Optimization of Back Reflectors for Bifacial Photovoltaic Modules

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2019 by the
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ARIZONA STATE UNIVERSITY

May 2019

ABSTRACT

Demand for green energy alternatives to provide stable and reliable energy solutions has increased over the years which has led to the rapid expansion of global markets in renewable energy sources such as solar photovoltaic (PV) technology. Newest amongst these technologies is the Bifacial PV modules, which harvests incident radiation from both sides of the module. The overall power generation can be significantly increased by using these bifacial modules. The purpose of this research is to investigate and maximize the effect of back reflectors, designed to increase the efficiency of the module by utilizing the intercell light passing through the module to increase the incident irradiance, on the energy output using different profiles placed at varied distances from the plane of array (POA). The optimum reflector profile and displacement of the reflector from the module are determined experimentally.

Theoretically, a 60-cell bifacial module can produce 26% additional energy in comparison to a 48-cell bifacial module due to the 12 excess cells found in the 60-cell module. It was determined that bifacial modules have the capacity to produce additional energy when optimized back reflectors are utilized. The inverted U reflector produced higher energy gain when placed at farther distances from the module, indicating direct dependent proportionality between the placement distance of the reflector from the module and the output energy gain. It performed the best out of all current construction geometries with reflective coatings, generating more than half of the additional energy produced by a densely-spaced 60-cell benchmark module compared to a sparsely-spaced 48-cell reference module.

A gain of 11 and 14% was recorded on cloudy and sunny days respectively for the inverted U reflector. This implies a reduction in the additional cells of the 60-cell module by 50% can produce the same amount of energy of the 60-cell module by a 48-cell module with an inverted U reflector. The use of the back reflectors does not only affect the additional energy gain but structural and land costs. Row to row spacing for bifacial systems(arrays) is reduced nearly by half as the ground height clearance is largely minimized, thus almost 50% of height constraints for mounting bifacial modules, using back reflectors resulting in reduced structural costs for mounting of bifacial modules.

DEDICATION

I dedicate this research to my family, friends, benefactors and all through which I have been able to accomplish this task.

ACKNOWLEDGMENTS

This study was accomplished under the mentorship of Dr. Govindasamy Tamizhmani and with immense help from the staff of Arizona State University Photovoltaic Reliability Laboratory especially Matt Prillaman, Shreyas Wagmare and Prathemesh Thorat. I am grateful for the work, and experience gained under Dr. Mani's mentorship. I would also like to extend my gratitude to my friends and family and the Mastercard Scholars Foundation at Arizona State University for supporting me throughout my master's program. Special thanks to Sai Tatapudi for his guidance and contribution - it was an added impetus to my work.

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INTRODUCTION

1.1 Background

1.1.1 Demand for Sustainable energy

One of the most utilized fundamental public commodities used in everyday life and essential to promoting the socio-economic development and growth is electricity. With the current trends in climate change, growing industrialization and the demand from both modern and developing countries due to increase in population growth, it has become more imperative that traditional fossil fuel energy systems are replaced by much greener and sustainable renewable energy technologies [1]. The effect if the change to renewable energy sources will be profound is not initiated. As the population of the world reaches 7.3 billion, the per capita energy use, especially that of developing countries is expected to increase rapidly [2].

Emissions from nuclear and coal powered plants and challenges associated with embargoes imposed on crude oil affecting supplies have also contributed to the recent switch to renewable energy such as hydroelectric, wind, biomass, geothermal and photovoltaic technology. In 2017, the total U.S. primary energy consumption was equal to about 97.7 quadrillion Btu (28 trillion KWh) as shown in figure 1 above. Notable, is the regressive growth of the coal industry which started in 2015 when environmental regulations were imposed on disposal of the by-products of coal power plants. These regulations increased the cost of maintaining a coal generating power plants hence causing the shutdown of many plants. Crude oil also benefited from cost-effective drilling and production technologies aiding production in states such as Texas and North Dakota.

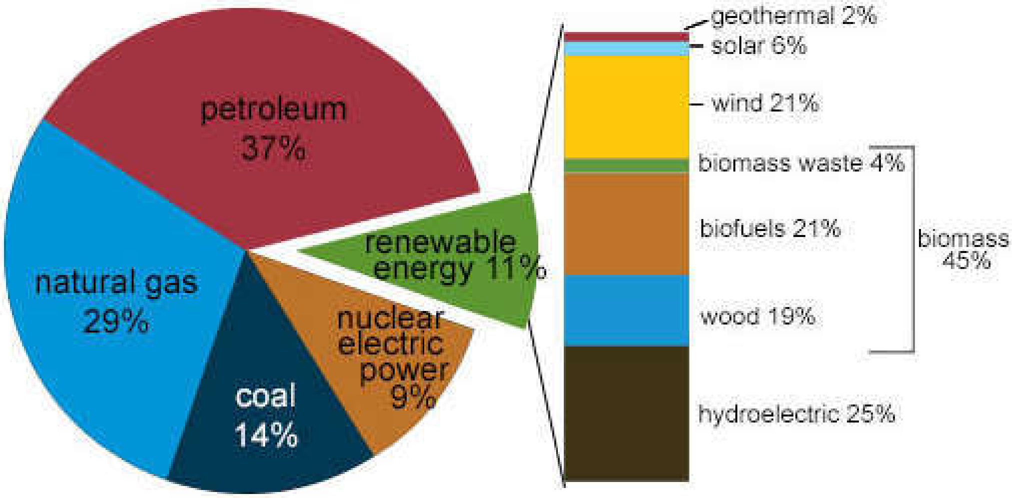

Figure 1: Snapshot of 2017 energy consumption in the U.S. [3]

The total renewable energy consumption reached record highs of about 11 quadrillion Btu in 2017. Increases in energy production from wind and solar, indicating record highs in 2017, helped to increase the overall energy production from renewable sources. With this growing outlook, renewable energy sources are set to increase in growth by 2023. According to the United States Energy Information Agency (EIA), Renewable energy plays an important role in reducing greenhouse gas emissions, using renewable energy can reduce the use of fossil fuels, which are major sources of U.S. carbon dioxide emissions.

1.1.2 Recent global trends in the Photovoltaic Industry.

The photovoltaic industry has grown since the discovery of the photoelectric effect, converting sunlight to electricity directly, in 1839 by Becquerel followed by Chaplin, Fuller and Pearson's development of the first solar cell in 1954. This growth is largely attributed to the advancements in the production of pure materials such as silicon sufficiently to manufacture solar cell of reasonable efficiency. This process hugely determines the cost of PV modules due to the high cost of producing the cells. Innovative ways have been developed of the years in PV module technology leading to the following types of modules;

a) Crystalline Silicon technology (c-Si): this technology is largely used due to its low cost in manufacturing and high efficiency. Its can be divided into two types depending on the type of Silicon (Si) wafer used, thus multi-crystalline and mono-crystalline. Its dominance in the PV markets can be associated with the breakthrough in the microelectronics field.
b) Thin film technology: Known for their unique manufacturing process which reduces the demand for highly purified and crystalline material and the simultaneous formation of solar cells into modules, this technology is made up of three distinct types of modules. These are cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si).

This growth in the development of cell technology for PV modules has led to the increase in the global installed capacity to about 500GW as shown in Figure 2. Utility-scale projects account for just over 60% of total PV installed capacity, with the rest in distributed applications such as residential, commercial and off-grid. Over the next five years, solar PV is expected to lead renewable electricity capacity growth, expanding by almost 580 GW.

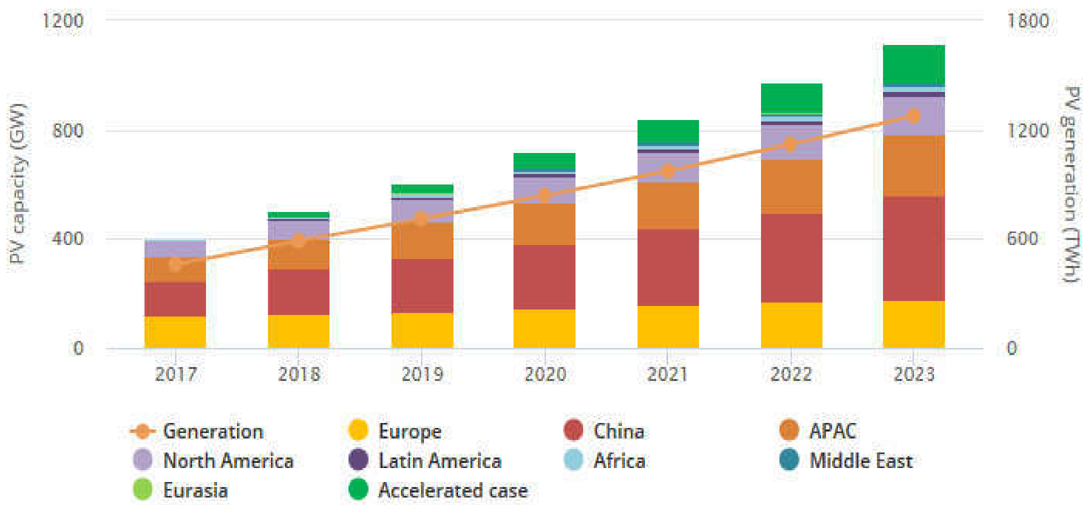

Figure 2: Solar PV generation and cumulative capacity by region (Renewables 2018)

However, the biggest challenge for the PV industry is achieving grid parity without subsidiaries. There are considerable uncertain factors affecting the Levelized Cost of Electricity (LCOE) driven by carbon tax, grid control system costs and investment in new transmission. For this reason, its more prudent to investigate innovative methods to reduce the cost of manufacturing and efficiency of installed PV systems.

1.1.3 Bifacial Photovoltaic Technology

Strives in research to find efficient alternatives in increasing efficiency of PV technologies thereby improving LCOE making it competitive with other sources of energy has led to a newly introduced type of module, which utilizes both the incident light on the front and rear side of the module, called the bifacial Photovoltaic module. The use of this new technology can largely increase the overall energy output for solar power plants. The absorbed rear irradiance is significant compared to the monofacial modules.

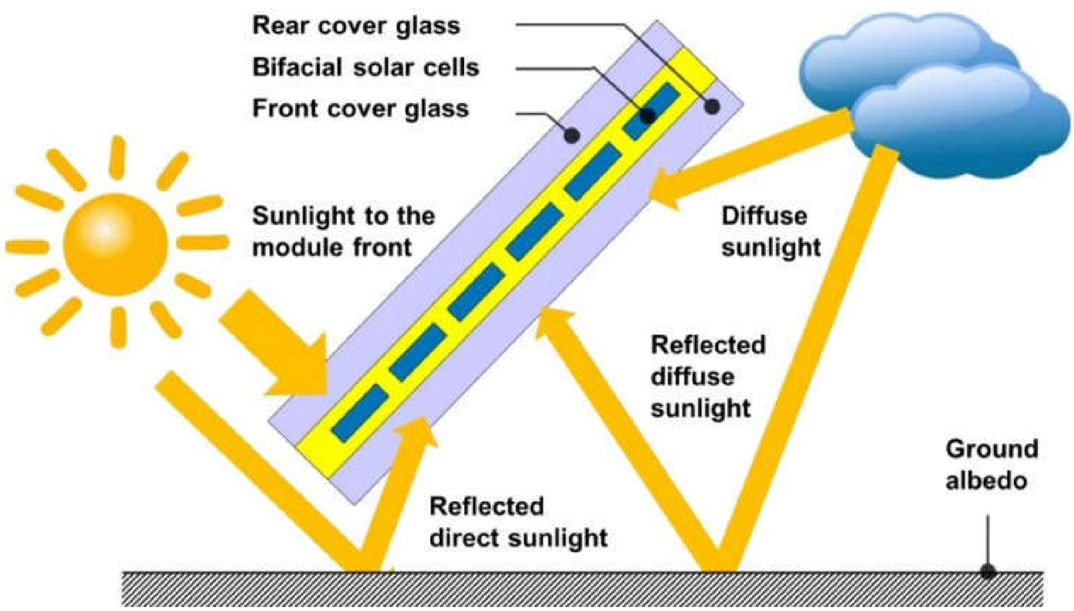

Figure 3: Principle of operation of Bifacial module (TÜV Rheinland Energy)

Key amongst several factors that affects the general output of bifacial modules the uniformity of the rear-side irradiance and the bifaciality. The bifaciality is the ratio of the power output of the front side to the power output of the rear side. The rear side irradiance is hugely affected by external factors such as the incident irradiance on the ground surface (which then reflects on to the solar cells on the rear side), shading from the racking system and modules, height of the module installation, spacing of cells in the module, and albedo.

1.1.4 Economics of Bifacial Photovoltaic systems.

The growth in the PV industry can be largely attributed to the significant cost reductions. The bifacial PV technology is not widely used due to the increased cost associated with its manufacturing as about two to six manufacturing steps may be added compared conventional cell manufacturing techniques. The gains from bifacial modules is more likely to outweigh this cost. They offer improved production and performance over the life of the system. Due to high conversion efficiencies offered by the bifacial modules which results in bifacial energy gains and improved durability, this can lower its levelized cost of energy (LCOE).

1.2 Statement of the Problem

Advancements in the design of photovoltaic (PV) modules aims to increase the output power of PV arrays while decreasing the cost of production. A more recent advancement in PV design includes the production of bifacial modules that can convert incident light on both sides of the module into power.

However, the power production of these modules is highly dependent on the albedo of the ground or back-surface reflector. This has led to many works and research into finding the right design and mechanism with higher reflectivity and low absorptivity and transmissivity. With the introduction of diffuse back reflectors, the overall output of bifacial module can be increased to more than 10%. [4] This approach reflects the diffuse light on to the rear side of the module, thereby increasing the bifaciality factor of bifacial systems.

A clear evidence was established in our previous work indicating the best design for a back reflector is a diffuse reflector with an inverted cone profile. This is as a result of the relatively greater uniformity achieved as compared to other profiles. Non-uniform irradiance on the back-side of the bifacial modules has the potential to severely decrease the power output of the modules and can cause the cells to perform in their negative bias, which results in power loss in the form of heat. This research seeks to identify the effects of controlled back reflector of various profiles placed at different distances from the bifacial module on factors that affects energy generation such as uniform albedo, nominal operating temperature of the module, etc.

1.3 Previous Work

The Arizona State University Photovoltaic Reliability Laboratory had previously investigated alternative methods to increase the energy generation of the bifacial PV technology. This research investigated the use of reflectors, mounted on the rear side of loosely packed 48-cell bifacial modules, installed on the back-side of bifacial modules in increasing the power output through enhanced uniformity of the back-side irradiance. The increased spacing of the modules increases the amount of light passing through the module to the back-side, which allows for a greater contribution to the total power from the back-side. The results indicated a calculated power generation boost of 10-14% over a baseline 48-cell module with only an uncontrolled ground reflection. The increased energy production of the modules results in increased power production of the modules which could potentially make 48-cell with reflector competitive with tightly packed 60-cell modules.

1.4 Thesis Objective and Approach

The major objectives of this research project are:

- To study the performance of bifacial photovoltaic modules and its dependence on various profiles of stationary reflectors
- To determine the optimum reflector placement distance from the back of the modules.
- To optimize the diffuse reflector surface profile yielding the best PV module performance

- To investigate the effect of reflectors on array row spacing for bifacial installation configuration.

1.5 Approach to Achieving the Objectives

The plan of action for this research project was divided into two major parts. The first part of this research study involved experimental investigations with outdoor testing of PV modules mounted with different profiles of stationary back reflectors. These back reflectors were placed at varied distances from the module. The aim was to investigate the effect on the uniformity of the reflection from the back reflector. The reflectors were mounted on the rear side of the module of the 48-cell module which are loosely packed. The increased in irradiance from the reflectors is as a result of the reflection of light passing through the spacing between the cells. Extra energy produced is aimed to compensate for the additional cost of the reflector as well as potentially make them competitive with tightly packed 60-cell modules without a reflector.

The second part focused on the effect of stationary reflectors on shading and array row spacing for bifacial power plants. This will be done by comparing the standard 60 cell reference module and Bifacial panels fitted with stationary reflector at optimum height from the studied. Simulations will be done in a program called System Advisor Model (SAM) to investigate the annual power and energy production, and levelized cost of energy (LCOE). Theoretical investigations with analytical methods and modelling were developed to predict the optimum reflector profile and placement distance from the module. After evaluating the results of these two investigations, conclusions were made about the validity of the experimental findings, and then verified by analytical results.

CHAPTER 2

LITERATURE REVIEW

2.1 Operation of Bifacial Photovoltaic Modules

Photovoltaics, a renewable energy source, converts the sun's electromagnetic (EM) energy into electrical energy utilizing the photovoltaic effect. Thus, the generation of energy when two dissimilar materials in close contact. The incoming photons energize the electrons, which move away from the junction and are collected by an external circuit. Thus, a direct correlation can be drawn between the incident light and the energy generated by a PV module. Hence, the desire of scientists and engineers to increase the incident insolation per unit area for a given module.

This led to the design of the bifacial module which utilizes solar insolation from both sides of the module. The research on Bifacial PV systems dates back as early as the 1960s when the Japanese researcher H. Mori designed the first fully functional prototype. It was until ten years later then the bifacial PV system was deployed was as a part of the Russian Space Program in the 1970s. Even though the technology has been around for many years, high production costs have prevented it from being commercialized in any large scale. The reason for it being more implemented in our society today is due to the rapid expansion of the solar cell market.

The global growing demand that has lowered the prices on PV technology and enabled the Bifacial technology to grow. [1] Most recent innovation in this area of research is the use of back reflectors to increase the incident insolation on the rear side of the module. The efficiency of this technology relies on several factors such as the profile of the reflector, the reflectivity of the material, shading and tilt angle.

