Section A-Research paper
ISSN 2063-5346

EXPERIMENTAL ANALYSIS AND COMPARATIVE PERFORMANCE ASSESSMENT OF PHOTOVOLTAIC TECHNOLOGIES USING ENERGY ENHANCING REFLECTORS

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Abstract

Solar energy is an abundant clean and renewable energy source, with both environmental and economic advantages. As it continues to become cheaper and more efficient, it is fast becoming a viable alternative for homes, businesses and factories. However, the PV technology, like all other equipment, suffers a drawback of reduction in output efficiency; whereby producing less energy from the same amount of sunlight. This is called "degradation". There are various causes for this phenomenon. Some of them are – weathering, (temperature and humidity changes), microcracks in the silicon of the solar cells during manufacturing process, during handling and post installation, improper design and installation etc. The weakening of electrical connections inside the panel then results into less energy being generated from such panels.

Various measures are taken during Research and development (R&D) stage by manufacturers to reduce the effects of this induced degradation; however, life expectancy of solar modules remains between 25 yrs to 30 yrs.

The present study investigates the effect of using reflector on the power generation of monocrystalline (mono) and polycrystalline (poly) photovoltaic (PV) modules. Aluminum material was used as reflector for the study. The experiment has been conducted under outdoor conditions in Delhi, India. The study compared the performance of the PV modules with and without reflectors, using both mono and poly technology. The results showed that the use of reflectors improved the power generation of both mono and poly modules. The average increase in power generation was found to be 10% for the mono modules and 9% for the poly modules. The research findings suggest that the use of reflectors can significantly improve the power generation of PV modules, and this can be of relevance for PV power plants to improve output energy yield of any solar power plant worldwide.

Keywords : Solar PV, Mono and poly PV modules, Aluminum Reflector, Solar Plant Payback

1. INTRODUCTION

Solar energy is a valuable resource for humanity, and one that is becoming increasingly important as the planet continues to experience the effects of climate change (Godina 2018).

ISSN 2063-5346

In recent years, it has become one of the most popular and discussed forms of renewable energy sources and is a crucial step towards a cleaner, greener and more sustainable future.

In addition to its environmental benefits, solar energy has economic advantages, too. The cost of solar energy has dropped significantly in recent years, making it more accessible to households and businesses alike. Additionally, the cost of generating electricity from solar energy is much lower than the cost of generating electricity from oil or natural gas sources (Stapelberg, 2017 and Kannel 2013).

Solar energy is derived directly from sunlight and converted into electricity, making it an abundant, renewable, and clean source of energy and is quickly becoming a major source of renewable energy worldwide. Solar photovoltaic (PV) technology is an important part of this rise, currently providing 3.6% of the global electricity supply (IEA 2022) and 5.9 % in India (PIB 2023).

As of 2022, the global installed solar PV capacity was estimated to be around 1 terawatt (TW). India is a major leader in the global solar PV market, with the country's total installed capacity reaching 64 GW in 2023. This growth is expected to continue, and India is expected to have installed solar PV capacity of 280 GW by the year 2030 (PIB 2023).

The growth in solar PV technology is due to a number of factors, including increased cost-efficiency, improved technology, and increased government support for renewable energy sources. As solar PV technology becomes more efficient and cost-effective, more people are able to access the technology, leading to increased installation and use. In India, with the Govt supported incentives for the installation of solar PV systems, including the reduction of duties and taxes, the creation of special solar parks, and a feed-in tariff to incentivize investment (Patadia, 2020), there is a rapid growth in the solar year on year solar energy capacity building.

PV efficiency has advanced significantly in recent years, thanks to two main technologies: Passivated Emitter and Rear Cell (PERC) – Mono PERC and Poly PERC and P and N Type solar cell technology.

The field of solar research continues to advance, and there is potential to reach efficiency levels of up to 50% in the near future (Geisz 2020). This could be achieved through the implementation of innovative cell designs, the improvement of existing materials, and the use of concentrated sunlight with reflectors. Overall, photovoltaic efficiency has seen tremendous improvement in recent years, and the current record of 29.15% efficiency marks an important milestone. With continued research and development, researchers are confident that even higher levels of efficiency are possible in the near future, making solar energy a viable solution to both current and future energy needs.

Despite the high theoretical efficiency, PV systems designed for residential use are more often limited to around 15-18% efficiency. This can be attributed to the fact that the available sunlight is significantly reduced due to weather conditions, location, and season, leading to decreased output. Additionally, the presence of dust, snow, and other debris can also decrease the efficiency of the system. Losses due to improper tilt angle, PV Cell temperature related loss of efficiency etc also pull down the conversion efficiency of solar modules. And hence

ISSN 2063-5346

there is a possibility to enhance more output from solar PV panels and hence from the entire electricity generating solar system using the same infrastructure by various means.

