Performance Analysis of Bifacial PV Module Based Multilevel Solar Panel System for Urban Areas

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A thesis submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Bachelor of Science in Electrical & Electronic Engineering

Department of Electrical and Electronic Engineering
Brac University
December 2019

Declaration

It is hereby declared that

1. The thesis submitted by our own original work while completing degree at Brac University.

2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.

3. The thesis does not contain material which has been accepted, or submitted for any other degree or diploma at a university or other institution.

4. We have acknowledged all main sources of help.

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Ethics

Abstract

The objective of this work is to carry out a performance analysis of bifacial module based multilevel solar panel systems. The proposed system will occupy less space and harness more solar energy than the existing mono-facial based multilevel system for its use in urban areas. As bifacial module harnesses energy from the both side of the module, this needs special consideration to calculate the irradiation on back surface of the module. Different parameter i.e. view factor, albedo factor and additional energy yield for ground clearance are taken into consideration throughout the study. Results show that, proposed system gives significantly more power than the existing system which is 55.63%. Also seasonal cloud impact is considered in this study. Cloudy days impact the system electrical output 31.24% than the no cloud condition. Besides albedo dependency on the output of the system is observed.

Keywords: bifacial, albedo, view factor, multilevel, cloud effect.

Dedication

To our parents because without their support it would not be possible for us to complete our

graduation.

Acknowledgement

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List of Acronyms

RTC   Real Time Clock

PV   Photovoltaic

GHI   Global Horizontal Irradiance

DNI   Direct Normal Irradiance

DHI   Diffused Horizontal Irradiance

SS   Stainless Steel

PERC   Passivated Emitter & Rear Cell

Chapter 1

Introduction

1.1 Introduction

Interest in clean and renewable energy sources is growing day by day. As more people recognize that fossil fuels like coal, oil, and natural gas are limited resources and that burning fossil fuels releases large amounts of carbon dioxide into the Earth's atmosphere. Among the many renewable energy alternatives, solar energy remains one of the most well-known and adaptable methods for producing electricity. For smaller, residential scale applications, solar energy is converted directly to electricity through photovoltaic (PV) solar panels. For larger, utility-scale applications, solar energy can feed vast PV solar panel farms. Increasing energy reliability, promoting economic growth, and reducing carbon emissions are the desired benefits that stem from the development of cost-competitive solar energy systems [1]. Also it is necessary to harness more energy from the systems.

In recent years, the bifacial solar module has gained much attention [2]. Modelling the field performance of bifacial modules presents a number of difficulties that are not present for mono-facial modules. The bifacial system modelling is significantly more complex than the mono-facial system modelling due to the need to estimate the rear illumination of the module, which depends on the percentage of diffused radiation, the sun elevation, the background reflectance, the height of the module above the ground and the module tilt angle. In addition, the field performance of bifacial modules is highly dependent on the location and system design. In this study bifacial based multilevel solar panel system has been proposed. The performance analysis

has been carried out considering environmental effects i.e. different height of modules, module tilt angle, ground albedos, diffuse radiation components, cloud effects and solar positions.

1.2 Background

The multilevel solar panel system is first ever proposed by Rahman *et al.* for its use in urban residential solar home systems in 2013 [3]. The system consists of three panels mounted in a rack one above another at a fixed distance from each other to minimize the floor area. Initial calculation shows that proposed system can harness above 18% more energy than the three conventional fixed panel systems with 33% less area. This study claimed that this proposed system will be useful for large urban city dwellers, especially in third world countries. Where not only electricity is in shortage but also availability of roof space to install solar panels is very limited. Later a detailed performance analysis of a three level solar panel systems is carried out by calculating the solar energy collected by the proposed system during different seasons and comparing it to that of fixed panel system of the same size [4]. An automated microcontroller controlled solar tracker is also developed to track the sun. Microcontroller calculates the sunrise and sunset times on each day using a set of equations and send signal to the controlling motors to rotate the panels at a predetermined time intervals by a fixed angle to track the sun. After that a prototype multilevel solar panel system with an automated solar tracker has been developed [5]. This implemented experimental design showed that the developed system can harness about 23% more energy. The proposed system is easy to construct and implement, takes less floor place and will be effective for urban areas. In 2017, Rahman *et al.* implemented an RTC (Real Time Clock) based multilevel solar panel system [6]. Here, the microcontroller reads the real time and dates from the real time digital clock and calculate the sunrise and sunset times for a given day. In the developed prototype, an RTC based microcontroller controlled the control circuit which

runs servo motors to rotate the solar panels at some precisely calculated time intervals to track the sun. As a result of vertical stacking of the panels, the proposed system with three can be operated within the space of two panels and can harness more energy than the conventional single level fixed panel system. This study ended up with an idea to use specially designed reflectors for the proposed system so that the amount of energy harnessed can be further increased. So there is scope of additional work for this multilevel solar panel system. Here in this study bifacial based module is replaced with the conventional mono-facial module.

The primary reason behind the use of bifacial photovoltaic (PV) modules is that it can accept light on both the front and rear surfaces. Also bifacial PV becomes a larger portion of the overall PV market [7].

The research of bifacial PV technology dates back to 1960 [8]. In the next 20 years, bifacial PV technology was largely ignored, except for some applications in Russian satellites. This PV technology received new attention by the PV community in the 1970s when researchers from Mexico and Spain presented their results of bifacial PV cell research in the first European Photovoltaic Solar Energy Conference held in Luxembourg [8]. During the 1980s, research groups from Spain published numerous scientific articles for high efficiency, high power gain bifacial PV cells. Sandia National Laboratories and the National Renewable Energy Laboratory are investigating bifacial PV performance and characterization in a joint project funded by the US Department of Energy [10]. However, Solar World has made bifacial solar cell which efficiency is 22.04% [11].

1.3 Objective

The objective of this work is to assess the performance of bifacial module based multilevel solar panel system considering environmental effects. It aims to harness more solar energy than the existing mono-facial module based multilevel system. This bifacial multilevel solar panel system will occupy less space and harness more solar energy than before for its use in urban areas.

1.4 Motivation

Solar energy has the largest potential among all renewable energies resources. Also solar energy is abundant and free. However, limited rooftop space in large apartment buildings restricts the use of PV panel for every household. A Multilevel PV Panel system that minimizes the floor area and maximizes the energy collection will help mitigate the problem. Recent research indicates that the output of the bifacial module is boosted up to 50% over the single-sided module depending on the backside environment [12]. This work will help harness more energy in less floor area than the existing mono-facial based system.

1.5 Outline

The rest of the book is organized in such an order to make it easy to understand for a reader. The book is structured as follows: Chapter 2 presents the theoretical background of this work; proposed system is discussed in Chapter 3. Chapter 4 describes the results and analysis of this study. Chapter 5 presents the conclusion and future works.

Chapter 2

Proposed System Description

2.1 Solar Cells

Solar Panel:

A solar panel is comprised of solar cells. As light hits a cell, electrons are separated from the cell's silicon atoms. The electrons flow through the cell, and that action produces direct current (DC) electricity. The DC electricity output is then sent to an inverter, which converts it into alternating current (AC) electricity. AC electricity is the kind of electrical power that is used in homes, offices, etc.

2.1.1 Monofacial Solar Panel:

Monofacial solar panel is the solar panel in which solar cells are placed on only one surface of the panel which is the front surface of the panel. In monofacial solar panel, light only enters through one side of the cell. That means monofacial solar panels can harness only the direct solar irradiance from the sun. this solar panel is widely used everywhere. As it can only receive direct irradiance from sun, the diffused and reflected irradiance from sun cannot enter this panel. So the energy gained from this panel is calculated for only the direct irradiance from sun.

2.1.2 Bifacial Solar Panel:

Unlike monofacial solar panel, light can enter from both front and rear surface of the bifacial solar panel. So along with direct irradiance, diffused and reflected irradiance from sun can also

be absorbed by bifacial solar panel. Bifacial solar modules offer many advantages over traditional solar panels. Power can be produced from both sides of a bifacial module, increasing total energy generation. They're often more durable because both sides are UV resistant, and potential-induced degradation (PID) concerns are reduced when the bifacial module is frameless. Balance of system (BOS) costs are also reduced when more power can be generated from bifacial modules in a smaller array footprint. The higher a bifacial module is tilted, the more power it produces from its bifacial properties. Bifacial modules mounted flush to a rooftop block any reflected light from reaching the backside of the cells. That's why bifacial modules perform better on flat commercial rooftops and ground-mounted arrays, because there is more room for tilt and bouncing reflected light to rear side of the panel.

2.2 Proposed System Design and Methodology

The proposed bifacial multilevel solar panel system is depicted in Fig. 2.1. The panels are mounted one above another separated by a fixed distance to minimize the floor space, and shifted horizontally by half the panel width to avoid the shading of the lower panels. Each of the panels will be equipped with a microcontroller controlled servo motor to track the sun.

In the proposed system, all the three panels are supported by a single SS bar which mounted on a vertical stand with heavy weight iron base in such a way that the SS bar can rotate around a pivot, properly maintaining the system's stability. This rotational movement along a certain arc path is achieved with the help of an actuator attached to the vertical stand as shown in Fig. 2.1. The panels are equipped with servo motors, precisely controlled with a Micro-controller to track the sun.

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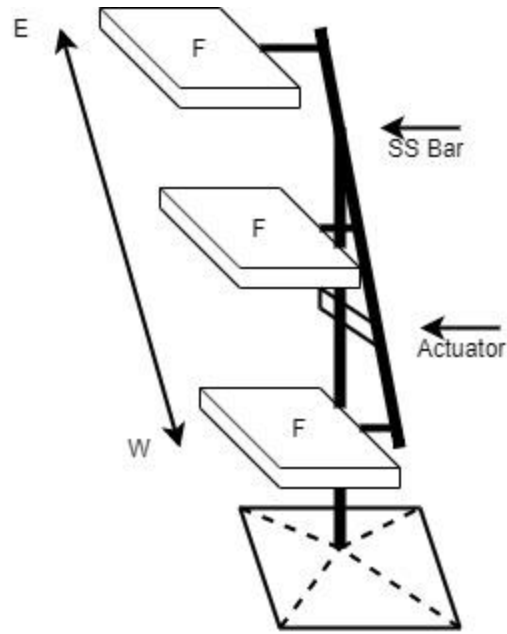
Fig. 2.1 2-D schematic side view of the proposed three level bifacial solar panel system

The orientation of the panels facing east in the morning allowing them to get full sun exposure is shown in Fig. 2.1 and that facing west in the afternoon allowing them to get full sun exposure are shown in Fig. 2.2.

The panels were south facing and were at 23.5 degree angle with the ground. All the 3 panels would track the sun throughout the day. The mid panel would get vertical from 10am-2pm every day to ensure that the bottom panel doesn't get shadowed.

Replacing the module with bifacial module can harness extra energy in the top and bottom panel. And most importantly the mid panel will get diffusion from both sides. Previously, this was not considered. From 10am-2pm the mid panel gave zero power, which is not the case.
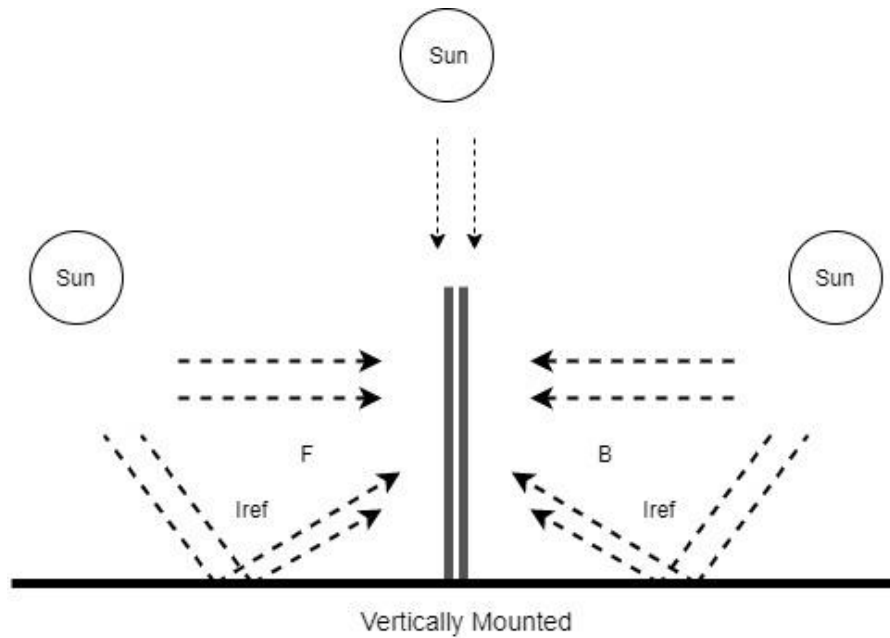
Fig 2.2 Diagram of a vertically Mounted Bifacial Panel getting diffused Irradiance

Proposed system's articulation throughout the day. Also because, the panels have different height, some boosting in power because of height occurs.