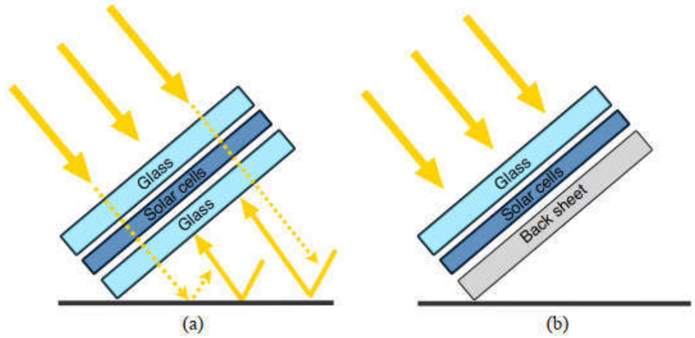

Figure 4: in (a), a Bifacial PV module. in (b), a standard PV module. [1]

The bifacial module primarily consists of glass sheets on both sides instead of the use of back sheet material allowing for optical transparency in the capturing of the incident light at the back side of the module as shown in figure 4. The total irradiance on the backside is a combination of diffuse light from the sun, light reflected on the surroundings and light passing through the module, which is possible due to its optical transparency. With same amount of silicon used, the bifacial module can produce more power than a standard monofacial cell without necessarily covering more physical area. Figure 5 represents the distinct differences in cell configuration for both monofacial and bifacial cells.

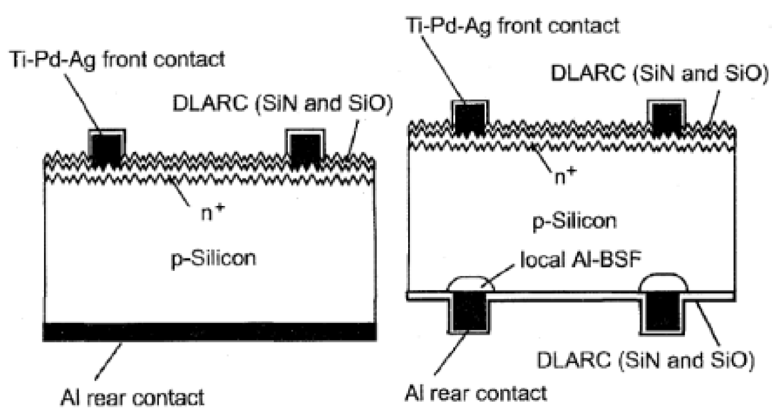

Fig 5: Schematic of monofacial (left) and bifacial (right) photovoltaic cell [2]

Bifacial cells incorporate selective-area metallization schemes to allow light between the metallized areas. The lower amount of metal changes how cell performance is optimized, potentially requiring tighter and expensive specs on the silicon and thin-film material used and increasing series resistance concerns. [1]

Consequently, the backside metal represents a non-trivial impediment to manufacturing bifacial cells with high performance and low cost. This added complexity and cost needs to be offset by the performance gain from increased light collection. The bifacial PV module behaves similarly as a monofacial module, as absorbed light incident light of the front side of the module through the front glass and converted into electricity. The current, Isc, increases larger due backside light that come from a variety of sources, such as reflection from the ground or a neighboring row of PV modules. This incident backlight increases the voltage of the cell slightly due to its logarithmic proportional relationship to irradiance and current. The formula that governs the additional rear collection power is given as:

$$\text{Rear collection} \propto (1 - \cos(180^\circ - \alpha)) \cdot \text{albedo} \cdot \text{GHI} \quad \text{--------} \qquad (1)$$

where α is the module's tilt angle and GHI is the Global Horizontal Irradiance (W/m^2).

Often, PV modules are aligned north-south and tilted at latitude angle to capture morning and evening sun by reducing the incidence angle. The bifacial PV technology offers various options in installation configuration. Thus, bifacial modules could be mounted either vertically, tilted or horizontally. Figure 6 shows the energy yield for different installation configuration of bifacial modules in different directions. A clear evidence of the ability of bifacial modules extra potential of enhanced energy generation with 50 – 100% of additional energy for a given tilt direction. The relative importance of tilt angle and albedos depends on the latitude/orientation of the modules and ground albedo at each specific site. [14]

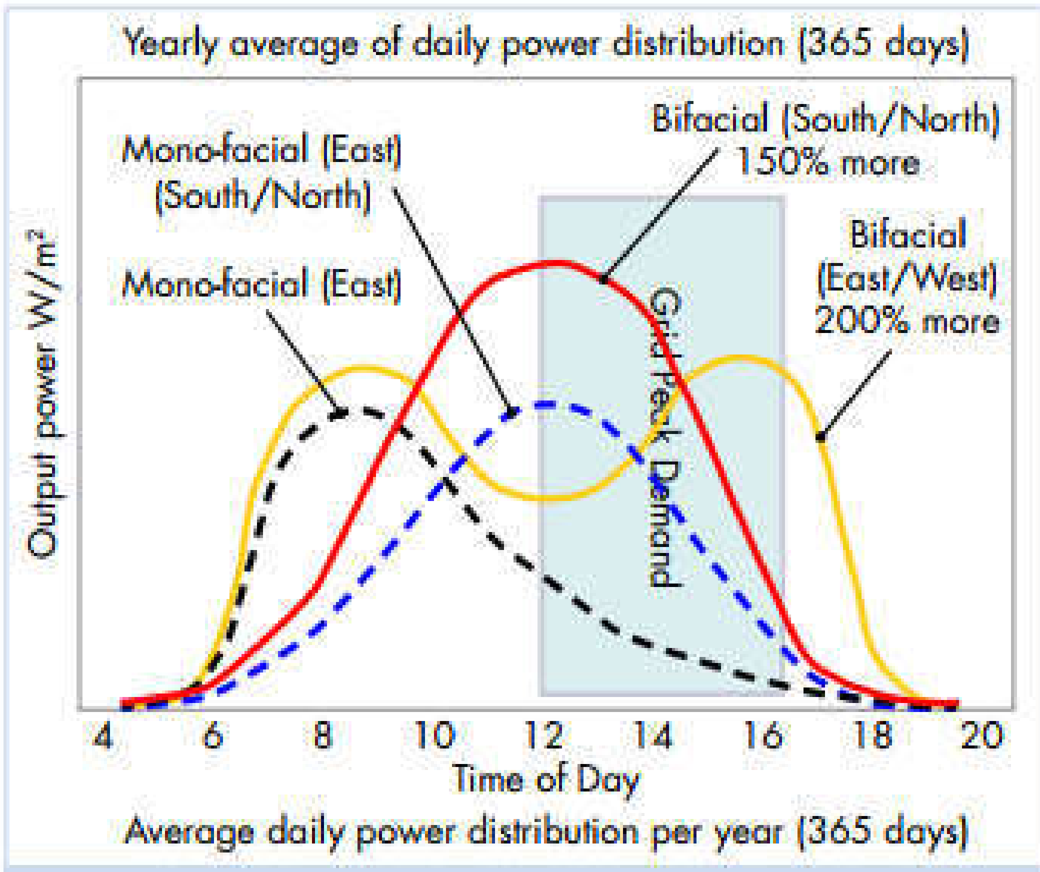

Figure 6: Daily Power Distribution for bifacial modules. [14]

2.2 Factors affecting efficiency of Bifacial PV technology

Newly introduced solar bifacial PV modules, with the capacity to increase the overall energy output using the diffuse ground reflected light, has shown potential of providing significant additional energy of about 20% more compared to monofacial PV modules. However, the efficiency of bifacial modules is dependent of the bifaciality gain (BGE) [3]. The ratio of the power output of the front side to the power output of the rear side is defined as the bifaciality gain. It is defined by;

$$BGE = (3\theta + 115h + 1.34\alpha) \times 10^{-1} \qquad \text{------------} \qquad (2)$$

where θ is the tilt angle of the modules (degree), h is the height above the ground of the lowest point on the module (in m), and α is the albedo of the ground surface (%) and the result is BGE in % (for module heights that range from 0.15m to 0.8m and for tilt angles less than 35˚).

The rear side irradiance is huge affected by external factors such as the incident irradiance on the ground surface (which then reflects on to the solar cells on the rear side), shading from the racking system and modules, height of the module installation, spacing of cells in the module, and albedo. The efficiency of the bifacial can be increased by improving the reflectivity of the surface of the ground or back reflected area. [3][4] A significant boost of up to 25% has been reported by SolarWorld [4] and Sandia National Laboratory in collaboration with University of Iowa [3].

The albedo is a measurement of the reflectivity of a body and is crucial for the energy output of a Bifacial module. The albedo of a surface corresponds to the ratio between the reflected light and the incident light. The albedo represents the amount of light reflected off a surface. [1] Numerous efforts has been placed into research of generating innovative ways to increase albedo, thus make it brighter and reflective. The albedo of bifacial systems can be improved using reflectors, trackers or/and increasing the ground material reflectivity.

Table 1: The albedo of different kinds of surfaces. [1]

Surface type	Albedo
Green grass	0.24
Red brick	0.24
White sand	0.67
Snow	0.85

The ground material plays a key role in the reflection of light unto the backside of the bifacial module. A perfectly reflective surface has an albedo of 1 whilst dark surfaces with high heat absorptivity has a 0 albedo. Commonly used technique in improving albedo of ground surfaces is the painting or coating with a highly reflective primer. The table below highlights various albedo of different ground materials

2.2.1 Concentrators/Reflective surfaces

Bifacial solar panels equipped with external reflectors are expected to produce extra electrical energy depending on the materials properties of the reflector and its location. Some of the key parameters for the reflector include its slope with respect to the panel plane, distance from the panel, and reflection efficiency. Figure 7(a) and 7(b) compares the basic principle of both mono- and bi- facial modules. The rear reflection is utilized by the bifacial module whilst heat is accumulated in the monofacial module.

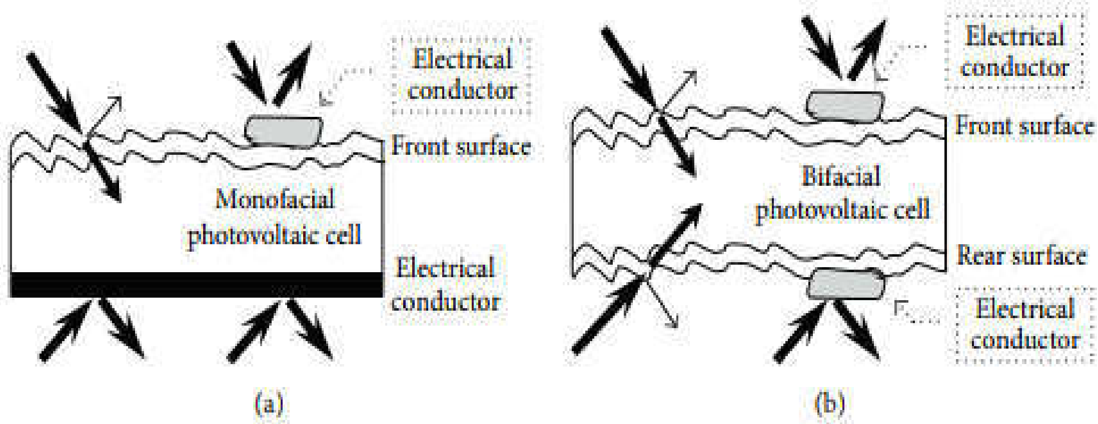

Figure 7: Cross-section configurations of (a) monofacial and (b) bifacial solar cells [5]

Studies and results from Bowersox 2018 [6] have indicated that the diffuse reflector have a higher boost due it's divergent dispersion of the reflected rays unto a large area of solar cells, thereby increasing the Isc or current/power of the module as shown in figure 8. The diffuse reflectors increase the incident irradiance on the rear side of the bifacial module which in turns is proportional to the overall energy output of the module.

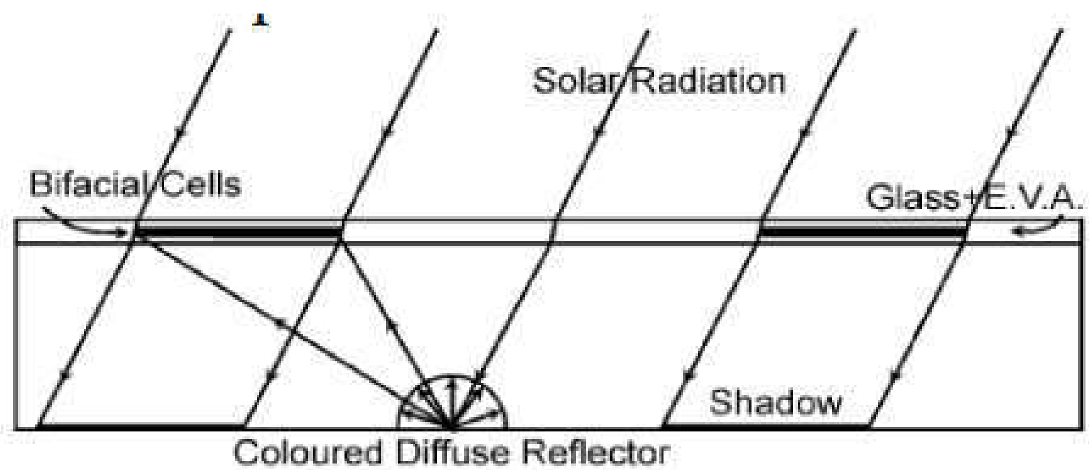

Fig 8: Bifacial PV equipped with diffuse reflector [4]

The design of the back reflectors primarily relies on the increase and uniformity of reflected light and albedo towards the rear side of the module. This core function of the reflector can be achieved through the careful design of the reflectors; thus, the reflective behavior and the reflection/incidence angles should be key factors to be considered in the construction of a back reflector. Figure 9(a) represents a mirror type reflection where only one beam of light is directed to the rear surface of the panel, while diffuse reflector scatters the reflected radiation over the rear surface of the bifacial panel/cell as shown in Figure 9(c). The semi-mirror reflector shown in Figure 9(b) reflects back a portion of solar radiation on rear surface, like a mirror type reflector, while a portion of solar radiation is scattered. [5]

Bifacial PV modules are usually positioned in the Plane of Array (POA) to enable the front side to capture the direct beam light from the sun while the diffuse shy radiation and ground reflected light is utilized by the rear side. Reflective surfaces have been investigated to highlight the nature of reflective material needed to provide optimum boost in the overall energy generation of bifacial modules. The following types of reflective characteristics; Mirror type (total reflection of incident light), diffuse type (scattering of incident light), and semitransparent reflection, which exhibits both spectral and diffuse properties, have been investigated for various bifacial PV panel applications. [7][8][9] [10]

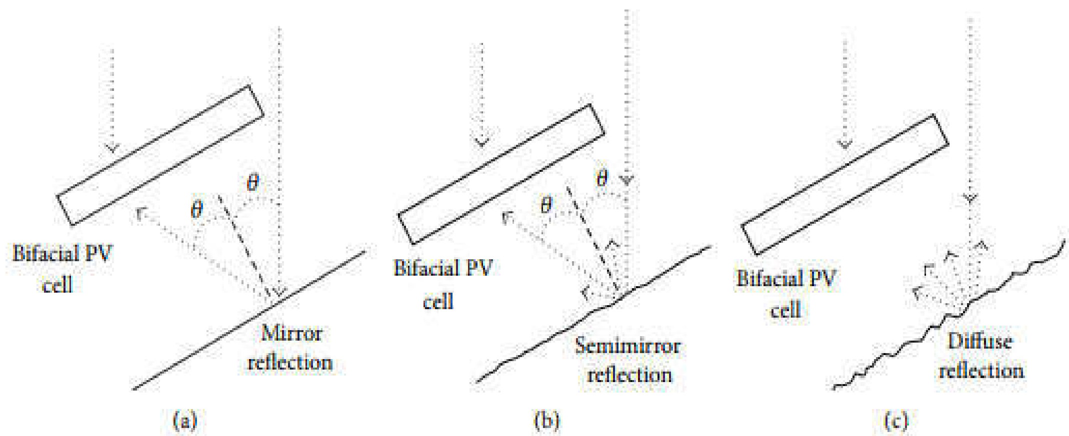

Figure 9: Bifacial PV panel integrated with (a); mirror type reflector (b); semi mirror type reflector and (c) diffuse type reflector [5]

From figure 9(a), 9(b) and 9(c), represents a mirror type reflection where only one beam of light is directed to the rear surface of the panel, while diffuse reflector scatters the reflected radiation over the rear surface of the bifacial panel/cell. The semi-mirror reflector shown reflects back a portion of solar radiation on rear surface, like a mirror type reflector, while a portion of solar radiation is scattered. [5]

Evidence provided by previous work done by the Photovoltaic Reliability Laboratory, ASU indicates that the scattering of reflected light over the rear side of the bifacial PV module provides the maximum increase in the overall energy generation, thus variation in solar radiation intensity on rear surface leads to a corresponding variation in electricity generation. The increase from a diffuse back reflector was found out to be about 10% of overall energy generation. Previously worked on reflector profiles have yielded significant improvements to the overall energy generation of bifacial PV systems. Work done by Bowersox 2018, investigated the effects of three diffuse reflectors. They are a flat reflector, Inverted V reflector and Inverted U reflector. Reflection performance of these reflectors is not only a function of its color but also the direction of the incident beam, the microstructure of the reflector and the surface roughness.

