capital recovery factor F_{DRF} - sinking fund factors
		i - Inflation rate N - Number of years
Enviroeconomic analysis (Carbon mitigation & credit)		
In a coal power plant, approximately 0.980 kgCO ₂ /kWh of average CO ₂ is emitted (Tripathi et al., 2017)		
Total CO ₂ per kWh emitted seems to be 2.04 kg.		
CO ₂ mitigation in tons per annum	$CO_2 M = \frac{CO_2 AE \times QEA}{1000}$	CO ₂ AE - Average CO ₂ emission for power production by coal (2.04 kg CO ₂ /kWh) QEA - Annual overall thermal energy
For global market, the range of CO ₂ price is between 13\$/t CO ₂ to 16\$/t CO ₂ & the average value of CO ₂ emission reduction is 14.5 \$/t CO ₂ has been obtained for numerical computation (Tripathi & Tiwari, 2019)		
Enviroeconomic cost (CO ₂ mitigation price per annum) is given by \$/annum	$C_{CO_2 M} = P_{avg} \times CO_2 M$	P_{avg} - Carbon price per tCO ₂ (Average price has been taken as 14.5 \$/t CO ₂)
Exergo-Enviroeconomic Analysis is same as Enviroeconomic analysis however instead of Energy terms an exergy term has to be considered.		

Experimental Results And Discussion

3.1 Diurnal changes of Solar intensity and Power

The daily average solar illumination received on the front side and rear side of the VBFM-EW on 22.5.2020 are 197.6 W/m² and 186.1 W/m². The front and rear side receiving daily average solar intensity of VBFM –SN on 22.5.2020 without tracking was found to be 171.4 and 116.5 W/m². The maximum total intensity reported on the day was 650 W/m² from the VBFM-EW module. The Sun position seems to be in the exact top of the module and so the module fails to extract the full intensity from Sun due to the position of module. Thereby the total intensity of the module drops to 419 W/m². After 2 PM, rear side of the module start utilizing the illumination. The Sun illumination on the VBFM-SN seems to be increasing from 6 AM to 11 PM and then decreasing thereby. The total power (front and back power) from the VBFM-EW and VBFM-SN module was 50.09 W and 46.62 W.

During the other day of summer on 25.7.2020, the VBFM-EW and VBFM-SN both are manually tracked only once in the day with complete 180° rotation. In which the module was able to receive the maximum total solar intensity of 559.52 W/m² in VBFM-EW and 328.922 W/m² in VBFM-SN. The pattern of hourly solar intensity of VBFM-EW was found to be increasing from 6 AM to 10 AM, later starts to decrease. Once the tracking is done, after 2 PM solar intensity received by VBFM-EW starts to increase. After tracking, the intensity has increased as the maximum capacity front side is made to face North direction and the direction of Sun path during may season. The total power from the VBFM-EW and VBFM-SN module was 96.95 W and 54.16 W. Therefore tracking seems to be beneficial and utilizes more power from the Sun when compared to non-tracked module.

The diurnal changes of the solar illumination received by the module and the related power output obtained from the EW module are given in the Figs. 3, 4, 5 and 6 with respect to summer without tracking, summer with tracking, winter without tracking and winter with tracking respectively.

The second set of experimentation was carried out on 27th and 26th day of January 2021. In these days, two modules of same capacity are kept in the vertical orientation. The annual average solar intensity received by both sides of the non-tracked module on 27th day of January from the VBFM-EW & VBFM-SN module was 335.15 W/m² & 371.8 W/m². This higher input towards VBFM-SN module was due to the fact behind the Sun trajectory during winter season as shown in Fig. 2. The Sun path is slightly curved towards South direction so the South facing module gets higher input though it is oriented vertically. The total power output from the VBFM-EW and VBFM-SN module was 67.65 W and 106.96 W which is of 58.10% increase from VBFM-SN. The diurnal changes of the solar illumination received by the module and the related power output obtained from the SN module are given in the Figs. 7, 8, 9 & 10 with respect to summer without tracking, summer with tracking, winter without tracking and winter with tracking respectively.