Fig 2.3 gives the idea on how our system will operate and track the sun throughout the day. It also shows how the 3 panels at different height get different irradiance at different positions. At sunrise, all the 3 panels will align with the sun's position facing east. The panels will keep the alignment with the sun with the help of the microcontroller, servo motor and the actuator. Fig 2.3 shows, all 3 panels are harnessing Direct Irradiance (I_{dir}), Reflected Irradiance (I_{ref}) and diffused Irradiance (I_{dif}) while tracking the sun. This tracking continues till 10 am, for the mid panel. Because after that mid panel becomes vertical so that bottom panel does not get shadows.
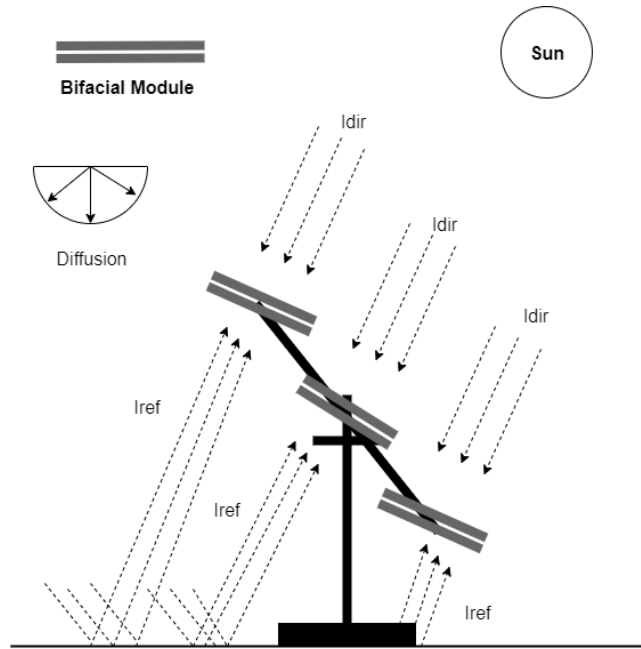
Fig 2.3 2-D Schematic Side View of Bifacial Multilevel Solar panel System at

Morning/Afternoon
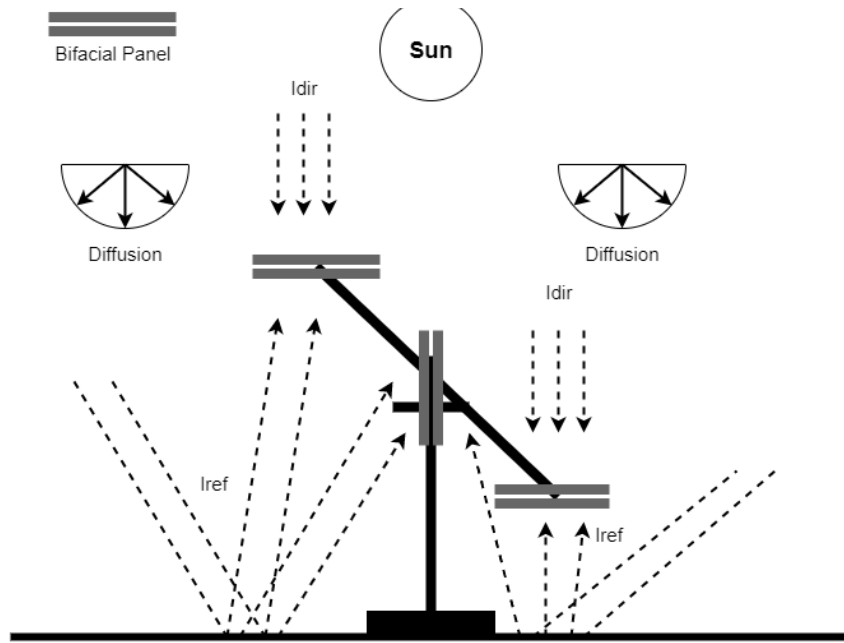
Fig 2.4 2-D Schematic Side View of Bifacial Multilevel Solar panel System

at Noon

Fig 2.4 shows, the position of the panels from 10 am to 2 pm. At 10 am, the middle panel goes to vertical position so that no shadow falls upon the bottom panel. This allows the bottom panel to keep harnessing the I_{dir}. In this period time, the top panel and bottom panel keep receiving I_{dir} and I_{ref}. As the middle panel goes to vertical position, it receives I_{ref} and I_{dif}. Especially at 12pm the top and bottom panel are directly in line with the sun the get highest irradiance. From 2 pm afterwards, all 3 panels track the sun as the sun descends to west in same way shown in Fig 3.3. The middle panel and the top panel receive additional energy due to the height they are stacked.

Fig 2.3 & Fig 2.4 gives the idea on how our system will operate and track the sun throughout the day. It also shows how the 3 panels at different height get different irradiance at different positions

2.3 Design Assumptions and Parameters

Table 3.2 shows the parameter which are taken into consideration throughout the work. Here albedo factor is 0.4, which is actually represents the cement surface. .Also here the area of the actual module has been considered. The height dependent additional energy yield has been collected from the reference paper [13].

There are some assumptions made, because no mathematical way was available to measure those particular parameters.

Assumptions:

1. No front panel diffusion is considered.
2. GHI is taken to be 10% more than DNI, as it depends on surroundings.

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Parameters:

Table 2.1 Design parameter values considering in this work

Sl. No	Parameter	Value
01	Albedo	0.4
02	Time Gap	15min/0.25hr
03	Panel height multilevel power boost	1.Top panel 1m-15% power boost 2.Mid panel 0.5m-10% power boost 3.Bottom panel- ground level-no boost
04	Panel Size	434mm by 272mm =0.120218m^2
05	Panel Efficiency	20%

Bifacial Panel Efficiency of Panel available in Market:

LG-NeON® 2 (N-Type Bifacial Panel)

Properties of Panel:

Number of cells - 72

Front Efficiency -23%

Rear Efficiency- 18%

Overall Efficiency – 20.5% ≈ 20%

Chapter 3

Theoretical Background

In order to fully comprehend the individual steps undertaken in this study and the various occurring effects which are discussed at a later point, a common ground of basic knowledge in several issues has to be established. Familiarity with the behavior of light passing through the atmosphere and the complete process of photovoltaic energy generation from solar module is required. Such knowledge will be attained in the following sub-chapters,

3.1 Monofacial Solar Cell & Bifacial Solar Cell

Bifacial cells are of 2 types commonly. The heterojunction and passivated emitted rear (PERC). Heterojunction cells use monocrystalline silicone while the PERC cell is available in both mono and poly crystalline variants. Bifacial cells are more complex to manufacture and this adds to the cost of the module.
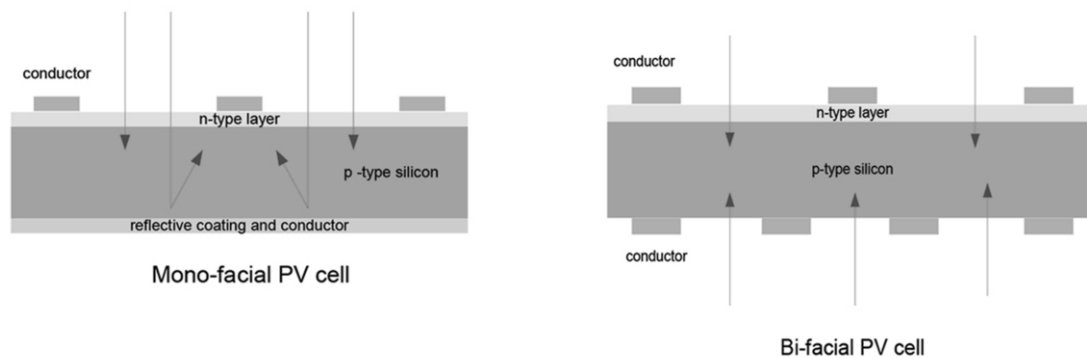
Fig.3.1 Monofacial and Bifacial Solar Cell Cross sectional view [15]

Monofacial crystalline silicone panels are usually encased in opaque encapsulates at the rear but this cannot be used for bifacial systems. The module must have transparent back and front

surfaces that ensures mechanical strength and cells must be enclosed in a layer of protective material polymer material. For that purpose, a UV resistant back sheet or solar glass layer is used to allow light to shine on the rear surface of the cell. Glass to Glass package is more rigid which reduces mechanical stress on cells. This has several advantages,

1. Lower cell temperature (Efficiency will not decay)

2. Lower Degradation rate

3. Higher mechanical Strength and less flexing

4. Reduction in microcracking and moisture corrosion

5. Higher flameproof rating

Bifacial Cell Double diode model:
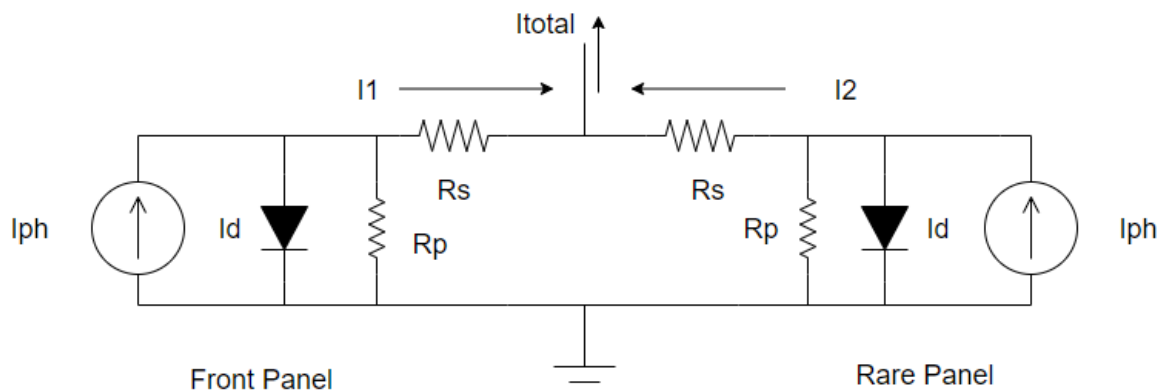
Fig. 3.2 Bifacial Cell Double Diode Model

Monofacial Cell single diode model:
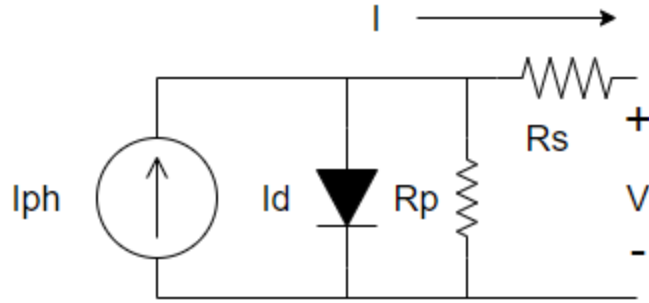
Fig. 3.3 Monofacial Cell Single Diode Model

In Fig 3.3,

R_p = Resistance in Parallel

R_s = Series Resistance

I_d = Diode Current

I_{ph} = Current Generated by Photon

I_{Rp} = Current through Shunt Resistance

So generated current I

$I=I_{ph}-I_d-I_{Rp}$

Here,

$I_d=I^{\circ}\{exp\left[\frac{Vp}{nVt}\right]-1\}$

Where,

I_o = reverse saturation current

n = diode ideality factor

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

$V_T=\frac{KT}{q}$, Thermal voltage $V_T = 0.025V$ at 25 °C

$V_p= I_{Rp} \times R_p$, Ohm's Law

This is for Monofacial Cell fig 2.3 but for bifacial Cell this same mechanism happens for the rear side. Fig 2.2 shows that, the produced currents from both front and rear come to same node and add up. So we have I_1 from front and I_2 from rear . I_{total} is the total current from the cell.

$$I_{total}= I_1+I_2$$

3.2 Solar Irradiance

Solar Irradiance is of 3 types. They are-

1. Direct Irradiance: This is the sun light that directly falls on the surface of earth. This type of irradiance is harnessed by monofacial panels and the front part of the bifacial panel.

2. Diffused Irradiance: Sunlight gets diffused by clouds, dust particles in the air. Monofacial module and front side of the bifacial module harnesses some of the diffused light call sky diffused irradiance.

3. Reflected Irradiance: Our ground reflects different type of light depending on ground material. This is harnessed by rear side of the bifacial module. Monofacial module cannot harness this reflected irradiance.

3.2.1 Direct Irradiance:

Cumulative incident energy is total of all incident values calculated over a given period of time period. For a particular day numerical integration of Incident energy can be used for a given time period like total number of hours available from dawn to dusk. The amount of solar energy incident can be calculated using the following equation [3]:

$$E_{inc} = A \int_{T_{SR}}^{T_{SS}} I_{inc} dt \tag{1}$$

Where, A is the area of the module, T_{SR} and T_{SS} are the sunrise and sunset times respectively, and I_{inc} is the incident solar energy.

For fixed axis tracker solar irradiance can be calculated as [9];

$$I_{inc} = I * \cos \delta \tag{2}$$
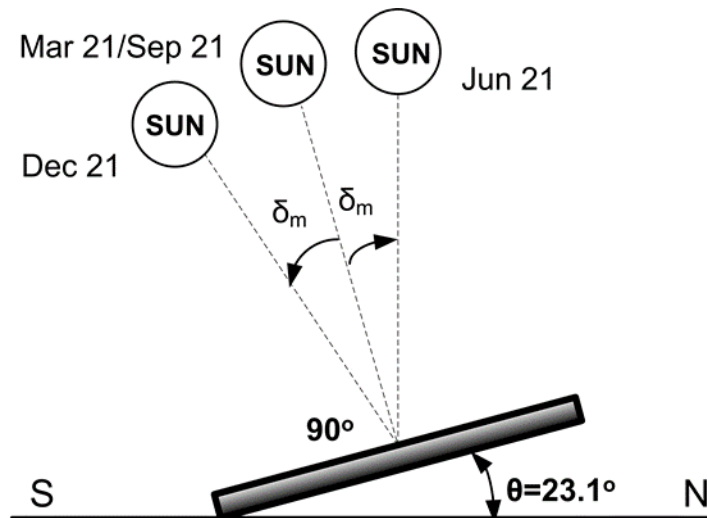
Fig.3.4 Direct Normal Irradiance of Panel [12]

where θ is the angle between the incident sunlight and the panel plane, δ is the angle of declination. For Dual Axis δ and θ both are zero. For Single Axis δ will Change with seasons but θ will remain unchanged. For Fixed Axis both will change with different time and season. The solar irradiance is given by the following empirical relation [3]:

$$I = I_0 * (0.7)^{AM^{0.678}} \tag{3}$$

where I_o = 1367 W/m^2 is the solar irradiance in space outside the atmosphere and $AM = \csc(\alpha)$ is the air mass which is a function of angle of incidence (α) of sunlight on earth's surface.

