Design and Empirical analysis of different photovoltaic technologies with Reflective Surfaces

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Abstract
Background: For many decades, harvesting the visible solar spectrum for generating electricity has become the new normal. There are a lot of photovoltaic (PV) technologies available for this purpose, and researchers have constantly been working to increase the efficiency of these technologies. This paper deals with a different approach to improving the efficiency of existing commercially available PV modules using various reflector materials.
Methods: A test bed setup was set up in "Bawana" district in Haryana State. PV module output by tracing the current-voltage correlation for multiple technologies with and without reflectors was assessed using an"IV Curvetracer". Raw data was analysed using comparative variable technique.
Result: The IV curves generated were analysed for the incremental gain using reflectors. It is seen that the polysilicon technology PV modules with reflector gave an approximate power output gain of 9%when a metal reflector is placed in front, than a PV module in same site test condition where there isno reflector. Monocrystalline PV technology received an increased power of only 3.7% with almost6.5% increment in surface temperature. No such gain was observed in Bifacial PV module technology when used with glass reflectors.
Conclusion:When reflectors are used with solar PVpanels, the output power and efficiency of the PV panel increase and further translate in to overall gain in electricity produced. However, this incremental gain is different for different technologies and will depend upon the material used as a reflector.

Keywords: *Solar Power Plant, Plant yield, Repowering, Reflectors, Photovoltaic Technologies, IV Curve, Temperature Rise*

1. Introduction

PV cells convert sunlight into electrical energy and have become increasingly popular due to the growing awareness of environmental issues. Using renewable energy resources is the best solution to the problem of energy waste and environmental pollution. Renewable energy resources are inexhaustible and cause less environmental pollution than the traditional coal and other fossil fuels. India has vast potential for renewable energy resources like solar and wind. These resources can be used to generate electricity without causing any environmental pollution. [37,38]Using renewable energy resources can help reduce the dependence on coal-based power plants as well as ensure long term sustainable living. The solar photovoltaic (PV) system uses solar modules to convert the light component of sunlight into electricity. These solar modules generate direct current or 'DC'. One component used in a typical solar system is an inverter which converts the generated DC to alternating current or 'AC' . Sometimes the system also comprises of a storage component in the form of batteries to dispense power during the non-sunlight hours. The rooftop systems are normally installed to provide electricity for the whole house. Various factors contribute to the power generated by these solar modules. Like the size or the surface area, angle at which sunlight is incident on the solar panel, ambient and module temperature and the technology used in the solar module. [39, 40] The manufacturers define the parameters of PV cell by voltage, current, power output etc. Now all these parameters are measured and defined in standard test conditions and at a standard test temperature of 25 degrees Celsius. [41,42] Temperature coefficient is another important parameter. This parameter defines the intrinsic and manufacturer property of the PV module of its performance with respect to temperature effects. After conversion of cell to module the voltage output of module is affected by the temperature coefficient. As an intrinsic property of semiconductor material, the output voltage of a module reduces with rise in temperature above 25 Degrees. This is in proportion to the temperature coefficient. In outdoor conditions, the solar panels are exposed to temperatures different than standard test temperature of 25 deg. The voltage and hence the power of a solar cell is impacted due to the different operating temperatures. Current produced and the power generated also depend upon the area of the solar cell. Larger area results in larger absorption of sunlight and hence larger amount of current is generated. Another aspect impacting the generation of solar cell/module is the angle at which the incident sunrays hit the cell surface. Maximum generation by a PV module is possible when incident sun light is at 90 degrees.

1.1 How does the PV module work?

When the visible light spectrum falls on a PV surface, some part of it gets absorbed while rest of it either gets reflected or just passes through the module.

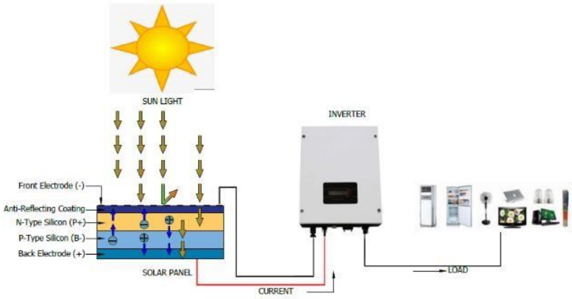


Figure.1: Working principle of Photovoltaic cell

Typical photovoltaics are made of Positive -Negative PN junction semiconductors, keeping N-type layers to be thin enough to let the light pass through them toward the junction. Photons in the light excite the electrons in the N-type material by transferring their energy to the electrons whereby the electrons travel toward the P-type material, thus generating electricity. This electricity then conducts itself through conducting metal strips and these busbars transfer this generated current to the junction box for extraction from the panel. Extracted energy is further used through an inverter which converts DC energy to AC energy which further powers various appliances in households. Figure 1 placed above explains this working of solar system.

1.2 Types of PV technologies

Most PV cell technologies are based on crystalline silico [43, 44]. These can be further classified into mono-crystalline and poly-crystalline based on the purity of the silicon crystal. Monocrystalline cells are more efficient than polycrystalline cells. [43,44]. This is because they are purer as, they have been cut from a single ingot of silicon, whereas polycrystalline cells are a mix of multiple ingots.
Another popular type is thin film type solar modules which are made by depositing thin layers of silicon (a-Si) or non-silicon materials like ‘Cadmium Telluride (CdTe) or Copper Indium Gallium di selenide (CIGS) on substrates like metal, glass or even plastic. [45,46]These deposit materials are not only rare but often toxic and a possible hazard for disposal. [47]. Further in high-efficiency requirements, multijunction (also known as hetero-junction) cells are used. These are manufactured using multiple layers of semiconductors to create multiple P-N junctions instead of a single one, the multiple layers provide various bandgaps for better absorption of solar radiation in its broad spectrum.[43,44,46,47]. In recent years there have been newer and better technologies like bifacial and PERC (Passivated Emitter and Rear Cell), where the innovation has been done at the receptor end instead of cell itself to make better absorption of the solar irradiation [22,23,43]. The below table (Table 1) summarizes the efficiency of present commercially available PV module technologies [1][2]:

Table1.PVmoduleefficiencies.Data from[1][2].S.No.	PVTechnology	Efficiency(η) %
1	Monocrystalline	19%
2	Polycrystalline	17%
3	Bifacial	20%
4	PERC(Passiveemitterrear contact)cell	24%
5	Multijunction	45%
6	CdTe(CadmiumTelluride)	18%
7	CIGS(Copperindium galliumselenide)	18%
8	a-Si(amorphousSilicon)	10%

