B. TECH. PROJECT REPORT

On

Feasibility analysis of Bifacial module in Ahmedabad

BY

RUSHIL PATEL	**AU1743021**
NISARG PATEL	**AU1743024**
JAINAM SHAH	**AU1743025**
DHRUVIL PATEL	**AU1743042**

Discipline of Mechanical Engineering

Ahmedabad University

SCHOOL OF ENGINEERING & APPLIED SCIENCE

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Feasibility analysis of bifacial photovoltaic module in Ahmedabad

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Submitted in partial fulfillment of the requirements for the award of the degrees

of

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in

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Submitted by:

RUSHIL PATEL	**AU1743021**
NISARG PATEL	**AU1743024**
JAINAM SHAH	**AU1743025**
DHRUVIL PATEL	**AU1743042**

Guided by:

Dr. Deepak Verma

Assistant Professor, Ahmedabad University

Ahmedabad University

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CANDIDATE'S DECLARATION

We hereby declare that the project entitled **Feasibility analysis of Bifacial Module in Ahmedabad** submitted in partial fulfilment for the award of the degree of Bachelor of Technology in Mechanical Engineering completed under the supervision of **Dr. Deepak Verma**, Assistant Professor, Ahmedabad University is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere. We certify that whenever we have used materials (data, images, theoretical analysis, and text) from other sources, we have given full credit to them in the text of the report and given their details in the references.

________________________________ Date: 12/05/2021

Rushil Patel

________________________________ Date: 12/05/2021

Nisarg Patel

________________________________ Date: 12/05/2021

Jainam Shah

________________________________ Date: 12/05/2021

Dhruvil Patel

CERTIFICATE by Project Guide

It is certified that the above statement made by the student is correct to the best of my knowledge.

________________________________ Date: 12/05/2021

Dr. Deepak Verma

Assistant Professor, Ahmedabad University

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ABSTRACT

India has very favorable conditions for harvesting solar energy due to its geographic position. Also the Government pledges to have India as one of the largest photovoltaic solar energy markets in the world by being the only country having a separate ministry to promote renewable energy sources. Inline with the government's vision of smart cities, where guidelines provide that 10% of the energy requirement of smart cities should come from solar energy to reduce greenhouse gas and carbon footprint of metropolitan cities like Ahmedabad.

Recently, bifacial modules are commercially available for photovoltaic application. A bi-facial solar panel produces power from both the sides and therefore it would be interesting to study the feasibility of such modules at such public sites as no study has been conducted in this region for Bifacial modules. Several existing approaches have been tested in this study to evaluate the PV bifacial module temperature, efficiency, bifacial gain as a function of solar irradiance, ambient temperature, wind and other parameters. In this study, Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) with front side and rear side irradiance has been calculated from Global Horizontal Irradiance. It has been deduced that the inclusion of cooling effects of wind plays an important role for a better evaluation of efficiency. Our results demonstrate that an optimally tilted angle of 43.5° gives highest efficiency of 24% at ambient temperature. Moreover, there is a culmination that bifacial modules give highest efficiency in the month of January in contrast to the August month when it is lowest. A detailed and systematic analysis of important parameters like installation, system designing, cost economics and carbon reduction validates the feasibility of the Bifacial system done in this study.

Keywords: Solar cells, Bifacial Modules, PV efficiency, Bifacial gain, Temperature, Solar irradiation, Cost economics.

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CHAPTER 1. INTRODUCTION

Fossil fuels have been a source of energy for humans for many centuries. Reliability and availability were two contributing factors for this long dependence. Today the world we live in is becoming more and more dependent on electrical energy. Unfortunately, production of electricity still heavily depends on fossil fuels. As we are aware that we have just 100 years of coal production left, 50 years of crude oil, and 50 years of natural gas. Shortage and negative repercussions of these resources is bound to happen in the future leading to impass to growth and development for coming generations of mankind. Additionally, burning fossil fuels produce pollution ranging from climate changing greenhouse gases to health endangering particles, which have reached record levels. Carbon Dioxide and other gases emitted from burning fossil fuels is a major contributor to global warming. Renewable sources of energy provide a perfect alternative to meet our ever increasing energy demands without inflicting self-destruction on our planet.

On the international level, various countries have joined hands and signed the Paris Agreement to fight against climate change. Affordable and Clean Energy is one of the UN sustainable goals, which shows awareness and motivation in people globally for shifting to clean energy sources. Hence the primary objective for turning to renewable energy sources is to reduce the pessimistic environmental effects associated with non renewable energy sources and improve public health. Unlike non-renewable energy, renewable energy is derived from energy sources that can be replenished in one human life-time, making it virtually inexhaustible. Also, it does not emit greenhouse gases during the energy generation process, making it the cleanest and most viable solution to prevent climate change.