As the angle of incidence of sunlight varies with the time of the day and also from season to season, so does the solar irradiance according to (2). The angle of incidence of sunlight at any time on a given day can be calculated using the following equations

$$\alpha = \sin^{-1}(\sin\delta\sin\gamma + \cos\gamma\cos\delta\cos\omega) \tag{4}$$

where φ is the latitude, and δ is angle of declination given by [3]:

$$\delta = 23.45°\sin\left\{\frac{360}{365}(n + 284)\right\} \tag{5}$$

where n= nth day of the year (i.e. January 1st means n=1). In (4), ω is the hour angle and represents the number of hours elapsed during the day from sunrise to sunset expressed in degree and can be calculated as below [9]:

$$\omega = -\omega_s + 2\frac{\omega_s}{T}(t - Sr) \tag{6}$$

where t is the time of day on a 24-hour clock, ω_s is the sunrise angle given by [9]:

$$\omega_s = \cos^{-1}(-\tan\delta\tan\gamma) \tag{7}$$
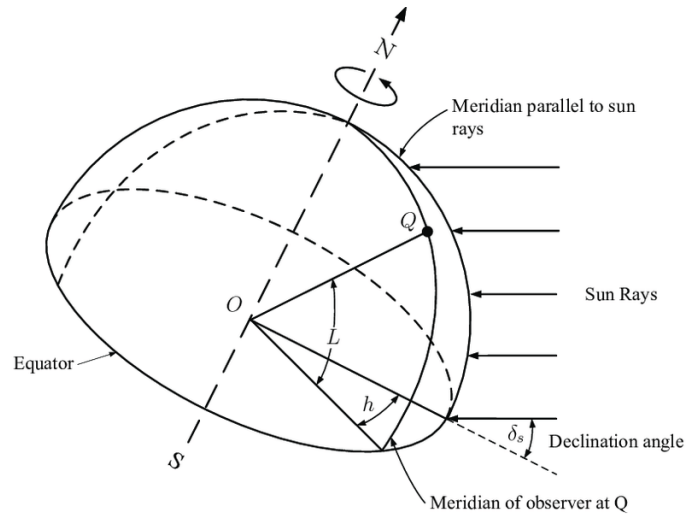
Fig.3.5 Solar Angles [12]

3.2.2 Diffused Irradiance:

Global horizontal irradiance is measure of diffused irradiance. For this irradiance solar panels do not give zero output even though there not direct facing sun. This comes to play a strong role in cloudy day. The global horizontal irradiance GHI is the total solar irradiance reaching Earth's surface on a horizontal plane with an area of 1 m2, and is given by

$$GHI = DNI + DHI \qquad (8)$$

DNI is the direct irradiance and DHI is diffused horizontal irradiance. GHI largely depends on the surroundings. It is a norm, where theoretically GHI is 10% more than DNI.

3.2.3 Reflected Irradiance:

Light gets reflected by the surface it falls on. A huge portion of solar energy is in these reflected beams. This energy cannot be harnessed by monofacial panel. Bifacial panel harnesses this energy. The amount of reflection remains largely on the surface light falls on. A factor determines what per cent of light gets reflected. That is called Albedo factor. Detailed discussion on albedo factor is done, during rear incident energy calculation.

Now, all these different types of irradiances are harnessed by bifacial module. So for Bifacial panel,

$$I_{total} = I_{dir} + I_{ref} + I_{dif} \tag{9}$$

where I_{dir}, I_{dif}, and I_{ref} are the direct, diffuse and reflected components of the solar irradiation on a tilted plane with an area of 1 m^2.
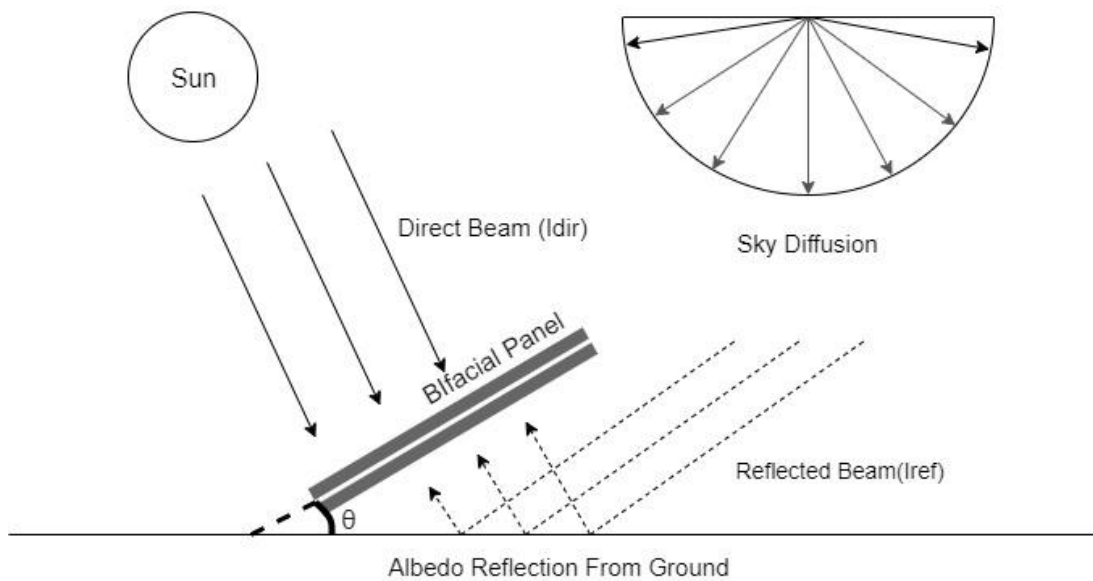
Fig 3.6 Irradiances on a tilted bifacial Solar Panel

3.3 Incident Energy Calculation for Bifacial module in multilevel System

The energy calculation for top and bottom panel are same, as they both are oriented in a similar way. Except, middle panel, as it remains vertical for a particular time period. During that that period a different approach is used to calculate energy.

3.3.1 Top & Bottom module:

Front side of bifacial module:

Front side of bifacial module harnesses only direct irradiance and some diffused irradiance.

$$I_{front} = I_{dir} + I_{dif} \tag{10}$$

Here, I_{dir} is given by eq(2) and I_{dif} is 10% of DNI. This is same as the incident energy of a monofacial module.

Rear side of bifacial module:

It is difficult to measure the irradiance on the rear side because of scattered and direct irradiance. Therefore the irradiance entering the rear of the module is divided into a diffusion component and a reflection component.

The amount of total irradiance (I_{Rear}) on the module by the rear environment is expressed as the sum of direct reflection and indirect reflection. Therefore, the total amount of irradiance on the rear side of the module is assumed to be as given by Equation (11).

$$I_{rear} = I_{dif} + I_{ref} \tag{11}$$

To express the direct irradiance and scattered irradiance, concept of view factor is used. Therefore, Equation (11) can be expressed by Equations (12) [11].

$$I_{rear} = \alpha_f DNI \frac{1 + \cos \beta}{2} + \alpha_f (GHI - DNI) \left(\frac{1 + \cos \beta}{2} - F_m \right) \tag{9}$$

Here, α is albedo factor and F_m is view factor. They calculated by following method.

These 2 topics and how they are measured are discussed below.

   a) View Factor

   b) Albedo Factor

a. View Factor:

The "View-Factor Method" calculates the radiation "emitted" from the underlying surface and received by each cell. The ground beneath the module is divided into two parts: the shaded and unshaded region; in the former only diffuse radiation is reflected, while in the latter both direct and diffuse radiation are reflected.

Numerically, the view-factor is defined as a geometric quantity that determines the fraction of radiation leaving a surface A_1 that directly impinges surface A_2. It depends on the relative orientation and distance between the two surfaces and, for finite surfaces, is given by

$$View\ Factor_{A1 \rightarrow A2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \times \cos \theta_2}{\pi r^2} dA_2 dA_1 \tag{14}$$

Where r is the distance between the differential areas dA_1 and dA_2 and θ_1 and θ_2 are the angles between the normal vectors of the surfaces and the line that connects dA_1 and dA_2, respectively.
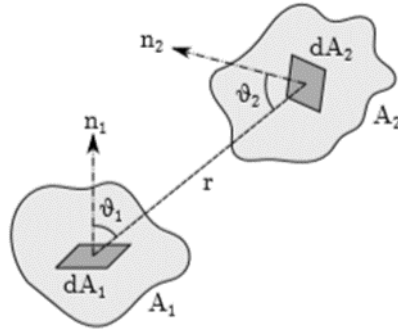
Fig 3.7 The View Factor between two surfaces [11]

View factor is defined by F_m. For that beta has to be calculated. β is the angle between ground and panel it is fixed in a fixed axis system. But when panel is tracking the sun the angle with ground changes. The change occurs in 3 dimension. To calculate the changing angle a practical approach is considered. Taking a look at Fig3.8 below,
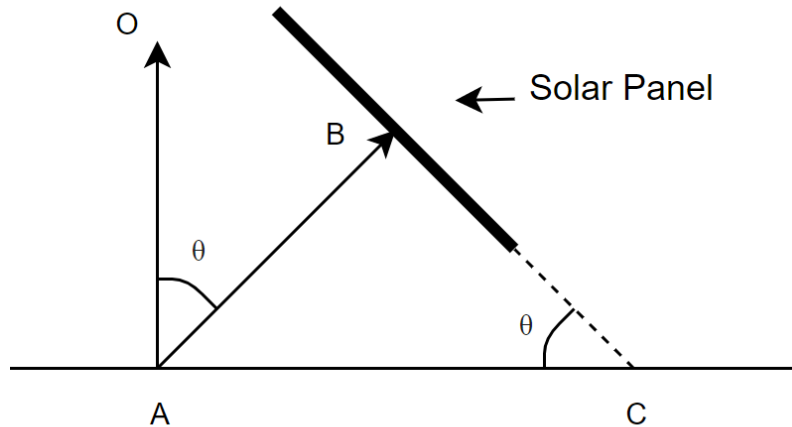
Fig. 3.8 Approach of calculating view factor.

From the Fig3.8,

ΔABC is a right angle triangle, where ∠B is right angle.

So,

∠A + ∠C =90°........... (i)

∠C is angle between ground and the panel.

Again OA is perpendicular on the ground.

So,

∠A + ∠θ = 90°......... (ii)

∠θ is angle between normal to the ground and the normal from the panel to the ground.

From eqn. (i) & (ii)

∠θ = ∠C

Which means, angle between ground and the panel, is same as angle between normal to the ground and the normal from the panel to the ground.

As it is seen the angle between ground and panel is same as angle between a normal from the panel to the ground and a normal to the ground. By using practical means the angle is calculated. Then a vector approach is considered to calculate the value. One vector normal to the ground. Another vector normal from the panel. That changes with hour angle and is tilted at 23.5. By finding the angle between 2 vectors beta is found.

This is verified by a math tool called "GeoGebra". In all three cases practical software and vector approach the values were within 5% of range each other. This is how β was found.

Then after putting β in the equation below we get the view factor F_m.

$$F_m = \frac{1 - \cos(180 - \beta)}{2} \qquad (15)$$
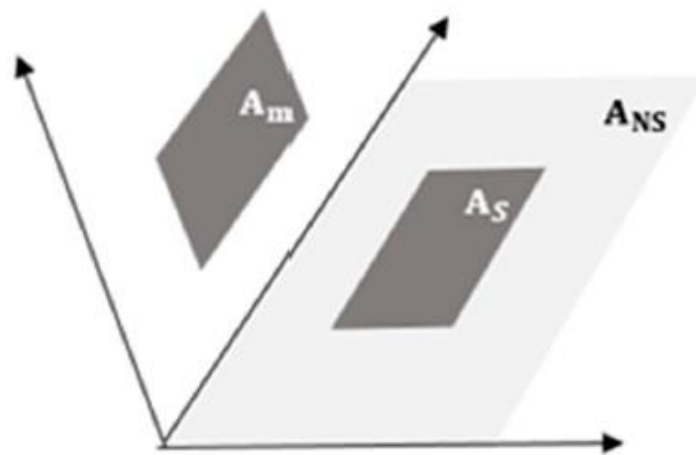
Fig 3.9 View factor of Surface A_m with respect to A_s[11]

b. Albedo Factor:

The albedo describes the reflectivity of a non-luminous surface. It is determined by the ratio between the light reflected from the surface and the incident radiation.

$$Albedo\ of\ the\ surface = \frac{Reflected\ light}{Incident\ light}$$

Albedo is a dimensionless quantity and is usually expressed as a percentage. The higher the reflectivity of a surface, the higher its albedo. For example, a black surface that absorbs a large amount of light has a low albedo, while a white surface that reflects a large amount of light has a high albedo. The greater the installation height of the bifacial photovoltaic module the greater the additional energy yield.

Albedo Factor depends on the material of the surface on which it is mounted. So a list of values of albedo for different surface materials is given below in the table 3.1.