One way to improve the power output and efficiency of photovoltaic (PV) modules is to use textured surfaces. According to a study by Xie et al. (2014), textured surfaces can improve the efficiency and output of PV modules by increasing light absorption in the bottom layer of the module. The authors found that textured surfaces feature more “bumpy” shapes and higher optical efficiency, which increases the absorption of light. Moreover, the use of textured surfaces decreases the surface reflection, which leads to a higher power output from the modules.

Xie et al. (2014) suggests several ways of improving the power output and efficiency of PV modules. These methods include the use of textured surfaces, high-efficiency cells, and bypass diodes. Each of these solutions is beneficial for increasing the efficiency and output of the PV modules and reducing cost and material usage.

In a study conducted by Ghassemi et al. 2018, micro texturing was found to improve the efficiency and power output of the PV modules by up to 16% and 13%, respectively. This was attributed to increased reflection and absorption of light due to the microtextured surfaces.

Huang et al. 2018 found that the application of nanostructured layers of ZnO and $TiO2$ to solar cells resulted in an improvement in device efficiency and power output of up to 28% and 11%, respectively. This was attributed to increased light absorption and optical path length due to the nanostructures.

Another strategy to improve PV module efficiency and power output is through the use of light-trapping structures such as back-reflectors, prisms, and periodic elements. In a study conducted by Qu et al., the application of a variety of light-trapping structures was shown to improve the efficiency and power output of the module by up to 24% and 16%, respectively. The improved efficiency was attributed to an increase in optical path length, enhanced reflection of light, and reduced transmission of light (Qu 2018).

By reflecting light onto the PV cells, reflectors help increase light intensity, leading to an increase in power output of about 20-30% (Pearce, 2004). Reflectors also help to reduce light losses due to dust, dirt, and soiling on the surface of the PV modules (Matsunaga, 2009). They can also be used to create a well-controlled and uniform irradiance on the PV modules, which helps to improve efficiency by 5-15% (Yousuf, 2016). Fresnel lenses are also used to increase the collection angle of the PV modules and to reduce the amount of light loss due to dust, dirt, and soiling (Dhomkar, 2007). Harwin et al (2015) investigated the use of an upper back-reflector to increase the power output of a non-tracking PV module, finding a 9.2% increase in energy output. However, they also noted that the back-reflector reduced cell temperature, leading to further power increases during the summer months.

Mondal et al. (2018) investigated the use of a polytetrafluoroethylene (PTFE) coated reflector to increase the power output of a tracking PV module in an urban environment, finding a 16.1% increase in power output. However, their study did not investigate the effect of any

ISSN 2063-5346

variable factors, such as mounting orientation and the size of the reflector, on the increase in power output.

Improving the power output and efficiency of photovoltaic (PV) modules is essential to making solar an increasingly viable option for energy. A number of strategies have been developed to increase the efficiency and power output of these modules. Research into the use of reflectors for improving the power output and efficiency of photovoltaic (PV) modules has been conducted in recent years. While the use of reflectors can increase the amount of power generated from a PV module, there are still a number of issues that need to be addressed before their use can become widespread. A research gap exists in the lack of studies to evaluate the effect of reflectors over the long-term on PV modules, optimization of the reflector design and economic feasibility. Additionally, the effect of mounting orientation, angle of incidence, albedo and the size of the reflectors need to be investigated.

The present study investigates the effect of reflector on the power generation of mono and poly photovoltaic (PV) modules. Aluminum material was used as reflector the study. The experiment was conducted under outdoor conditions in a Delhi, India. The study compared the performance of the PV modules with and without reflectors, using both mono and poly technology. The economics of reflector uses with pay back has also been presented in the paper.

2. Experimental Details

A test bed was set up with an objective to find out the effect of reflector on the performance of PV module. Two PV technologies has been tested, poly and mono crystalline. This section of the manuscript discusses the details of experiments.

2.1. Location details

The experiments have been performed at the outdoor location of the system was installed on the roof of a warehouse in Bawana, Delhi, India (28.7932° N, 77.0483° E). The location receives an average of 5.13 kWh/m^2/day of radiation. Two PV technologies, mono and poly have been tested. Solar modules of these different technologies were utilized are JA Solar-315 WP Poly full cell, and Vikram Solar-405 WP Mono perc Half Cut.

2.2. Experimental setup

The block diagram and the actual photograph of the setup is presented in Fig 1 and Fig. 2 & Fig. 3 respectively. Two modules of same make and size have been installed parallel to each other with and without reflector to check the performance of modules. Reflector was installed at 60 degrees with respect to ground. Solar radiation measurement has been done using pyranometer installed on the module structure only.

Micro Inverter, Hoymiles Product – M 1000/1200/1500 was used. It has 4 Input, Dual MPPT, NEMA IP67 Compliant inverter. The invertor measures the DC power, I_{sc} and V_{oc} captured from the DC input side ports of the inverter. It also measures the AC output from the installed system like power, voltage and current. Power output from microinverter was used to power the load of warehouse through the grid. The cumulative power of both inverters supported a load of up to 1~1.1 KW. The use of inverter facilitated the single point measurement using

ISSN 2063-5346

the input port monitoring capability of Hoymiles micro inverter. TrackSo datalogger (STD GPRS WT 800) was utilized to store the input data and monitor the current, voltage and power from the inverter. The details of the setup with data acquisition system is presented in Table 1 and Table 2.