It is noted that daily average solar intensity received on the VBFM-EW and VBFM-SN are 374.6 and 459.87 W/m², respectively on 26th January 2021. Similarly, maximum front side intensity from received on the VBFM-EW and VBFM-SN are 618 and 623 W/m², respectively.

The maximum rear side intensity from received on the VBFM-EW and VBFM-SN are 198.4 and 180 W/m², respectively. The maximum total solar intensity received on the BPVM at East-West direction is 753.3 W/m² and the North-South direction is 803 W/m². The total power output of VBFM-EW and VBFM-SN are 69.77 W and 109.05 W, respectively. This suggests the bifacial module customers to mount in vertical orientation.

3.2 Diurnal changes of wind speed

Diurnal changes of wind speed for the different experimentations with vertically oriented modules facing with and without tracking are plotted in Fig. 11. It shows that wind speed is maximum in the case of Summer without tracking. The maximum wind speed of 6.6 m/s was measured on 22.5.2020. The maximum and minimum daily average wind speed of 3.82 and 3.2 m/s was obtained on all the days of experimentation, respectively. The power output depends also on the wind speed on the particular day.

3.3 Diurnal changes of ambient temperature

Ambient temperature for the different experimentations of vertically oriented modules facing EW and NS directions with and without tracking are noted. Figure 12 shows the diurnal changes in the ambient temperature from 6 AM to 6 PM. The maximum ambient temperature of 36, 39, 28 and 32 °C on 22.5.2020, 25.5.2020, 27.1.2021 & 26.1.2021, respectively. The daily average ambient temperature of 31.84, 32.07, 24.92 and 26.38 °C was calculated on summer without tracking, summer with tracking, winter without tracking and winter with tracking, respectively.

3.4 Efficiency of the VBFM

The efficiency of the VBFM-EW and VBFM-SN installed at Minjur during the Summer and winter season as given in the Figs. 17 & 18 respectively. For both the seasons, the Maximum average efficiency for the module tracked in both EW and SN. The maximum efficiency was observed as 8.83 % from the VBFM- SN module on 26th Day of January 2021. This is because of the less heat during the winter season. During summer season, maximum efficiency of 7.66 was obtained by VBFM-SN module on 25th day of May 2020.

3.5 Exergy Analysis

Table III Showing the Input Exergy, Thermal Exergy and Exergy Efficiency for 2 sets of experimentation (a) Summer without tracking, (b) Summer with tracking, (c) Winter without tracking & (d) Winter without tracking

(a) Summer without trackin

Time	Total solar intensity		Power (or) Electrical Exergy		Input Exergy		Thermal Exergy		Output Exergy		Exergy Efficiency (%)	
	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
6	63.00	39.20	1.14	2.05	119.48	74.34	0.52	1.17	0.62	0.87	0.52	1.17
7	492.80	236.60	38.41	23.17	934.59	448.71	0.57	2.25	37.84	20.92	4.05	4.66
8	221.00	216.80	22.27	26.67	419.05	411.08	2.01	2.01	20.26	24.65	4.83	6.00
9	536.00	340.00	101.18	66.34	1015.77	644.33	0.49	1.11	100.68	65.23	9.91	10.12
10	650.00	484.00	128.32	92.96	1231.59	917.06	0.98	0.98	127.33	91.98	10.34	10.03
11	536.00	472.00	74.98	97.18	1015.03	893.83	1.28	1.99	73.70	95.19	7.26	10.65
12	419.00	452.00	57.27	89.84	793.32	855.80	0.39	0.39	56.87	89.45	7.17	10.45
13	359.50	337.00	45.51	62.97	680.54	637.95	0.31	0.08	45.19	62.89	6.64	9.86
14	473.00	351.00	68.70	61.74	895.73	664.69	6.02	1.52	62.68	60.22	7.00	9.06
15	338.00	305.90	36.41	40.73	639.84	579.08	3.15	0.79	33.26	39.94	5.20	6.90
16	320.50	209.50	27.26	19.20	606.94	396.73	0.75	0.19	26.51	19.01	4.37	4.79
17	504.00	245.00	48.13	21.52	954.43	463.96	0.19	0.00	47.94	21.52	5.02	4.64
18	76.40	55.70	1.63	1.83	144.76	105.54	0.14	0.54	1.50	1.29	1.03	1.22