Table3.1 Different Values of Albedo with respect to different Surfaces [13]

Sl. No.	Surface	Albedo
01.	Concrete (10-Year-Old)	0.16
02.	Green Field	0.23
03.	White Gravel	0.27
04.	Cement/ Sand	0.40
05.	White Roofing Material	0.56
06.	Light Grey Roofing Foil	0.62
07.	White Roofing Foil (Solar Application)	0.80

Albedo factor Also Impacts the Amount of extra energy we will get due to height.
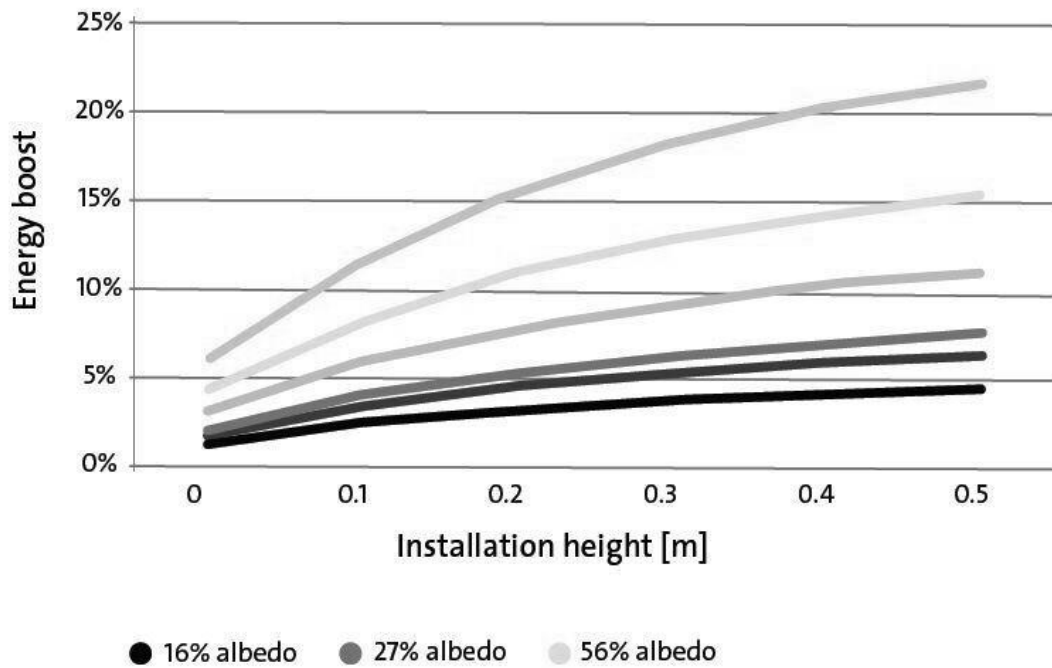
Fig. 3.10 Energy Boost because of different Albedo and Height [13]

For our system Albedo will be 0.4 since most roofs are covered with Cement in urban areas. Also Our panels will have no boost, 10% boost and 15% boost for bottom, mid and top panel for that albedo of 40%.

So, total irradiance at any time,

$$I_{total} = I_{front} + I_{rear} \qquad (10)$$

3.3.2 Mid module:

Mid module gets to a vertical position from 10am to 2pm. So the energy calculation for mid panel is a bit different from top or bottom one.

The side that is facing the sun in morning is the front side and the other side is the rear side.

For mid panel,

$$I_{front} = I * cos\delta * sin\theta \tag{17}$$

Here, panel is in a fixed position, but we need to take sine component of direct beam. As cosine component does not hit the panel.

For the rear,

$$I_{rear} = I * 0.1 \tag{18}$$

We take that 10% of DNI just diffusion and little reflection hit the vertical back side of the module.

After 12pm the sun switches sides now front side becomes rear side and vice versa.

3.4 Electrical Energy Calculation

The incident power calculated from the formulas above we plot it against time. After that we need to calculate the area under the curve to get Total Solar Energy for the Day. That comes at kWh/m². That area under the curve is calculated using Multiple Segments Trapezoidal Rule.
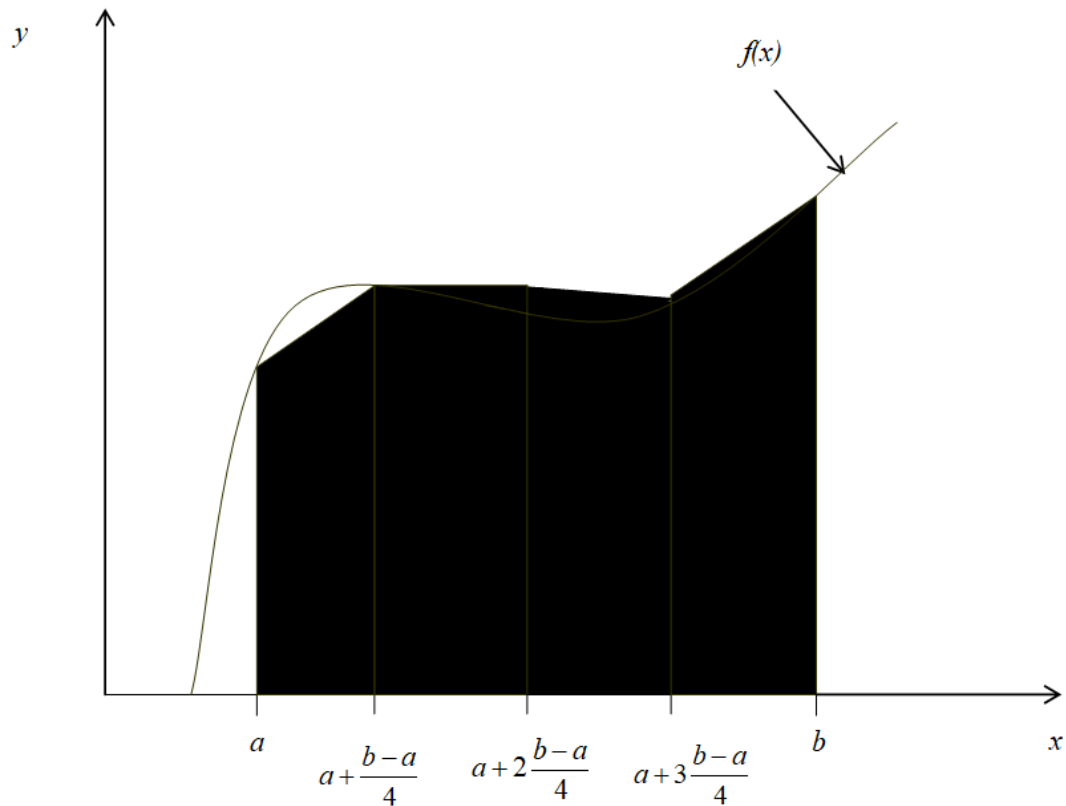
Fig. 3.11 Trapezoidal Rule for calculating area[16]

The formula then is,

$$\int_a^b f(x)dx = \frac{b-a}{2n}[f(a) + 2\{\sum_{i=1}^{n-1} f(a + ih)\} + f(b)] \qquad (19)$$

Where, a=lower limit

       b=upper limit

       h=spacing between each point

In our case, a=sun rise time

b=sun set time

h=Time Interval (15min)

After getting the Solar Energy per meter sq. we need to multiply that with the area of our panel, and then efficiency of our panel. Efficiency varies from panel to panel.

Electrical Output for one day = Area of Panel (m^2) × Efficiency of the panel × Solar Energy Harnessed in one day (kWh/m^2)

3.5 Cloud Effects

The presence of cloud adversely affects solar energy conversion efficiencies. Solar insolation is the measure of sun's radiation energy that is received by a given horizontal surface on a given time window that apparently relies on the altitude of the sun and cloud coverage. The data of month wise insolation throughout the year is collected from reference [10]. Here energy of sunny day refers to the energy that is received on a pure shiny day while having the sun directly overhead and cloudy days' energy refers to 20% of the energy on sunny day [12]. The related mathematical equations are provided below:

$$E_{sunny} = \int_{T_{SR}}^{T_{SS}} (I sin\alpha + 0.1I)\, dx \tag{20}$$

$$E_{Cloudy} = \int_{T_{SR}}^{T_{SS}} 0.2I\, dx \tag{21}$$
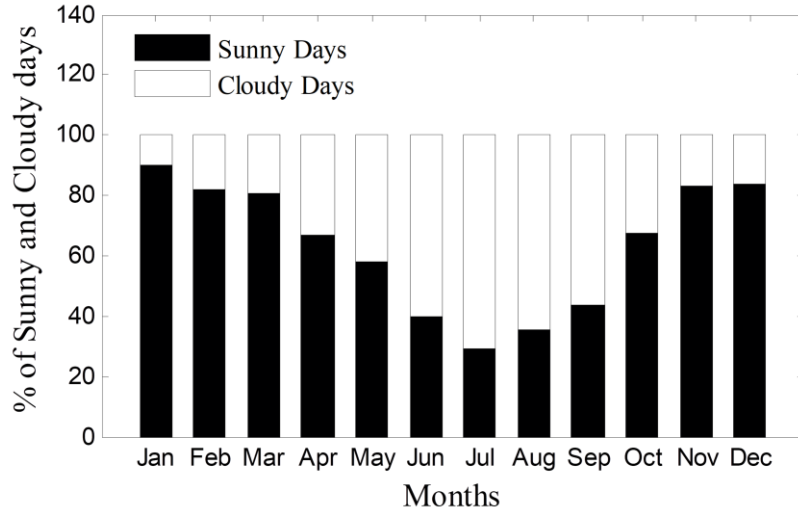
Fig 3.12 Number of Sunny & Cloudy Days through the year in the context of Bangladesh[12]

Next approach was to find the approximate number of sunny days and cloudy days by using the subsequent equations:

$$E_{total} = x * E_{Sunny} + y * E_{Cloudy} \tag{22}$$

$$x + y = Total\ Days_{particular\ month} \tag{23}$$

By using the following set of equations finally figured out the number of sunny and cloudy days. In the equation (15), E$_{Direct}$ refers to the energy that we procured from insolation.

$$E_{Direct} = Total\ Days_{particular\ month} * E_{Insolation} \tag{24}$$

30

Table 3.2 Number of Sunny and cloudy days in each month

Month	Num. of Sunny days	Num. of Cloudy days	Total Days
Jan	28	3	31
Feb	23	5	28
Mar	25	6	31
Apr	20	10	30
May	18	13	31
Jun	12	18	30
Jul	9	22	31
Aug	11	20	31
Sep	13	17	30
Oct	21	10	31
Nov	25	5	30
Dec	26	5	31
Total	231	134	365

Chapter 4

Results & Analysis

To discuss about the results in a comparative basis, first daily basis energy calculation is described. Then monthly energy calculation is presented. After that yearly variation is shown along with environmental impact. . Finally, the proposed system is compared with the existing system and conventional fixed system.

4.1 Daily Energy Calculations of different systems

Bifacial Single Axis Tracking System:
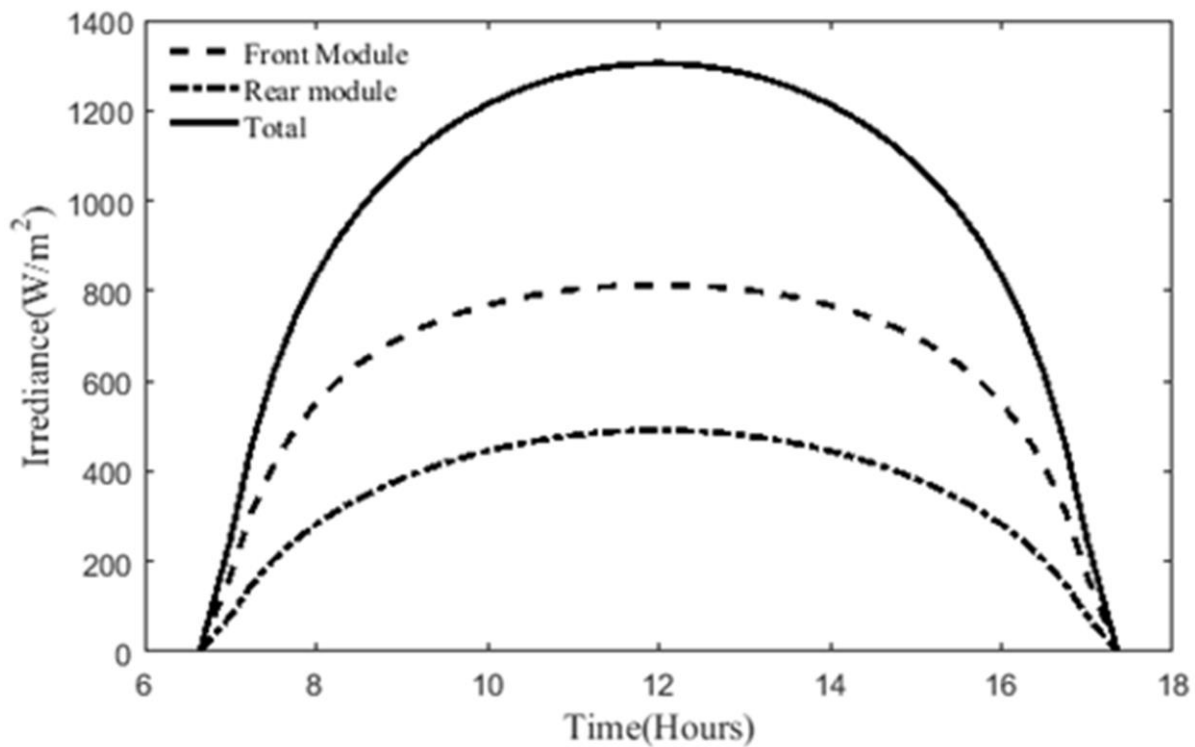
Fig 4.1 Daily incident solar intensity of bifacial module based single axis tracker for a specific day Jan 15th

Daily solar intensity is calculated by using the equations depicted in the chapter 2. For easy understanding only one day data (15th January) is explained throughout the analysis. Fig. 4.1.

It shows the solar intensity of bifacial based single axis tracking system of 15th January. The front module of this tracker actually represents the mono-facial module output. Figure shows that rear module contributes significant energy into the system. Calculations shows that for January 15th, total incident energy of bifacial single axis tracker is 10.586 kWh/m^2 and the front module incident energy is 6.767 kWh/m^2. That means mono-facial module (front module) receives 36.94% less energy than the bifacial module.