Other available but not so commercially successful technologies include Perovskite solar cells, organic photovoltaics, Quantum dots, etc.[48,49,50]

1.3 Repowering

Re-powerliterally means giving energy again. The Wikipedia definition of Repowering states: "Repowering is the process of replacing older power stations with newer ones" [51,52] In the context of solar power PV plants, repowering can be of relevance at different stages. Either end of life cycle or cases of nonperforming plants not yet reached the end of their designed life or simply an opportunity to improve the profitability of a performing plant by replacing/ retrofitting components for better yield and hence, profitability. Economic advantages of repowering can be ascertained basis of multiple factors like the life stage of PV the plant, tariff of the Power Purchase Agreement(PPA) umbrella, issues related to performance and the cause and cost of replacement etc.[51,52] Repowering of solar PV plants is derived here as a way of enhancing the generation yield of solar system by either retrofitting modifications or replacing the eroding components while utilizing existing evacuation infrastructure and land.

1.4 Repowering options

While the past decade has not seen much in solar repowering, the concept has gained momentum in more mature sectors like wind and hydropower. [53]There are several business cases that merit repowering and retrofitting such as restoring or improving system performance or extending them past their useful lifetime of 20 – 25 years. When a solar system that is already in operation is repowered using enhancement techniques, more electricity can be produced while using the same infrastructure like evacuation points, terrain, transmission lines, substations etc. [51,52,53] This improves the Least Cost of Electricity (LCOEs.). While the existing plants globally are reaching an end of life or are between mid-life to end of life, this generates a huge opportunity for repowering of such plants in the current decade from 2020 to 2030.

1.5 Solar PV reflectors

A reflector was used for the first time by Tabor [15] in 1958. The reflector directed solar radiation incident on its own surface onto the collecting surface which was a solar module. This method has since then been evaluated by researchers and few commercial solutions are also developed for smaller systems. The financial implication of using additional PV panels to generate more power is much higher than using reflector to achieve the same amount of power [3-6]. Other means of increasing power output are usage of single and dual axis tracking mechanisms. However, using reflector is more cost-efficient way to generate same additional power: using reflectors, researches have shown 20% to 30% more power depending upon the location, time of the year and the material of reflecting surface [7-10].

1.6 Analysis of PV module performance using reflectors

As we discussed earlier in 'Introduction' section in this article, the output of a PV module depends on various factors including strength of the incident light, among other factors; if the irradiation increases, the outcome would also increase. However, increased irradiation might also increase the module temperature, which might negatively impact the output power. An easy way to increase the incident irradiation would be to use reflectors by placing them such that PV modules get irradiation corresponding to the area more than their surface area. The installation of reflectors between the PV rows is a retrofitting solution that will help mirror incoming solar radiation. Aside from the evident advantage of not requiring the acquisition of additional surfaces, (since the inter PV row space of existing plant can be used for installing reflectors)this solution is also profitable and can be implemented quickly in practice. The benefits of reflectors have been demonstrated many times over, as in a crucial study by professor of engineering at Michigan Technology University, Joshua M. Pearce.[54,55] This experiment, performed in partnership with a study group in Canada has shown that the use of reflectors could enhance output of solar panels by as much as 30%. The testing of their model in Kingston, Ontario produced impressive results: the efficiency went up by 45% in case of poorly-angled panels, and by 18% in case of optimally-angled panels. As the findings of Pearce's study suggest, with the inclusion of reflectors, the energy collected should rise on average by 30% in most cases with well-placed solar arrays. Further confirmed by the test results of a two-year pilot phase in Southwest Germany, a study that deployed an innovative reflector and calculation system known as "pA reflect" from plusAmpere GmbH, the result saw a 14% average annual increase on the yield conducted under real-life conditions. [11-14].

Companies around the world have already begun to innovate and capitalize on the clear benefits of reflectors, as seen in the 30% to 40% increase in efficiencies using high efficiency modules as well as thin film coated reflectors, achieved by TenK Solar of Minneapolis. They came up with a system that puts thin-film reflectors in the small spaces between tilted solar panels. A sheet of plastic is used to laminate these reflectors and then this sheet is covered with a cool mirror coating of a thin layer of film. These cool mirrors enhance the energy output as they capture the radiation between the rows and incident them on the solar panels. The Cool mirror coating also acts as a great filter, preventing heat from reflected sunlight from heating the solar cells and bringing down efficiency. For this study, a test bed is setup where PV modules of different technologies are installed to compare their output with and without reflectors.

1.7 Choosing reflectors

There are a lot of commercially available metallic and non-metallic materials which can be used as reflectors or in such an application. The factors to be considered [15-20] for making this choice are including but are not limited to:

[1] Heat emissivity: The relative power to radiate heat of a surface with respect to the power to radiate heat by a black body, both being at the same temperature is defined as emissivity of that material. The higher the emissivity value, the better it would be as a reflector. The maximum possible emissivity of 1 would imply that incident heat is wholly absorbed.

[2] Thermal conductivity: Higher thermal conductivity implies a high heat transfer rate; therefore, materials with lower thermal conductivity would make a better choice as a reflector.

[3] Strength: A reflector would be subjected to the same wind speed and force as the PV module; therefore, it should be strong enough to hold on to the wind force of the location of the solar plant.

[4] Weight: Although strength is the desired factor for a reflector, its lower weight would also ensure lower civil and structural costs.

[5] Availability: The material should be readily available for future scalability and better commercial usage.

[6] Ease of installation: This would be a crucial factor if this study gives conclusive evidence supporting the usage of reflector materials and the retro fitment of the solar PV system.

[7] Ease of cleaning: The suitable reflector material should be easy to clean to ensure the equal spread of reflected radiation on the module surface.

[8] Price: Any commercial step would depend on the cost-benefit analysis of the proposal; the cost of the proposal should not outweigh the gain in energy generation using the reflector.

2. Methods

For this study, a test bed is setup where PV modules of different technologies are installed to compare their output with and without reflectors. These technologies are installed- each with a reference module and another one without reflector. 2 different types of reflectors are chosen for this study basis the desktop assessment of different reflecting surfaces. Polycrystalline PV module and Monocrystalline module technology is assessed using aluminium sheet reflector and Mono PERC bifacial technology is assessed using glass as a reflecting surface. The technology, make, model and initial wattage of solar modules selected are placed below in Table 2:

Table 2. Details of selected solar modules.