Renewable energy gives a greater degree of independence in terms of energy to each household. Armed with solar panels, energy can be produced and accessed at any remote location without relying on a power grid. This independence is a boon to developing countries where the majority of population is left out from access to clean and affordable energy.

1.1. Need of Photovoltaics

India has taken the lead in generating and promoting Solar energy as an initiative of the International Solar Alliance of 121 countries in November 2015. Factors like accessibility and affordability are leading to solar energy becoming the fastest growing energy source in the world. This year there will be more than 115 GW of solar panels installed across the globe, which is more than all other generation technologies combined. In sunnier countries like India, grid parity for solar energy is already achieved. Also technology advancement will do nothing but reduce the cost of energy generation, making the Levelized Cost of Electricity unbeatable compared to fossil fuels. These factors clearly point towards a brighter future for solar energy in coming years.

The foundation of solar energy is the solar cells, which generate electricity based on the principle of photovoltaic effect. Photons from sunlight strike and ionize semiconductor material on the solar cells, causing outer electrons to break free of their atomic bonds. Due to semiconductor structure, the electrons are forced in one direction creating a flow of electrical current. Below figure shows the working principle of photovoltaic effect for energy generation.

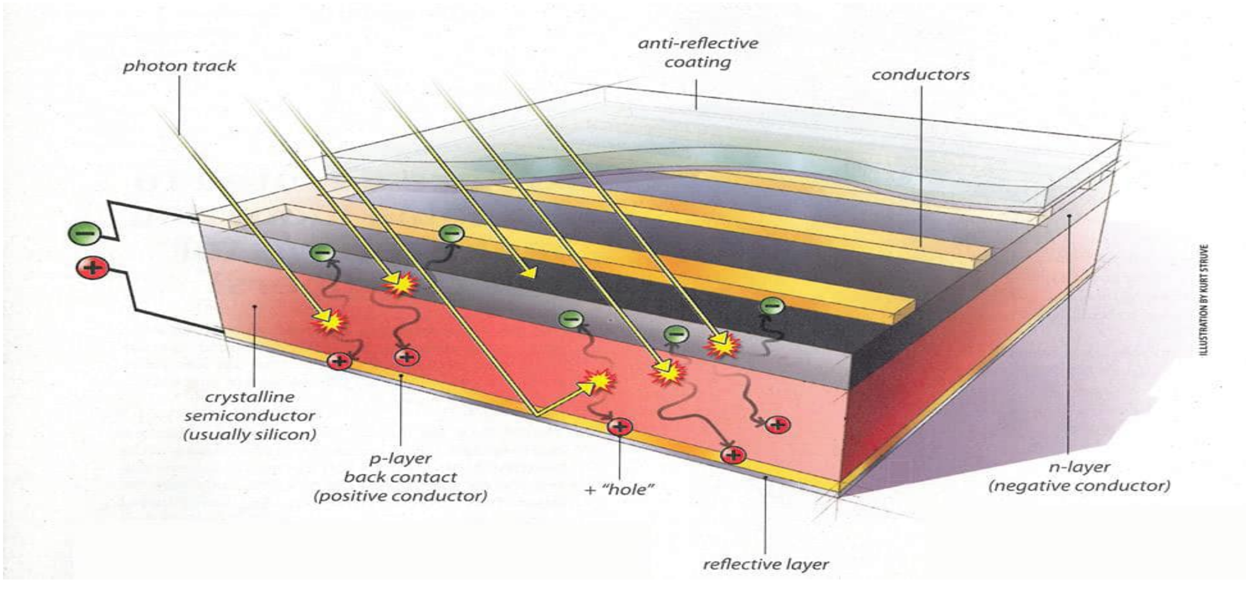


Figure: 1.1 Diagram of Typical Silicon Solar Cell [1]

There are three most prominent solar PV technologies in the market which are Monocrystalline, Polycrystalline and Thin-film solar modules. Monocrystalline and Polycrystalline are made from silicon wafer but vary in its composition. Monocrystalline wafers are made from a single pure crystal of silicon whereas Polycrystalline wafers are composed of fragments of silicon that are melted together. Thin-film solar cells are from a variety of materials like cadmium telluride(CdTe), amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS). Depending upon factors like site location and desired system characteristics one of them is chosen accordingly for energy generation.

1.2. *Bifacial Photovoltaic Modules : The best alternative*

Depending upon the structure of the module Monocrystalline and Polycrystalline solar modules are further divided into monofacial and Bifacial modules. Monofacial modules produce their electrical power output as a function of direct and diffused radiation captured on the front side of the panel only. By contrast, bifacial modules convert light captured on both front and back sides of the module into electrical power. This unique feature allows the bifacial to produce greater power output compared to monofacial PV modules. Other advantages include high power density, significant Balance of Solar systems (BOS) savings, high energy yield, better low light performance and lower temperature coefficient over monofacial modules. For producing the same degree of solar power as a typical monofacial solar array, fewer bifacial solar panels are needed. This makes bifacial more suitable for residential applications. Also they have an aesthetic appeal which makes them easily integrated into the home's appearance. Below figure shows fundamental difference in working of these two types of modules.