Comparison between mono-facial and bifacial module:
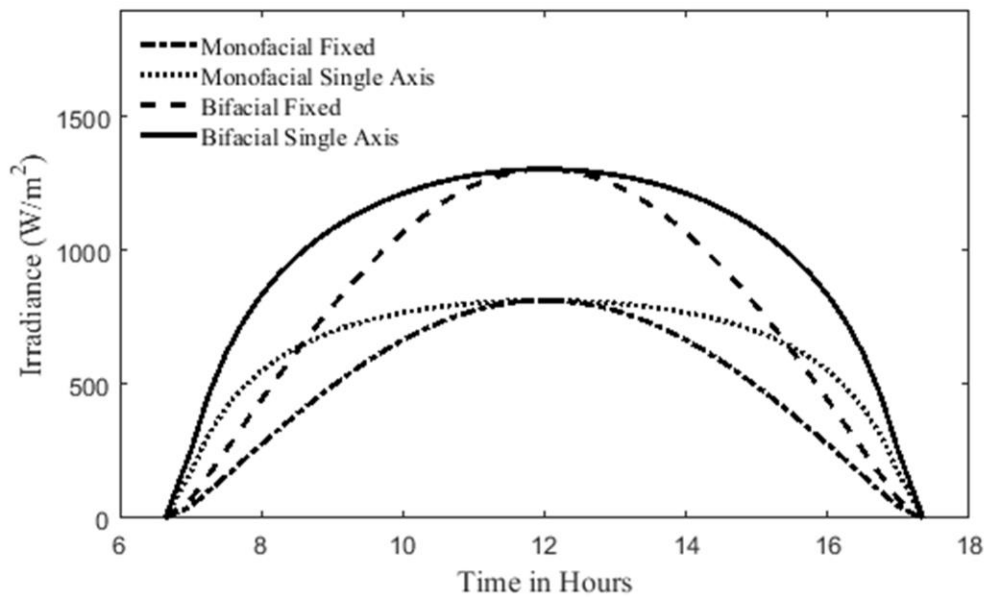
Fig. 4.2. Comparison of daily incident solar intensity of mono-facial and bifacial module

Figure 4.2 presents the comparison of solar intensity of mono and bifacial based fixed and single axis tracking system. It is clear that single axis tracker collects more energy than the fixed axis tracker as well as bifacial module harnesses more energy than that of mono-facial based module-based system. Here, Mono facial fixed module gathers total incident energy of 5.324kWh/m^2, and Mono facial Single Axis Tracker collects total incident energy of 6.767kWh/m^2. Similarly bi-facial fixed Panel harnesses total incident energy 8.536 kWh/m^2 and bi-facial single axis tracker collects total incident energy of 10.586 kWh/m^2. Results shows mono facial single Axis tracker gives extra 27.1% more Energy than Fixed module and Bi-facial single axis tracker gives extra 24.01% more Energy than fixed one. These results point out that single axis tracker collects significantly more energy than the fixed one. Also bifacial module based single axis tracking system shows the highest energy accumulation among the presented systems in Fig. 4.2.

Vertically mounted bifacial module:

Fig 4.3 Daily incident solar intensity of vertical mounted bifacial module for a specific day 15th January

Bifacial module has advantage as it collects energy from the both sides of the module. As a result this module can set up conventional fixed horizontal system, tilted position or vertically. The most commonly used system is vertically mounted module. Usually this system is used in the middle of roads where there is small space. The incident energy is lower than Mono facial module because when Irradiance is highest during noon module does not get direct irrad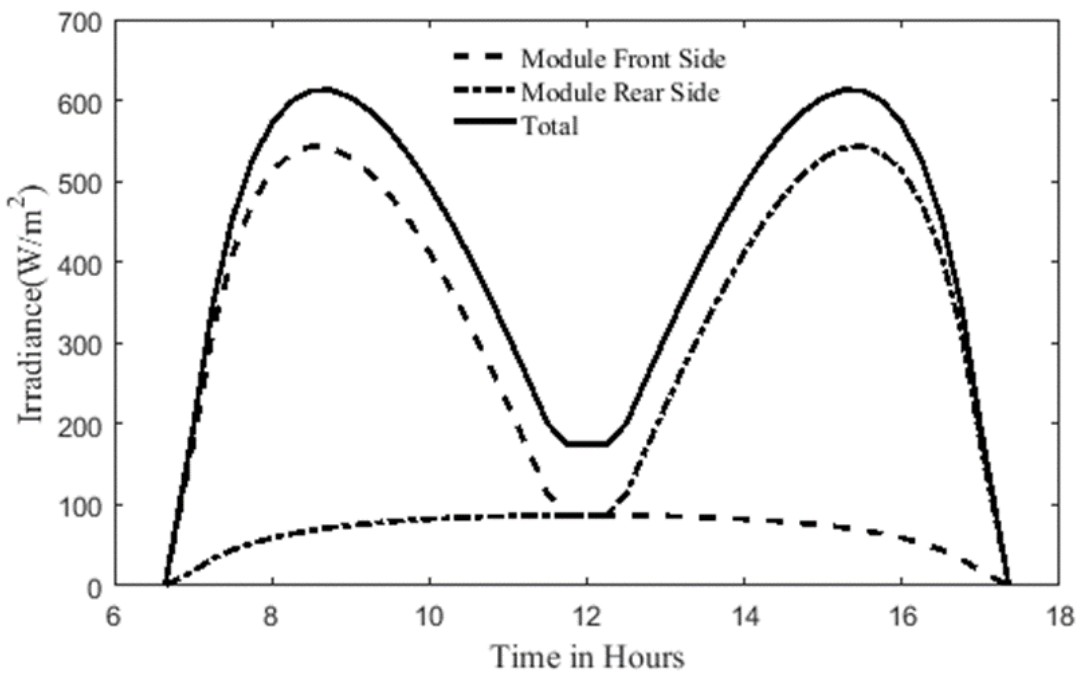iance. Notable thing here is that during Sunrise and sunset the graph is stiff because during those times Panel is in direct line of sight with the solar irradiance. So' from sunrise to around 9a and from 3pm to sunset the system works like a single axis tracker. But DNI itself is low during that time compared to noon or around 12pm time DNI which is lost because panel is in parallel with the incident DNI so panel cannot harness the solar power. Still it is a usable system as this system consumes very less space. Fig 4.3 shows the daily irradiation change of a vertically mounted bifacial module set up. At noon incident solar intensity dips down. Because direct beam irradiation can't fall upon the module. Only diffused irradiation and reflected irradiation fall on the two sides of the module. Total Incident Energy is collected 4.471 kWh/m^2.

Energy Calculation of Mid module:

The multilevel solar panel system has three level: top module, mid module and bottom module. At noon the mid module gets the shading from top one and it also shades the bottom one. So, to avoid the energy harness of the bottom panel, and as the mid panel will get shadowed by top panel also, it was in our best interest to keep the mid panel vertical or almost vertical during that time. That's why it won't get the direct beam on that particular time. However, it will collect diffused irradiation. In the previous design diffused energy couldn't be taken into consideration. But in this proposed bifacial based system mid module will get diffused energy at noon. This

consideration will impact on the total output of the system. Fig 4.4 shows the daily irradiation of the mid module. Mono facial Mid module collects 6.391 kWh/m^2. Bifacial Mid Module gives 56.14% Extra energy.

As we can see from the graph that from 10am to 2pm the harnessed energy takes a dip. Because this is the time when mid panel remains vertical or almost vertical so that bottom
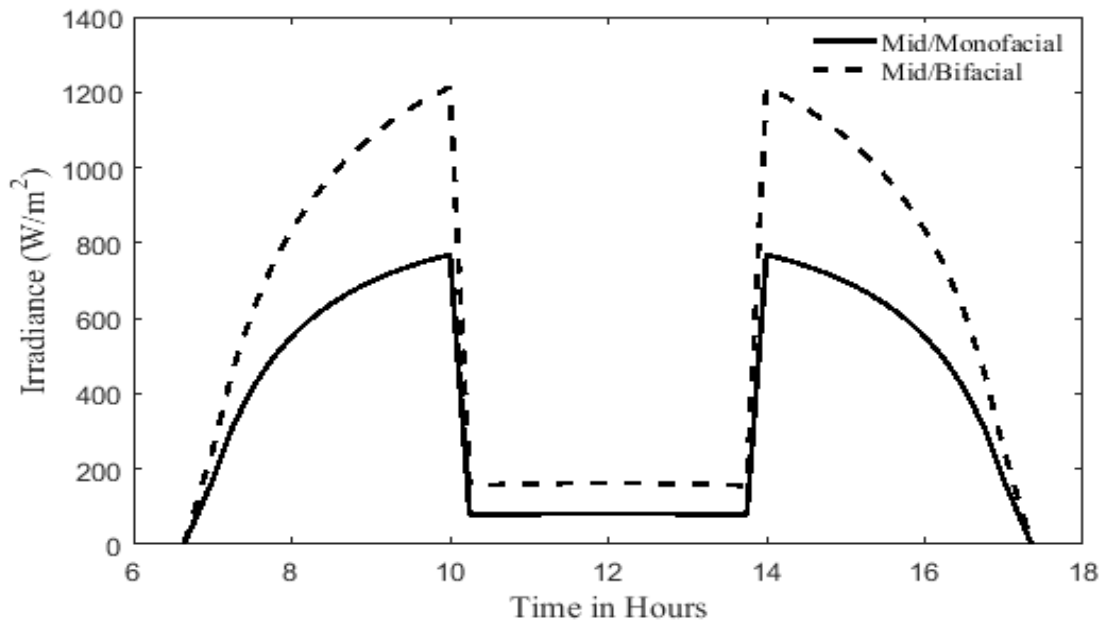
Fig 4.4 Daily irradiance of mid module from the proposed system for a specific day of 15th January

panel does not get any shading. Now in this simulation, we considered the diffused irradiance that mono facial panel also gets in one side. At sharp 12pm for the mono facial system the panel rotates 180degree from east to west so that it can track the sun again after 2pm. Diffusion was taken to be 10% of the DNI at the moment. For bifacial panel the diffusion collected from that

time will be two times because bifacial panel collects irradiance from 2sides at any given moment. And the bifacial panel doesn't even have to rotate since it can collect simply collect direct energy from whichever side that is facing the sun.

4.2 Monthly Energy Calculations of different systems
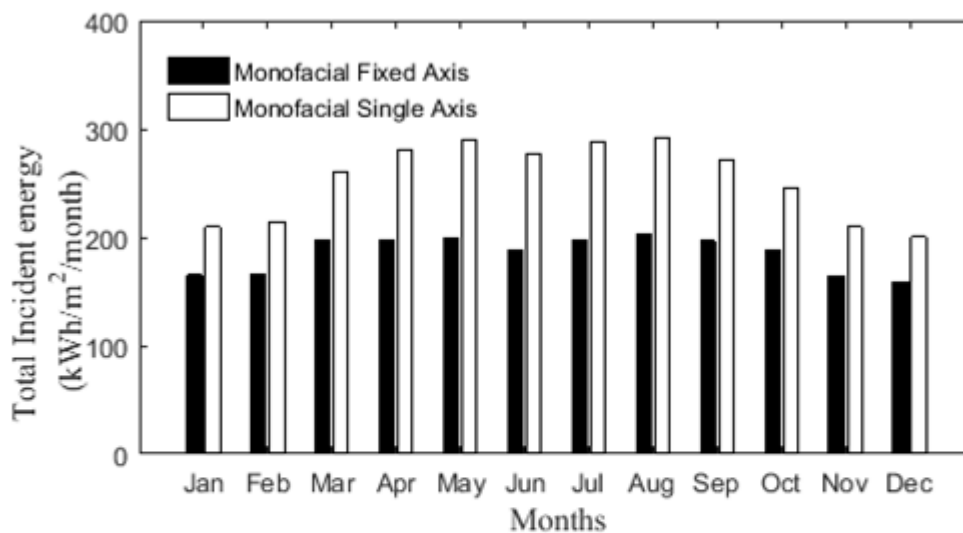
Fig. 4.5. Month wise incident energy calculation for mono facial based fixed and single axis tracking system.

Figure 4.5 shows the monthly accumulation of incident energy of mono facial module in a fixed and single axis tracking system. In this part cloud coverage is not considered. For Mono facial module, during summer single axis tracker gives 45.6% extra energy and in winter it gives 26.14% extra energy. The mono-facial fixed module accumulates yearly incident energy of 2.22 MWh/m^2/year and single axis tracker accumulates 3.04 MWh/m^2/year energy. Calculation shows fixed system accumulates 26.97% less energy than the single axis tracker.
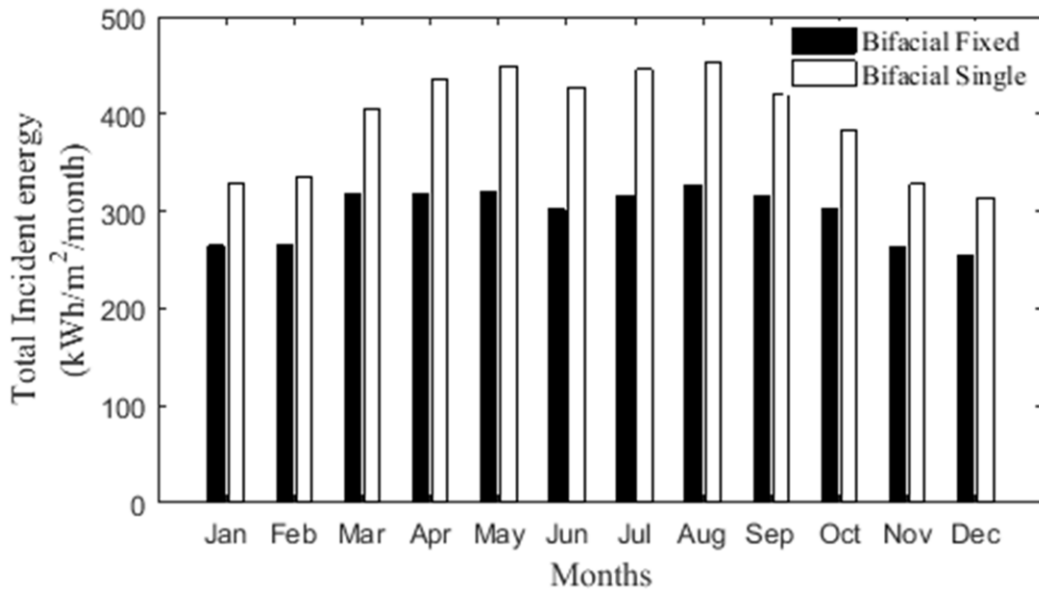
Fig. 4.6. Month wise incident energy calculation for bifacial based fixed and single axis tracking system.