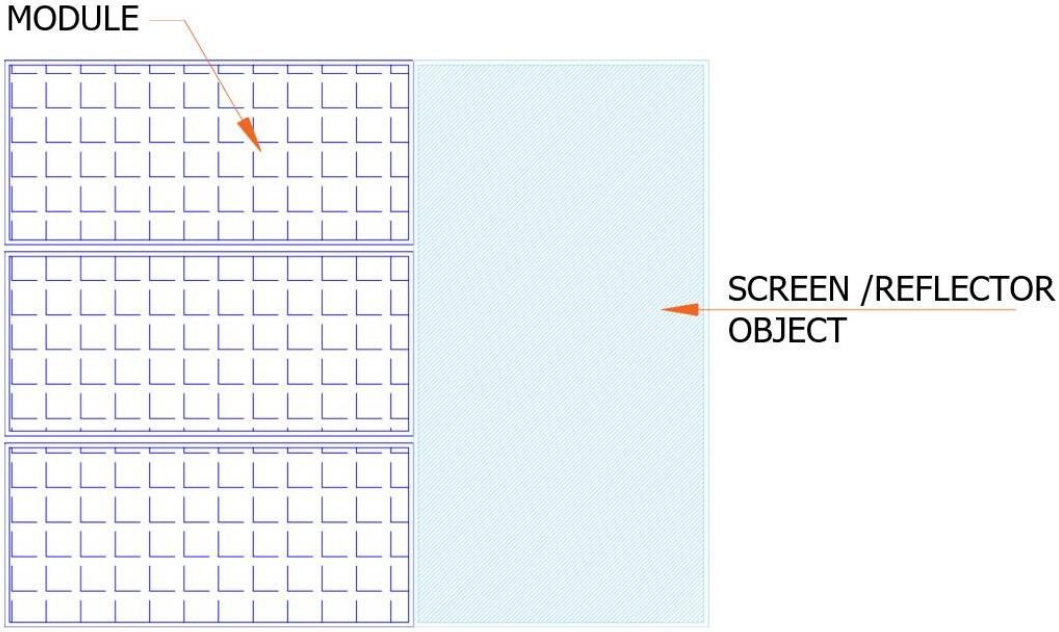
Technology	Make	Model	Initialtestedwattage	Measuredwattage(Beginningoftestperiod)	Serieslaunchedinandtested	Datasheetsource
Polycrystalline	JA Solar	JAP6	320 Wp	317.8 Wp	Jan-15	http://www.solardesigntool.com/components/module-panel-solar/JA-Solar/4287/JAP6-72-320-4BB/specification-data-sheet.html
MonoPERC	Vikram Solar	SOMERA	405 Wp	403 Wp	Oct-17	https://cdn.enfsolar.com/Product/pdf/Crystalline/5e7314404aa69.pdf
Bifacial	VikramSolar	PREXOSSERIES6	440 Wp	440 Wp	Jan-20	https://www.vikramsolar.com/products/prexos-up-to-450w-120-cell/

2.1 Optimization of the installation angle of the reflector to ensure maximum radiation on the PV module

This section covers the design of angle of reflector to be placed opposite the solar module surface with the aim to obtain maximum reflection on the solar panel. This reflecting surface is placed at a distance from the lower side of the PV module which is the collecting surface. The calculation of the optimum angle for placing the reflecting surface is done for the location of "Bawana", Delhi, India. The said experimental setup is placed at E-55, DSIDC, Bawana Industrial Area Sector-05, Bawana, Delhi 110039 and is also installed accordingly to monitor the actual gain. A reference module without the reflector placed in front is also designed and installed for the comparative performance assessment.

2.2 Analytical model of PV modules (collectors) with bottom reflectors

Equations proposed by Mulugata et al [12-13], are further expanded by using optometric equations a mathematical calculative model is prepared for PV modules (collector) placed facing a south direction[20]. The angle at which collector (solar module) is placed is "β". As known in solar geometry, this angle is always equal to the latitude of the location and this can be further optimised for specific locations using solar, optometric and trigonometric equations [12-13], [20]. As shown in Figure 2 below, an aluminium metal sheet reflector of plain reflecting surface and architecturally stable thickness is placed opposite the solar module (see section Equipment details for further specifications). This reflector is expected to enhance the radiation on the solar module surface (collector) by directing reflected radiation on the collector surface.



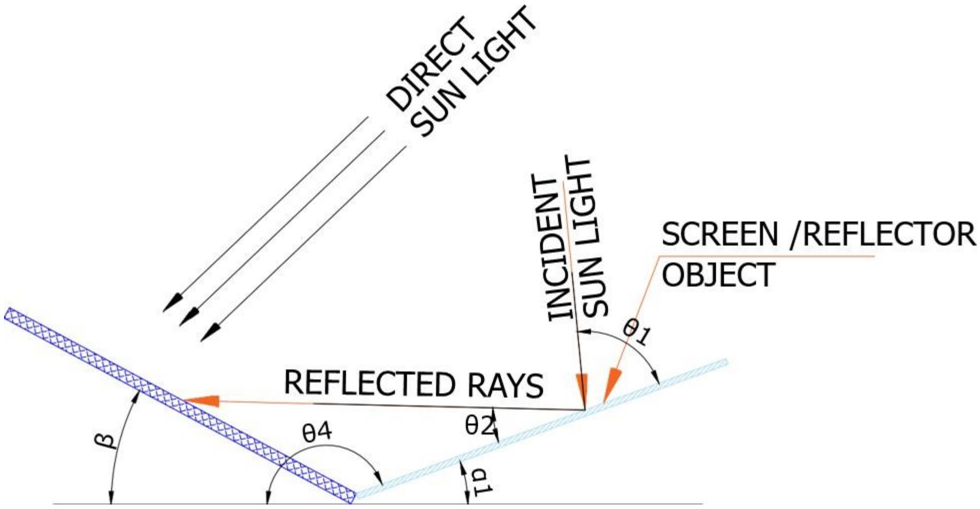


Figure 2. Graphical representation of Reflected Solar Radiation Angle

The horizontal surface is indicated by the black line. The construction line in blue colour indicates the direction of direct sunlight at this location and is called “solar latitude angle line”A’-B’ is a construction line representing a line parallel to solar latitude angle line. The solar panel which is the collector surface is inclined at an angle (β).This angle depends upon the position of the sun and latitude of the location. Further, the angle of reflector with respect to the ground can then be determined as explained with Figure 3.