Exergy efficiency is factor to mention on the exact input converted into output considering losses are tabulated in Table III. The average Exergy efficiency on the 22nd day of May 2020 was found to be 5.64 % from VBFM-EW with average solar intensity of 383.78 W/m² and 6.89 % from VBFM-SN with average solar intensity of 288.05 W/m². During this period the modules were facing the Sun vertically so the solar intensity of EW module was not found to be constant. SN module has received the solar intensity maximum in the rear end of the module. No tracking was carried out therefore rear side of the module has received more intensity.

(b) Summer with tracking

Time	Total solar intensity		Power (or) Electrical Exergy		Input Exergy		Thermal Exergy		Output Exergy		Exergy Efficiency (%)	
	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
6	216.20	116.90	2.61	4.46	410.02	221.70	0.14	0.14	2.47	4.32	0.60	1.95
7	594.00	250.90	38.86	19.97	1126.51	475.83	15.20	3.20	23.67	16.77	2.10	3.52
8	746.70	330.60	135.43	39.18	1415.59	626.75	17.40	6.70	118.03	32.49	8.34	5.18
9	729.50	341.40	138.21	41.98	1382.73	647.11	19.18	3.91	119.02	38.07	8.61	5.88
10	730.00	468.00	171.57	84.63	1383.17	886.75	8.67	3.34	162.90	81.29	11.78	9.17
11	654.00	488.00	115.03	89.21	1237.36	923.29	2.56	1.78	112.47	87.42	9.09	9.47
12	435.00	442.50	55.21	86.48	823.62	837.82	6.95	5.34	48.26	81.14	5.86	9.68
13	572.00	499.00	95.58	108.77	1082.81	944.62	3.53	0.14	92.05	108.62	8.50	11.50
14	656.00	416.20	131.03	79.56	1242.28	788.16	21.81	3.87	109.22	75.69	8.79	9.60
15	799.00	390.00	176.38	63.32	1512.53	738.28	15.42	2.51	160.97	60.80	10.64	8.24
16	756.00	334.40	160.97	43.78	1431.91	633.37	24.81	3.76	136.16	40.01	9.51	6.32
17	325.00	165.13	38.53	38.08	615.57	312.76	0.61	0.61	37.92	37.47	6.16	11.98
18	60.40	32.96	0.99	4.68	114.44	62.46	0.14	0.14	0.85	4.54	0.74	7.27

VBFM – EW has the average Exergy efficiency of 6.97% on 25th Day of May 2021 when the average solar irradiation was 559.52 W/m². The VBFM – SN has the average Exergy efficiency of 7.67% on 25th Day of May 2021 when the average solar irradiation was 328.92 W/m². The increase of 10.04% is due to the effective way of converting the energy in a useful format. The tracking on E-W module does not pay any increase towards the exergy efficiency from the module.