Figure 1: Block diagram of the experimental setup

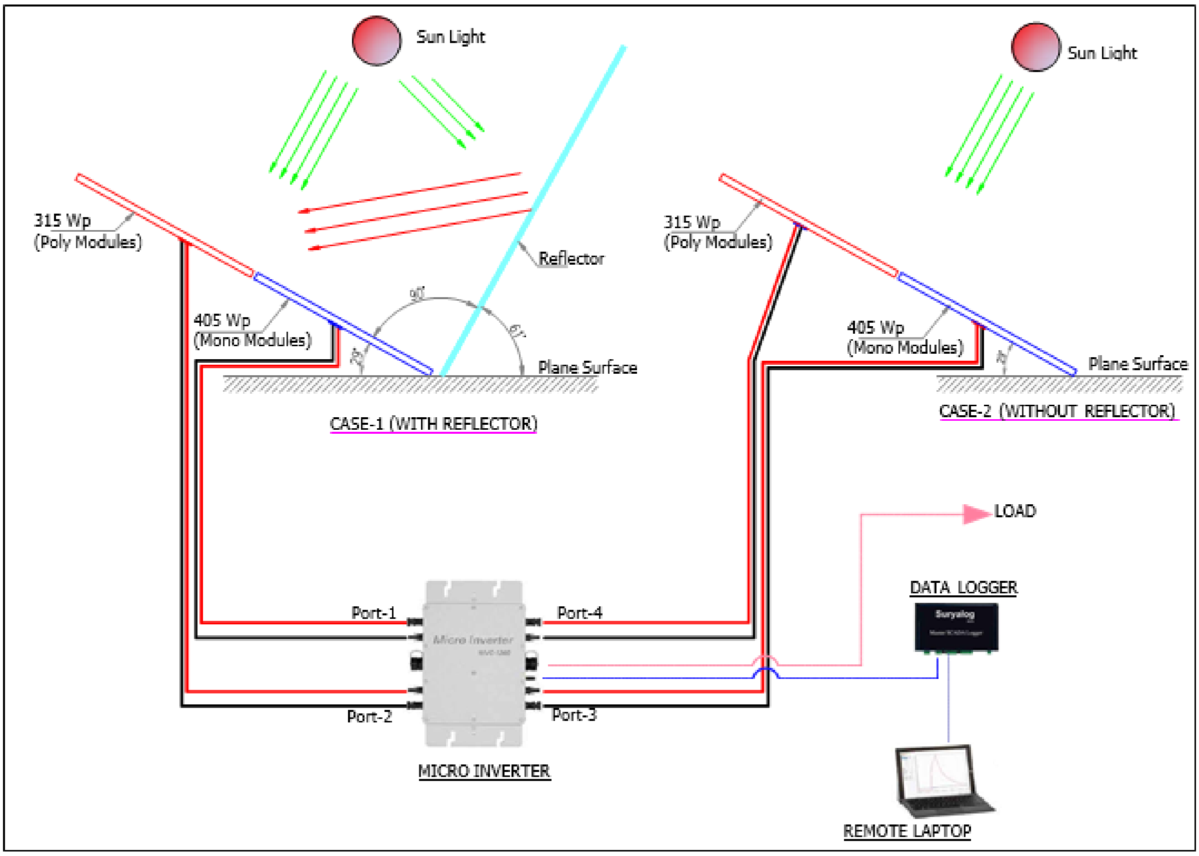

Figure 2: Actual photograph of the experimental setup

Figure 3: Actual photograph of the experimental setup

Table 1: Specifications of PV modules

Specification	**Mono**	**Poly**
Make	Vikram Solar 405 W_P	JA Solar 315W_P
Model	SOMERA VSMH. 72.AAA.05	JAP6 72/300-320/3BB

Maximum power point voltage (Vmax)	41.70	37.28
Maximum power point current (Imax)	9.71	8.45
Open circuit voltage (Voc)	49.90	45.60
Short circuit current (Isc)	10.48	8.91
Module Size (mm)	2065 x 1001 x 40	1956 x 991 x 45
Temperature coefficient (short circuit current)	+0.06%/°C	+0.058%/^{o}C
Temperature coefficient (open circuit voltage)	- 0.28%/°C	-0.033%/^{o}C

Table 2: Specifications of data acquisition system

Instrument	Details
Micro invertor with voltage, current and power measurement capability	Make: Hoymiles Model: MI-1000/1200/1500
Datalogger	Make: Trackso Model: STD GPRS WT800
Temperature measurement	Make: Trackso Model: MSPT 100V
Solar Radiation measurement	Make: Trackso Model: PYRA 300 V

2.3.Reflector details

Aluminum sheet material of 2 mm thickness has been selected for the reflector sheet. Decision to select the reflector material was taken using multi criteria decision analysis. Various parameters like cost, ease of availability, heat emissivity, thermal conductivity, ease of cleaning and strength were evaluated.