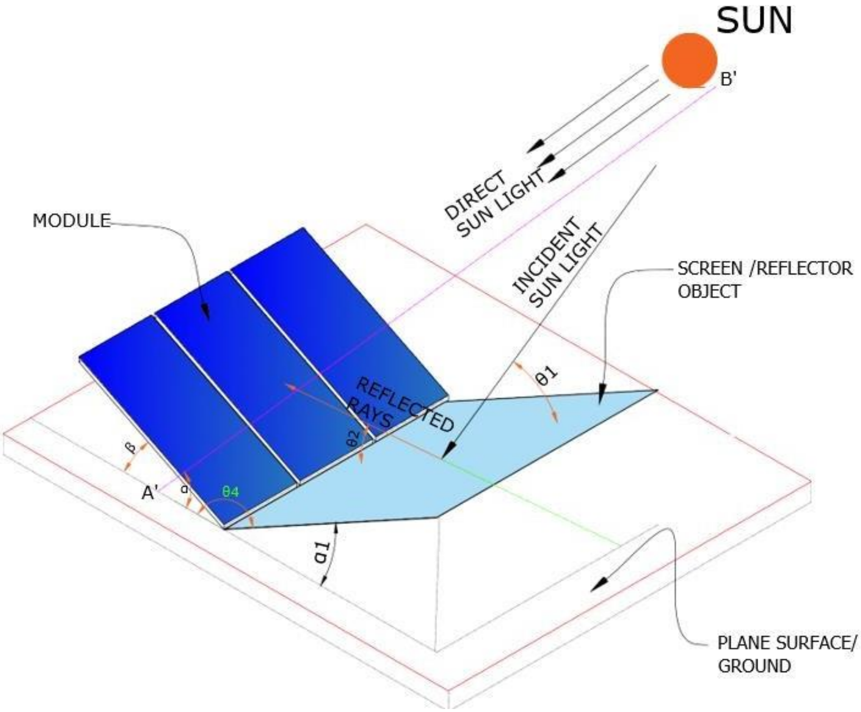


Figure 3. Geometrical construction of sunlight from the ground reflector to the collector

α is the angle at which the direct sunlight meets the horizontal ground surface. Angle at which incident sunlight falls on the reflector surface is θ1. Angle at which the sunlight gets reflected out from the reflector surface in the direction of collector surface is θ2 The angle between the reflector and the ground plane surface is θ4. Authors' own figure.

By simplegeometry,thisanglecanbecalculatedas:

$\theta4= 180–(\alpha1+\beta)$ ....(1)

LetusdefineX1astheangleatwhichthereflectingsurfacereflectsthesunlightincidentonitontothecollectorsurface.

Thisanglecanbe calculatedas :

$X1= \theta4 +\theta1=180$ .... (2)

$X1= 180-180+ \alpha1 +\beta–\alpha+ \alpha1$

$X1 = 2 \alpha1 + \beta – \alpha$ ....(2a)

Asper theabovemethodology,wearriveatthe bottomangle reflector(α1) asbelow:-

$X1+ \theta1 +\theta4=180°$ ....(3)

Where:

$X1= 180- (\alpha+\beta)$............(3a)

$\theta1 =(\alpha –\alpha1)$ ....(3b)

$\theta4=180–(\alpha1+ \beta)$............(3c)

β =AngleofPVmodule installed =29°

(as per latitude of test location)

$180° - (\alpha + \beta) + (\alpha – \alpha1) + 180° - (\alpha1 + \beta) = 180°$ $\alpha1 = (180° - 2 \beta)/2$

$\alpha1 = (180° - 2 (29))/2$

$\alpha1 = (122°)/2$

$\alpha1 = 61°$, where α1 is the angle of bottom reflector ....(4)

2.3 Experimental setup

A test-bed was set up to test the impact of reflectors on photovoltaics using different technologies and different kinds of reflector materials. Solar modules of these different technologies were utilized for JA Solar-315 WP Poly full cell, Vikram Solar-405 WP Mono perc Half Cut as shown in Fig 4 and Fig 5 and Vikram Solar-440 WP Mono PERC half Cut bifacial modules, as shown Fig 6, were selected. Each technology had two modules – one with reflector and one without reflector. Reflector was installed at 60 degrees with respect to ground. For the Micro Inverter, Hoymiles Product – M 1000/1200/1500 was used. It was a 4 Input, Dual MPPT, NEMA IP67 Compliant inverter. Power measured was DC power, Isc and Voc captured from the DC input side ports of the inverter. Power output from microinverter was used to power the load of warehouse through the grid (the system was installed on the roof of a warehouse in Bawana, Delhi, India). Warehouse is owned privately and permissions were received to carry out the installation. The cumulative power of both inverters supported a load of up to 1~1.1 KW. Load study or application of load was not included in the scope of this study. However, an inverter utilized as a straight method for capturing the DC parameters. The alternative was to use meters with inbuilt CT/PT for each parameter – current, voltage, and power. The use of inverter facilitated the single point manufacturing using the input port monitoring capability of Hoymiles micro inverter. Datalogger Tracks STD GPRS WT 800 was utilised to capture the DC input data and monitor the current, voltage and power from the inverter.

Figure 4 : Reflector installed at the bottom of the solar module

Figure 5: Aluminum sheet reflector with poly and mono crystalline PV modules

Figure 6. Mirror reflector with bi-facial PV module

2.4Equipment Details

The experimental setup has been done using solar modules and inverter of reputed makes and high accuracy measurement devices like solar radiation sensor and temperature sensor. The details of all the equipment used in test setup are given below in Table 3.

Table 3. List of equipment makes and model

SolarModules			
Make	JASolar315WP	Vikram Solar405WP	Vikram Solar440WP
Model	JAP672/300-320/3BB	SOMERAVSMH. 72.AAA.05	PREXOSVSMDHT. 72.AAA.05
Technology	Polycrystallinefullcell	MonopercHalfCut	MonoperchalfCut bifacial
Datasheet	http://www.solardesigntool.com/components/module-panel-solar/JA-Solar/4287/JAP6-72-320-	https://cdn.enfsolar.com/Product/pdf/Crystalline/5e7314404aa69.pdf	https://www.vikramsolar.com/products/prexos-up-to-450w-120-cell/
	4BB/specification-data-sheet.html		
Micro Inverters			
Make	Hoymiles		
Model	MI-1000/1200/1500		
Datasheet	https://www.hoymiles.com/products/microinverter/		
DataLogger			
Make	Trackso		
Model	STDGPRSWT800		
Datasheet	https://trackso.in/datasheets/		
ModbusConverter			

Make	Trackso
Model	6HAnalogtoModbusConverter [TR621]
Datasheet	https://trackso.in/datasheets/
Module TemperatureSensor	High
Make	Trackso
Model	MSPT100V
Datasheet	https://trackso.in/datasheets/
SolarRadiation Sensor	
Make	Trackso
Model	PYRA300V
Datasheet	https://trackso.in/datasheets/

The output of this setup is used to support the load of the warehouse. As shown in Figure 7, the output of all modules are connected to inverters and data is monitored using laptop through the internet web access. The indicative line diagram of this installation experimental setup is shown in Figure 7.