We did not compare with dual axis tracker because a recently published paper showed that, dual axis tracker is not economically feasible for our country as the extra energy harnessed is not worth the extra mechanical systems needed to track the sun in 2 axis.

Figure 4.6 shows the monthly accumulation of incident energy of bifacial module in a fixed and single axis tracking system. For bifacial module, during summer single axis tracker gives 40.3% extra energy and in winter it gives 23.14% extra energy. Harnessed extra energy in winter is more effective as during winter daytime is low and also due to declination of the sun the DNI becomes low itself. The bifacial fixed module accumulates yearly incident energy of 2.48

MWh/m^2/year and single axis tracker accumulates 4.44 MWh/m^2/year energy. Calculation shows fixed system accumulates 44.14% less energy than the single axis tracker.
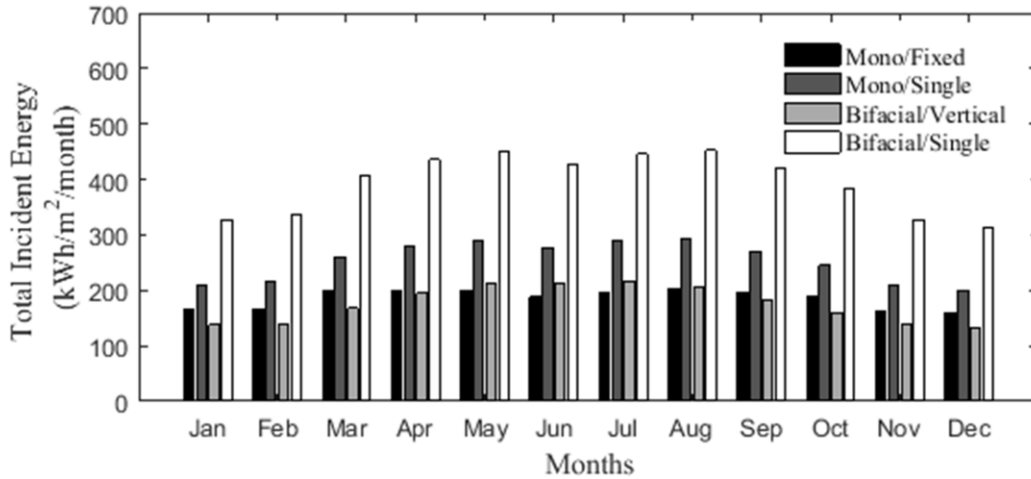

Fig. 4.7. Comparison plot of month wise incident energy calculation for mono and bifacial based fixed, single axis tracking and vertical mounted system.

Figure 4.7 shows a comparative plot among the mono-facial and bifacial based fixed system,single axis tracking and vertical mounted system. It is clear that bifacial single axis tracker shows the highest monthly incident energy throughout the year. Also figure shows that vertically mounted module collects the least energy throughout the year with respect to other three systems.

For fixed axis system, Bifacial Panel gives extra 60.34% extra energy than monofacial panel in summer and 60.35% energy in winter. Again for single axis system Bifacial Panel harnesses 54.59% extra energy than monofacial panel in summer and 56.54% energy in winter.

Table: 4.1. Yearly energy collection of different systems

System	Bifacial Vertical	Mono facial Fixed	Mono facial Single Axis	Bi-facial Single Axis
Yearly Incident Energy (MWh/m^2)	2.1025	2.2229	3.0405	4.4452
(%) Decrease from Bifacial Single Axis	-52.7	-49.93	-31.53	

So no matter what the seasonal impact is bifacial panel always gives more power and monofacial panel.

Table 4.1 presents the total incident energy of these systems and the percentage difference from the bifacial single axis tracking systems.

From the table it is clear that bifacial single axis tracking system collects the highest energy among other systems. That's why in this study existing mono-facial module based multilevel system is replaced by the bifacial module. As the multilevel system is developed along with single axis tracking system, it will give the highest energy.

4.3 Energy Calculation of proposed systems

Daily incident energy:

Figure 4.8 represents the daily energy harnessed by the multilevel system. We have 3 panels so 3 plots and a total energy plot. The plot is done for January15. The sunrise time is 6:43am and sunset time is 5:32pm.

40
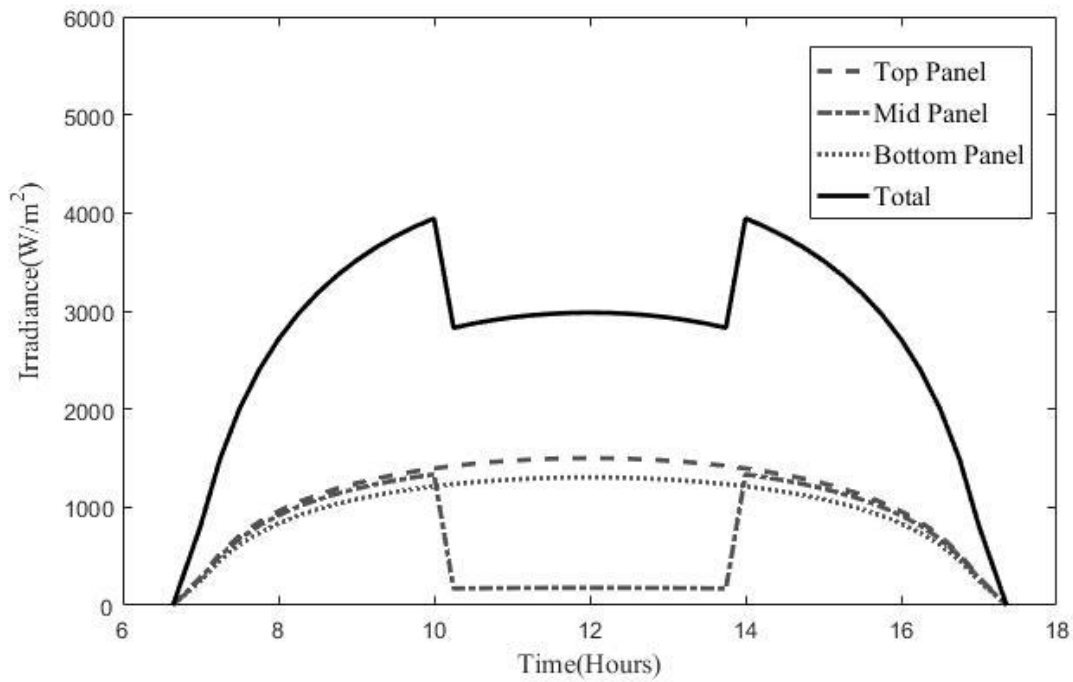
Fig. 4.8. Proposed Bifacial Multilevel System Output for January 15

We can that the Bottom and top panel harness almost same power the top panel just gets high boost of 15%. The mid panel gets some power from 10-14 previously which was taken to be zero. The shape of output from top and bottom panel are same, top is slightly higher because of energy boost due to the height. Three panel individually harnesses solar energy

Table 4.2 Proposed Multilevel Bifacial System Energy on January 15

Panel	Energy (kWh/m^2)
Top	12.147
Mid	07.030
Bottom	10.586
Total	29.790

The table 4.2 shows the output of the system panels and total system. As expected, mid panel gives lowest energy.
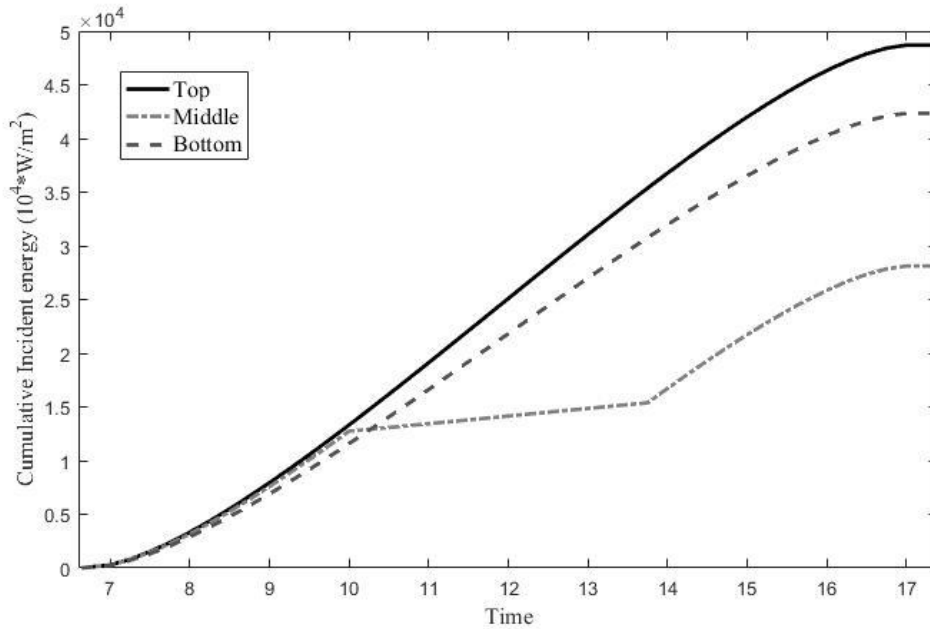
Fig 4.9 Cumulative Energy of the different Panels of Bifacial Multilevel System on January 15

Fig 4.9 shows the cumulative energy of the 3 panel as time progressed on Jan15. Fig 4.9 shows that top and bottom energy increases linearly as day goes by. And mid panel energy slope becomes close to zero when panel get vertical so very low amount of energy is added in that time.

Figure 4.10 presents the daily incident solar intensity of multilevel solar panel systems with the conventional fixed module. As multilevel system has three level of modules, fixed system represents same three modules which are considering placed in ground level. That's why conventional system takes extra space. The figure depicts that at 10 AM the intensity of multilevel module based systems falls down. And after 2 PM it rises again. The reason behind

this the mid module gets vertical at this time. As a result direct sun light can't get through it. Only diffused and reflected irradiance is collected by the mid module. It is also be noted that, the mono-facial based multilevel system collects energy from one side. That's why the energy at noon shows lower than the bifacial based multilevel system. The conventional fixed modules harnesses total 15.972 kWh/m^2 energy. Calculations show the proposed system gives 56.63% more energy than the previous system & 86% more than the conventional system.

Fig. 4.10. Comparison of monthly incident solar intensity of mono and bifacial module based multilevel solar panel system with conventional fixed system without cloud impact

The cumulative output of the systems can be seen in the Fig 4.11 below,
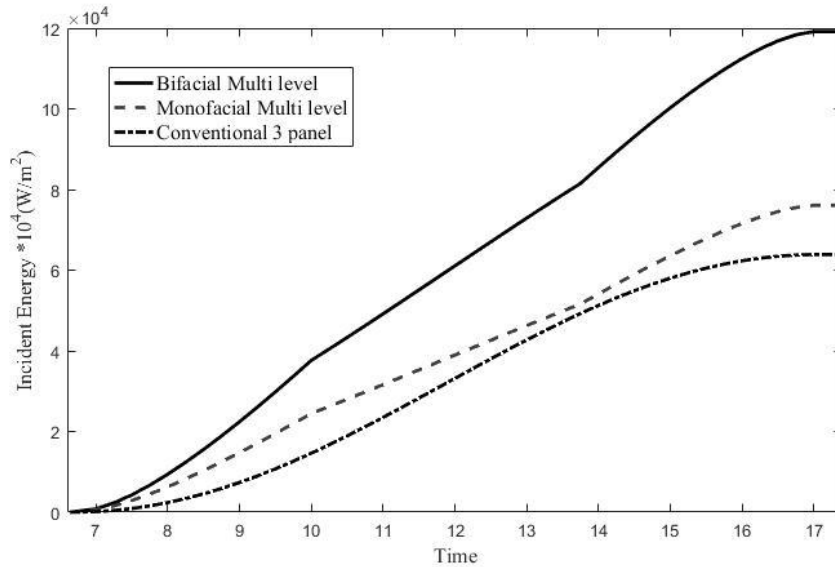
Fig 4.11 Cumulative Energy of Proposed Bifacial System, Previous Mono Facial System &

Conventional 3 Monofacial Fixed panel for Specific day January 15th

The cumulative Energy of the systems show that during 12-2pm Monofacial multilevel and conventional 3 panel the cumulative energy difference is lower because during noon multilevel system mid panel is vertical so it gets no direct energy from the sun where as in that pick solar irradiance hour 3 panels all harness more energy. Thus the difference is lower. But none of the systems fail to come closer to energy harnessed by bifacial multilevel system.

Monthly incident energy:

Comparison of monthly incident energy of multilevel mono and bifacial module based system with conventional fixed system shows in Figure 4.12. Here no environmental impact has been considered. Fig 4.12 shows that, bifacial based multilevel system has higher energy collection

than the mono-facial based and fixed system. It shows during the summer energy is higher due to the sun position. It shows winter has lower energy gain.