3. Experimental Methodology

The experimental setup consisted of PV module with and without reflector connected to invertor, continually generating power. The modules have been installed at the fixed angle of 61^{o}C from the ground. The experiments were performed from January 2022 to December 2023, complete one year and the data analysis has been done for different performance parameters of the PV module like PV power output. The performance of two different PV technologies has been compared in the study.

A. The details of various equipment used is as follows :

- Solar Modules
  - JA Solar-315 Wp Poly full cell
  - Vikram Solar-405 Wp Mono perc Half Cut
  - Vikram Solar-440 Wp Monoperc half Cut bifacial

- Micro Inverter : Hoymiles Product – M 1000/1200/1500
  - 4 Input, Dual MPPT
  - Compatible with 72 Cells, 1500 V

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  - NEMA IP67 Compliant, Natural cooling

- Data Logger : Trackso STD GPRS WT 800
  - Supports all major inverters with MODBUS RS485
  - 16 MB datalog flash memory
  - ARM Cortex CPU With 12 V to 24 V operation

- Modbus DATA Converter: Trackso 6 Channel TR621
  - Can measure upto 4 Voltage and 2 current through RS-485
  - Transmission protocol: Modbus RTU
  - Operating temperature: 0°C -/+ 50°C

- Module Temperature Sensor: Trackso – MSPT 100V
  - Onsite 2-point calibration, loop powered.
  - Sensor Type: RTD PT100 Ω
  - Measuring Range: 0 to 100◦C, Accuracy: ± 0.5 ◦C

- Solar Irradiation Sensor: Trackso – PYRA 300 V (Datasheet)
  - Silicon Photodiode Transducer
  - Range: 0 to 1800 W/sqm
  - Accuracy: +/- 5% of full scale

B. Parameters monitored

Using the Datalogger and Modbus Converter, the Isc (A), Voc (V) and Pmax values (W) are monitored. Measured daily at an interval of 10 Min. Duration of partial shading are excluded in both time stamp of with and without reflector

Same are corelated with Module temperature (Deg C) and Irradiation (W/Sqm) at site. Measured daily at an interval of 10 Min.

4. Results & Discussions

The objective of the study is to compare the long-term performance of mono and poly modules with and without the reflectors. The results obtained from the experimental work conducted at the outdoor location of Delhi, India is presented and discussed in this section.

4.1. Effect of reflector on electrical parameters of Mono and poly module

The seasonal variation of electrical parameters of mono crystalline module is ploted in figure 3 and 4. The experimental result of one of day from each season is plotted over time. The average voltage of mono module during winter, summer and monsoon season without and with the reflector is calculated to be 34.7 V & 34.3 V, 38.4 V & 38.0 V and 35.0 V & 34.0 V. The average current of mono module during winter, summer and monsoon season without and with the reflector is calculated to be 1.9 A & 1.9 A, 7.54 A & 7.46 A and 3.74 A & 3.7 A. The variation of solar radiation has also been plotted on the graph to understand the module behavior with respect to change in the radiation. It can be concluded from the average voltage and current measured during the experiment that the increase in current is smaller than the increase in voltage because of use of reflector compared to without reflector module. The power variation during all three seasons with and without reflector is plotted in figure 4. The percentage increase in cumulative power over a day is calculated to be in the range of 8% to 40%.