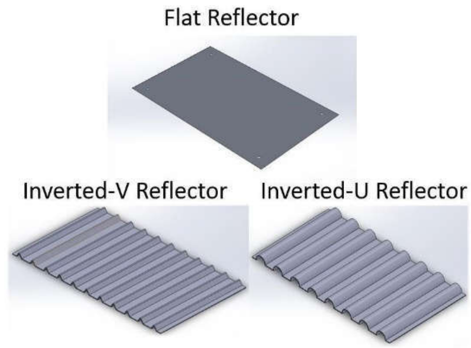

Figure 10: Sample profiles of back reflectors [6]

2.2.2 Reflectivity of Materials

Work done by the Arizona Photovoltaic Reliability Laboratory (ASU-PRL) estimates a potential theoretical enhancement by use of a 48-cell bifacial PV module with reflector of up to 25% in energy generated in comparison with conventional 60-cell bifacial PV panel without a reflector. To achieve this target, the metal reflectors are coated with a primer, which serves as both an anti-corrosion agent and surface finisher. Moehlecke et al [15] indicated that white color was an optimum diffuse painted reflector with approximately 75% average reflectance followed by yellow, orange, red, green, blue, brown, purple, grey, dark blue, and dark green with 61%–32% reflection variation. From Figure 11, the reflective power of sampled materials is tested to find their relative performance with respect to visible light and Ultraviolet (UV) light. The flat white primer and the high-performance enamel showed relatively similar reflectivity indicating both paints can be used for high diffuse reflectance. The specialty metallic paint showed 78% high specular reflectivity in the visible region and in the range of 80-100% for the UV region below 400nm.

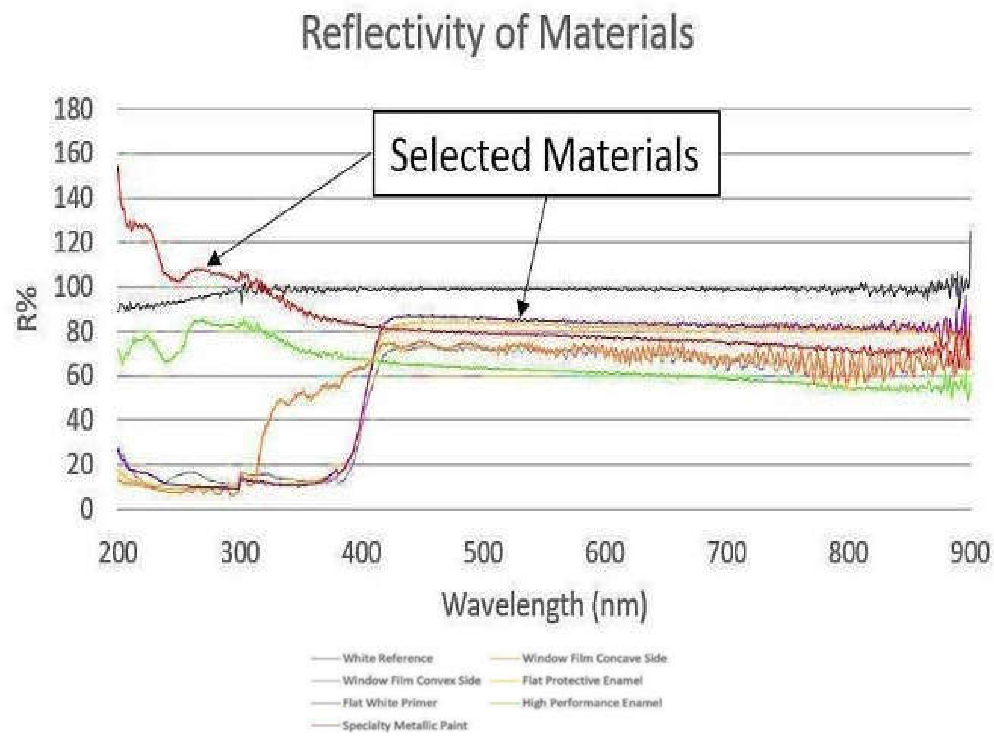

Figure 11: Reflectivity of sampled materials. [6]

The high reflectivity of this paint could prove to be ideal if the back encapsulant is not browned due to higher level of reflected UV. The directly reflected light can greatly increase the Isc (short circuit current), though non-uniformity can result in a much smaller total power output of the module in comparison to any gains in Isc. A combination of a high reflective enamel and a design profile for a reflector, the reflection can be increased significantly to boost energy generation by the bifacial PV module. As shown in figure 12, T. Uematsu et. Al [16] placed a v-groove reflector with 88% reflection efficiency at the back and they left gap between bifacial PV and top glazing to maximize uniform solar gain via multi reflection by top glazing. [9]

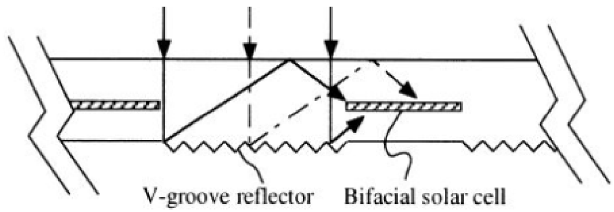

Fig 12: Bi-PV equipped with v-groove reflector [9]

The profile of such reflectors focuses parts of solar radiation unto reflect on rear side of bifacial module. Coupled with a tracking system will maximize the solar gain but imposes high investment and maintenance cost. The use of solar tracking PV panels in absence of solar concentration gives relatively small increase (around 30 %) in the solar energy collection and electric energy production, and therefore could be practical only with very economic tracking systems.

Larger effect could be achieved with bifacial PV panels, which production cost is not much higher than that of standard modules of the same area, and an increase in energy production caused by effective use of a rear face with a simple system of flat mirrors could be 50 – 60 %. Figure 13 illustrates a example of a tracking system developed Poulek 2015. [10]

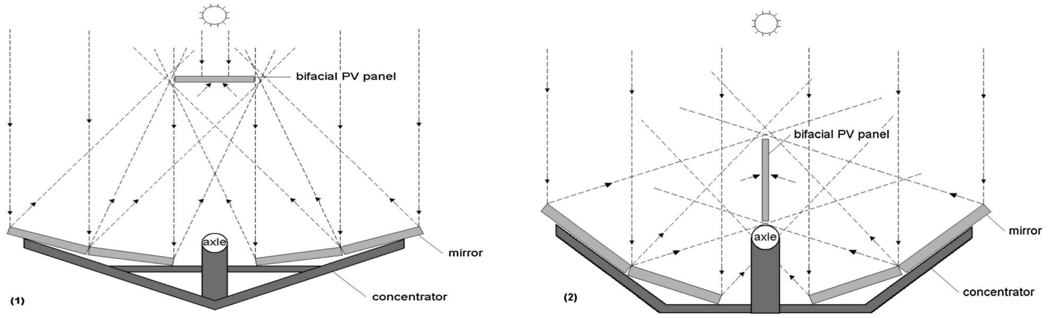

Fig. 13: Scheme of 1st & 2nd variant of pseudo parabolic concentrator with bifacial PV panels

2.2.3 Shading

Shading affects the performance of solar Photovoltaic modules. The shade could be caused by various agents such as dust, shadow cast by nearby objects etc. The decline in performance has direct proportional with the amount of shading on the surface of the module. String become obsolete when one or more cells is shaded. Performance of bifacial modules increases with elevation above the ground. Highly elevated modules suffer considerably less from self-shading, thereby making elevation a crucial design parameter to optimize the performance of bifacial solar modules. However, as the elevation continues to increase, the loss due to self-shading diminishes gradually until its effect is completely negligible. Hence, for infinitely large ground reflectors, the energy production of bifacial modules plateaus at high elevation above the ground and elevating the module further does not improve energy yield.

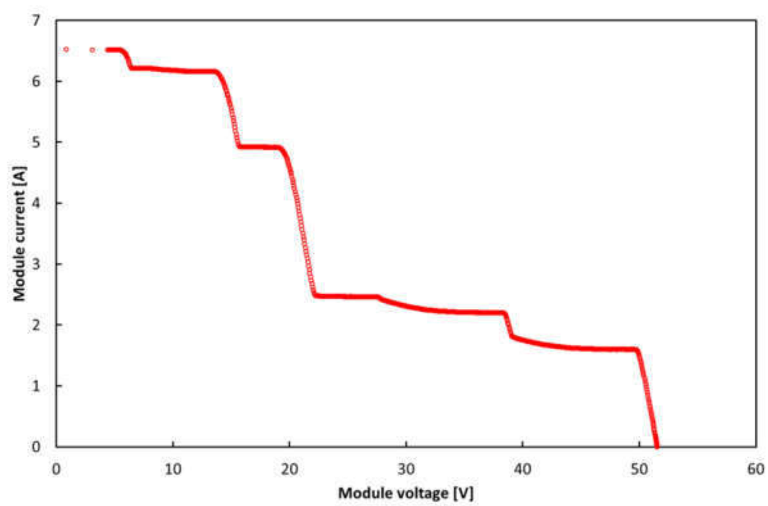

Figure 14; Effects on shading on Bifacial module. [17]

Figure 14 illustrates the typical response of shaded modules. The bypass modules are activated when a string of modules is shaded. Back side shading as a result of junction boxes does not damage a bifacial module, it does result in yield losses. To optimize bifacial energy gains, system designers need to avoid shading the back side of the array.

2.2.4 Cell temperature

High temperature affects the efficiency and life time of PV systems in general. Solar cells are sensitive to increases in temperature which in turn reduces the band gap of a semiconductor, affecting the material characteristics. Increasing the temperature reduces the band gap and bond energy since the temperature gain causes and increase in the electron energy of the semiconductor material and hence lowering the energy needed to break the electron bonds. Most affected by an increase in temperature is the open-circuit voltage as shown in figure 15. Observed effect of combined heat input and transfer is that only at rear irradiance fractions beyond 15% the additional heat input can cause the bifacial modules to be hotter than their monofacial modules, but the energy yield is still much higher due to the large bifacial gain. [17]

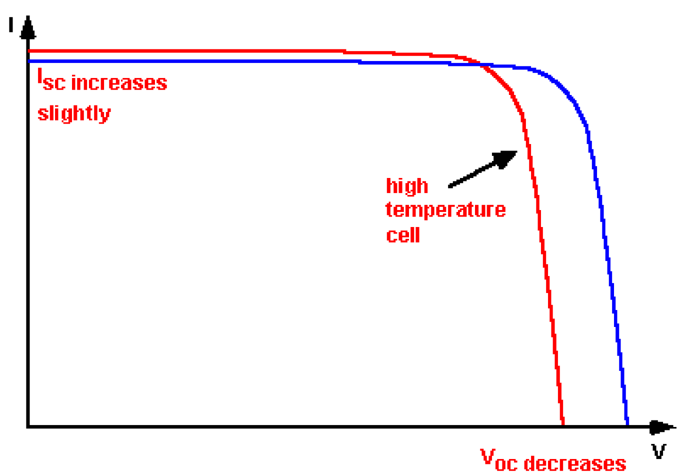

Figure 15; The effect of temperature on the IV characteristics of a solar cell [17]

2.3 Levelized Cost of Energy for Bifacial PV Technology

As expected, the lower costs of solar have driven the spectacular growth. Nearly all regions of the have participated in the growth, and Europe has started to accelerate its installations once again. From figure 16, the total amount of solar (plus other renewables) was approximately 12% of all power generation in 2017. It shows the possible predicted trajectories for solar growth in the next 5 years. Under optimal conditions, the total installed PV capacity would be more than 1.2 TW – but even using the more conservative, the world total will still exceed 1TW by 2022. But this target can only be achieved with favorable LCOE.

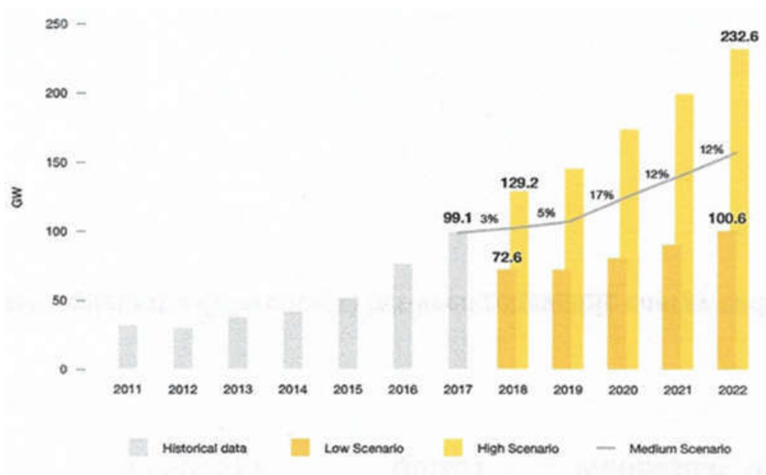

Figure 16; Annual forecast of solar installation growth [18]

The levelized cost of Energy (LCOE) of PV systems in the United States are largely reduced by subsidies introduced under the Sunshot 2020 systems costs. LCOE cost largely depends on the size of plant under consideration since the costs reduce from residential to commercial use and furthermore when it comes to industrial use. The inclusion of additional state incentives coupled with good climate for PV enables very low discount rates. Current target for the sunshot 2020 have been re-examined due to increase in the grid price parity and the achievement of nominal financing by industry as shown in figure 17. The inverse proportionality between system efficiency and prices are closely related over a system utility to achieve the targets of the sunshot 2020. Given a constant degradation rate, system lifetime and financial pricing of modules, the difference between the curves in figure 18 which illustrates the impact of lifetime charges could decreased to achieve the sunshot 2020.

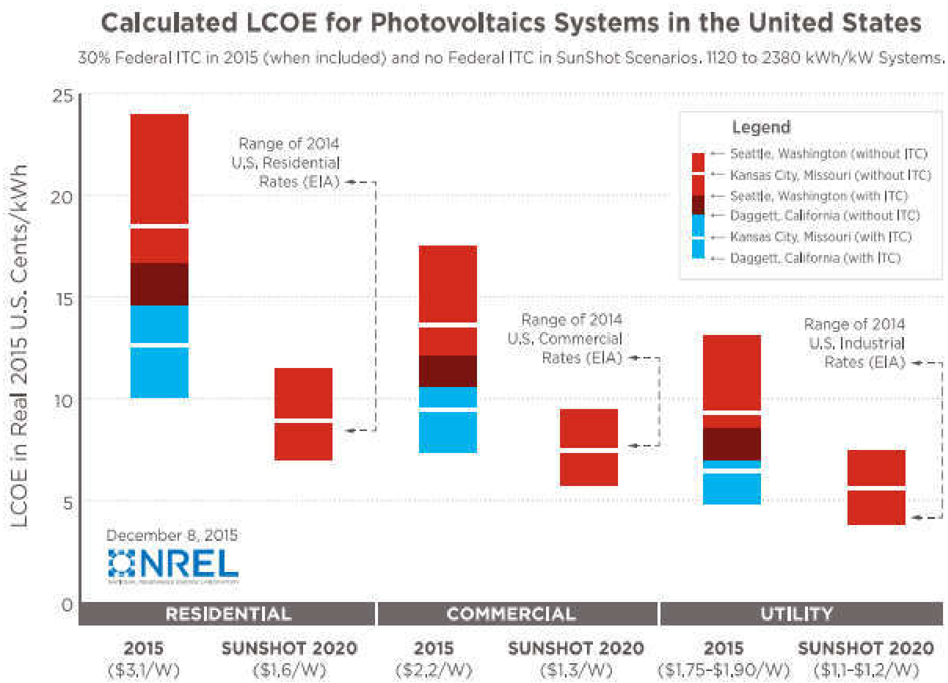

Figure 17; LCOE for PV Systems in the United States [18]

External factors such as labor costs, hardware costs and electrical costs directly affects the pricing of modules and these reduction in these costs' variables will lead to price fall and high demand for all module types. To achieve grid parity, alternative means to increase efficiency and reliability of modules must be established. Costs of modules contribute largely to the overall LCOE of the PV system with huge emphasis of system reliability and efficiency.

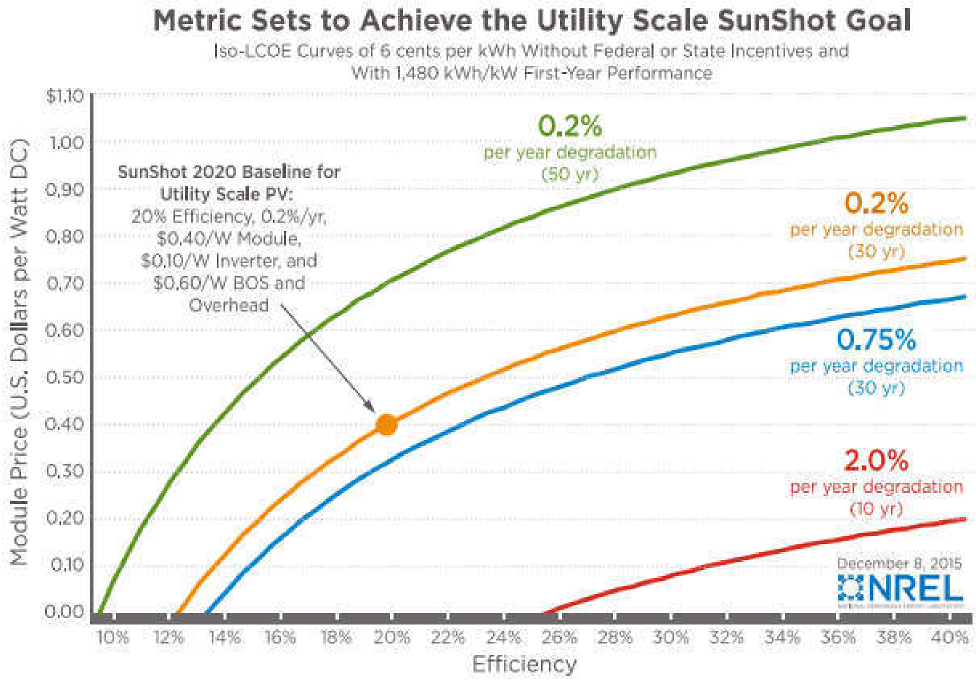

Figure 18; Utility Sunshot Goal [18]

Permutations of the key metrics of module price, efficiency, degradation rate, and system lifetime that could enable the utility scale SunShot target of 6 cents per kWh with energy yield around 1480 kWh/kW. Thus, some concurrent innovation in the non-module components is also assumed. [18]

Operating temperature, temperature coefficient, and spectral sensitivity, efficiency, concentration level and tracking are major factors influencing the determination of LCOE of a PV system. When efficiency increases, the incremental impact of additional efficiency improvements reduces, hence few modules will be needed to achieve the grid parity targets with little CapEx. Electrical costs have higher incremental rate for residential fixed area setup as the efficiency of these system enhance. Including the contributions of module cost reductions, improving residential system efficiencies gives the greatest absolute reductions in cost evaluation. The degradation rate also influences the total energy output of a PV system. The reliability and durability of a PV technology impact LCOE by influencing how much energy is produced over a PV system's lifetime.