(c) Winter without tracking

Time	Total solar Intensity		Power (or) Electrical Exergy		Input Exergy		Thermal Exergy		Output Exergy		Exergy Efficiency (%)	
	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
6	15.90	14.10	0.14	0.091	30.18	26.76	0.00	0.00	0.14	0.09	0.45	0.34
7	78.80	73.90	1.90	2.34	149.58	140.28	0.00	0.00	1.90	2.34	1.27	1.67
8	351.50	329.50	31.71	30.48	667.34	625.58	6.37	8.29	25.35	22.19	3.80	3.55
9	584.50	522.50	86.01	96.9	1109.10	991.46	3.46	6.73	82.55	90.17	7.44	9.09
10	719.70	730.20	137.59	195.168	1365.15	1385.07	40.83	32.90	96.76	162.27	7.09	11.72
11	375.30	384.50	25.76	45.563	711.62	729.07	0.10	4.69	25.66	40.88	3.61	5.61
12	473.70	623.20	184.95	224.9	898.04	1181.46	17.26	28.17	167.69	196.73	18.67	16.65
13	287.10	303.20	177.60	215.265	544.58	575.12	39.41	70.27	138.19	144.99	25.38	25.21
14	633.80	789.40	116.42	205.794	1201.77	1496.81	4.15	13.72	112.27	192.08	9.34	12.83
15	602.30	661.20	100.10	201.91	1142.05	1253.73	5.43	18.38	94.67	183.53	8.29	14.64
16	133.40	257.10	11.53	28.919	252.99	487.59	1.03	5.55	10.50	23.37	4.15	4.79
17	76.40	116.70	5.54	142.56	144.87	221.28	0.48	1.07	5.06	141.49	3.49	5.96
18	25.00	28.50	0.27	0.594	47.40	54.04	0.00	0.12	0.27	0.47	1.00	1.20

VBFM – EW has the average Exergy efficiency of 7.23% on 27th Day of January 2021 when the average solar irradiation was 335.18 W/m². The VBFM – SN has the average Exergy efficiency of 8.71% on 27th Day of January 2021 when the average solar irradiation was 371.85 W/m². There was no tracking incorporated during this day of experimentation, also due to the Sun trajectory the South facing module gets more input insolation than East facing module. Hence, VBFM-SN has more exergy efficiency. So efficient choice is to make the module to face South during winter season to achieve better efficiency.

(d) Winter with tracking

Time	Total solar intensity		Power (or) Electrical Exergy		Input Exergy		Thermal Exergy		Output Exergy		Exergy Efficiency (%)	
	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
6	15.90	14.10	0.14	0.09	30.18	26.76	0.00	0.00	0.14	0.09	0.45	0.34
7	43.00	33.30	0.55	0.56	81.59	63.19	0.00	0.00	0.55	0.56	0.67	0.89
8	567.00	332.00	37.34	36.78	1075.90	629.98	6.67	1.69	30.67	35.09	2.85	5.57
9	741.90	566.00	119.19	104.72	1407.52	1073.80	31.48	9.05	87.71	95.67	6.23	8.91
10	753.30	733.00	149.84	206.54	1428.62	1390.12	26.41	2.67	123.43	203.87	8.64	14.67
11	699.40	762.30	90.99	201.91	1326.16	1445.43	11.61	34.86	79.39	167.05	5.99	11.56
12	363.40	803.00	40.36	206.79	688.43	1521.21	1.68	2.62	38.68	204.18	5.62	13.42
13	316.80	779.20	58.66	204.56	600.15	1476.12	0.12	19.31	58.54	185.25	9.75	12.55
14	289.30	688.30	118.79	174.99	548.55	1305.11	24.31	34.68	94.48	140.31	17.22	10.75
15	315.40	615.40	129.17	159.35	597.93	1166.67	18.56	28.72	110.61	130.62	18.50	11.20
16	255.10	379.10	101.01	59.99	483.71	718.83	17.71	17.71	83.30	42.28	17.22	5.88
17	496.20	262.70	61.03	61.34	940.69	498.02	11.46	2.90	49.57	58.44	5.27	11.73
18	13.20	10.00	0.15	0.07	25.04	18.97	0.14	0.00	0.01	0.07	0.04	0.38

VBFM – EW has the average Exergy efficiency of 7.57% on 26th Day of January 2021 when the average solar irradiation was 374.61 W/m². The VBFM – SN has the average Exergy efficiency of 8.3 % on 26th Day of January 2021 when the average solar irradiation was 459.88 W/m². Tracking is incorporated during this day of experimentation. Even though the Sun trajectory was the South facing module gets more input insolation than East facing module, the E-W module receives more input due to tracking. Hence, VBFM-EW has more exergy efficiency. It's efficient to make the module to face South during winter season.