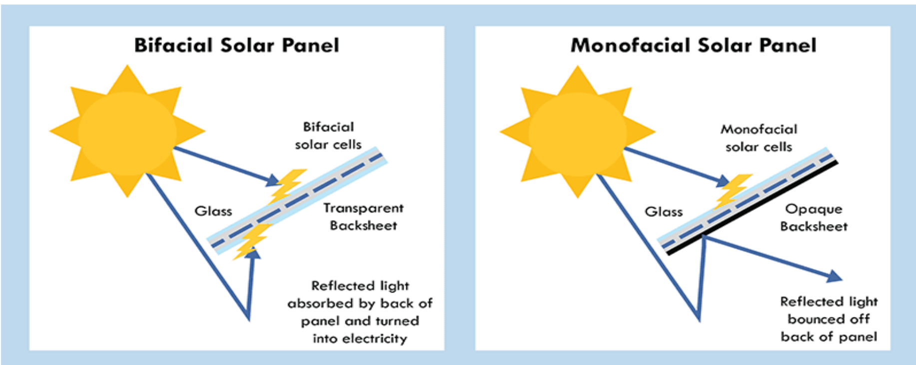


Figure: 1.2 Difference between Bifacial and Monofacial [2]

1.3. Motivation

Bifacial modules have been around since the 1960's, yet recent development of PERC (Passivated Emitter and Rear Cell) technology in both monofacial and bifacial PV modules has significantly increased their efficiencies. Also due to technological advancement the cost of bifacial modules has fallen drastically over the last two decades, so has the cost gap between monofacial and bifacial modules. Higher efficiency and little cost gap explains why bifacial module market share is predicted to continue to increase to 40% by 2028 making bifacial the next breakthrough in the solar PV market. India has very favorable conditions for harvesting solar energy due to its geographic position. Also the Government pledges to have India as one of the largest photovoltaic solar energy markets in the world by being the only country having a separate ministry to promote renewable energy sources. These factors motivate our feasibility study of bifacial modules in the region of Ahmedabad.

1.4. Expected Outcomes

In this report, there will be an exploration for the feasibility of bifacial modules for Ahmedabad city along with the following objectives:

- Understanding the photovoltaic systems in detail and constraints for such systems
- Understanding the effect of various parameters like temperature, wind, orientation, albedo etc. on Bifacial PV power output.
- Exploring the integration of bifacial modules in building
- Understanding the challenges of commercial designing of photovoltaic systems
- Cost-benefit and CO_2 reduction analysis for a given Bifacial PV system.

CHAPTER 2. LITERATURE REVIEW

This section will extensively explore the research relevant to determining the power output from bifacial solar modules. Specific emphasis is given on factors affecting efficiency of bifacial solar panels and existing methodologies used to determine rear-side power generation from bifacial modules. This review is done keeping in mind the aim to better understand how outdoor conditions of Ahmedabad city influence the performances of PV, working of bifacial modules and determining a model to predict output of the proposed system.

2.1. Notable work in Bifacial Technology

A global optimization study [3] for bifacial modules concluded that bifacial gain for ground mounted modules is less than 10%, considering a low albedo of 0.25. But, by improving the albedo to 0.5 and keeping the clearance height of 1 meter, bifacial gain can increase upto 30%. They also found that ground mounted, east-west facing modules will outperform south-north facing modules by 15% for a latitude below 30 degrees, having an albedo of 0.5.

Validate study done by [4] on the single-axis tracking system for the bifacial modules, concluded that when 1-axis tracking system is used for bifacial modules, it can increase energy output by a global average of 9%; which is an addition to the typical 15-25% gain obtained by using a single-axis tracking instead of fixed tilt system. They also experimented with bifacial and monofacial panels side by side at Albuquerque, New Mexico and reported the bifacial gain to be 10-15%. Also by using smart tracking algorithms we can increase annual energy output by 1%.

A Comparison had been done among five solar rear irradiance models for bifacial systems [5], that is Prism Solar and Solar World, which are empirical fits; commercially available like PVSyst and NREL View Factor and the most complex NREL Radiance. They analyzed them by varying parameters like tilt angle, row spacing and clearance height, and found that some configurations can get us bifacial gain as high as 20%. Also, there is a better agreement among these models for a clearance that is lower than 0.75 times of the module width. However, at higher clearance height there was a better uniformity in rear side irradiance. Overall empirical models were less accurate and from the non-empirical ones, NREL View factor was the most accurate. Also, by conducting field tests, the measurement results were in agreement having error within 2% for most configurations.