Project financing is a key issue in system evaluation and LCOE calculation. Risk in PV plants could be reduced in much research works are commissioned to find alternatives to increase the efficiencies of these systems. The LCOE of a module depend on the reliability hence a direct proportionality is been established. Overall future LCOE reductions may require cost tradeoffs between the metrics such as types of tracking systems. Collaborative efforts to LCOE could yield effective realistic results. LCOE increases as module reliability worsens since manufacturing cost are done at the expense of reliability

Labor and system hardware costs are also included, as is innovation to PV module and system designs that have the potential to impact those costs. Improving module efficiency also contributes some reductions to the module price and hardware and labor costs. SunShot goals is expected to enable LCOE equivalence between PV systems and conventional electricity sources need for technology advancements in all the key metrics becomes even greater in the 3 cents per kWh case. The impact on LCOE due to changes in key PV technology metrics, focusing on module cost, efficiency, and reliability. The lifetime is the period over which the system is assumed to operate for the purpose of the financial analysis.

2.4 Contributions by this thesis

With the increasing demand for stable and reliable energy solutions, bifacial solar photovoltaics (PV) technology has the capacity to provide additional energy generation for installed power systems due to its ability to utilize both direct beam and ground reflected light. Back reflectors have been designed to increase the efficiency of the cell found on the rear side of the module by utilizing the intercell light passing through the module to increase the incident irradiance.

This work focuses on the performance of bifacial photovoltaic modules and its dependence on various profiles of stationary reflectors and the optimum placement distance of stationary controlled reflector from the back of the bifacial module. Hence, the effect of the reflectors on array row spacing for bifacial installation configuration. The effect of back reflectors on the overall energy output of bifacial PV modules using different six different profiles of reflectors placed at varied distances from the plane of array (POA) was examined. Bifacial modules have the capacity to produce additional energy with the use of effective stationary controlled back reflectors.

CHAPTER 3

METHODOLOGY

This study consists of data collection through outdoor performance monitoring and analysis and analytical modelling. This section discusses the various parameters and tests used to study the effects of the stationary back reflectors on the performance of the bifacial module.

3.1 Experimental Procedure

This experimental procedure characterizing the outdoor performance monitoring and analysis was conducted on a set of five new modules consisting of four identical 48-cell bifacial modules and a 60-cell bifacial module. These modules were mounted on a rack above the ground and the experiment was done in four parts.

Figure 19: Test Setup with (1) 60-cell benchmark module with natural ground reflection, (2) 48-cell benchmark module with natural ground reflection, (3) 48-cell module with inverted-U reflector, (4) 48-cell module with inverted-V reflector, and (5) 48-cell module with flat reflector

3.1.1 Test Modules

Uniformly spaced four 48-cell bifacial modules and one 60-cell module were mounted on a single rack set to latitude tilt (33°). Diffuse reflectors with flat, inverted-V, and inverted-U profiles was mounted behind module 3, 4, and 5 respectively avoiding the generation of low and high temperature currents, thereby minimizing thermal and electrical mismatch leading to and non-uniformity in back reflection, temperature variation and also reduce the variability due to wind and soiling effect.

Each reflector was mounted at varied distances from the rear surface of the module. Modules 1 and 2, bifacial 60-cell and 48-cell module without reflectors respectively, where used as a reference for the modules with reflector to determine additional power gain. Module rating are summarized in table 2. The 60-cell module has a potential to produce about 26% more additional energy than the 48-cell bifacial module due the additional cells found in the 60-cell module.

Table 2: Summary of Module Parameters

Module No.	Configuration	PV Technology	Pmax (W)	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	$Pmax_B$ (W)	Isc_B (A)
1	60-cell reference	Bifacial	290	32.4	8.95	40.2	9.48	368	12
2	48-cell reference	Bifacial	230	25.9	8.87	32.2	9.39	292	11.9
3	48-cell with inverted U reflector	Bifacial	230	25.9	8.87	32.2	9.39	292	11.9
4	48-cell with inverted V reflector	Bifacial	230	25.9	8.87	32.2	9.39	292	11.9
5	48-cell with flat reflector	Bifacial	230	25.9	8.87	32.2	9.39	292	11.9

Table 3 highlights the summarized sequence of experiment execution on the modules. The first set of experiment was the baseline characterization of the module, then followed by IV characterization of the modules with reflectors of different profiles (cone heights) at varied distance of 25cm, 50cm, 75cm and 100cm from the module. An example of such placement is illustrated in figure 20.

Table 3: Summary of Executed Experiments.

Experiment	60-cell module	48-cell module	48-cell module	48-cell module	48-cell module
1	NR	NR	NR	NR	NR
2	NR	NR	UR-3cm	VR-3cm	FR
3	NR	NR	UR-6cm	VR-6cm	FR
4	NR	NR	UR-9cm	VR-9cm	FR
UR - Inverted U reflector		VR - Inverted V reflector			
FR - Flat Reflector		NR - No Reflector			

The modules were tested with non-destructive performance characterization techniques including outdoor IV curve tracing, and infrared (IR) imaging to achieve a baseline performance profile for these modules. These measurements were taken on a clear sunny day at various times of the day.

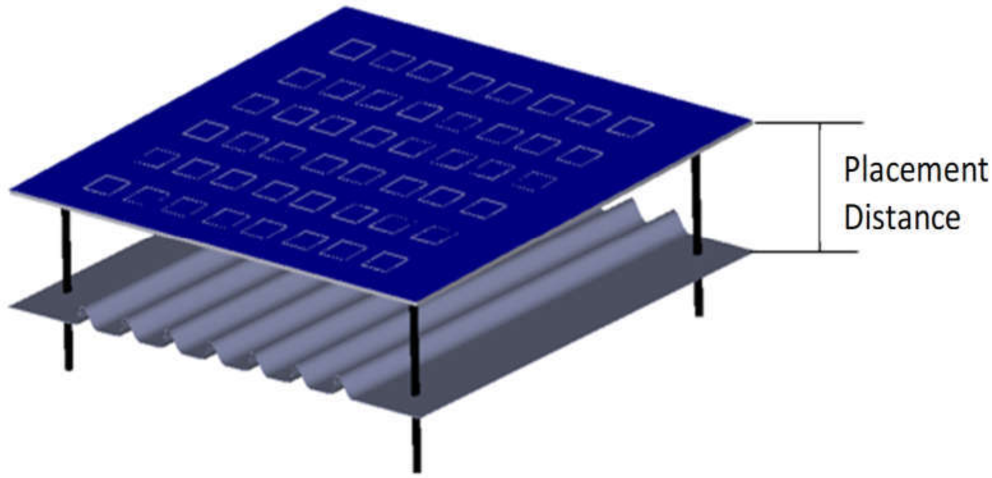

Figure 20: Sample configuration of inverted U reflector placed at 50cm from the module.

3.1.2 Reference Cells

Irradiance measurements were taken from three sources: A pyranometer was mounted at latitude tilt near the modules and two reference cells mounted between Modules 1 and 2, aligned coplanar with the plane of the array (one facing backward and the other forward facing). Data were taken every 30 seconds by the pyranometer whilst the reference took data every 15seconds to ensure accuracy in incident irradiance on the Plane of Array (POA) and accurately compared both set of data to determine the approximate contribution to the total power generation by the rear side of the modules.

Figure 21: Mounting of reference cell; In(a) fully mounted double-faced reference cell (b) front facing reference cell (c) rear facing reference cell.

3.1.3 Thermocouple Location

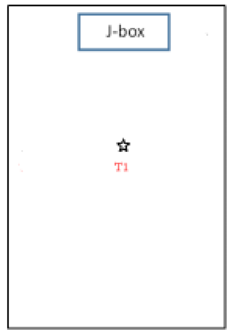

Figure 22: Thermocouple Location for each module

The temperature sensors were located, as indicated in figure 22, at the center location of the rear glass of the test modules in order to account more accurate equilibrium and study overall module temperature. The data was monitored using MT5 multicurve tracer and retrieved periodically. This multi-data logger proved to be very convenient providing ease of simultaneous data collection and retrieval for long-term period.

3.1.4 Weather Parameters

The determination of the day's weather conditions, clear sunny sky or cloudy sky day was determined by recording by a weather station placed about 4 feet away from the experiment setup. The station was made up of irradiance sensor, wind sensor and rain gauge, installed to monitor various weather parameters like solar irradiance, ambient temperature, wind speed and wind velocity using a Campbell CR1000 Scientific data logger as temporary storage. The irradiance sensor used was a Kipp and Zonen pyranometer with an ultrasonic wind sensor and rain gauge were mounted horizontally to measure the wind speed and precipitation.

3.1.5 Electrical Conditions

The performance monitoring was done on the test modules under different electrical conditions for an IV curve traced from the module to ensure accurate characterization of the module's performance.

A. Short-Circuit Condition

A test module under short-circuit condition is operating at zero voltage and has largest current drawn from the module. In this situation, no load is connected with the module. The test modules undergo short-circuit condition for short period to avoid damaging the module.

B. Open-Circuit Condition

A test module under open-circuit condition is operating at its maximum voltage available whilst the net current through it is zero. The test modules were also monitored under open-circuit condition for a short time.

C. Maximum Power Point Tracking Condition

The Daystar, Inc. MT5 multi-curve tracer comprising of load and control unit was used to run all the modules under maximum power. It was also used to take IV curves at every 15-minute interval simultaneously. I-V Measurements were taken using the RD-3200 multicurve tracer from 5:00 am to 8:00 pm daily to ensure adequate insolation.

3.1.6 Baseline Characteristic Measurements

To prove achieve a baseline performance for the 5 modules, an IV tracing was conducted for the modules without a reflector for neither of them. The incident irradiance was from the uncontrolled diffuse reflection form the ground. This test was conducted of 3 clear sunny days which much emphasis on the behavior of the modules at solar noon. Baseline test gave a clear indication of the performance of the rear side cells as the front side was covered on the second day of experiments to find the IV characteristics of the rear cells. Table 4 provides a summarized procedure of the baseline characteristic measurements.

Table 4: Baseline Experiments Outline

Day	Test Description
1	IV measurements of full module without reflectors and coverings.
2	IV curve tracing of rear side of module without reflectors and covered front side.
3	IV measurements of front cells of module without reflectors and covered rear side.

3.1.7 Design and Use of Reflectors

Reflectors made of inverted cones of various heights were placed at the back of three of the 48-cell the modules as shown in figure 19. The reflectors were designed such that the incident light passing through the space in between the sparsely arranged cells falls directly unto the cones. All modules are installed at 33º latitude tilt for Phoenix, AZ. The 48-cell and 60-cell modules with no reflectors, thus utilizing the natural ground reflection are serve as a benchmark to ensure comparative analysis of energy gains of the modules with back reflectors of different profiles. Seven different profiles shown in Figure 23 of reflectors were tested to determine the optimal construction for increasing the power output of the bifacial modules.

Figure 23; Profiles of reflectors utilized

Figure 24; Mounting Techniques for reflector profiles (a) front view (b) side view

3.1.8 I-V Curve measurements for Performance Monitoring and Evaluation

The multi- curve tracer was programmed to trace, monitor and log the performance of all the modules simultaneously every 15 minutes over a period of one week for a set of experiment in order not to have variations in the incidence angle. These recorded I-V curves would then be translated and relatively evaluated based on the measured readings from the 48-cell reference module. This approach helps to analyze the effect of the reflectors on module output energy variability on performance prediction.

3.1.9 Power and Energy Measurements

Similar to the procedure in the IV curve measurements, the multi- curve tracer was programmed to trace, monitor and log the performance of all the modules simultaneously over the period of 4months, thus from the October 3rd 2018 to February 17th 2019, in order to have enough data to make comparative analysis on the energy gain for each reflector profile.

3.1.10 Thermography under Steady State Conditions

Infrared (IR) imaging allows analysis of thermo-electrical failures in PV modules under working conditions to study the temperature variations induced by supplying external current or by incident light to the modules. The IR imaging was performed at both sides of the module at a view angle close to 90^o using uncooled-IR camera, shown in Figure 25, on a clear sunny day during the solar window. This process detects the module convective heat transfer defects and temperature gradients.

3.2 Analytical Modelling

This part of the research utilized analytical models, thus mathematical models with closed form solution to describe changes in the bifacial PV system as a mathematical analytic function to estimate and compare with experimental results. LCOE calculations primarily involves the initial capital invested in setting up a PV plant. Therefore, a couple of plant modelling software such as PVsyst and System Advisor Model (SAM) were used to estimate the effect of the use of back reflector on the cost components in terms of land size, material use, array row spacing etc. needed for such as system.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses obtained results from both experiments and analytical modelling from this work. It seeks to provide vivid evidence of the effect of stationary back reflectors of different profiles placed at varied distances.

4.1 I-V Measurements

4.1.1 Baseline I-V Measurements

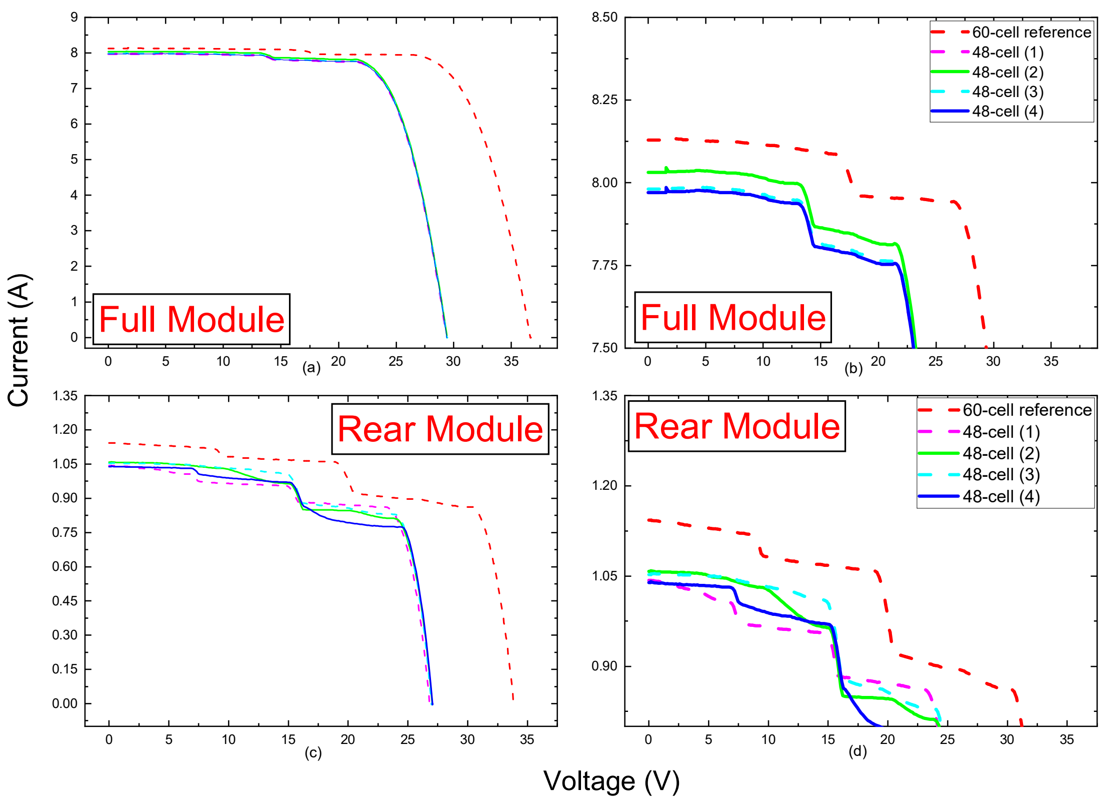

Figure 25: Baseline Measurements in (a) and (c) for full module, in (b) and (d) for rear side of module at solar noon on October 8, 2018.

The baseline IV performance was taken of a clear sunny day to establish the identicality of the 48-cell module and characterize their performance in relation to the 60-

cell module. It could be identified from the graphs in figure 25 that, the 60 -cell module provides additional energy as a result of extra cells there effectively utilizing the incident irradiation on both sides of the module. The 48-cells were found out to identical due to their operating the parameters. The open circuit voltage, V_{oc} of the modules were approximately equal. This corresponds with the name plate rating provided in table 2.

The difference in the short circuit current, I_{sc} is as a result of non-uniform incident irradiation on the rear side of the module and albedo. This is more evident in the I-V trace from the rear side of the module, as step-wise sharp decline can be seen in the traced curves. The is tracing techniques also established the low contribution of the rear cells to the performance of the bifacial module, indicating about 12.5% of total performance.

The performance of 48-cell modules used in this study are not perfectly identical due to the Rear side irradiance for bifacial modules changes based on the shading and ground surface behind modules. To account for any variation in power output in relation to these factors using the baseline I-V curves taken for each of the five modules without any reflectors for multiple sunny days. The power output of 48-cell benchmark module was used to determine correction coefficients which could be used to correct the power output of the other modules, ensuring normalization to the output as presented in the following equation:

$$\text{Correction Factor (C.F)} = \frac{P_{mp}\ \text{(48-cell module without reflector)}}{P_{mp}\ \text{(module x)}}$$

where C.F is the correction coefficient, and P_{mp} (module x) is the average power output of the other 48 and 60 cell modules (thus 1,3, 4, or 5). The correction coefficient was evaluated for each module for all readings throughout the solar window.