3.6 Energy production factor and Life cycle conversion efficiency

Table IV Energy production factor and Life cycle conversion efficiency for life time period, n = 10, 15 and 20 years.

Orientation	Annual obtained energy or exergy EOUT (kWh/year)	Energy production factor (EPF)	Annual solar irradiation	Life cycle conversion efficiency (LCCE)
Life Time Period = 10 Years				
Summer without tracking - EW	171284.96	2.0	4989.20	0.064
Summer without tracking - SN	160153.32	1.9	3744.70	0.074
Summer with tracking -EW	303471.85	3.5	7273.80	0.111
Summer with tracking -SN	180528.68	2.1	4275.99	0.082
Winter without tracking -EW	205468.89	2.4	4357.40	0.102
Winter without tracking -SN	324164.35	3.8	4834.00	0.183
Winter with tracking - EW	204406.30	2.4	4869.90	0.090
Winter with tracking - SN	341139.73	4.0	5978.40	0.158
Life Time Period = 15 Years				
Summer without tracking - EW	171284.96	3.0	4989.20	0.085
Summer without tracking - SN	160153.32	2.8	3744.70	0.102
Summer with tracking -EW	303471.85	5.3	7273.80	0.125
Summer with tracking -SN	180528.68	3.2	4275.99	0.107
Winter without tracking -EW	205468.89	3.6	4357.40	0.126
Winter without tracking -SN	324164.35	5.7	4834.00	0.205
Winter with tracking - EW	204406.30	3.6	4869.90	0.112
Winter with tracking - SN	341139.73	6.0	5978.40	0.176
Life Time Period = 20 Years				
Summer without tracking - EW	171284.96	4.0	4989.20	0.095
Summer without tracking - SN	160153.32	3.7	3744.70	0.116
Summer with tracking -EW	303471.85	7.1	7273.80	0.133
Summer with tracking -SN	180528.68	4.2	4275.99	0.119
Winter without tracking -EW	205468.89	4.8	4357.40	0.138

Orientation	Annual obtained energy or exergy EOUT (kWh/year)	Energy production factor (EPF)	Annual solar irradiation	Life cycle conversion efficiency (LCCE)
Winter without tracking -SN	324164.35	7.6	4834.00	0.216
Winter with tracking - EW	204406.30	4.8	4869.90	0.123
Winter with tracking - SN	341139.73	8.0	5978.40	0.185

Considering the Life time period of module as 10, 15 & 20 years and various parameters such as exergy output, Energy production factor, Annual solar irradiation, Life cycle conversion efficiency were tabulated in Table IV. On comparing set-I and set- II experiments, vertically mounted module with tracking provides faster payback period during both summer as well as winter. From the life cycle conversion efficiency, it is evident that the bifacial module can be oriented in E-W with tracking during summer and S-N without tracking during winter will provide more output.

3.7 Uniform end of annual cost (UYC) and Exergetic cost

Table V Uniform end of annual cost (UYC) and Exergetic cost of VBFM-EW and VBFM-SN for 15, 20, 25 and 25 years.

The Uniform end of annual cost and corresponding Exergetic cost of different facing are calculated and tabulated by considering different combination of working period of the system and interest rate.