An overview of the bifacial photovoltaic system is done in the study [6] by considering the principle of bifaciality, structure of a module and various losses during the energy production. They have analyzed through numerical modeling, simulation in softwares, future economical aspects, affected parameters and performance of the system. Their results show that the specific structure of a bifacial PV module gives around 5-30% more power output which results in 2-6% less LCOE than the other solar PV modules (Mono-facial). Further, they have concluded that more electricity can be generated with a tracking system, optimal tilt angle, more surface albedo and optimal elevation. And added to that they have covered basic information of non-uniform rear side irradiation energy production in the literature for further research and development in the bifacial photovoltaic technology.

Effect of non-uniformity on the rear side irradiance has been done in [7]. It was found that using white gravel for the ground surface can reduce non-uniformity as low as 10%. Also, the modules in the center of the panel had a slight increase in value above 10% during early mornings and late afternoons. However, it is not guaranteed because non-uniformity depends on module position and time of the day. It was also observed that non-uniformity was least during a cloudy day compared to a clear sky day.

2.2. Market Overview and Applications of Bifacial Technology

Bifacial solar module market is expected to grow from $2.5 billion in 2019 at a CAGR of 16.2% during the forecasted period of 2020-2025. The major factor driving the bifacial solar market is the need for new technological innovation in the solar industry. Other factors like growing affordability, government support and clear advantages of bifacial over monofacial modules are also likely to boost the installations of bifacial solar panels. Moreover many leading solar panel manufacturers such as LG, Solar, Lobgi and Canadian Solar are offering more flexibility in terms of panel power rating.

Currently most common types of bifacial modules available in the market are based on mono-crystalline p-PERC technology. Although not best in terms of efficiency and bifacial coefficients, the fact that it is produced in large numbers gives p-PERC based bifacial modules the highest market share of all bifacial technologies. The n-typed based bifacial modules are considered as the compromise between main-stream p-PERC and more expensive HJT modules.

Global Bifacial solar market has been segmented based on cell, type, end-use and region. Based on end-use, the global market has been segmented into commercial, residential and industrial. The commercial segment is expected to dominate the global bifacial solar market. As the bifacial solar panels are best suited for commercial or utility-scale solar installations due to their ability to absorb energy on both sides. When they are mounted on ground as in the case of most commercial systems, ground reflected albedo plays an important role in energy generation. Additionally, this surface can be adjusted to get more or less light reflected for higher efficiencies. For residential applications, bifacial should be considered when you are installing a ground mounted solar system instead of a rooftop installation.

CHAPTER 3. THEORY

Keeping in view the objectives of this analysis, the first task was to explore working of solar cells then exploring various available cell technologies. At last this section describes the effect of various parameters affecting the efficiency of bifacial modules. This effect of various parameters are learnt and explored by a close study of various research papers discussed above in literature review.

3.1. What is a Photovoltaic cell ?

A Photovoltaic cell is basically a p-n junction diode which converts light into electricity through photovoltaic effect. They are primarily made of silicon which emits photons from the sun's rays. Silicon wafers are doped and electrical contacts are put in place to connect one solar cell to another. Each cell produces voltage of around 0.5 volts, hence they are combined together to form a solar panel with significant output voltage.

Electrical characteristics of solar cells like, voltage, current and resistance vary when exposed to sunlight. These electrical characteristics of PV cells are summarized in a relation between current and voltage produced on a typical solar cell I-V characteristics curve. Intensity of solar irradiation incoming on solar cells controls the current(I) while subsequent increase in temperature of solar cell reduces the voltage. The diagram below shows current-voltage (I-V) characteristic curve for typical silicon PV cells operating under normal conditions.

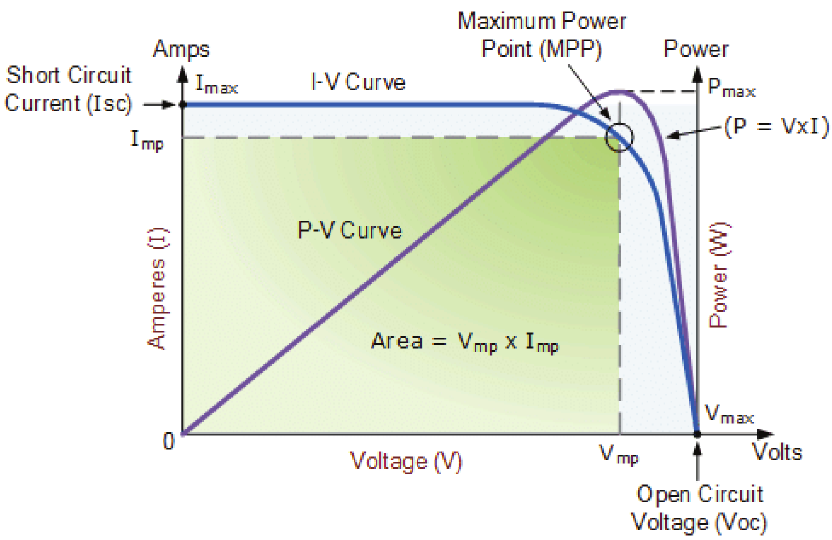


Figure: 3.1.1 Solar Cell I-V Characteristic Curve [8]

As we can see from the graph above, that power delivered by a single solar cell is given by (I x V). If the multiplication is done for all voltages ranging from short circuit to open circuit voltages, then we obtain the above power curve for given irradiation. Rating of a solar panel depends on different parameters which are discussed below. They also provide information on efficiency of solar cells.