Table 5: Correction Factors applied

Module	Correction Factor
60-cell benchmark (module 1)	None
48-cell module with inverted U (module 3)	0.996
48-cell module with inverted V (module 4)	0.998
48-cell module with flat reflector (module 5)	0.998

4.1.2 I-V Measurements for reflector profile

In Figure 26, IV curve of the bifacial modules fitted with back reflectors at varied distances of 25cm incremental at solar noon. The overall performance of the bifacial modules with reflectors improved in comparison with the 48-cell bifacial module with no reflector. The I_{sc} value for these modules increased due the increased incident irradiation on the module. This increase in irradiance is attributed to the rear side of the module as the front side of all the modules only utilizes the incident beam insolation. This indicates the effectiveness of the back reflector in increasing reflected and incident light unto the back of the bifacial modules.

However, one key observation found in this trace was the approximately no change in V_{oc} of the module. The modules irrespective of its fitting with a reflector at different displacement from the module or not, did not show a change in its V_{oc} as increase in irradiance does not affect the open circuit voltage of the bifacial module. This phenomenon is seen in figures 26, 27 and 28.

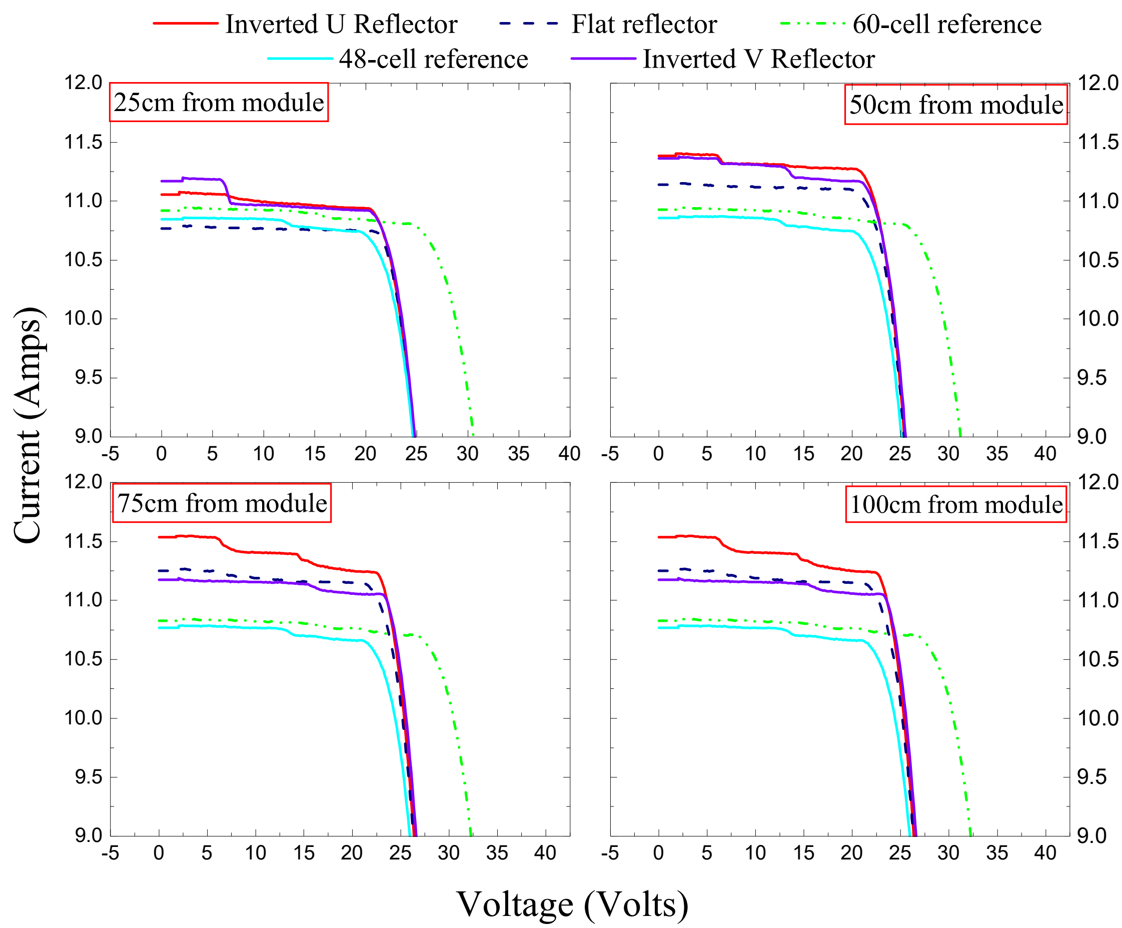

Figure 26: I-V Measurements for 3cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

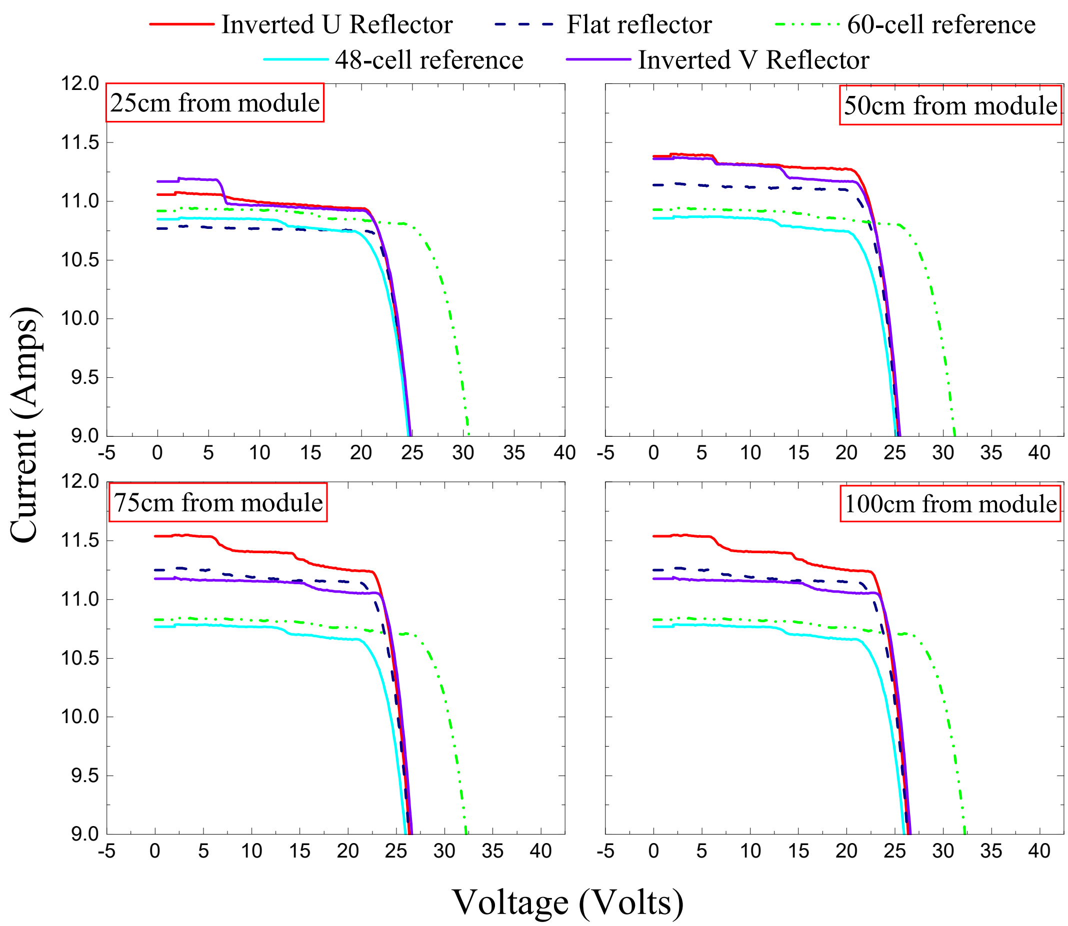

Figure 27: I-V Measurements for 6cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

The performance of the modules increased with increased displacement between the module and the reflector for all reflector profiles. The reflectors placed at 100cm from the module show a higher increase in the output current of the module as compared to the modules with reflectors placed at closer distances, thus 75cm, 50cm and 25cm. Hence a direct proportional relationship can be drawn between the I_{sc} of the module and the displacement of the back reflector, but this relationship is not true for all displacements above 120cm for all reflectors as a decline in performance can be seen in reflectors with higher cone height. Figure 29 illustrates the effect of the displacement between the module and the reflector.

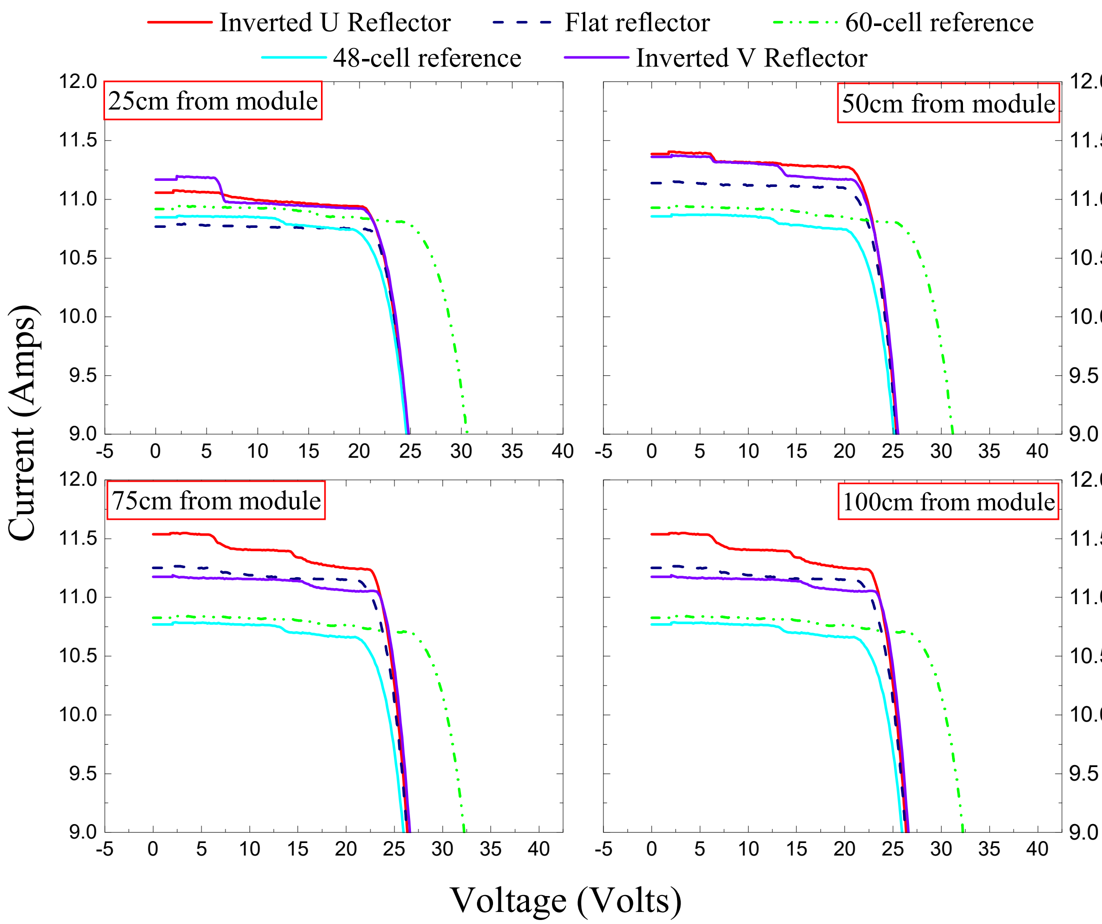

Figure 28: I-V Measurements for 3cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

The steps in the curves indicates the spread of reflected lights on the rear cells of the bifacial module. In figure 26, the inverted U reflector exhibits 3 distinct steps in its IV curve. This indicates a three different levels of irradiation incident on the three stings of cells in the module. This ensures the gradual slope seen the curve which translates to a better output performance. The inverted V reflector, however, concentrates most of the light unto one string of cells, therefore rendering the other strings less efficient. The 48-cell and 60-cell reference modules exhibit a clear evidence of two levels of illumination on the back side of the module. Hence, the step in the curve occurs mid-way in the modules V_{oc}. This behavior of the modules with or without reflectors is also evident in figure 27 and 28.

In figure 29, the inverted U reflector of height 3cm produces more additional power as it provides high gain in the short circuit current of the bifacial module. This is as a result of its high uniformity in reflected light incident on the rear cells of the modules and the effective distribution of reflected light on the rear side of the module.

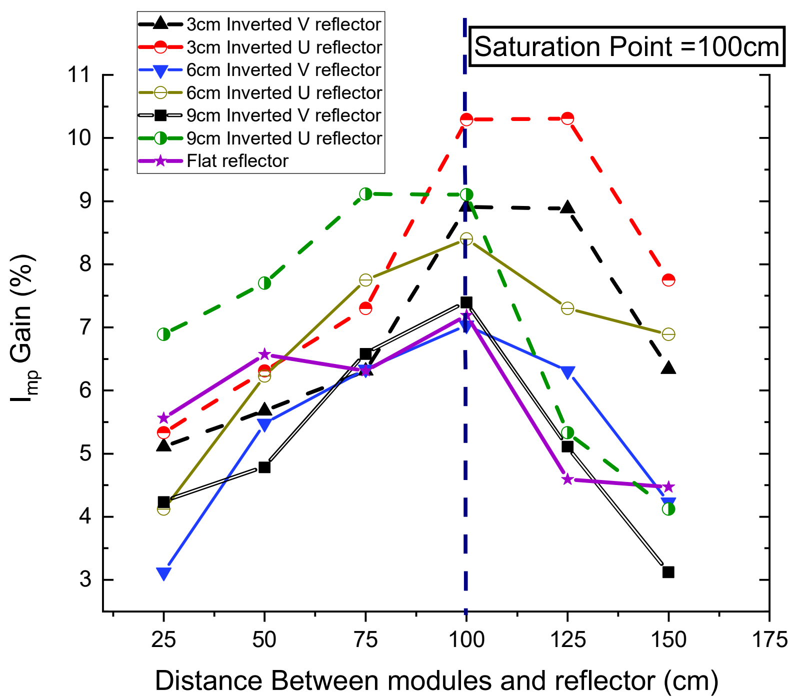

Figure 29: Distance optimization: I_{sc} gain (%) around solar noon (11:30am-1:30pm from October 21st to November 1st, 2018) for various reflector profiles.

4.2 Irradiance and Temperature Measurements

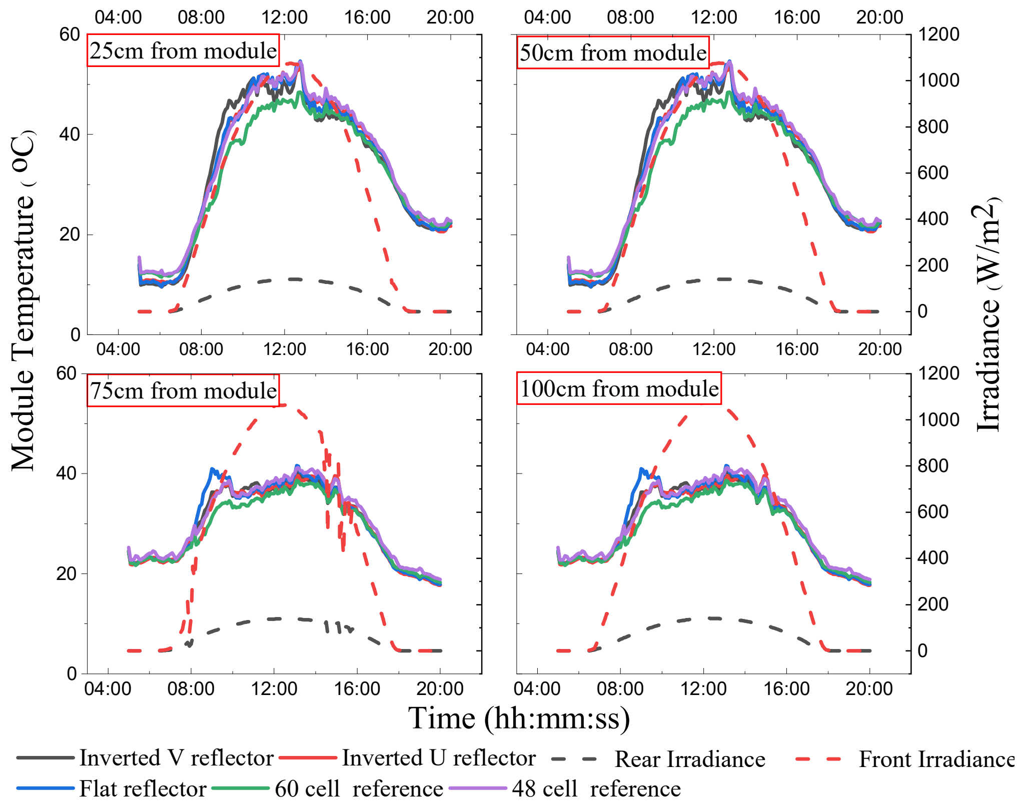

Figure 30: Irradiance and Temperature Measurements for 3cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

High nominal module operating temperature (NMOT) caused as a result of excessive heat can significantly reduce the output of a PV system resulting in unexpected energy loss in an array. Solar panel efficiency is affected negatively as its temperature rises. Name plate readings of the modules indicated rated performance values at a temperature of 25 degrees C (STC), and heat can reduce output efficiency by 10-25% depending on their installed location. A closer look was taken at the effect of the reflectors on the NMOT of the modules. The voltage output is reduced linearly as the temperature of the solar panel increases but its output current increases exponentially.