(a) Summer without tracking

N (years)	I (%) (interest)	EAST - WEST				NORTH - SOUTH			
		F_{CRF}	F_{SRF}	UYC (Rs.)	R_{exergo} (kW h/Rs)	F_{CRF}	F_{SRF}	UYC (Rs.)	R_{exergo} (kW h/Rs)
15	2	0.08	0.06	4673.34	0.04	0.08	0.06	4673.338	0.034
15	5	0.10	0.05	5792.54	0.03	0.10	0.05	5792.542	0.028
15	10	0.13	0.03	7913.98	0.02	1.00	0.00	60265.33	0.003
20	2	0.06	0.04	3673.63	0.05	0.06	0.04	3673.634	0.044
20	5	0.08	0.03	4826.97	0.04	0.08	0.03	4826.967	0.033
20	10	0.12	0.02	7073.49	0.02	1.00	0.00	60263.56	0.003
25	2	0.05	0.03	3077.71	0.06	0.05	0.03	3077.708	0.052
25	5	0.07	0.02	4269.79	0.04	0.07	0.02	4269.793	0.038
25	10	0.11	0.01	6636.18	0.03	1.00	0.00	60263.5	0.003
30	2	0.04	0.02	2683.64	0.06	0.04	0.02	2683.643	0.060
30	5	0.07	0.02	3915.88	0.04	0.07	0.02	3915.881	0.041
30	10	0.11	0.01	6390.95	0.03	1.00	0.00	60263.5	0.003

(b) Summer with tracking

N (years)	I (interest)	EAST - WEST				NORTH - SOUTH			
		F _{CRF}	F _{SRF}	UYC (Rs.)	R _{exergo} (kW h/Rs)	F _{CRF}		UYC (Rs.)	R _{exergo} (kW h/Rs)
15	2	0.08	0.06	4673.34	0.06	0.08	0.06	4673.34	0.04
15	5	0.10	0.05	5792.54	0.05	0.10	0.05	5792.54	0.03
15	10	0.13	0.03	7913.98	0.04	0.13	0.03	7913.98	0.02
20	2	0.06	0.04	3673.63	0.08	0.06	0.04	3673.63	0.05
20	5	0.08	0.03	4826.97	0.06	0.08	0.03	4826.97	0.04
20	10	0.12	0.02	7073.49	0.04	0.12	0.02	7073.49	0.03
25	2	0.05	0.03	3077.71	0.10	0.05	0.03	3077.71	0.06
25	5	0.07	0.02	4269.79	0.07	0.07	0.02	4269.79	0.04
25	10	0.11	0.01	6636.18	0.05	0.11	0.01	6636.18	0.03
30	2	0.04	0.02	2683.64	0.11	0.04	0.02	2683.64	0.07
30	5	0.07	0.02	3915.88	0.08	0.07	0.02	3915.88	0.05
30	10	0.11	0.01	6390.95	0.05	0.11	0.01	6390.95	0.03

(c) Winter without tracking

N (years)	I (interest)	EAST - WEST				NORTH - SOUTH			
		F _{CRF}	F _{SRF}	UYC (Rs.)	R _{exergo} (kW h/Rs)	F _{CRF}	F _{SRF} F _{SRF}	UYC (Rs.)	R _{exergo} (kW h/Rs)
15	2	0.08	0.06	4673.34	0.04	0.08	0.06	4673.34	0.07
15	5	0.10	0.05	5792.54	0.04	0.10	0.05	5792.54	0.06
15	10	0.13	0.03	7913.98	0.03	0.13	0.03	7913.98	0.04
20	2	0.06	0.04	3673.63	0.06	0.06	0.04	3673.63	0.09
20	5	0.08	0.03	4826.97	0.04	0.08	0.03	4826.97	0.07
20	10	0.12	0.02	7073.49	0.03	0.12	0.02	7073.49	0.05
25	2	0.05	0.03	3077.71	0.07	0.05	0.03	3077.71	0.11
25	5	0.07	0.02	4269.79	0.05	0.07	0.02	4269.79	0.08
25	10	0.11	0.01	6636.18	0.03	0.11	0.01	6636.18	0.05
30	2	0.04	0.02	2683.64	0.08	0.04	0.02	2683.64	0.12
30	5	0.07	0.02	3915.88	0.05	0.07	0.02	3915.88	0.08
30	10	0.11	0.01	6390.95	0.03	0.11	0.01	6390.95	0.05