- Short Circuit Current (Isc) : It is the maximum current value provided by a solar cell at optimised conditions when the output terminals are short-circuited together. Its value is much higher than current at MPP, which relates to its normal operating circuit current.
- Open Circuit Voltage (Voc) : It is the maximum voltage a solar cell provides when no load is connected. It depends on the number of panels connected in series and techniques of manufacturing.
- Maximum Power Point (MPP or Pm) : It is a point where power supplied by a solar cell when connected to load is at its maximum. As we can see from the above diagram, it occurs at the bend point of the V-I characteristic curve. It is given as, Pm = (Im) * (Vm)
- Current (Im) & Voltage (Vm) at MPP : The current and voltage at which maximum power occurs.
- Fill Factor (FF) : It is the ratio between the maximum power that solar cells can provide at optimised conditions to the product of open-circuit voltage and short-circuit current. The Fill Factor gives an idea about the quality of a solar cell. Closer the FF is to unity, more power it can provide. It typically ranges between 0.7-0.8. Formula for fill factor is given as:

$$Fill\ Factor = \frac{P_m}{I_{sc} \times V_{oc}}$$

- Efficiency: It is the ratio between maximum electrical power output of a solar cell to the amount of solar irradiation hitting the cell. Radiation power on earth is considered as 1000watt/square meter. Considering area of surface as A, formula for efficiency can be given as:

$$Efficiency(\eta) = \frac{P_m}{P_{in}} \approx \frac{P_m}{1000A}$$

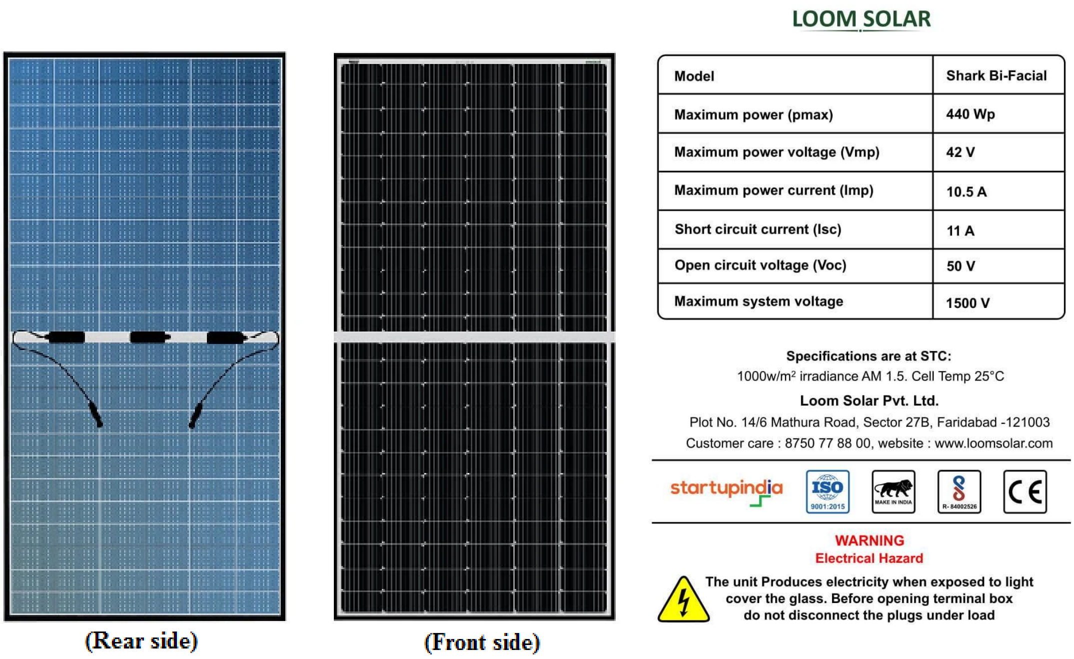


Figure:3.1.2 Front and Rear Image of a real Bifacial Panel [9]

A PV cell can also be represented by an equivalent circuit model as shown in figure below. It includes light induced current source (I_L), a diode that generates a saturation current, shunt resistance (r_{sh}) and series resistance (r_s). The series resistance is due to the resistance of metal contacts, impurity concentrations, junction depth and ohmic losses whereas the shunt resistance is the loss due to crystal defects or impurities near the p-n junction. Ideally, series resistance should be 0 and shunt resistance should be infinite. When external load is connected then total current becomes;

$$I = I_S * (\exp(q*V / kT-1)) - I_L$$

Where, I_S = current due to diode saturation and I_L = current due to optical generation.