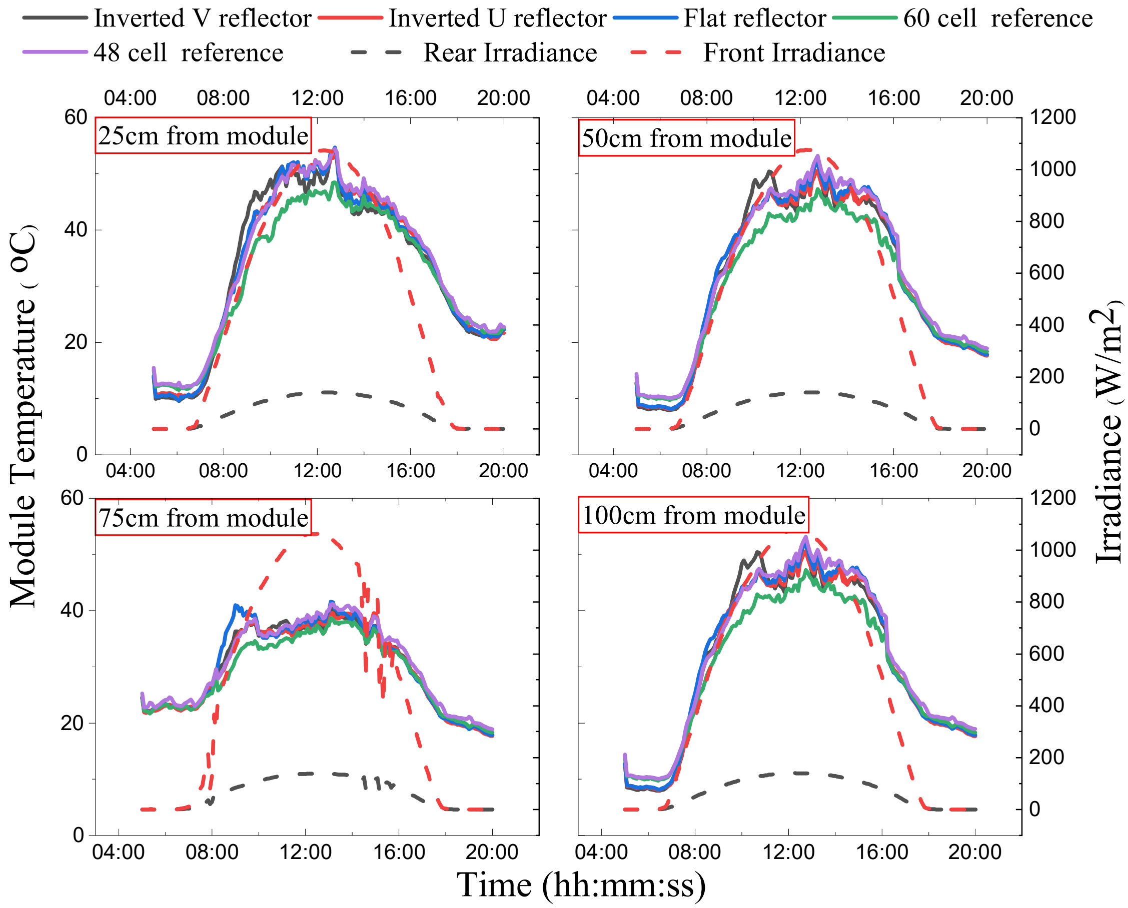

Figure 31: Irradiance and Temperature Measurements for 6cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

The temperature of the modules obtained over a period indicated both 60-cell reference and 48-cell reference modules exhibited the lowest profile throughout the experiment, indicating a rise in the NMOT of the modules with reflectors for all configurations shown in figures 30, 31 and 32. The inverted U reflector contributed largely to the rise in temperature of the module as it concentrated more reflected light on the module to increased its I_{sc}. However, the rise in temperature did not affect the V_{oc} of the modules as they recorded relative similar values as the reference module.

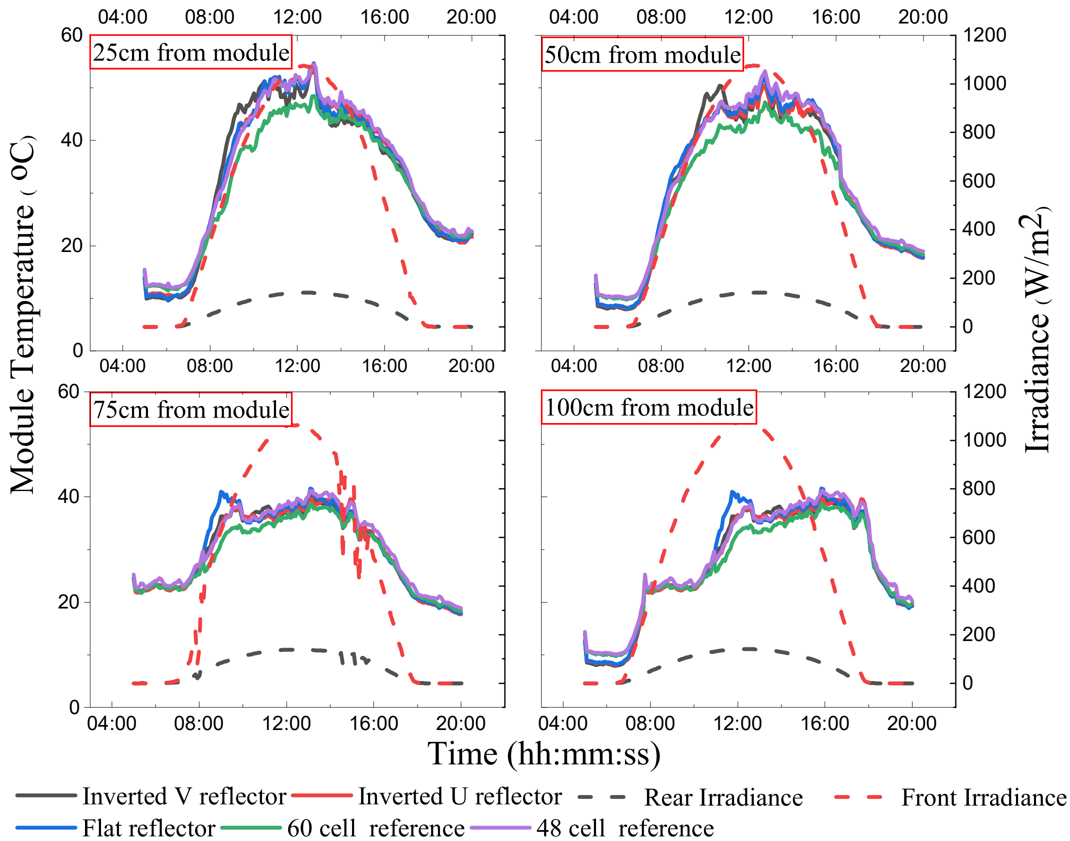

Figure 32: Irradiance and Temperature Measurements for 9cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module.

It could also be seen that the temperature profiles reduced as the displacement between the modules in increased. Least readings when recorded for the highest displacement for all profile configuration as shown in figures 30, 31 and 32. The modules with the reflectors have higher temperatures in the morning since the sun rises from the east and thus these modules are due in the same direction. Irradiance readings taken from the both front and rear side of the array on the POA indicated an approximate 20% of reflected light from the ground. Thus, only 20 percent of the front irradiance was incident on the rear side of the module.

4.3 Output Power Gain

From figures 33, 34 and 35, most of the energy production is evident during the solar window, the rear side of the module experiences about 16-20% of the irradiance on the front side for this setup. This incident irradiance is due to ground reflected light. Design optimization increased the irradiance largely around solar noon. This potentially had the greatest impact on the total energy production of the module.

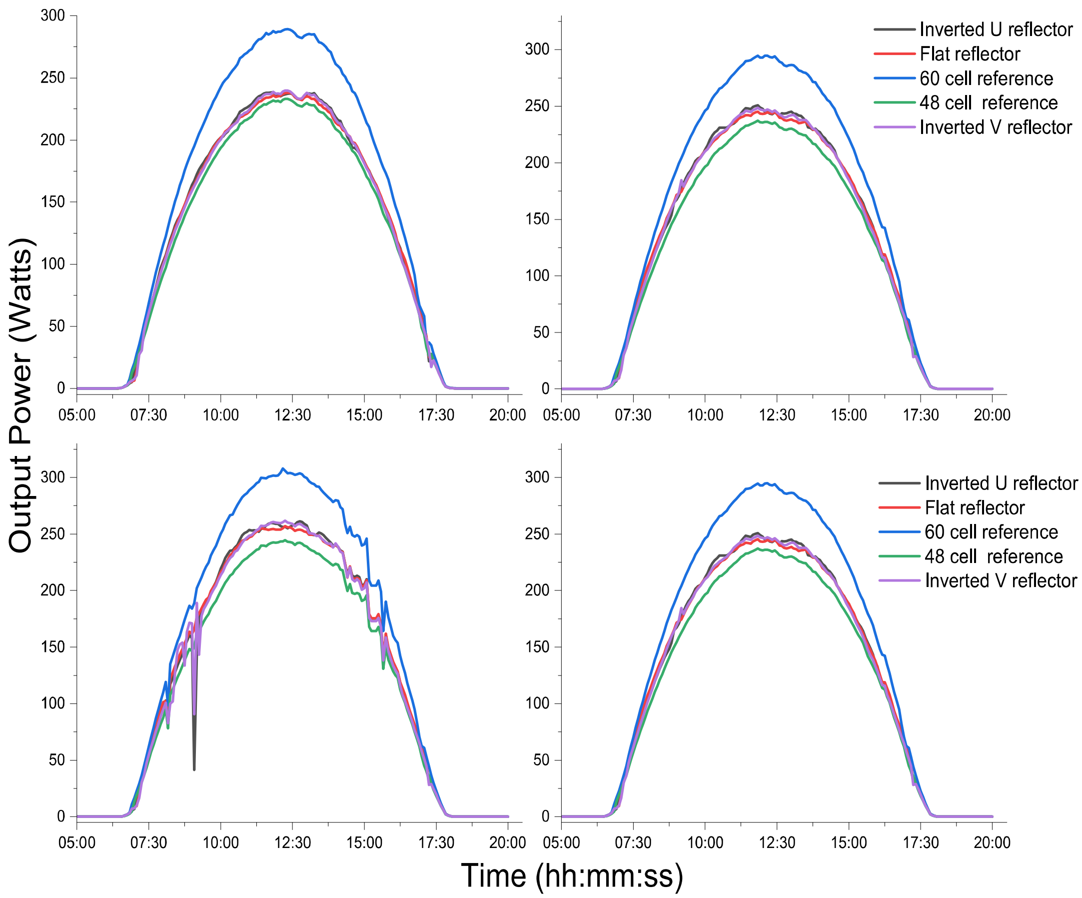

Figure 33: Output Power Gain for 3cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module

The performance of all five modules was measured on a clear sunny day with diffuse coated reflectors of three profiles; inverted U, inverted-V and flat construction geometry, respectively behind Module 3, Module 4, and Module 5. In general, the 60-cell reference module performed relatively higher that the 48-cell modules in all instances as indicated in figures 33, 34 and 35. This as a result of higher number of cells.

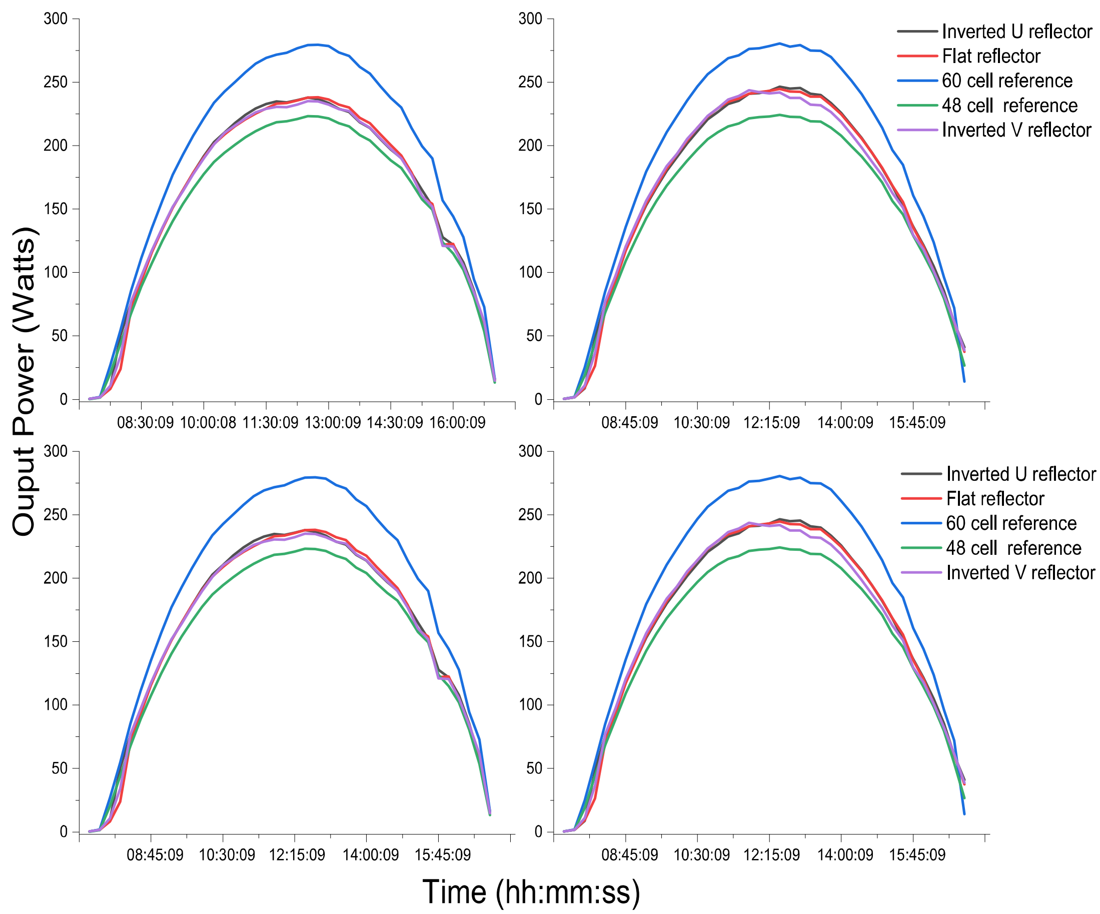

Figure 34: Output Power Gain for 6cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module

Power variation between modules with reflectors with respect to 48-cell reference module varied differently throughout the day, with a closer power output performance during the morning and the evening, for each module. Greater variation was experienced during the solar window from 10am to 2pm, when the highest solar irradiance and the incident angle is minimized. Highest performance of the reflectors occurred at solar noon. The displacement of the reflectors also played a key role as the power output increased with increased distance between the module and the reflector for all profile configuration of the reflectors.

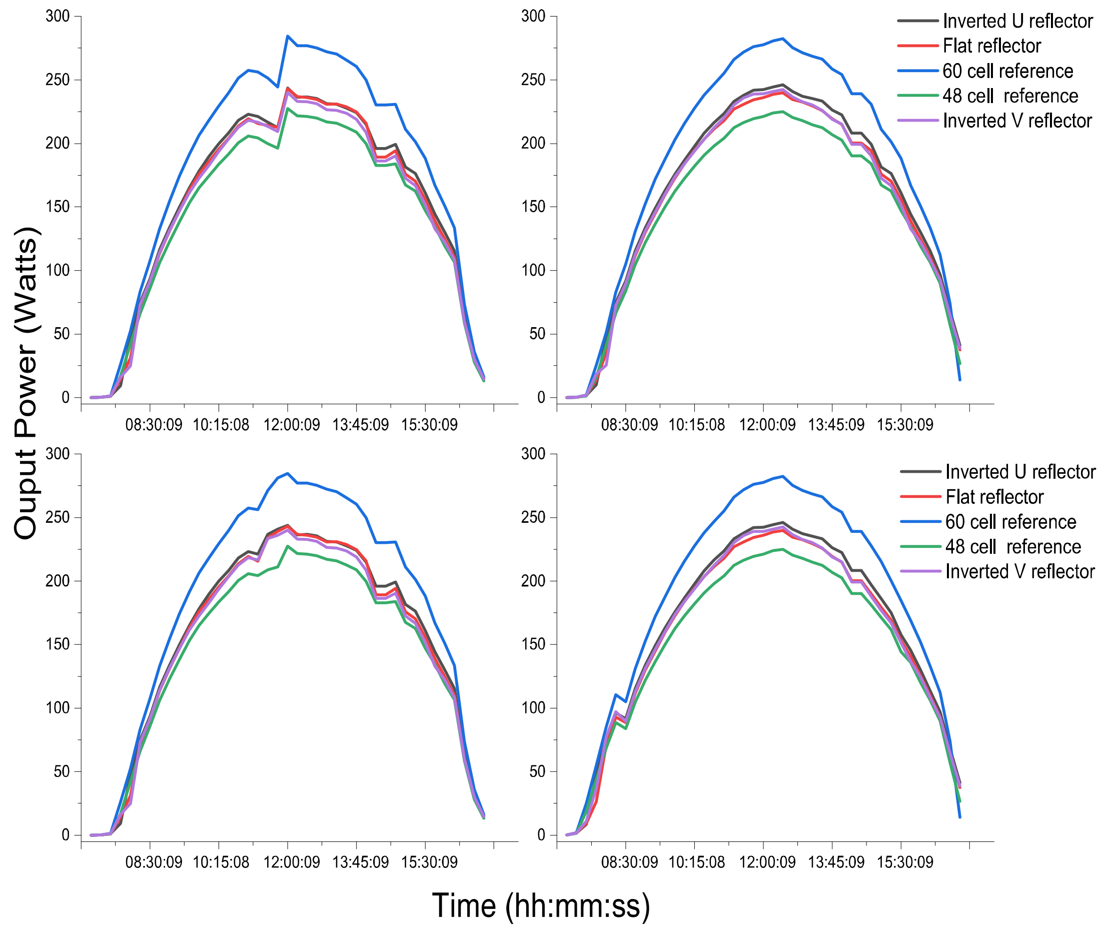

Figure 35: Output Power Gain for 9cm reflector profile at (a)25cm, (b)50cm, (c) 75cm and (d) 100cm from the module

4.4 Energy Gain Analysis

The boost in performance with a reflector in producing additional energy is highly significant as it could offer opportunities in improving the LCOE for bifacial PV systems leading to a rise in the current usage of the bifacial technology. A better understating of how the energy generation is affected by the introduction of each reflector is the estimation of the total energy production boost of the 60-cell reference module and 48-cell modules with reflectors as a function of gain with respect to the 48-cell reference module.