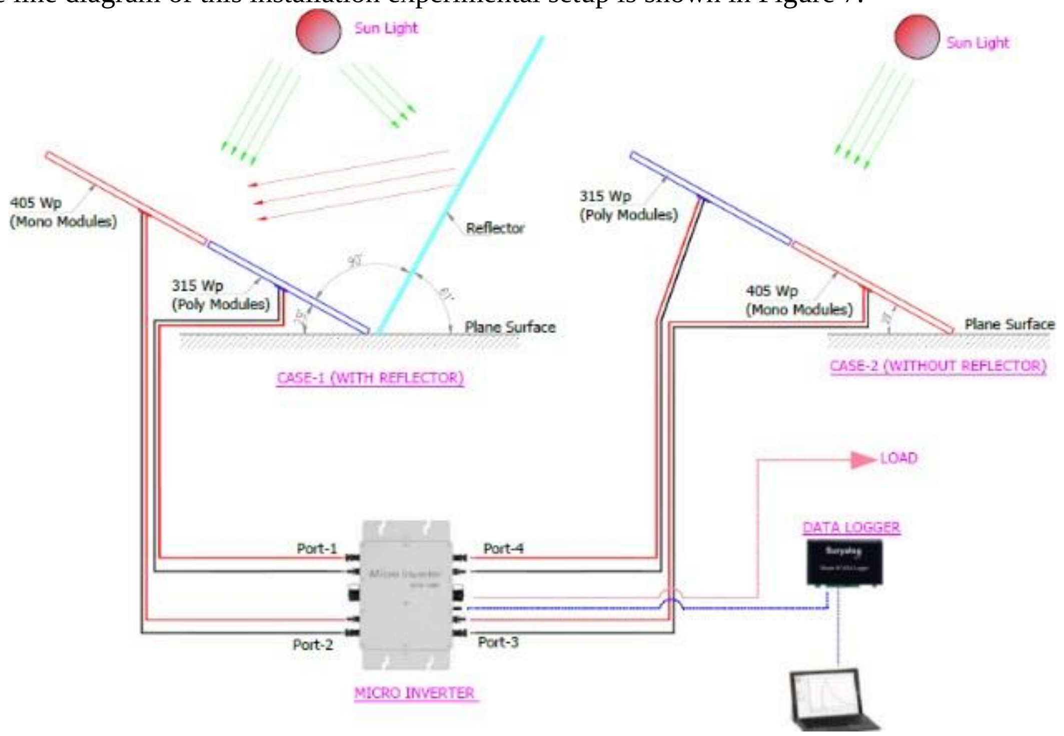


Figure 7. Test setup line diagram of mono and polycrystalline modules

2.5 Nameplate rating of modules

Table 4 gives nameplate ratings of photovoltaic modules which have been used in this experiment, this data is provided by manufacturers and it depicts the maximum power o2utput (Pmax or Pmp) of the PV module when it is generating maximum current (Imp) at a maximum voltage (Vmp). It also states the short circuit maximum current value and open circuit maximum voltage of the photovoltaic.

Table 4. Name plate rating of PV Modules used in experimental setup

Make	JASolar	VikramSolar	VikramSolar
Model	JAP672/300-320/3BB	SOMERAVSMH. 72.AAA.05	PREXOSVSMDHT. 72.AAA.05

Technology Type	Poly-crystalline	Mono-crystalline	Bifacial
Isc [A]	8.91	10.48	11.56
Imp[A]	8.45	9.71	10.62
Voc [V]	45.6	49.9	48.8
Vmp[V]	37.28	41.8	41.5
Pmp [WP]	315	405	440

2.6 Test equipment

Table 5 provides the model number, serial number and calibration details of IV curve tracer instrument and reference PV sensor equipment which were used for observing and measuring the readings of the test setup. IV curve tracing is from Solmetric.

Table 5. Technical specification of the test instrument.

Equipmen tName	Make &Mode l	Seria lNo.	Testcond ition	Last/ NextCalib ration
PVA Analyzer	Solmetric PVA–1500	7252012	On-Site	16-3-22/ 15-3-25
Wireles sPV Reference Sensor	Solsensor	5150276	On-Site	16-3-22/ 15-3-25

2.7 Equipment accuracy

Any instrument is useful only if it is accurate at least by the industrial standards and benchmarks. Table 6 gives the calibrated accuracy level of all the test equipment used for measurement of data.

Table 6. Accuracy of testing instrument

Sr. No	Parameter	Uncertaint y
1	Irradiance Measurement	±2%
2	Module Temperature Measurement	< 2°C
3	Current Measurement	±0.5%
4	Voltage Measurement	±0.5%
5	Tilt	± 2°

3. *Results*

IV curve graph and data

An IV curve is a graph the demonstrated the association of module current (I) and module voltage (V) of a solar cell with respect to various input parameters like radiation, temperature, cooling arrangements, etc. This graph summarizes the significant electrical properties of the photovoltaic cell and its behavior under different conditions. Theoretically, with increased radiation the current output of the cell increases, whereas an increase in the cell temperature lowers the output voltage parameter. Now, as the power output is a product of current and voltage and increased current but a decreased voltage might result in some uncertain output which we intend to measure through this experiment. [23] In our experiment, we have drawn IV curves of solar panels (refer Figure 8, Figure 9 and Figure 10) in outdoor conditions while they have been exposed to sunlight and are not in a controlled laboratorywith measured input values, which provides us with a better understanding of photovoltaic performance in real-time situation.

JA Solar 320WP polycrystalline

Two PV polycrystalline modules of JA Solar make and 320Wp rated output power have been used in the experiment, both PV modules have been placed on the same tilt angle however one of the modules has been placed with a reflector facing it so as to see the impact of the reflector. Figure 8 shows the comparative IV curves of polycrystalline-type PV modules, the purple curve is the measured output of the polycrystalline PV module without any reflector placed whereas the green curve is the measured output of polycrystalline PV module with a reflector placed in front of it.