Comparison of monthly incident energy of multilevel mono and bifacial module-based system with conventional fixed system shows in Figure 4.13. Here energy calculation is done considering cloud impact. All the calculations are completed using the equations from cloud effects described in theoretical background chapter. Result shows that, these systems get less
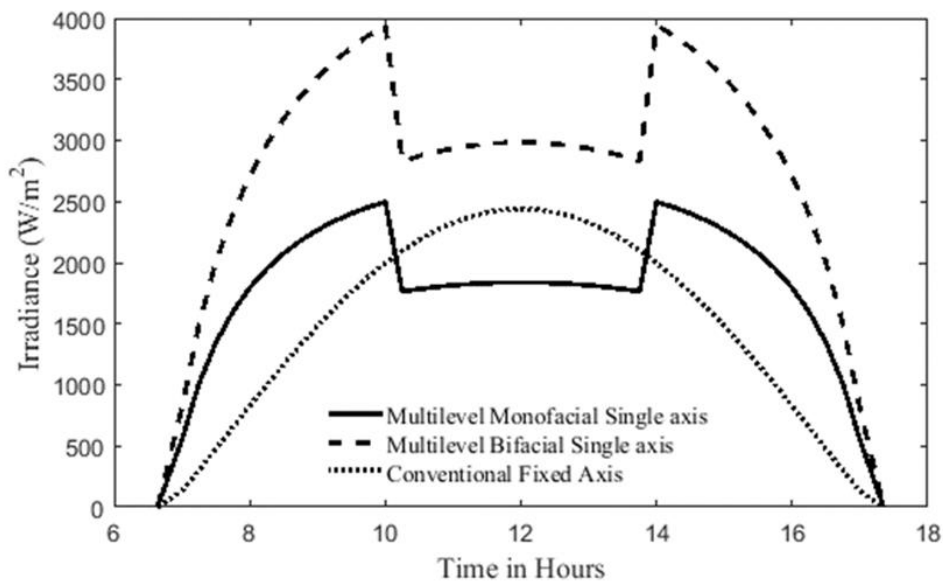

Fig 4.12 Comparison of monthly incident solar intensity of mono and bifacial module based multilevel solar panel system with conventional fixed system without cloud impact.

energy during the months of June to September. March to May shows moderately high energy. Though these months have the highest irradiation considering sun position. But in real scenario clouds impacts the most on those months. During summer bifacial module based system gives 94.57% extra energy compared to Conventional system and 56.05% extra energy compared to Mono facial Based System. During winter proposed system gives 84.77% extra energy compared
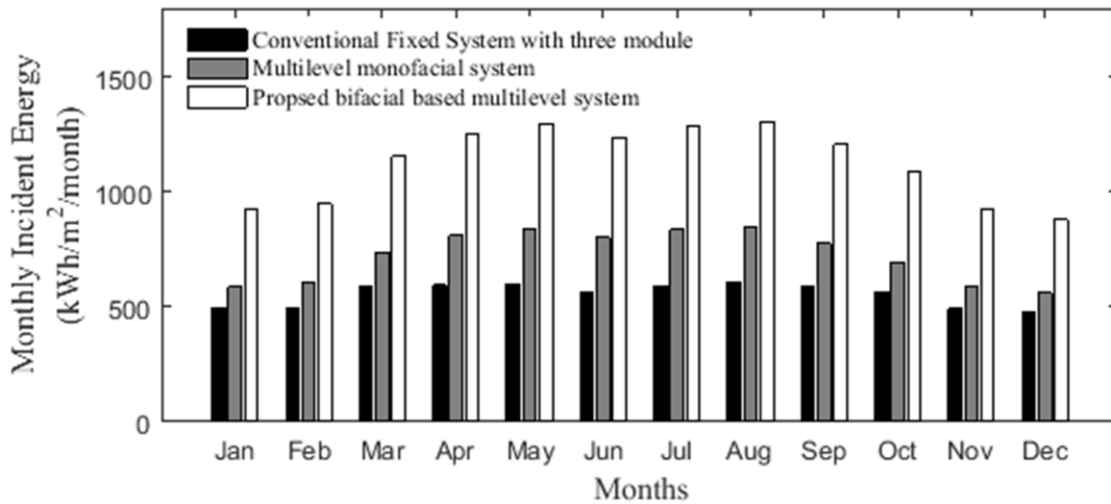
Fig 4.13 Comparison of monthly incident solar intensity of mono and bifacial module based multilevel solar panel system with conventional fixed system considering cloud impact.

to Conventional system and 56.7% extra energy compared to Mono facial Based System. The proposed system shows
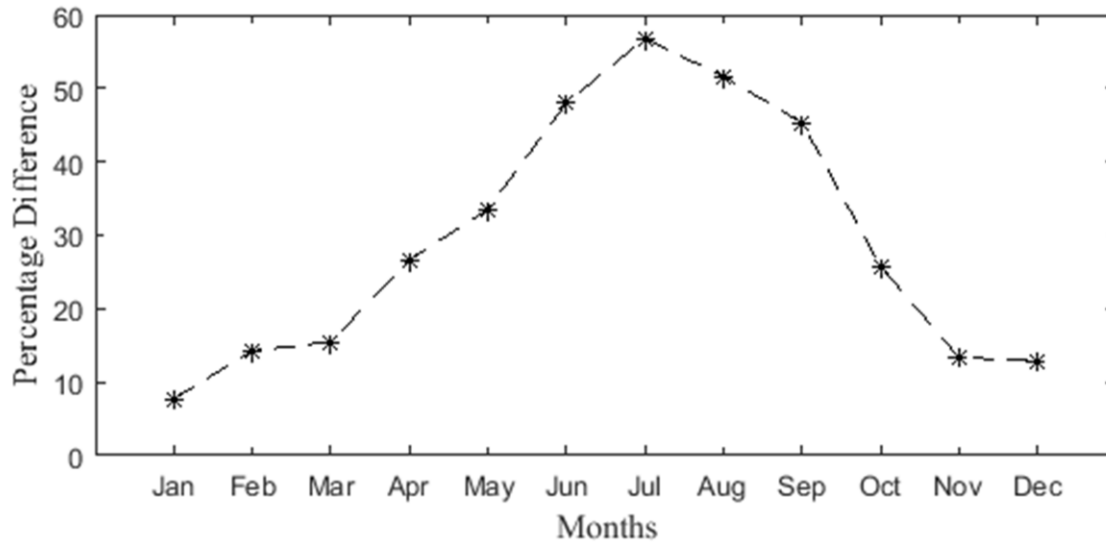
Fig 4.14 Percentage decrease from without cloud condition of bifacial based multilevel system.

Figure 4.14 shows decreased percentage value of bifacial multilevel system from no cloud consideration. It shows significant energy decrement from May to September. That is the rainy season in our country. So, energy is much lower than the other months. In our country cloud and rainy days affects these months greatly around 50%.

4.4 Electrical Output considering cloud cover

Monthly electrical output of the proposed system is shown in Fig. 4.14. Also the cloud impact output is shown in Fig. 4.15. Like as incident energy calculation results shows less electrical output in the months of June to September. Percentage differences remained same as incident energy calculations.
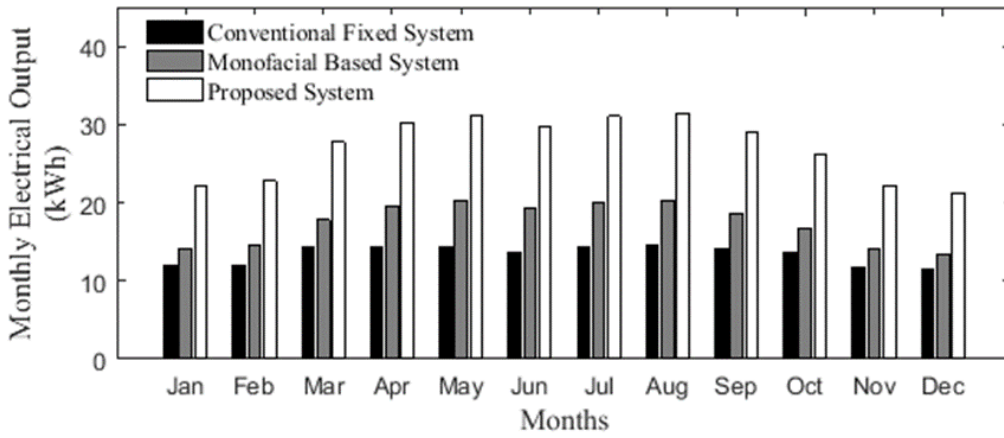
Fig 4.15 Comparison of monthly electrical output of mono and bifacial module based multilevel solar panel system with conventional fixed system considering without cloud impact.
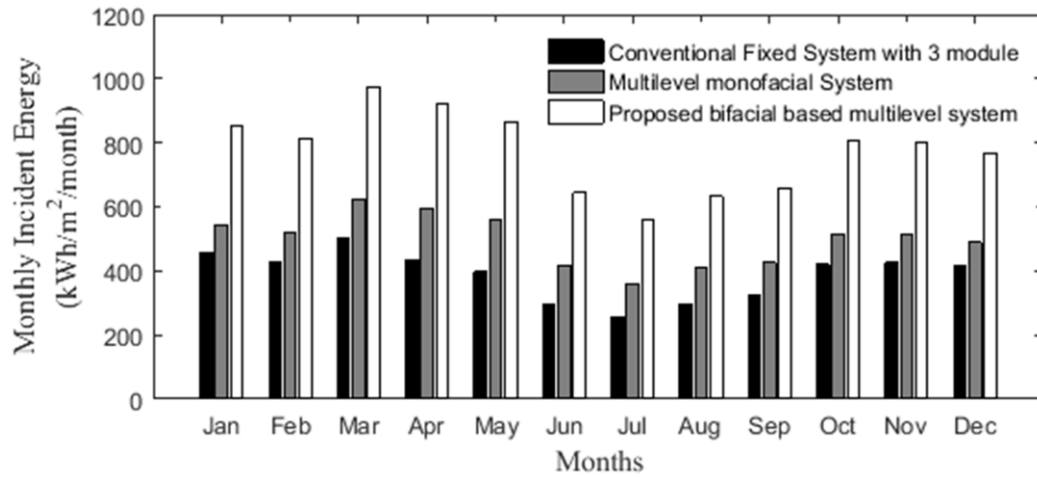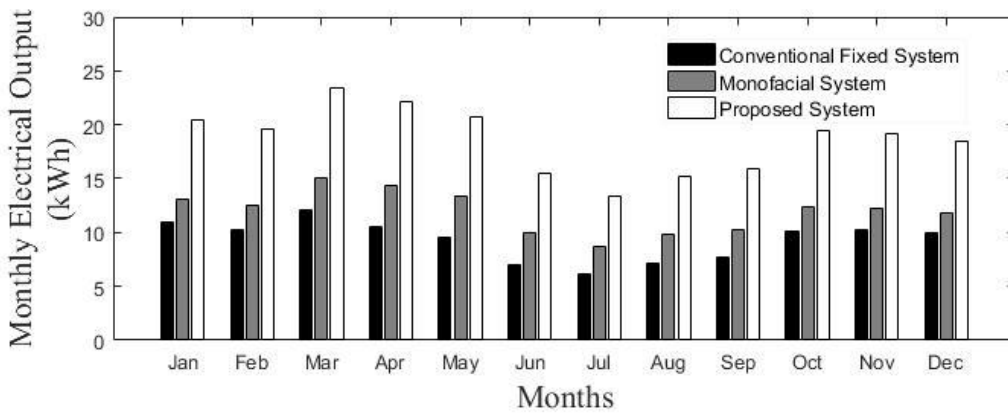

Fig 4.16 Comparison of monthly electrical output of mono and bifacial module based multilevel solar panel system with conventional fixed system considering without cloud impact.
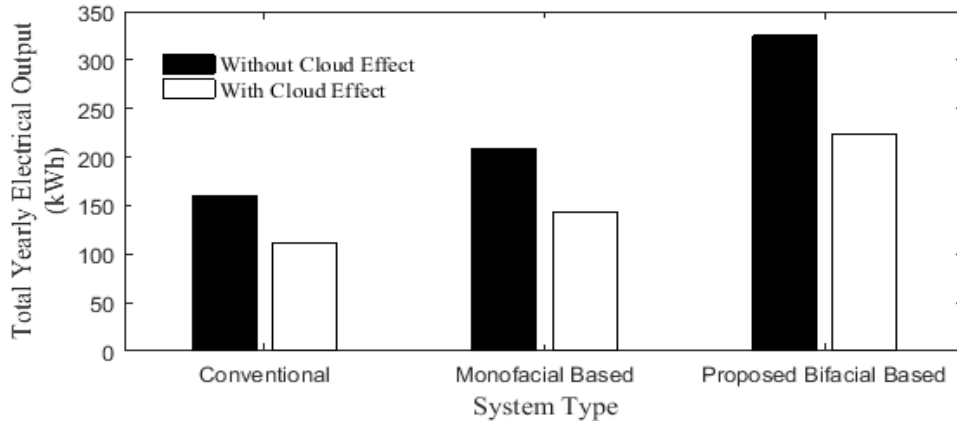
Fig 4.17 Yearly electrical output of proposed multilevel system along with conventional and mono-facial multilevel system considering cloud and without cloud condition.

Figure 4.16 shows the electrical output comparison. Table 4.3 presents the total output results. The percentage denotes the cloud impact difference from the no cloud condition. It gives 100.06% more Electrical Output than Conventional system and 55.63% more Electrical output than previous Mono facial system.