The percentage energy gain is mathematically defined by the following equations;

Energy Gain =

$$\left[\frac{(48\text{−cell module with reflector} - 48\text{−cell reflector without reflector})}{48-cell\ module\ without\ reflector}\right] \text{x}\ 100\% \quad \text{------(4)}$$

OR

Energy Gain =

$$\left[\frac{(60\text{−cell module without reflector} - 48\text{−cell reflector without reflector})}{48-cell\ module\ without\ reflector}\right] \text{x}\ 100\% \quad \text{---(5)}$$

Averaging the area under the curve of the power graphs over the solar window resulted in gains for modules with reflectors. The energy gain is the percent gain of energy obtained from the quotient of the difference in energy output between either 48-cell with reflector or the 60- cell without reflector over the 48-cell reference module without a reflector.

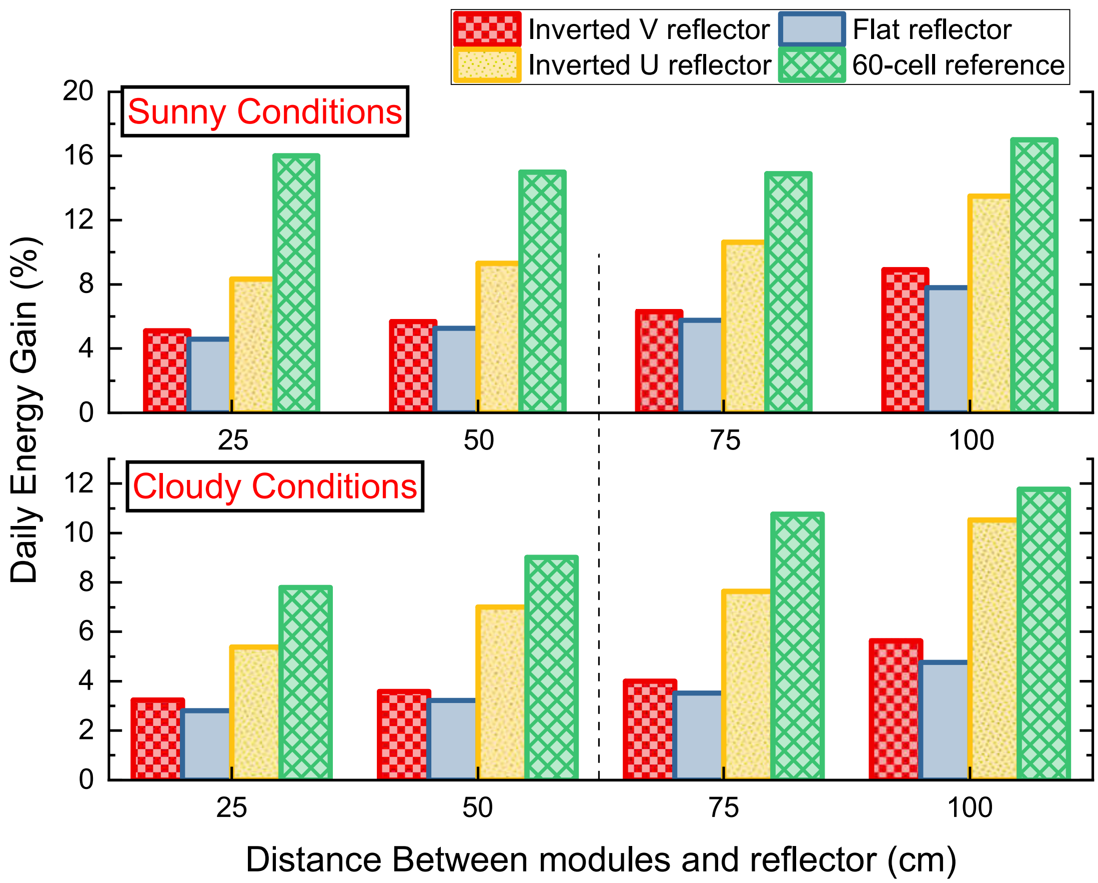

Figure 36: Energy gain for 3cm reflector profile at various distances.

In figure 36, the inverted U reflector performed more than half of the additional energy produced by the 60-cell module. This is as a result of increased incident irradiance on the rear side of the module, uniformity of reflected light, reflectivity of reflector materials and dispersion of reflected light over large cell areas. As shown figures 36 and 37, the inverted U reflector has the higher energy gain compared to the flat and inverted V reflector for both the 3cm and 9cm profile reflectors. This is due to reduced incident angle on the reflectors. Significant gain could be seen when the reflector is placed at a higher distance from the module.

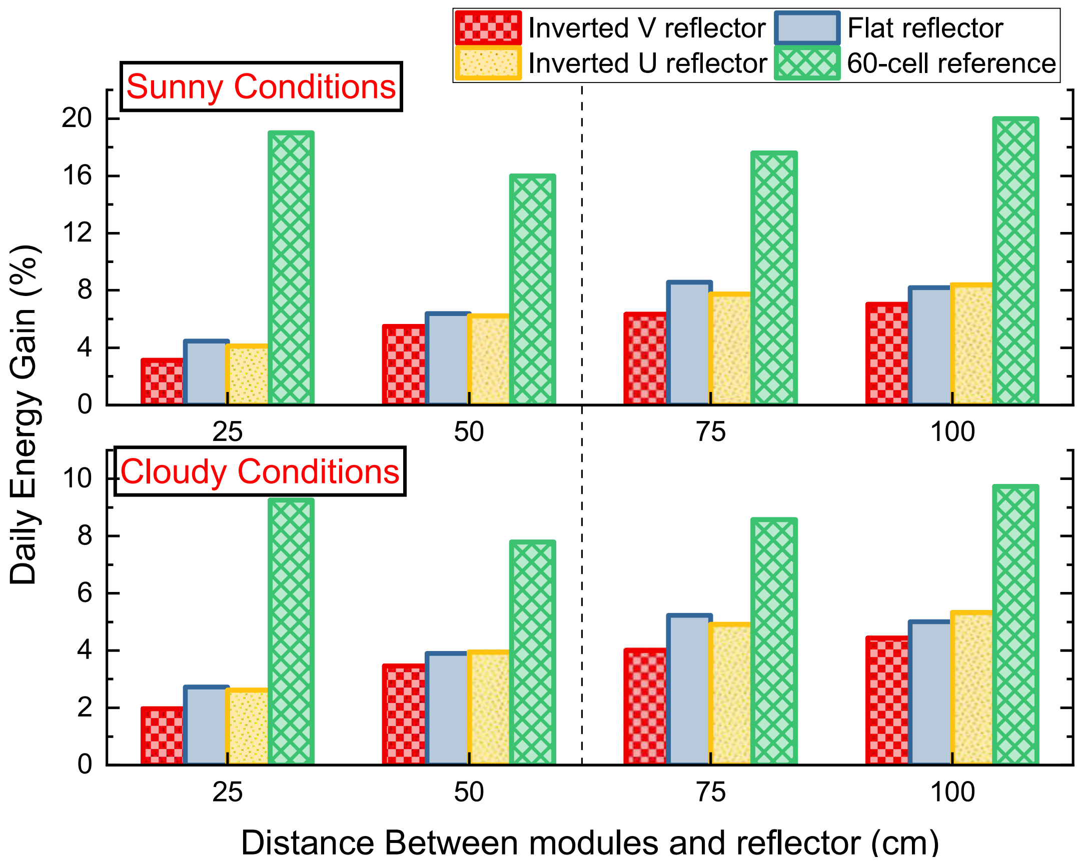

Figure 37: Energy gain for 6cm reflector profile at various distances.

Both the inverted U and V profiles performed poorly for the 6cm cone height. The flat reflector however, in this instance had the higher additional energy as compared to the later and a nearly half gain in additional energy produced by 60-cell reference module. Paramount amongst the reasons for this occurrence, is the high incidence angle on the reflector surfaces leading to an increase in the non-uniformity of reflected incident on the rear side of the bifacial module. It is clear from the figure above that, as the distance between the modules and the reflectors increased, the inverted U and V reflector showed significant gains. The inverted V reflector has potential for greater additional energy for the 9cm reflector profile at farther distances from the module and hence should be investigated using different mounting techniques.

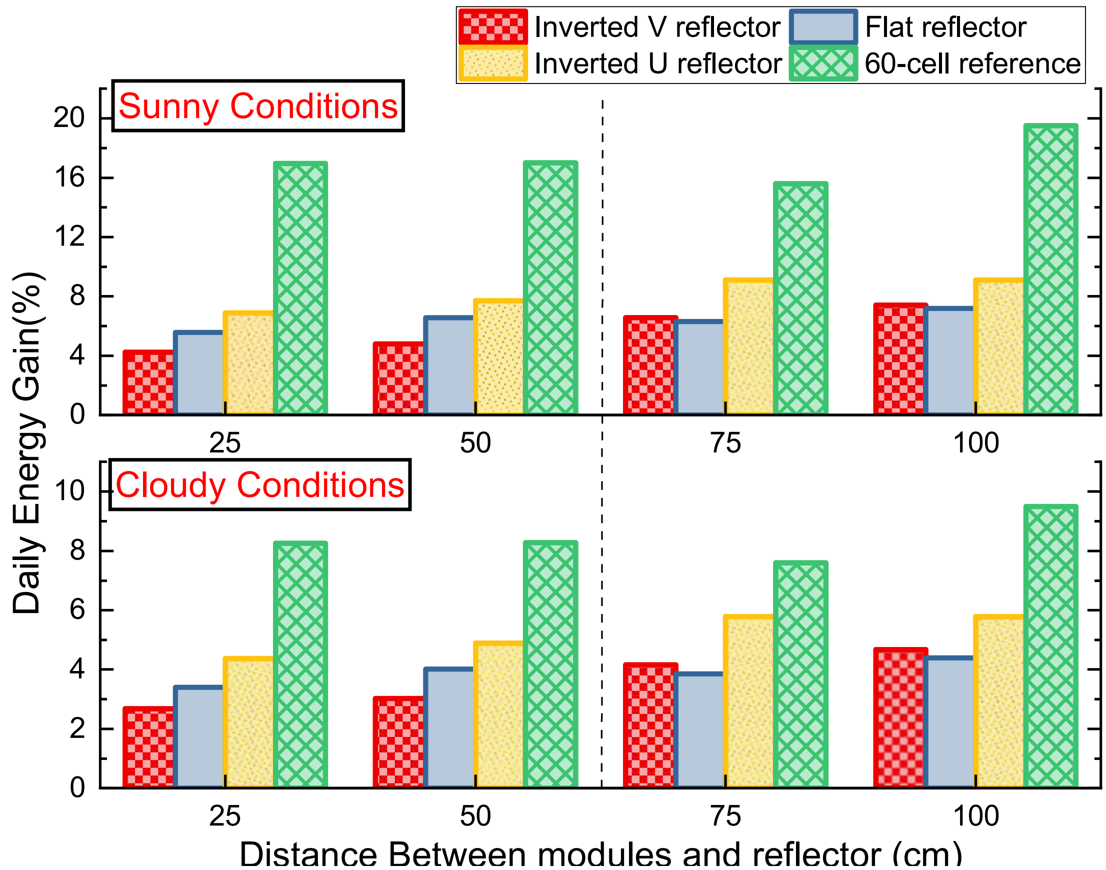

Figure 38: Energy gain for 9cm reflector profile at various distances.

4.4 Plant Modelling

One key component of initial cost and investments made into PV installations is as a result of land siting and sizing. With the use of back reflectors for bifacial PV modules, the constraints imposed by ground height clearance will be resolved. Bifacial modules are mounted at height to ensure effective collection of ground reflected light. Utilizing models from System Advisor Model (SAM), MATLAB and PVsyst, the effect of ground height clearance on the annual energy output, ground cover ratio and optimal row to row spacing.

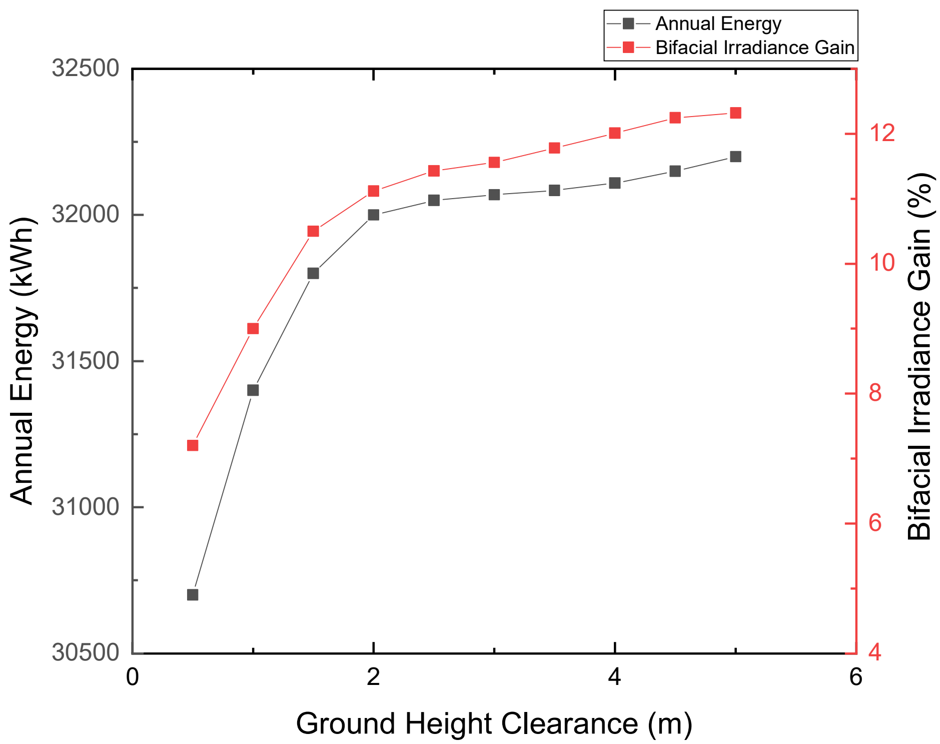

Figure 39: Effect of Ground Height Clearance on Performance of Bifacial Modules (Based on calculation done by ASU-PRL using SAM software of NREL).

As indicated in figure 39, increasing ground height clearance increases the annual energy output and the bifacial irradiance gain as more light is incident on the rear cells of the module. The ground height clearance also plays a role in the row to row spacing for bifacial modules. Hence, its effects on bifacial modules with or without reflectors was duly investigated with models found in figures 40 and 41 with the program code found in appendix 1.

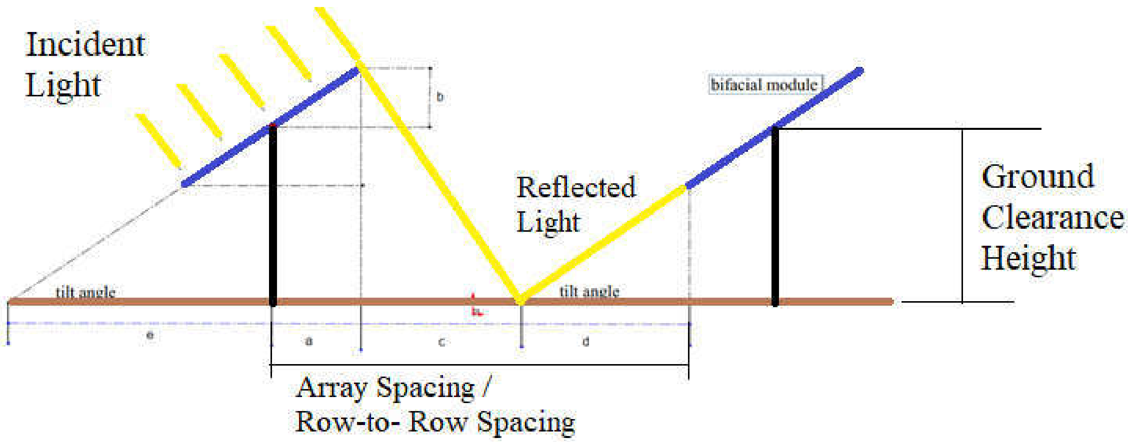

Figure 40: Row to row spacing configuration for bifacial modules without reflectors.

(Source: PVsyst)

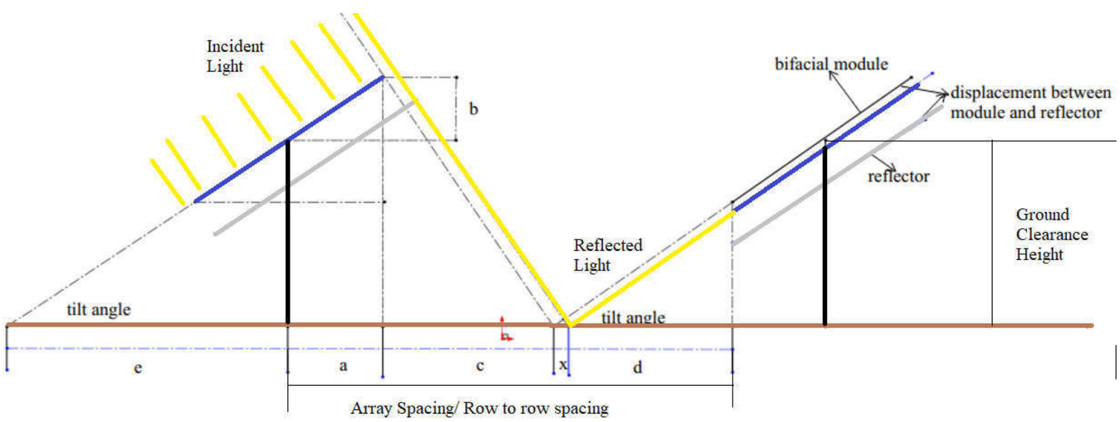

Figure 41: Row to row spacing configuration for bifacial modules with reflectors

(Source: PVsyst)

Although the bifacial irradiance gains increased with an increase in the ground clearance height, more land size will be needed to put up a design bifacial system since the row to row spacing increases with increasing ground height clearance as shown in figure 42. This largely affects the initial invested capital and the levelized cost of electricity.