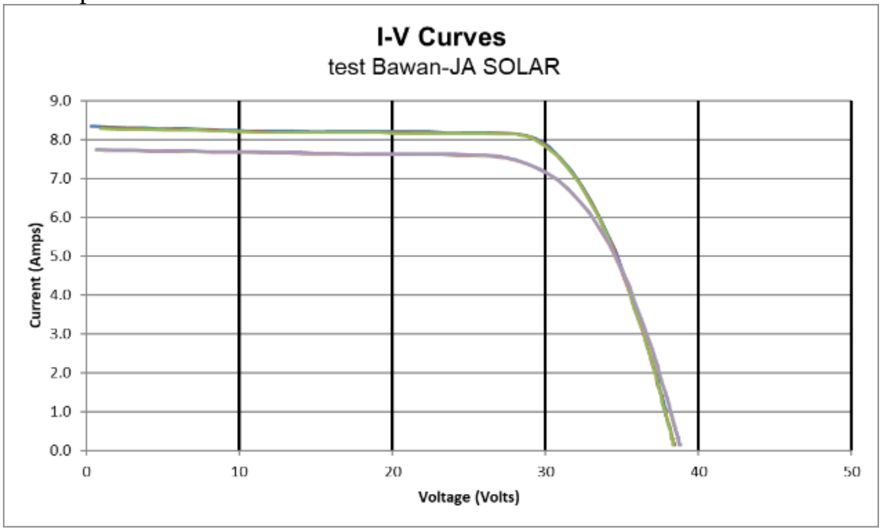


Figure 8. IV Curve comparison of 320WP Polycrystalline PV Modules (with & without reflectors)

Table 7 below shows multiple readings taken at different radiation values of the polycrystalline PV module test setup.

Table 7 : IV Characteristic test data of 320WP Polycrystalline PV Modules (with & without reflectors)

Parameters		WithReflector			WithoutReflector		
Irradiance	W/m2	881	880	879	871	874	875
Module Temp.	°C	58.9	58.8	58.9	57.3	57.2	58
Pmax	(W)	236	235	235	215	216	216
Vmax	(V)	29.9	29.9	29.9	30.1	30.1	30.1
Imax	(A)	7.9	7.9	7.9	7.2	7.2	7.2
Voc	(V)	38.5	38.5	38.5	38.9	38.9	38.9
Isc	(A)	8.34	8.3	8.29	7.75	7.77	7.78
FF	(%)	73.5%	73.6%	73.7%	71.5%	71.5%	71.5%
Measured Pmaxnormalized toSTC (W)		311	310	310	285	285	285

Vikram Solar 405WP monocrystalline

Two PV monocrystalline modules of Vikram Solar make and 405Wp rated output power have been used in the experiment, both PV modules have been placed on the same tilt angle however one of the modules has been placed with a reflector facing it so as to see the impact of the reflector. Figure 9 shows the comparative

IV curves of monocrystalline-type PV modules, the purple curve is the measured output of the monocrystalline PV module without any reflector placed whereas the muddy green curve is the measured output of the monocrystalline PV module with a reflector placed in front of it.

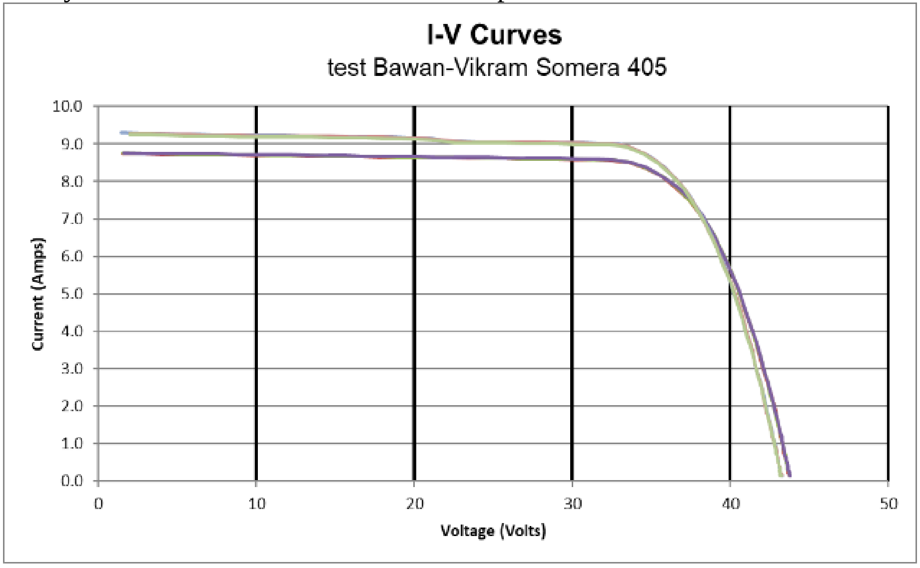


Figure 9. IV Curve comparison of 405WP Monocrystalline PV Modules (with & without reflectors)

Table 8 shows multiple readings taken at different radiation values of the monocrystalline PV module test setup.

Table 8. IV Characteristic test data of 405WP Monocrystalline PV Modules (with & without reflectors)

Parameters		WithReflector			WithoutReflector		
Irradiance	W/m2	881	879	877	869	865	866
Module Temp.	°C	56.7	57.7	56.4	53.8	53	53.6
Pmax	(W)	302	302	301	291	290	291
Vmax	(V)	34.9	34.9	34.9	35.3	35.3	35.4
Imax	(A)	8.67	8.67	8.64	8.25	8.23	8.21
Voc	(V)	43.3	43.3	43.3	43.8	43.8	43.8
Isc	(A)	9.31	9.28	9.25	8.78	8.75	8.76
FF	(%)	75.1%	75.3%	75.3%	75.9%	75.8%	75.9%
Measured Pmaxnormalized toSTC (W)		385	387	384	372	371	372

Vikram Solar 440WP bifacial

Two PV bifacial modules of Vikram Solar make and 440Wp rated output power have been used in the experiment, both PV modules have been placed on the same tilt angle. However one of the modules has been placed with a reflector beneath it so as to see the impact of the reflector on its rear side. It is usually recommended to place bifacial modules on white/light-coloured ground surfaces so as to capture the reflected radiation from the ground on its rear face. At our experiment site, the ground has a light-coloured surface and therefore we have placed a mirror instead of an aluminium reflector beneath the bifacial PV module to test whether the energy gain is more with the mirror as compared to the ground.