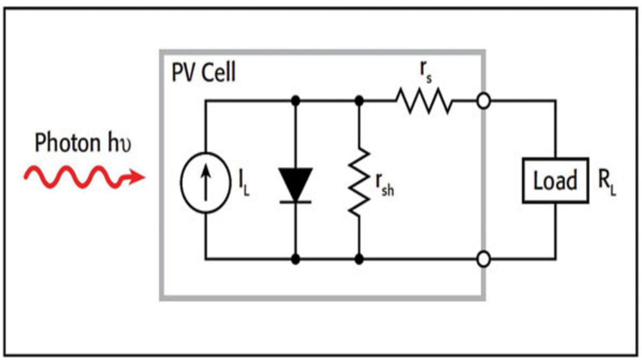


Figure:3.1.3 Circuit of a Solar Cell [10]

3.2 Bifacial solar cell technologies.

In today's PV industry bifacial technology is one of the key ways to improve annual energy output of PV systems and alongside further reduce the levelized cost of energy (LCOE). Bifacial technology is driven by the fact that all advanced solar cell technologies beyond Al-BSF are bifacial or can be made bifacial with minor adjustments. Bifacial properties vary significantly with different solar cell technology. There are three dominant technologies with different bifacial properties: p-PERC, n-PERT, and Hetro-Junction technology (HJT).

1. **p-PERC Technology**: It is the most dominant solar cell technology, due to the fact that it requires only minor changes in manufacturing process to achieve a bifacial p-PERC solar cell. A fine grid of aluminium (Al) is printed on the rear side of the cell for this technology.

2. **n-PERT technology**: This technology has longer carrier lifetime and no light-induced degradation due to absence of boron in the bulk wafer material. These reasons contribute to higher efficiency typical 10-20% of n-type cells over p-type cells. Also, aluminum is not required on the rear-side of solar cells making them bifacial by nature. Only disadvantage is they are more expensive and the cell manufacturing process is less widely accepted, hence they are sold at a premium.

3. **Hetero-Junction technology(HJT):** These cells have a different manufacturing process involving less number of steps, which requires sophisticated and expensive production equipment. This in turn increases the cost of ownership. Though they have higher efficiencies than p- or n-type technologies along with very high bifacial coefficient of >90%. HJT also requires high quality and more expensive n-type wafers for cell manufacturing. It is expected that with increase in volumes of HJT technology, cost for manufacturing will also come down and it will become a dominant solar cell technology in the long run.

3.3 Parameters

There are some important parameters which affect the efficiency of PV bifacial modules. A variety of factors such as temperature, sunlight, dirt, wind etc. are efficacious in calculating cell performance.

There are also some overlooked parameters like deposition of dust on cells, bird droppings, water stains, humidity and wind velocity, which are affecting solar bifacial modules performance and rationally should be considered for design purposes. Here, an analysis of the majority of factors like the effect of wind, dust, humidity, tilt angle, albedo, latitude, and other climatic conditions in terms of efficiency will be elaborated.

3.3.1. Effect of ambient temperature

As discussed about the semiconductor devices in the previous chapter, solar cells are sensitive to temperature. If there is an increase in the temperature, it reduces the bandgap of a semiconductor and therefore will affect its material parameters. As a result, there will be an increase in the energy of the electrons of a semiconductor and a decrease in the band gap of a semiconductor with the increasing temperature. The bond model, which is used as a visualization aid in the analysis of semiconductor devices to study the atoms of the crystals, says that a reduction in the energy also reduces the bandgap. As a result, increasing the temperature reduces the bandgap.

In any particular solar cell, open-circuit voltage is the most affected parameter by an increase in temperature. The reaction of increasing temperature is shown in the figure: 3.3.1,

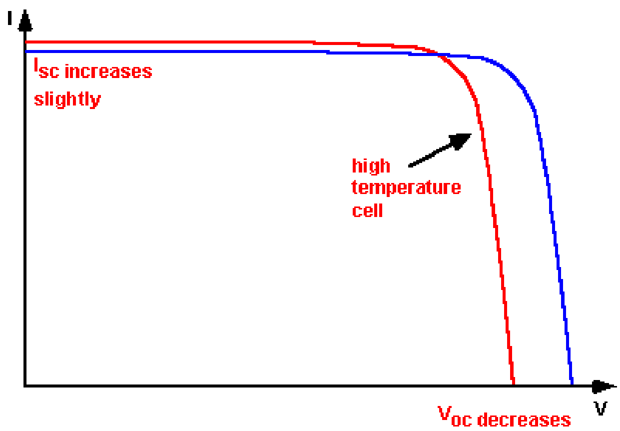


Figure: 3.3.1. Effect of temperature on power output of Solar cell [11]

The Voc decreases with temperature because of the temperature dependence of I_0. The equation for I_0 from one side of a *p-n* junction is given in [11] as;

$$I_0 = qA \frac{Dn_i^2}{LN_D}$$

where:

q: Electronic charge; A: Area; D: Diffusivity of the minority carrier; L: Minority carrier.diffusion length; N_D: doping; n_i: Intrinsic carrier concentration.