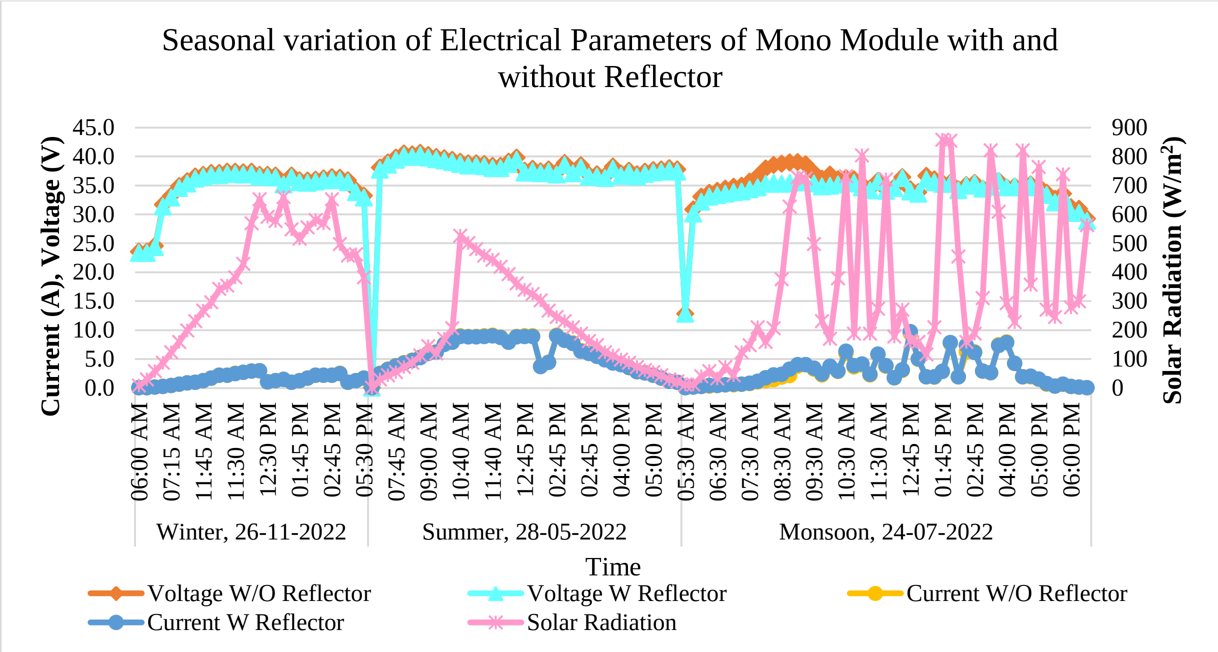

Figure 3: Seasonal variation of current, voltage of mono module with and without reflector

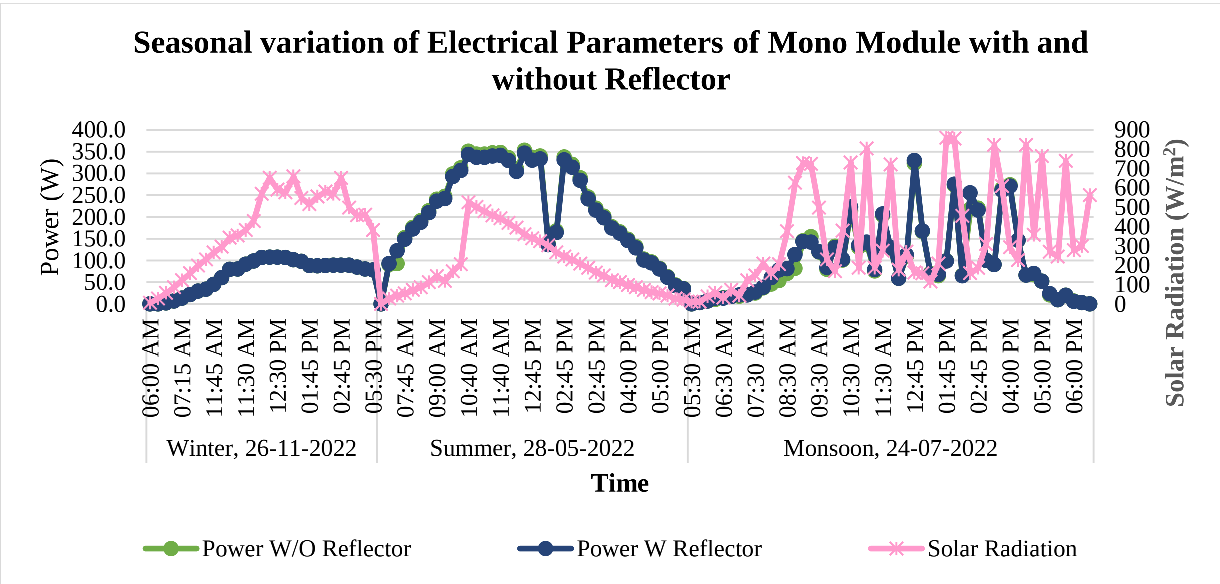

Figure 4: Seasonal variation of power of mono module with and without reflector

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The seasonal variation of electrical parameters of poly crystalline module is plotted in figure 5 and 6. The average voltage of mono module during winter, summer and monsoon season without and with the reflector is calculated to be 33.6 V & 34.0 V, 37.2 V & 37.6 V and 33.9 V & 35.0 V. The average current of mono module during winter, summer and monsoon season without and with the reflector is calculated to be 1.9 A & 1.9 A, 7.3 A & 7.4 A and 3.6 A & 3.7 A. It can be concluded from the average voltage and current measured during the experiment that the increase in current is smaller than the increase in voltage because of use of reflector compared to without reflector module in case of poly modules too. The power variation during all three seasons with and without reflector is plotted in figure 6. The percentage increase in cumulative power over a day is calculated to be in the range of 10% to 49%. The effect of reflector is more visible in mono module compared to poly module. The year long analysis shows an 10% overall increment in mono and 09% overall increment in poly modules when used with reflector, as compared to reference module.