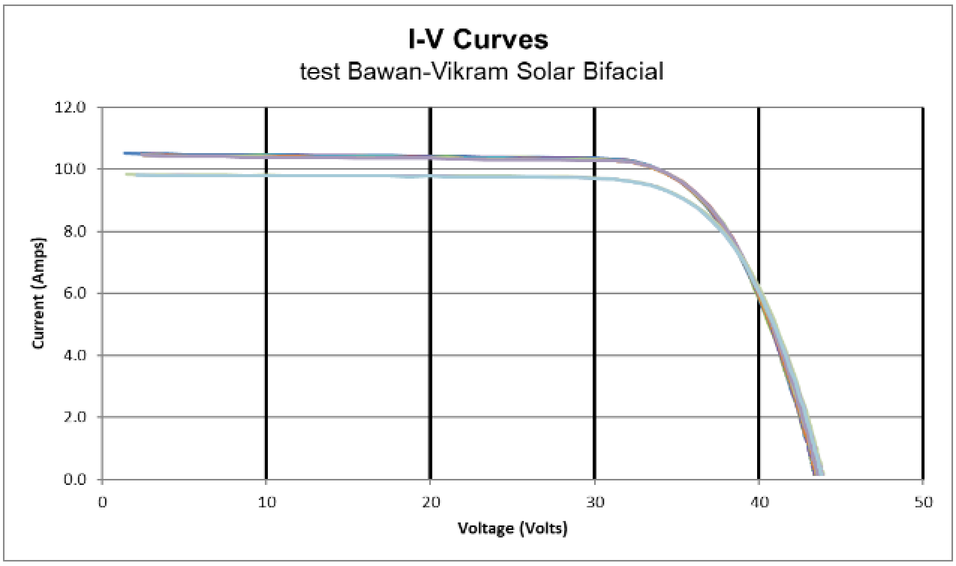


Figure 10. IV Curve comparison of 440WP Bifacial PV Modules (with & without reflectors)

Figure 10 shows the comparative IV curves of bifacial-type PV modules, the blue curve is the measured output of the monocrystalline PV module without any reflector placed whereas the purple curve is the measured output of the monocrystalline PV module with a reflector placed beneath it. Table 9 shows multiple readings taken at different radiation values of the bifacial PV module test setup.

Table 9 : IV Characteristic test data of 440WP Bifacial PV Modules (with & without reflectors)

		WithReflector			WithoutReflector		
Irradiance	W/m2	900	899	896	888	886	884
Module Temp.	°C	55.1	55.1	54.4	54.1	54.1	54.4
Pmax	(W)	340	339	339	334	334	333
Vmax	(V)	34.4	34.4	34.4	34.8	34.7	34.7
Imax	(A)	9.87	9.86	9.86	9.62	9.61	9.6
Voc	(V)	43.4	43.5	43.5	43.8	43.8	43.8
Isc	(A)	10.53	10.51	10.52	10.33	10.31	10.3
FF	(%)	74.2%	74.3%	74.2%	74.0%	74.0 %	74.0 %
Measured Pmaxnormalized toSTC (W)		422	422	422	420	420	421

Also, another set of IV curve testing has been done by covering the back side of the bifacial module using a black cloth to see the actual impact of the back side reflection on module performance. In this case, there should be no difference due to reflectors, as the back side is covered.

Table 10 : IV Characteristic test data of 440WP Bifacial PV Modules with back side covered with black cloth

Back side coveredwithBlackCloth		WithReflector			WithoutReflector		
Irradiance	W/m2	890	889	889	872	873	871
Module Temp.	°C	53.5	53.4	53.8	55.12	55.72	56.22

Pmax	(W)	322	321	321	313.67	312.78	311
Vmax	(V)	35.1	35	35	34.65	34.65	34.52
Imax	(A)	9.17	9.17	9.16	9.05	9.03	9.01
Voc	(V)	44	43.9	43.8	43.54	43.51	43.44
Isc	(A)	9.83	9.81	9.81	9.69	9.67	9.62
FF	(%)	74.4%	74.5%	74.5%	74.0%	74.0%	74.0%
MeasuredPmax normalized to STC(W)		402	401	401	402	402	401

Table 10 shows additionally measured data set to observe the impact/ contribution of the back side of the bifacial module by placing a black cloth at the back side of the bifacial module in one reading set.

4. Discussion

From the measured data, we have observed some similar patterns in the Polycrystalline test set and Monocrystalline test set, which are as given below.

Polycrystalline PV modules

With a reflector, there is an enhancement of radiation received by the solar module. This incremental value is 0.76%, also the solar PV module generated 9.7% more current than the current generated by the module without a reflector. Corresponding to the increased current, the measured power of PV module increases by over 9%.The module surface temperature also increased by 2.4% due to reflected radiation and heat.This increase in module temperature led to the decrease in open circuit voltage or Voc of the PV module with reflector by more than 1%. [25-28]Further, the fill factor which is a clear indication of a PV module's efficiency also increased by almost 3%.

Monocrystalline PV modules

With a reflector, there is an enhancement of radiation received by the solar module. This incremental value is 1.4%. Due to the reflector installed in front of it, the solar PV module generates 5.2% more current than the current generated by the module without a reflector. Corresponding to the increased current measured power of PV module increased by over 3.8%. The module surface temperature also increased by 6.48% due to reflected radiation and heat. This temperature rise is much more substantial than what we had observed in polycrystalline. This increase in module temperature led to the decrease in open circuit voltage or Voc of the PV module with reflector by more than 1%. [29-30]. Contrary to the observations made for polycrystalline PV, the fill factor decreased by almost 0.8%. This means that the power output gain has been achieved due to increased radiation through the reflector surface, but the increased temperature of the module has actually decreased its efficiency.

Bifacial modules

Our observation of Polycrystalline and Monocrystalline PV modules has been very encouraging and adhering to our belief of reflectors in tandem with photovoltaics; however, we did not see any such benefits when being used with bifacial PV modules. Bifacial PV module with reflector gave a low gain of 0.4% in Pmax compared to Bifacial modules with no mirror and placed on tilt at ground level. When the back side of the Bifacial PV module is covered with a black cloth, there was a tremendous drop in output power Pmax by more than 5%. Therefore, it can be deduced that the back side of the Bifacial modules contributes 5% power of the total output of the module, assuming that black cloth had fully covered it with trespassing of light to the backside.

We will be discussing our comparative observations made from IV curve data in the next section.