In the above equation, many of the parameters have some temperature dependence, but the most remarkable effect is due to the intrinsic carrier concentration, n_i. This parameter depends on the bandgap energy of the cell and on the energy of the carriers. For silicon solar cells, which we have used in our analyses, I_0 approximately doubles for every 10 °C increase in temperature after 25°C.

The below equation shows that the temperature sensitivity of a solar cell depends on the open-circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature:

$$\frac{dV_{OC}}{dT} = \frac{V_{OC} - V_{G0}}{T} - \gamma \frac{k}{q}$$

For silicon, γ as 3, with k as a boltzmann constant gives a reduction in the open-circuit voltage of about 2.2 mV/°C per ℃.

3.3.2 Effect of wind

One of the other important parameters in calculating the efficiency of the module is the effect of wind. The efficiency of the module and cell temperature are inversely proportional to each other. Cell temperature is a function of ambient temperature, wind velocity, solar irradiance, cell material, plate absorption, glazing cover transmittance etc. Therefore: Tc = *f* (Ta, V, Gs, material…).

As indicated in the below figure, there are three modes of heat transfer occurring into or out of the PV control surface. To solve and to find the effect, the heat transfer is assumed one dimensional with the velocity of wind (V) is considered horizontal and uniform.

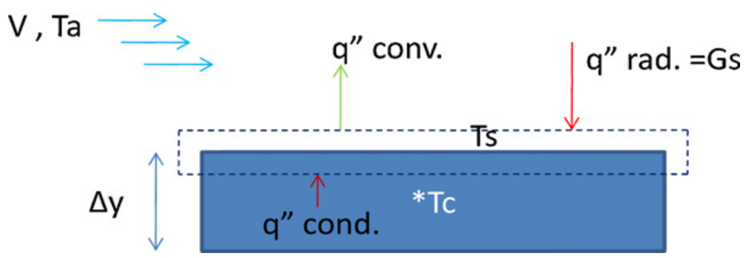


Figure: 3.3.2. The heat transfer scheme of a typical PV cell [12]

So, the conservation of energy equation should be: q''cond. = q''conv. – Gs (radiation)

We have, q''cond. = -2 * k * (Tc-Ts) / Δy , where k = Thermal conductivity

Therefore, q''conv. = h * (Ts -Ta)

To find h (heat transfer coefficient), there is a requirement of Nusselt number (Nu), Prandtl number (pr) and Renault number (Re).

$h = (Nu * k) / L$

So that the energy conversion principle can be implemented which will be:

$-2 * k * (Tc - Ts) / \Delta y = h * (Ts - Ta) - Gs$

We can observe from the equation below that as the wind velocity increases the cell temperature will decrease and better PV cell efficiency will be obtained.

$$\eta = \eta_{Tref} [1 - \beta * Tref * (Tc - Tref)]$$

Apart from the raw method of thermodynamics, there are also many models like Skoplaki, Koehl, Mattei, Kurtz which directly calculate cell temperature and then efficiency is calculated. We have used the Kurtz model in our analyses to calculate the cell temperature of a bifacial module.

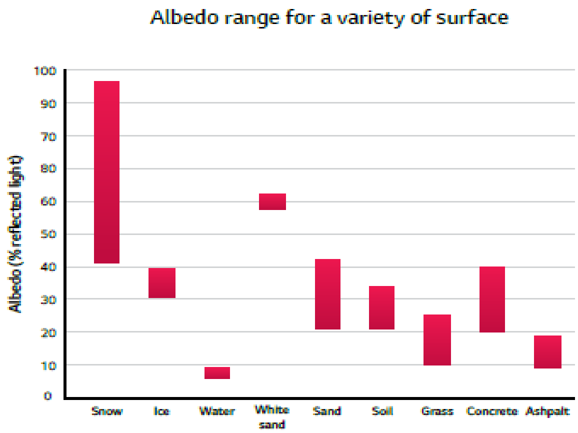
3.3.3. Effect of Albedo

Albedo is defined as the ratio of reflected solar rays from the various surfaces to the incident solar rays on the surface. Basically, Albedo is dependent on the ground reflectance and it is also called Solar Reflectance. Albedo plays an important role in bi-facial PV module output. If albedo is high means reflected light is more, then the light strikes on the backside of the module is more and because of that more power is generated.