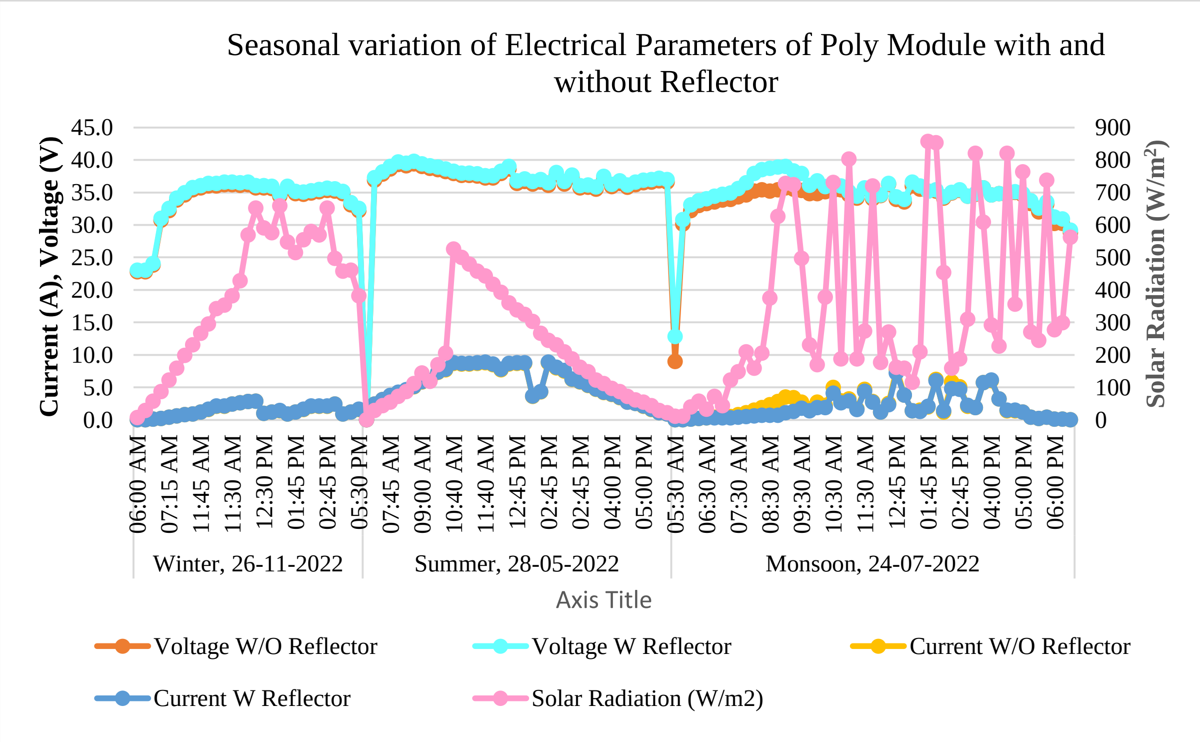

Figure 5: Seasonal variation of current, voltage of poly module with and without reflector

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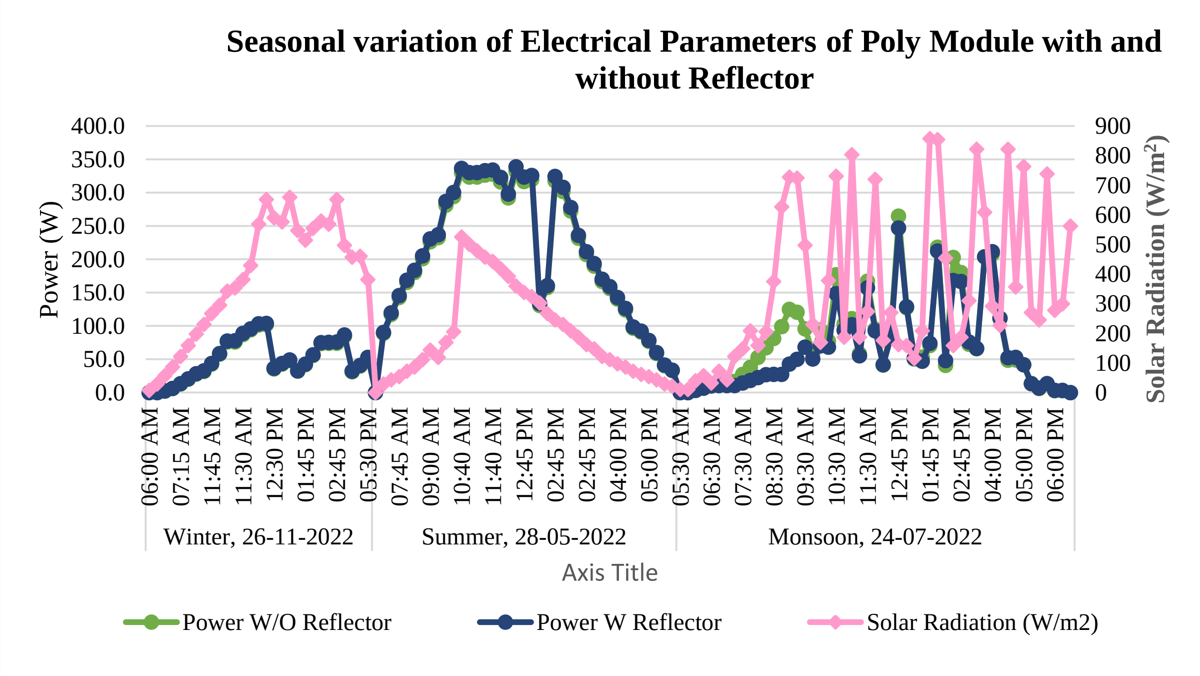

Figure 6: Seasonal variation of power of mono module with and without reflector

4.2.Month-wise effect of reflector on mono and poly module performance

Previous section discussed the daily variation of electrical parameters of module with and without reflector and showed the performance of both technologies improved because of reflector in all three days of various season in the experimental site. Only three days of result can be misleading and hence this section of the manuscript discusses the average monthly performance of module with and without the reflector.