Impact of reflector on IV curve data of polycrystalline PV modules

In Table 11, the mean measured output values of the 320Wp Polycrystalline modules have been given along with the calculated difference between the module with a fitted reflector and the one without a reflector.

Table 11 : Mean IV Characteristic test data of 320WP Polycrystalline PV Modules

		WithReflector	**Without Reflecto r**	**o%**
ModuleTemp.	°C	58.87	57.50	2.38%

Pmax	Watt	235.33	215.67	9.12%
Vmax	Volt	29.90	30.10	-0.66%
Imax	Ampere	7.90	7.20	9.72%
Voc	Volt	38.50	38.90	-1.03%
Isc	Ampere	8.31	7.77	7.00%
FF	(%)	73.60%	71.50%	2.94%
PmaxatSTC	Watt	310.33	285.00	8.89%

With reflector, current values Imax and Isc see an increase of 9.7% and 7.8%, respectively. Also, using a reflector reduces the output voltage parameters Vmax and Voc by 0.66% and 1%, respectively. Further, the fill factor sees a definite improvement of ~3% with the use of reflectors. The standard Test Condition normalized Pmax sees a very high gain of 8.9%, which would be translated to output energy in kWh as well. In contrast, with an increase in output power, module surface temperature also increases by ~2.4%, which would be acceptable for regions not having very high temperatures in summer. Another pertinent point is that the reflector's tilt angle is optimized to compensate for low radiation time. Usually, during summers, when the sun is at a high elevation angle, the reflector would not be able to reflect more light & heat on the PV module.

Impact of reflector on IV curve data of monocrystalline PV modules

Similar to the previous test set of Polycrystalline in the case of monocrystalline PV modules, the above-given Table 12 presents the difference between the mean values of output characteristics of 405Wp monocrystalline PV module with and without a reflector.

Table 12 : Mean IV Characteristic test data of 405WP Monocrystalline PV Modules

		WithReflector	**Without Reflector**	**o%**
Module Temp.	°C	56.93	53.47	6.48%
Pmax	Watt	301.67	290.67	3.78%
Vmax	Volt	34.90	35.33	-1.23%
Imax	Ampere	8.66	8.23	5.22%
Voc	Volt	43.30	43.80	-1.14%
Isc	Ampere	9.28	8.76	5.90%
FF	(%)	75.23%	75.87%	-0.83%
Pmax atSTC	Watt	385.33	371.67	3.68%

With reflector current values Imax and Isc see an increase of 5% and 5.5%, respectively. Using a reflector reduces the output voltage parameters Vmax and Voc by 1.24% and 1.15%, respectively. However, contrary to other findings, the Fill factor decreases by 0.84% with the use of reflectors. Standard Test Condition normalized Pmax sees a gain of 3.55%, which would be translated to output energy in kWh as well.In the case of Monocrystalline PV modules, the module surface temperature increased by ~6.5%, which is very high and can be a cause of serious concern as hotspot formations may result in loss of efficiency, PV modules damage, and even fires in some instances.

Impact of reflector on IV curve data of bifacial PV modules

In the case of the Bifacial module test set, the data outcome was very different from the test sets of Polycrystalline and Monocrystalline PV modules. The IV curve tracer obtained the data in four sets of three observations each. We have the mean value of all the observations for comparing the sets with each other. Table 13 represents the same.

Table 13 : Mean IV Characteristic test data of 440WP Bifacial PV Modules

		With areflector	Reflectorwithcloth	Without reflector	Without areflectorwith cloth
Module Temp.	°C	54.87	53.57	54.20	55.69
Pmax	Watt	339.33	321.33	333.67	312.48
Vmax	Volt	34.40	35.03	34.73	34.61
Imax	Ampere	9.86	9.17	9.61	9.03
Voc	Volt	43.47	43.90	43.80	43.50
Isc	Ampere	10.52	9.82	10.31	9.66
FF	(%)	74.23%	74.47%	74.0%	74.0%
Pmax atSTC	Watt	422.00	401.33	420.33	401.67

Comparing reflector module data with the data of the module without a reflector, power gain of only 0.4% at STC is seen; however, the module surface temperature increased by 1.23%. The two modules (with and without a reflector) were compared again with a black cloth put on the back side to subdue the effect of the bifacial feature. The results were quantitively similar except for slight differences in surface temperature, which might have been due to the time difference between the two readings. Interestingly when we compare the bifacial module (either with a reflector or without a reflector), the obtained data shows an average power gain of ~5%, which refers to the contribution of energy generation through ground-reflected radiation falling at the back side of the bifacial panel.

5. Conclusions

Using reflectors with solar PV panels gives a definite boost to its effective power and efficiency which further translates to energy units as well. However, the impact of reflectors is different for different photovoltaic technologies, in our given test setup and duration the polycrystalline PV technology saw a significant gain of ~9% whereas monocrystalline PV technology received an increased power of only 3.7% with almost 6.5% increment in surface temperature. Contrary to our findings with EVA back sheet PV modules, no such gain was observed in Bifacial PV module technology. This result is being summarized in Table 14.

Table 14. Summarizing gain in PV technologies with reflector

Technology	ReflectorMaterial	EnergyGain Δ
Polycrystalline	**AluminumSheet**	**9%**
Monocrystalline	**AluminumSheet**	**3.70 %**
Bifacial	**Mirror**	**1.70 %**

Data availability

Underlying data

Figshare: IV Curve comparison of 320WP Polycrystalline PV Modules (with & without reflectors).

https://doi.org/10.6084/m9.figshare.21617310.v1
This project contains the following underlying data:
- Figure-8 IV Curve comparison of 320WP Polycrystalline PV modeules.xlsx
Figshare: RAW IV Curve Data. https://doi.org/10.6084/m9.figshare.22006802.
This project contains the following underlying data:
- Bawana 325Wp.csv (Raw data measured by IV Curve tracer).
- Bawana 405Wp.csv (Raw data measured by IV Curve tracer).
Bawana 440Wp.csv (Raw data measured by IV Curve tracer).
Figshare: IV Curve comparison of 405WP Monocrystalline PV Modules (with & without reflectors).
https://doi.org/10.6084/m9.figshare.21617325.v2
This project contains the following underlying data:
- Figure-9 IV Curve comparison of 405WP Monocrystalline PV modeules.xlsx
Figshare: IV Curve comparison of 440WP Bifacial PV Modules (with & without reflectors).
https://doi.org/10.6084/m9.figshare.21617340.v1
This project contains the following underlying data:
- Figure-10 IV Curve comparison of 440WP Bifacial PV Modules.xlsx
Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication)

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