(d) Winter with tracking

N (years)	I (interest)	EAST - WEST				NORTH - SOUTH			
		F_{CRF}	F_{SRF}	UYC (Rs.)	R_{exergo} (kW h/Rs)	F_{CRF}	F_{SRF}	UYC (Rs.)	R_{exergo} (kW h/Rs)
15	2	0.08	0.06	4673.34	0.04	0.08	0.06	4673.34	0.07
15	5	0.10	0.05	5792.54	0.04	0.10	0.05	5792.54	0.06
15	10	0.13	0.03	7913.98	0.03	0.13	0.03	7913.98	0.04
20	2	0.06	0.04	3673.63	0.06	0.06	0.04	3673.63	0.09
20	5	0.08	0.03	4826.97	0.04	0.08	0.03	4826.97	0.07
20	10	0.12	0.02	7073.49	0.03	0.12	0.02	7073.49	0.05
25	2	0.05	0.03	3077.71	0.07	0.05	0.03	3077.71	0.11
25	5	0.07	0.02	4269.79	0.05	0.07	0.02	4269.79	0.08
25	10	0.11	0.01	6636.18	0.03	0.11	0.01	6636.18	0.05
30	2	0.04	0.02	2683.64	0.08	0.04	0.02	2683.64	0.13
30	5	0.07	0.02	3915.88	0.05	0.07	0.02	3915.88	0.09
30	10	0.11	0.01	6390.95	0.03	0.11	0.01	6390.95	0.05

From Table V, it is evident that when life of the system is considered as 15 years with an interest rate of 0.02 provides higher conversion efficiency from East-West module for all the orientations obtained.

3.8 Enviroeconomic and Exergo- enviroeconomic analysis

Table VI Enviroeconomic and Exergo- Enviroeconomic analysis for different cases

Orientation	ENVIROECONOMIC ANALYSIS					EXERGO-ENVIROECONOMIC ANALYSIS			
	Energy gain	Annual energy output	n	CO ₂ AE(Energy)	C _{CO2M} (Energy)	Exergy gain	Annual energy output	CO ₂ AE(Energy)	C _{CO2M} (Energy)
without tracking - EW	651.1910	175.8216	15	5.38014	5701.90	0.9811	0.2649	0.0081	8.59
Summer without tracking - SN	606.1890	163.6710	15	5.00833	5307.86	0.9811	0.2649	0.0081	8.59
Summer with tracking - EW	1260.3980	340.3075	15	10.41341	11036.18	8.6721	2.3415	0.0716	75.93
Summer with tracking - SN	704.0830	190.1024	15	5.81713	6165.03	3.3367	0.9009	0.0276	29.22
Winter without tracking - EW	879.5010	237.4653	15	7.26644	7701.01	40.8312	11.0244	0.3373	357.52
Winter without tracking - SN	1262.1800	340.7886	15	10.42813	11051.79	32.8951	8.8817	0.2718	288.03
Winter with tracking - EW	907.1920	244.9418	15	7.49522	7943.47	26.4084	7.1303	0.2182	231.23
Winter with tracking - SN	1417.6940	382.7774	15	11.71299	12413.48	2.6723	0.7215	0.0221	23.40

The inference from the Enviroeconomic and Exergo-Enviroeconomic analysis gives the information on carbon mitigation and its credits earned with respect to energy and exergy respectively. On comparison with different set of experimentation during summer and winter season are tabulated above in Table VI.

Conclusion

This paper presents the best orientation for the summer and winter season with and without the effect of one time manual tracking in the specific site in Tamilnadu. The experimentation was carried out by considering that the Bifacial solar module are meant for its niche application of Building integrated system. The performance of VBFM-EW and VBFM-SN is analysed through the outdoor experimentation during both the seasons. This experimentation aims to integrate the Bifacial module into building which best fits out object to transform power and does not occupy most of the area in our building. Therefore the Bifacial solar module is experimented with vertical and are considered for incorporating in window, Sunshade, car parking, etc. The modules where made to fed the DC load and the conclusion of experimental results are listed below.