The temperature of modules was recorded with and without the reflector for both the technology as a reflector placed behind a solar module increases the performance of module by increasing the amount of light that reaches the module by reflecting sunlight that would have otherwise been lost but at the same time will also increase the temperature of module. The month-wise percentage increase in module temperature with and without the reflector in both poly and mono modules are plotted in figure 7. The yearlong average percentage increase is 3 % and 2% in poly and mono module temperatures with and without reflector respectively.

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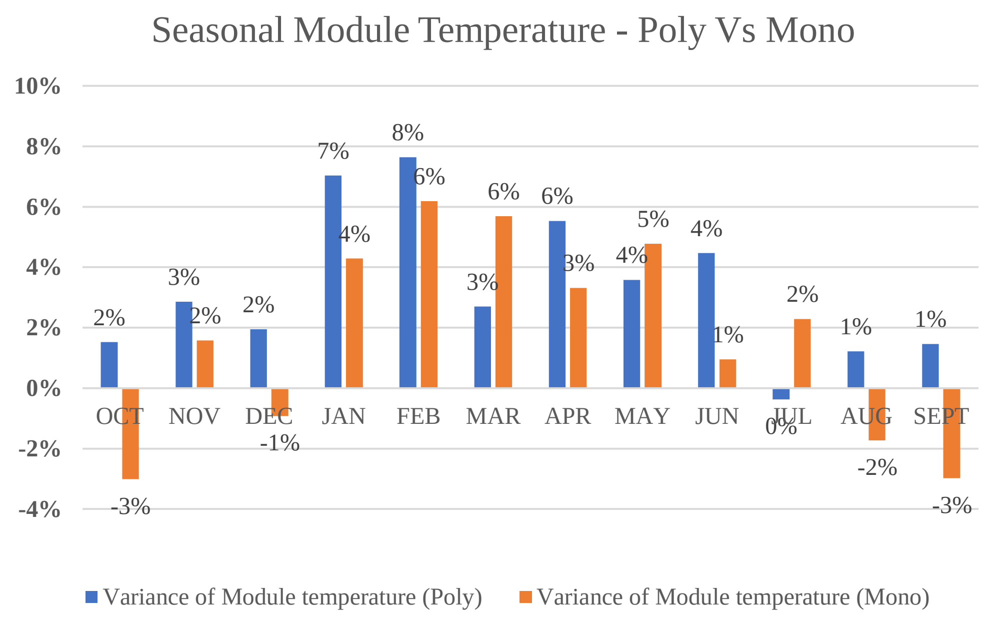

Figure 7: Monthly average variation of poly and mono module temperature with and without reflector

The month wise percentage increase in cumulative generated power output with and without reflector is compared for poly and mono modules in figure 8. The monthly increase in the power output of poly technology modules with and without reflector is in the range of 2% to 20%. The highest increase in power output is obtained in the month of January, whereas the lowest increase is recorded in the month of June. The reason for this variation can be attributed to the module temperature. The monthly increase in the power output of mono technology modules with and without reflector is in the range of 1% to 32%. The highest increase in power output is obtained in the month of February, whereas the lowest increase is recorded in the month of July.

This increase in the power output from both technologies is attributed to increase in the amount of light that reaches to the individual cells of the module. However, it's important to note that using reflectors also increases the temperature of the solar cells as shown in Fig. 7, which can have a negative impact on performance. The increase in module temperature is more prominent in poly module as compared to mono as plotted in fig. 7.

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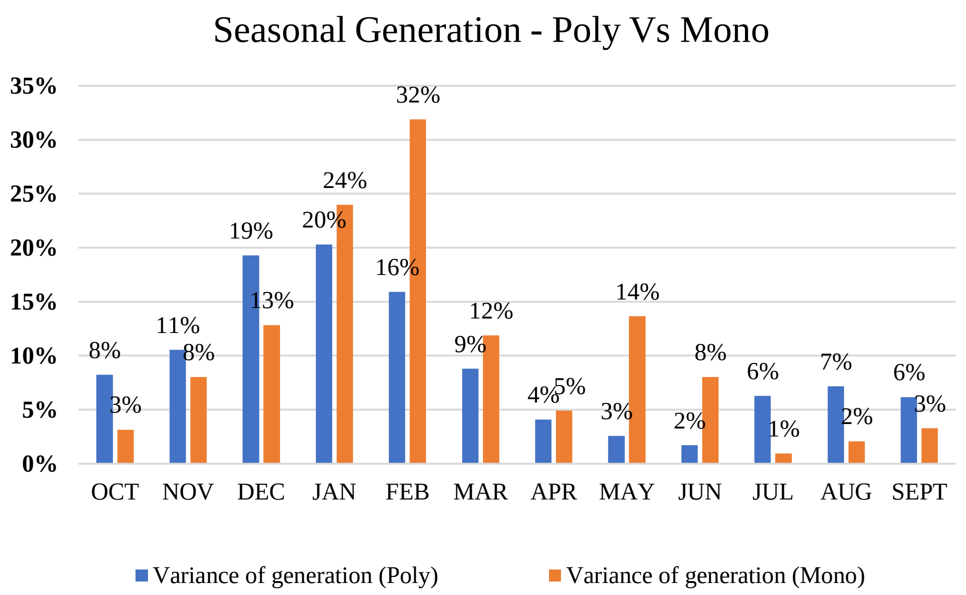