Table. 4.3. Comparison of Yearly Electrical output

System Type	Yearly Electrical Output Without Cloud Effect (kWh)	Yearly Electrical Output With Cloud Effect (kWh)	(%) Difference
Conventional 3 Mono facial Fixed Panel	160.338	111.700	-30.33
Mono facial Multilevel Single Axis Tracker	209.083	143.590	-31.32
Bi-facial Multilevel Single Axis Tracker	325.014	223.470	-31.24

4.5 Incident Energy Considering Albedo Factor

Higher albedo gives additional energy. So, there is a linear relation between Albedo and Energy harnessed. In this study albedo value is taken 0.4 which is not very high. Because in urban areas the system rooftops are mostly covered with cement layer. Figure 4.15 shows that the proposed system harness more energy on higher albedo. As well as electrical output is increased along with the increment of albedor factor. This is the advantage of using bifacial module in the proposed system.

Fig. 4.18. Yearly electrical output and incident energy change with albedo factor of proposed system

Chapter 5

Conclusions and Future Work

In this work a bifacial based multilevel solar panel system has been proposed and studied. Conventional module harnesses energy but it requires more space. But multilevel system needs less space. Previous 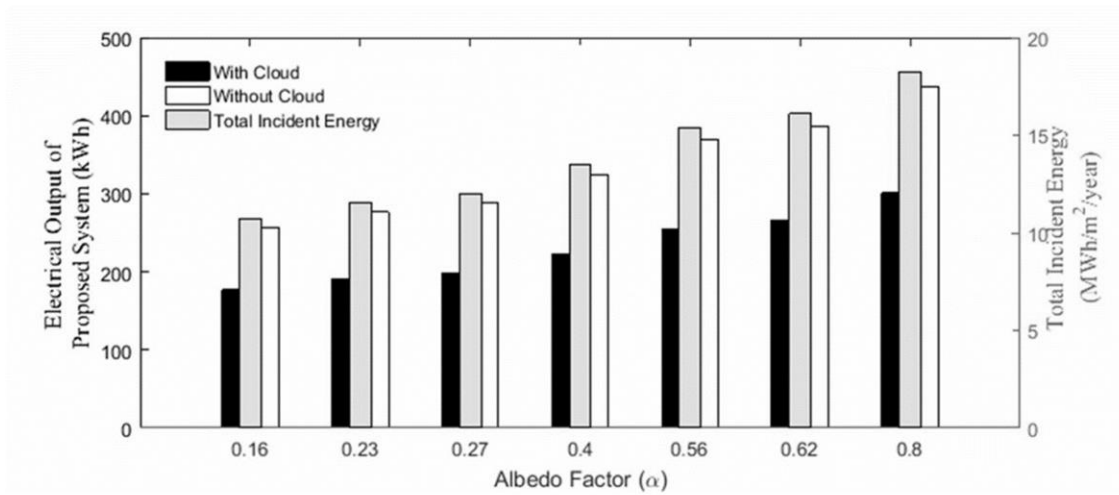works has been done using mono-facial based module. But recently bifacial module has considered one of the most promising module for photovoltaic system. In this study the proposed Bifacial Multilevel based System gives significantly more power (55.63%) than the mono-facial system. In previous study the mid module can't harness energy due the shading. In the proposed system bifacial module harness diffused and reflected energy, which impact on the output. As well as rear module gets the albedo impact which increases the energy yield. As the system has already designed with ground clearance almost 1m from the ground to top module, it will yield additional energy. (10%-15%). It is not considered in previous system. Also Seasonal variation has greatly affects the output. In previous system, seasonal impact is ignored. It shows that seasonal variation impacts the proposed system. The proposed bifacial system shows 31.24% less electrical output than the no cloud condition. As albedo factor depends on the reflectivity of the ground, it is possible to increase additional energy yield by changing the ground reflectivity and material. Thus energy boosting can increase the electrical output of multilevel system.

In future the implementation of bifacial module based multilevel solar module system will be done. Also how the environmental parameter such as albedo can affect the proposed system will also be considered.

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[16]

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FORTRAN, Pascal and C++,(revised), Universities Press

Appendix A.

1. Matlab Code:

```
x1=[10.586 11.973 13.092 14.525 14.491 14.25 14.379 14.593 14.03 12.366
10.918 10.114];
x2=[8.536 9.483 10.231 10.589 10.323 10.069 10.196 10.53 10.497 9.749
8.763 8.213];
x3=[4.063 4.733 5.288 6.246 6.350 6.285 6.324 6.329 5.898 4.925 4.223
3.837];
x4=[6.391 7.421 8.272 9.669 9.801 9.691 9.754 9.784 9.164 7.715 6.637
6.043];
x5=[4.471 4.973 5.408 6.519 6.902 7.057 6.997 6.698 6.058 5.114 4.592
4.295];
x6=[6.767 7.668 8.396 9.376 9.374 9.224 9.304 9.429 9.035 7.923 6.983
6.461];
x7=[5.324 5.914 6.381 6.604 6.438 6.280 6.359 6.567 6.547 6.080 5.465
5.122];
m1=[29.790 33.905 37.247 41.865 41.937 41.297 41.644 42.138 40.245 35.075
30.773 28.393];
m2=[19.019 21.693 23.868 27.028 27.138 26.745 26.960 27.233 25.913 22.453
19.658 18.112];
sunny=[28 23 25 20 18 12 9 11 13 21 25 26];
cloudy=[3 5 6 10 13 18 22 20 17 10 5 5];
days=[31 28 31 30 31 30 31 31 30 31 30 31];
sunnyenergy=x.*sunny;
```

```
cloudyenergy=x.*cloudy*(0.2);

monthlywithoutcloud=x.*days;

monthlywithcloud=sunnyenergy+cloudyenergy;

yearlywithoutcloud=sum(monthlywithoutcloud);

yearlywithcloud=sum(monthlywithcloud);

electricoutputwithcloud=0.120218*.2*monthlywithcloud*3;

electricoutputwithoutcloud=0.120218*.2*monthlywithoutcloud*3;

a=sum(electricoutputwithoutcloud)

b=sum(electricoutputwithcloud)


em1=[14.1758    14.6042    17.7901    19.4955    20.2274    19.2914    20.0947
20.2982    18.6913    16.7354    14.1795    13.4998];

em2=[13.0784    12.5179    15.0355    14.2967    13.4414    10.0315    8.6861
9.8217    10.2179    12.4166    12.2889    11.7579];


eb1=[22.2040    22.8256    27.7621    30.1976    31.2578    29.7879    31.0394
31.4076    29.0290    26.1432    22.1968    21.1628];

eb2=[20.4850    19.5648    23.4635    22.1449    20.7713    15.4897    13.4170
15.1972    15.8692    19.3966    19.2372    18.4321];


mf1=[11.9048    11.9443    14.2683    14.2906    14.3957    13.5894    14.2191
14.6842    14.1672    13.5952    11.8258 11.4531];

mf2=[10.9831    10.2380    12.0590    10.4797    9.5662    7.0665    6.1463
7.1052    7.7447    10.0868    10.2491    9.9753];
```

Appendix A.

2. Matlab Code:

```
function I=Intensity(n,t)
q=23.5;
a=q*(sind((360/365)*(n-80)));
Sr=12-((1/15)*(acosd(-tand(a)*tand(q))));
Ss=12+((1/15)*(acosd(-tand(a)*tand(q))));
ws=acosd((-tand(a)*tand(q)));
T=Ss-Sr;
w=(-ws+(((2*ws)/T)*(t-Sr)));
A=asind((sind(a)*sind(q))+(cosd(a)*cosd(q)*cosd(w)));
Za=90-A;
AM=(1/cosd(Za));
Io=1367*((0.7)^(AM^(0.678)));
I=Io*cosd(a)*cosd(w);
end
```

Appendix B.

3. LG Neon®2 Datasheet

LG NeON® 2 BiFacial

LG395N2T-A5 | LG390N2T-A5

Electrical Properties (STC*)

| | | LG395N2T - A5 | Bifaical Gain** | | | | LG390N2T - A5 | Bifacial Gain** | | | |
			5%	10%	20%	30%		5%	10%	20%	30%
Maximum Power (Pmax)	[W]	395	415	435	474	514	390	410	429	468	507
MPP Voltage (Vmpp)	[V]	41.8	41.8	41.8	41.9	41.9	41.4	41.4	41.4	41.5	41.5
MPP Current (Impp)	[A]	9.46	9.92	10.39	11.31	12.26	9.43	9.90	10.36	11.28	12.22
Open Circuit Voltage (Voc)	[V]	49.3	49.3	49.3	49.4	49.4	49.2	49.2	49.2	49.3	49.3
Short Circuit Current (Isc)	[A]	10.19	10.70	11.21	12.23	13.25	10.15	10.15	11.17	12.18	13.20
Module Efficiency	[%]	18.7	19.6	20.6	22.4	24.3	18.5	19.4	20.3	22.1	24.0
Operating Temperature	[°C]	-40 – +90									
Maximum System Voltage	[V]	1,500(UL) / 1,000(IEC)									
Maximum Series Fuse Rating	[A]	20									
Pmax Bifaciality Coefficient***	[%]	76									
Power Tolerance	[%]	0 – +3									

The nameplate power output is measured and determined by LG Electronics at its sole and absolute discretion.
* STC (Standard Test Condition): Irradiance 1,000 W/m², cell temperature 25 °C, AM 1.5(Measurement Tolerance : ±3%, Electrical Parameter Tolerance : ±5%)
** Bifacial Gain: The additional gain from the back side compared to the power of the front side at the standard test condition. It depends on installation condition.
*** Pmax Bifaciality Coefficient 25years warranty based on front output warranty. tolerance±7%

Mechanical Properties

| Cells	6 x 12
Cell Type	Monocrystalline / N-type
Cell Dimensions	161.7 x 161.7 mm / 6 inches
≈ of Busbar	12(Multi Wire Busbar)
Dimensions (L x W x H)	2,064 x 1,024 x 40 mm
	81.26 x 40.31 x 1.57 in
Front Load	5,400 Pa / 113 psf*
Rear Load	4,300 Pa / 90 psf*
Weight	22.0 kg / 48.72 lb
Connector Type	MC4 (MC), PV-JM601A (JMTHY)
Junction Box	IP68 with 3 Bypass Diodes
Cables	1,200 mm x 2 ea / 47.24 in x 2 ea
Glass	High Transmission Tempered Glass
Frame	Anodized Aluminium

* Please refer to the installation manual for the details

Electrical Properties (NOCT*)

Model		LG395N2T-A5	LG390N2T-A5
Maximum Power (Pmax)	[W]	292	289
MPP Voltage (Vmpp)	[V]	38.7	38.3
MPP Current (Impp)	[A]	7.55	7.54
Open Circuit Voltage (Voc)	[V]	46.0	45.9
Short Circuit Current (Isc)	[A]	8.20	8.17

* NOCT (Nominal Operating Cell Temperature): Irradiance 800 W/m², ambient temperature 20 °C, wind speed 1 m/s
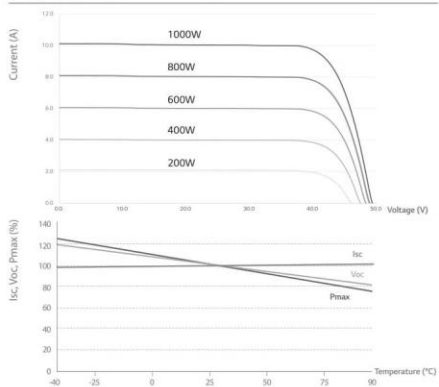
Certifications and Warranty

|	UL 1703
Certifications	IEC 61215, IEC 61730-1/-2
	IEC 61701 (Salt mist corrosion test)
	IEC 62716 (Ammonia corrosion test)
	ISO 9001
Module Fire Performance	Type 1(UL 1703)
Fire Resistance Class	Class C (ULC/ORD C1703, IEC 61730)
Product Warranty	25 Years
Output Warranty of Pmax	Linear Warranty*

* 1) 1st year: 98%, 2) After 1st year: 0.5% annual degradation, 3) 86% for 25 years

Temperature Characteristics

NOCT	[°C]	45 ± 3
Pmax	[%/°C]	-0.36
Voc	[%/°C]	-0.27
Isc	[%/°C]	0.03

Characteristic Curves

Dimensions (mm / inch)
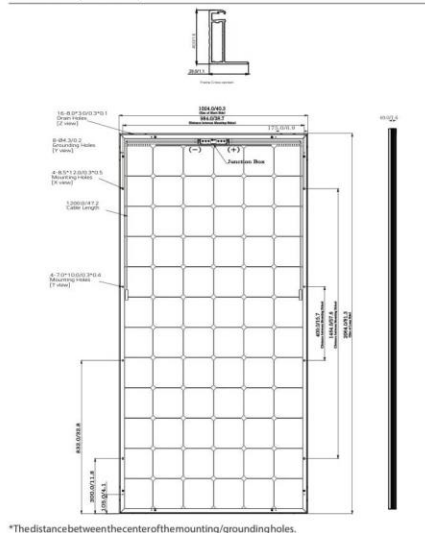
*The distance between the center of the mounting/grounding holes.

LG Electronics Inc.
Solar Business Division
LG Twin Towers, 128 Yeoui-daero, Yeongdeungpo-gu, Seoul 07336, Korea
www.lg-solar.com

Product specifications are subject to change without notice.
DS-T5-72-W-G-P-EN-80510

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Appendix C.

4. Geogebra Code

$B = (0, 0, 1)$

$C = (0, 0, 0)$

$U = \text{Vector}(C, B)$

$\rightarrow \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

$A = (0.4, 0, 0.92)$

$V = \text{Vector}(C, A)$

$\rightarrow \begin{pmatrix} 0.4 \\ 0 \\ 0.92 \end{pmatrix}$

$\alpha = \text{Angle}(\text{Vector}(A), \text{Vector}(B))$

$\rightarrow 23.5°$

Geogebra plot