- The maximum average illumination of 559.52 W/m² is received by VBFM –EW with tracking involved on summer. The second maximum average illumination was received during winter by VBFM – SN with tracking is 459.88 W/m².
- After comparing the average power received by the modules, during summer with tracking VBFM-SN module produced power up to 109.05 W and during winter with tracking VBFM-EW module produced up to 96.95 W.
- Average efficiency of the VBFM during summer and winter was calculated and the highest value is reported in the month of January from SN module of 8.83%. During summer, the maximum average efficiency was 7.66%

- iv. Higher average Exergy Efficiency was reported in the month of January from VBFM-SN module without with 8.71 % and during winter again VBFM- SN module with tracking provides 7.67 % average.
- v. The energy matrices were calculated by considering the lifetime of the system as 10, 15 and 20 years. Total Embodied energy of 2525.04 kWh is involved in the process of making the system.
- vi. When comparing the Life cycle conversion efficiency of the system under different season, LCCE of 0.185 is the maximum reported from VBFM-SN module with tracking during winter season by considering the life of the system as 20 years. Similarly considering the life of the system as 15 years, 0.176 of maximum LCCE was obtained from the same module. Similarly for life of the system equal to 10 years, VBFM-SN module provides 0.158 is the maximum LCCE.
- vii. Exergetic cost of the system is computed by considering various combination of number of years of the system (15 years, 20 years, 25 years and 30 years) and Interest rate (2 %, 5% and 10%). The 30 years operated horizontally oriented system with 2% interest rate provides 0.13 kWh/Rs VBFM –NS during winter season.
- viii. Enviroeconomic and Exergo-enviroeconomic analysis, when comparing the VBFM-EW and VBFM- SN oriented module, Energy maximum value of Rs.12413 and Exergy maximum of Rs. 357 from VBFM-NS module with tracking during Winter and VBFM-EW without tracking during Winter was achieved respectively.

Abbreviations

Bifacial Photo-Voltaic Module – BPVM

Monofacial Photo-Voltaic Module – MPVM

VBFM- EW – Vertically oriented Bifacial Module facing East- West

VBFM- SN – Vertically oriented Bifacial Module facing South – North

Declarations

Ethical Approval

Not Applicable

Consent to Participate

Not Applicable

Consent to Publish

Not Applicable

Authors Contributions

Conceptualization, Methodology, Resources, Formal analysis, investigation and Writing - original draft preparation were carried out by Ms.M.Vimala; Review, editing and Supervision were carried out by Dr.Geetha Ramadas.

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Figures

Figure 1

Experimental arrangement showing two bifacial modules organized in Vertical orientation of the proposed system (i) Vertical Bifacial Photo-Voltaic Module facing South direction and (ii) Vertical Bifacial Photo-Voltaic Module facing East direction.

Figure 2

Sun trajectory based on season

Figure 3

shows the diurnal variation of Solar illumination, Power and Panel temperature of the EW module during summer without tracking condition

Figure 4

shows the diurnal variation of Solar illumination, Power and Panel temperature of the EW module during summer with tracking

Figure 5

shows the diurnal variation of Solar illumination, Power and Panel temperature of the EW module during Winter without tracking condition

Figure 6

shows the diurnal variation of Solar illumination, Power and Panel temperature of the EW module during Winter with tracking

Figure 7

Shows the diurnal variation of Solar illumination, Power and Panel temperature of the NS module during summer without tracking condition

Figure 8

Shows the diurnal variation of Solar illumination, Power and Panel temperature of the NS module during summer with tracking condition

Figure 9

Shows the diurnal variation of Solar illumination, Power and Panel temperature of the NS module during Winter without tracking condition

Figure 10

Shows the diurnal variation of Solar illumination, Power and Panel temperature of the NS module during Winter with tracking condition

Figure 11

Shows the Hourly variation of Wind speed - East-West orientation

Figure 12

Shows the Hourly variation of ambient temperature of East-West orientated module

Figure 13

Shows the Hourly variation of Efficiency of East - West oriented module

Figure 14

Shows the Hourly variation of Efficiency of South- North oriented module