Figure 8: Monthly average variation of poly and mono module cumulative power generation with and without reflector

The monthly cumulative power generated by poly and mono modules with and without reflector is shown in the figure 9. The maximum increase in cumulative power of mono as well as poly technology is recorded in the winter months December-February). This is because of low ambient temperature the increase in module temperature due to increase in the radiation has lesser effect during winter.

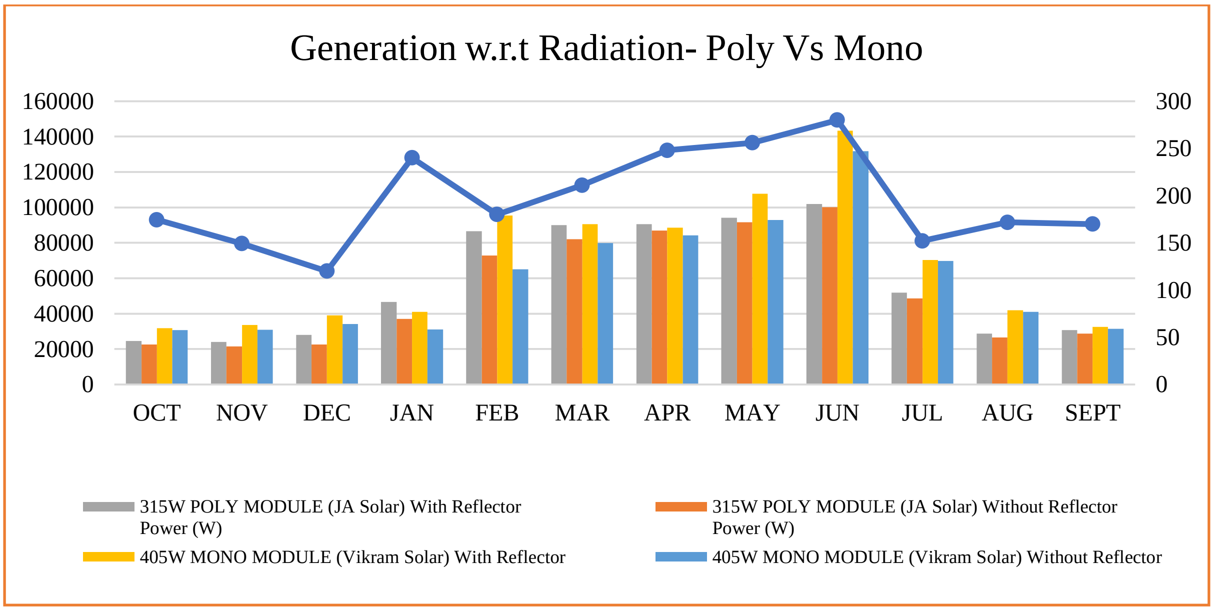

Figure 9: Monthly cumulative power variation of poly and mono module with and without reflector

5. Conclusions

The present study investigates the effect of reflector on the power generation of mono and poly photovoltaic (PV) modules. Aluminum material was used as reflector the study. The experiment was conducted under outdoor conditions in a Delhi, India. The study compared the performance of the PV modules with and without reflectors, using both mono and poly technology. Following conclusions are drown from the study.

1. It can be concluded from the average voltage and current measured during the experiment that the increase in current is smaller than the increase in voltage because of use of reflector compared to without reflector module.
2. The percentage increase in cumulative power over a day is calculated to be in the range of 8% to 40% in mono module with reflector compared without reflector.
3. The percentage increase in cumulative power over a day is calculated to be in the range of 10% to 49% in poly module with reflector compared without reflector.
4. The yearlong average percentage increase is 3 % and 2% in poly and mono module temperatures with and without reflector respectively.
5. The monthly increase in the power output of poly technology modules with and without reflector is in the range of 2% to 20%. The monthly increase in the power output of mono technology modules with and without reflector is in the range of 1% to 32%. This increase in the power output from both technologies is attributed to increase in the amount of light that reaches to the individual cells of the module.
6. The IRR of the SPV system with mirror is expected to be between 8% to 10%

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