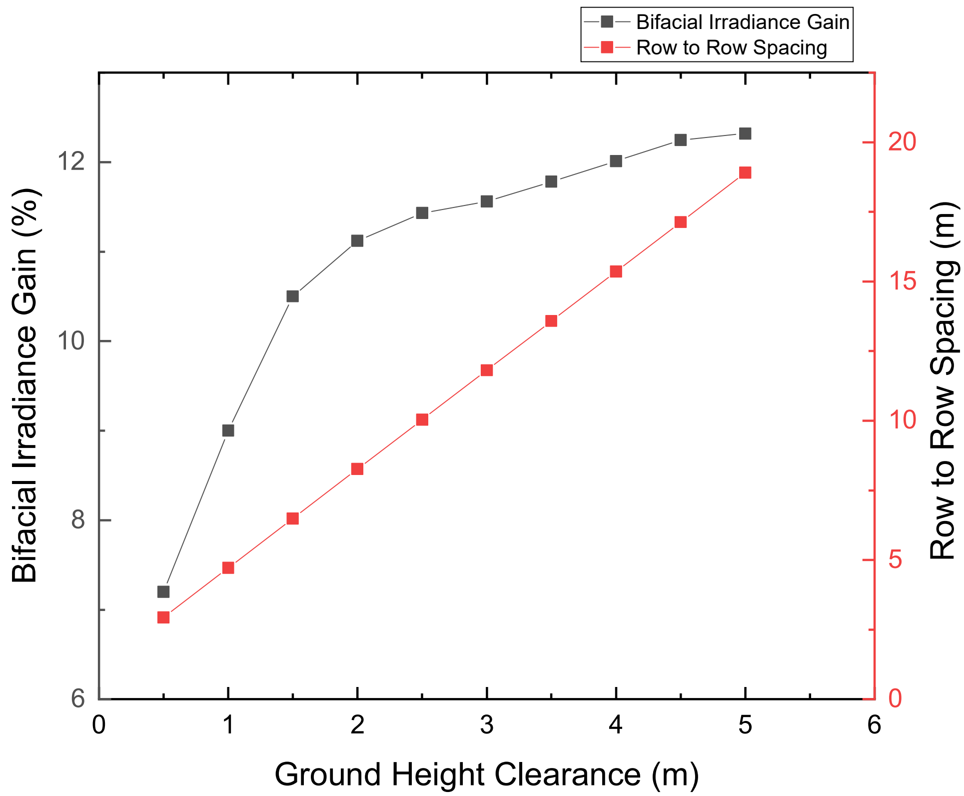

Figure 42: Row spacing for bifacial modules without reflectors (Based on calculation done by ASU-PRL using MATLAB developed code).

The increase in the row spacing is due to the self-shading cast on other arrays. However, the use of the back reflectors largely reduces the both ground height clearance and the row to row spacing shown in figure 43. The minimum ground height clearance is calculated for each displacement configuration of reflectors from the module. The maximum height clearance of 1.62m above ground occurs when the back reflector is placed 1m away from the module. In figure 43, the row spacing of bifacial modules increases with increasing reflector displacement. The figure also shows that the row to row spacing for installations with reflectors is far less than that of the reflector's installation of bifacial module. This indicates the potential for effective land utilization and reduction of material cost by half for the bifacial systems with reflectors.

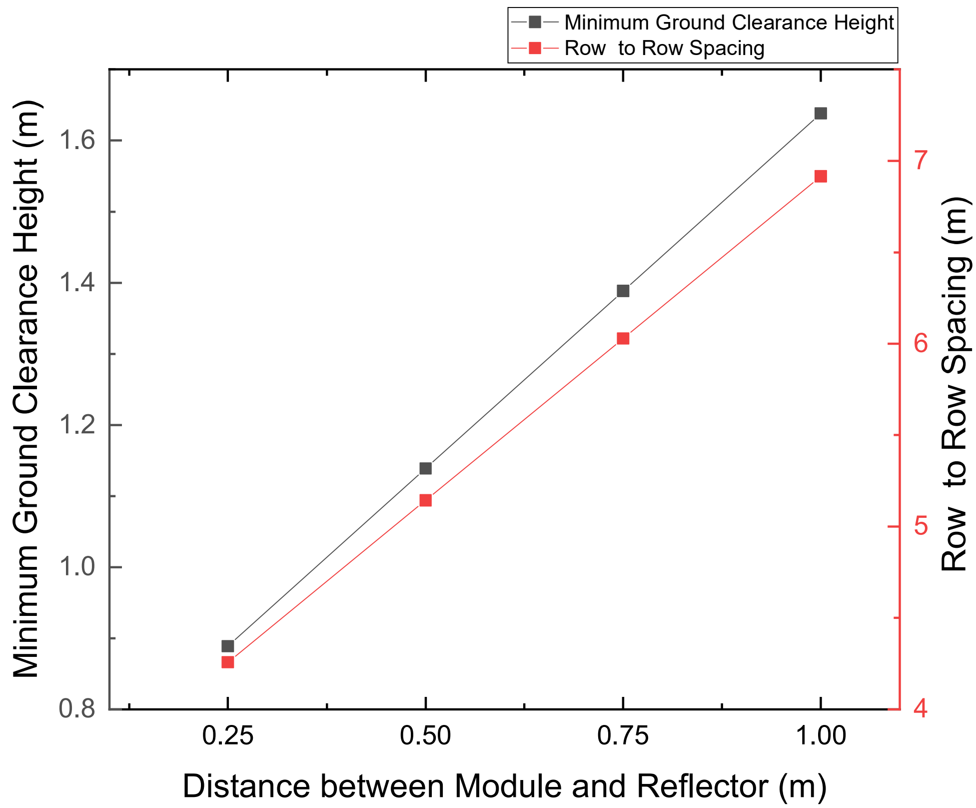

Figure 43: Row spacing for bifacial modules with reflectors (Based on calculation done by ASU-PRL using MATLAB developed code).

CHAPTER 5

CONCLUSION AND RECOMMENDTION

5.1 Overview of the chapter

This study aimed at studying the performance of bifacial photovoltaic modules and its dependence on various profiles of stationary reflectors and determine the optimum reflector placement distance from the back of the modules leading to its effect of reflectors on array row spacing for bifacial installation configuration as indicated in Chapter One. The findings have indicated that there are different of performance response of applying this approach on bifacial modules in this study. The findings have suggested the importance of back reflectors in improving the LCOE of PV systems by reducing initial invested capital. This chapter provides conclusions and recommendations on the usage of back reflectors on bifacial modules based on findings, sets out significant findings in relation to the research objectives, and describes suggestions and implications for future research.

5.2 Conclusion from the study

As Bifacial PV systems make a strong comeback into the mainstream solar industry from being a novelty for a long time, this technology has shown its capacity to produce additional energy than the traditional photovoltaic modules. The ability of the bifacial modules to utilize not only incident beam insolation but the diffuse and reflected light components, gives it a competitive advantage over not only the monofacial technology but other renewable energy sources. This means that additional energy will be produced with relatively same initial capital as installations factors such as land size and material cost for array construction do not largely change. The expansion of the bifacial PV market requires the understanding and identification of factors that influence the optimal installation and operating conditions at a specific location.

The bifacial technology does not only represent a paradigm change in the efficiency and output energy generation of solar PV systems but the levelized cost of electricity (LCOE) of solar installations. Hence, the addition of back reflectors clearly has the potential to increase the power output of bifacial PV systems. It is noted from this research that loosely packed 48-cell bifacial modules fitted with stationary back reflectors has shown significant calculated power generation boosts of 11-14% over a 48-cell reference module with ground reflection. Several factors such as the irradiance, the short circuit current (I_{sc}) and the nominal module operating temperature (NMOT). The use of the back reflectors increases the incident irradiance on the rear side of the module leading to a rise in the I_{sc} of the module. This significant boost leads to a rise in output power as the voltage of the systems primarily sees no change causing an increase in the product of the current and voltage of the bifacial systems. The boost in I_{sc} also increases with increased displacement of the reflector due to increased incident irradiance on the rear side of the module, uniformity of reflected light, and dispersion of reflected light over large cell areas. Temperature rise in modules caused lost in energy output as the open circuit voltage, V_{oc} reduces. The use of the back reflectors on the bifacial PV modules did not significantly increase the overall NMOT of the module as the average rise in temperature is calculated to be about 0.5 – 1.5^{o}C more that the NMOT of the 48-cell reference module. The temperature change reduced with increased distance between the module and the back reflectors.

The reflectors recorded a higher boost during the solar window as the profiles are optimized to increase its performance. The most suitable reflector profile is the inverted U reflector. This reflector type produces higher energy gain when placed at farther distances from the module. It performed the best out of all current construction geometries with reflective coatings, generating more than half of the additional energy produced by a densely-spaced 60-cell benchmark module compared to a sparsely-spaced 48-cell benchmark module.

Table 6; Summarized Findings

	60-cell bifacial	48-cell bifacial with Inverted U Reflector placed 100cm from the module	Takeaway
Energy Gain (%)	19	13.67	Generation of half of additional energy with 50% less additional cells
Cell Temperature Gradient (ºC)	0.5	.45	No significant rise in NMOT
Ground Clearance Height (m)	3	1.67	Reduction of column height by nearly half leading to material cost savings
Land Size (Row to Row spacing) m	11.85	7	40% reduction in land size required.

Land size utilization is key to achieving the LCOE of PV systems that helps achieves grid parity for bifacial installations. Material costs and initial capital is reduced with the use of back reflectors as the ground height clearance and the row to row spacing is reduced by nearly of the installation of bifacial modules without reflectors. It becomes clear that the use of the stationary back reflectors not only improve the output energy and efficiency of bifacial module but also the potential to reduce the LCOE of bifacial systems through cost reduction in material and effective land usage.

In conclusion, not only does an inverted U reflector increase energy output of the bifacial reflector, the material and land costs involved in setting up bifacial systems are largely reduced as shown in table 5. This is an indicator of the potential of bifacial PV modules to improve the LCOE of the solar technology and increase its use.

5.3 Recommendation

The flat reflector could be of choice when shorter distances between modules are considered due factors such as inadequate land size and possibly shading by other modules. The inverted V reflector could provide greater boost with different mounting techniques. This research has revealed some perspectives on the potential of back reflectors on bifacial modules. It however prudent to investigate the possibility of optimizing the flat and inverted reflector using different profile heights and minimized cone spacing. Due to the scope of the issue and the limitations of the study, the results are not able to represent the effects of a tracking condition for designed for the back reflectors on the energy gain and albedo of the bifacial module. This study only looks at fixed latitude tilt configurations. However, further studies could focus more on the analysis of this issue, perhaps using a combination of quantitative and qualitative modelling research approaches.

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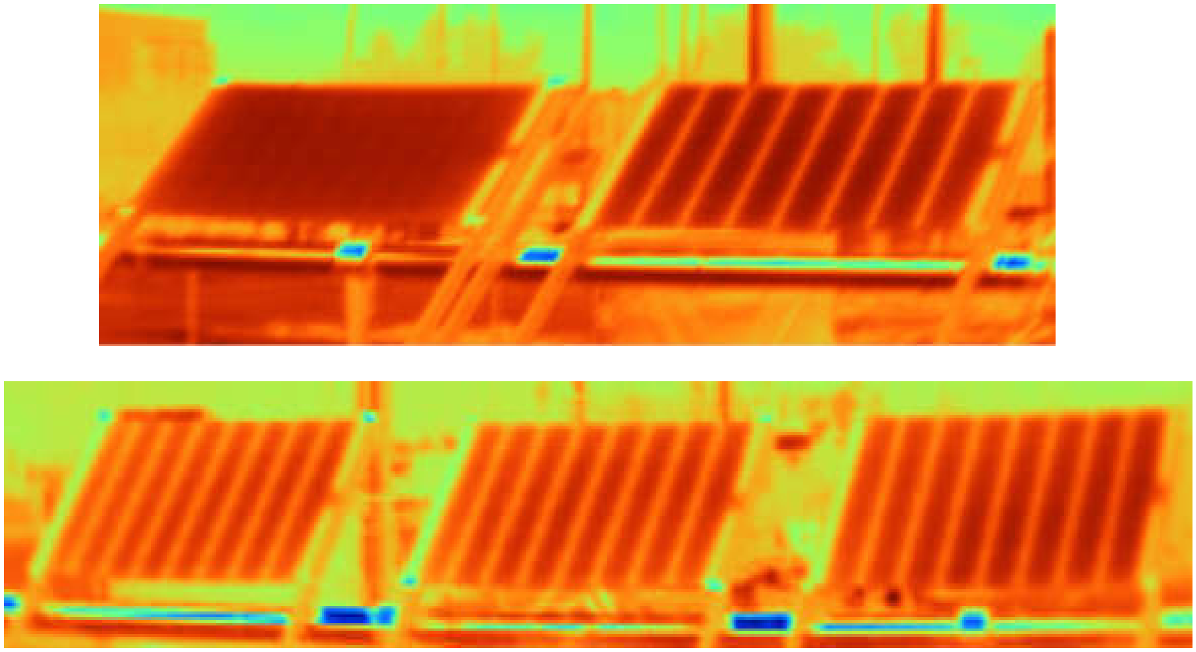
APPENDIX

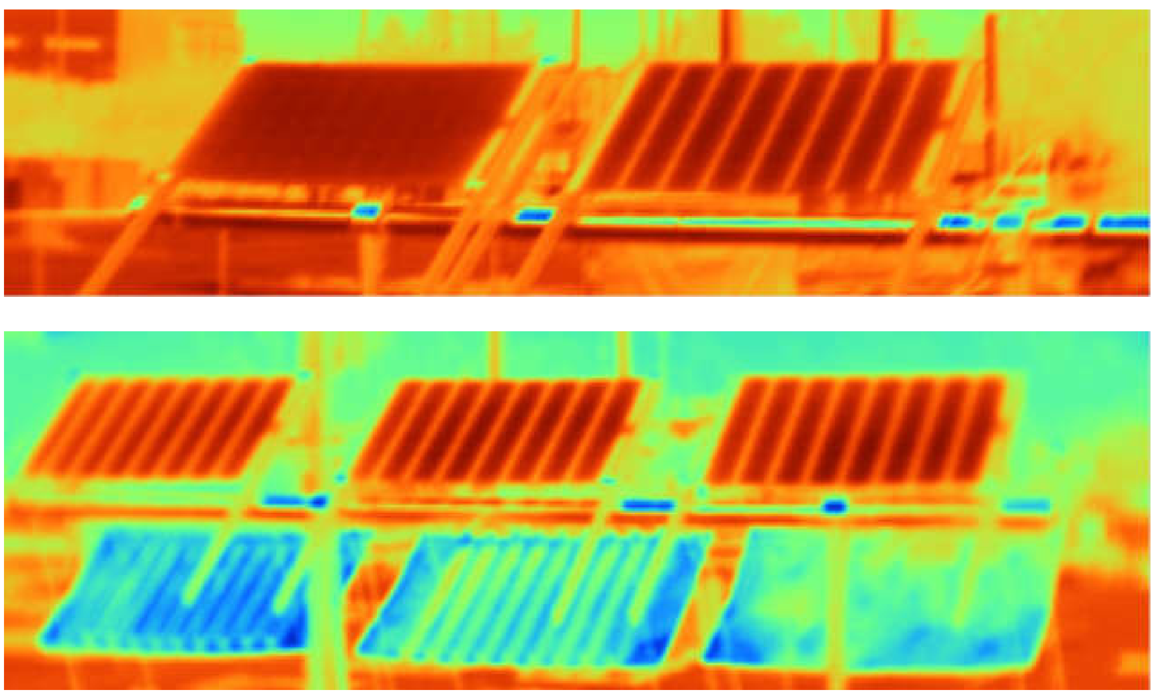
Appendix A: Row to row spacing MATLAB code

```
l=1.28; %l is module width in meters
t=33.5; %t is tilt angle (latitude) for location, i.e. Mesa, AZ in degrees
h=(0.5:0.5:6); % ground clearance height in meters for mounting bifacial without
reflector
x=[.25; .50; .75; 1]; %displacement of reflector from module
B= 90-t; %traditional bifacial installation configuration without reflectors
a=0.5*l*sin(B);
b=0.5*l*cos(B);
c=(b+h)*tan(t);
e=h*tan(t);
d=e-a;

rtr= abs(e+a+c) %row to row spacing for mounting bifacial without reflector

%proposed bifacial installation configuration with reflectors
y=x*cos(B);
hm=b+y    % hm is the minimum ground height clearance for bifacial module with
reflector
a1=0.5*(l+.05*l)*sin(B);
b1=0.5*(l+.05*l)*cos(B);
c1=(b+hm)*tan(t);
e1=hm*tan(t);
d1=e1-a1;

rtr1= abs(e1+a1+c1+(.05*l)) %row to row spacing for mounting bifacial with reflector
```

Appendix B: Thermography of modules



IR graphs for baseline measurements



IR graphs for modules with reflectors