Albedo is measured from 0 to 1 the surface which reflects 100% of the solar light then the albedo is 1 and the surface which absorbs 100% of the solar light (Black body) then the albedo is 0 for that surface. There are different values of albedo based on ground surfaces. Although, the Albedo changes accordingly with surface conditions and weather conditions. So, it is a little bit difficult to decide the exact value of Albedo.

Surface	Albedo
Grass	0.15 - 0.25
Fresh snow	0.82
Wet snow	0.55-0.75
Dry asphalt	0.09-0.15
Concrete	0.25-0.35
Aluminum	0.85
New galvanized steel	0.35
Very dirty galvanized	0.08

* Source : PVsyst



* Source : Helmholtz Alfred-Wegener Institute and the National Renewable Energy Laboratory (NREL)

Figure: 3.3.3 Albedo values corresponding to the surface [13]

The reason, albedo is taken into consideration in this study is because it affects significantly to the bifacial gain, as bifacial gain is mainly dependent on the rear side energy production. Here one can see from the following graph how albedo changes with bifacial gain. Albedo can be measured from the pyranometer and also the PVsyst software can be used to determine the value of albedo for a particular site. And also nowadays there is an instrument called Albedometer that is used to measure the Albedo.

3.3.4 Effect of Module Elevation

Module height is the distance between the lowest or bottom part of the module and the ground or surface. This height is also called Module elevation. The module elevation should be optimum to get more solar rays' reflectance, for higher bifacial gain. Because of this module elevation is also an important affecting factor for bifacial power output.

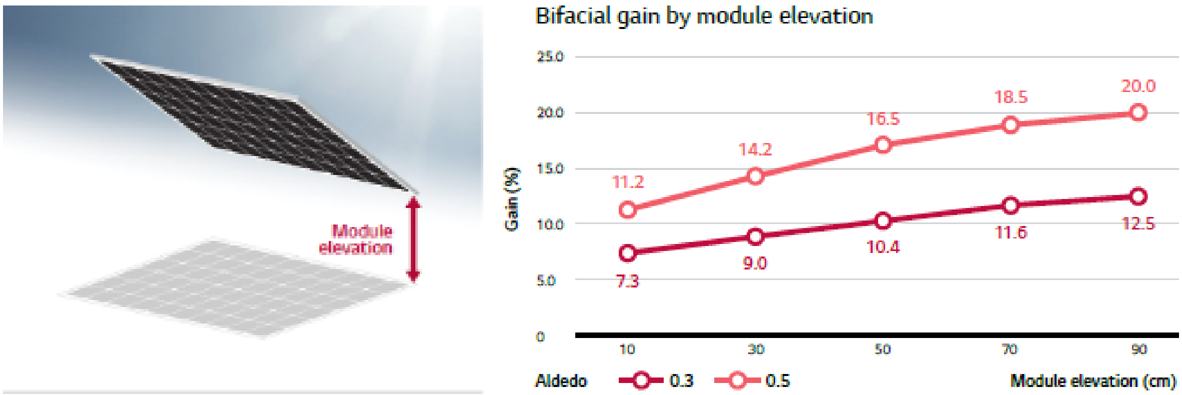


Figure: 3.3.4.. Module elevation and Bifacial Gain [13]

Bifacial gain increases with increased module elevation but the optimum module elevation is found approximately 1 m, but more than this distance may reduce the power output because of the lower reflected solar rays and which results in lesser rear side energy production. If the module elevation has taken lower then its own shadow may affect solar irradiance uniformity and generate lesser rear side energy and which also results in lower bifacial gain.

3.3.5. Effect of latitude and orientation

Location of the solar pv plant and module orientation are important parameters to produce greater power output. PV module orientation depends mainly on azimuth angle, zenith angle, tilt angle and latitude.

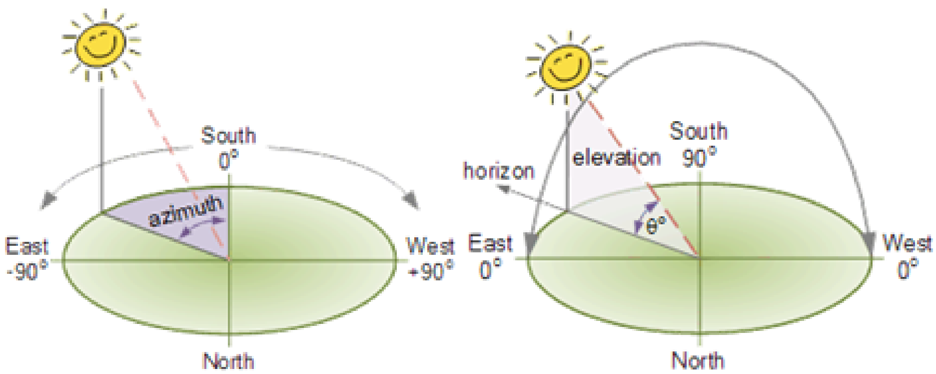


Figure: 3.3.5. Azimuth angle and Zenith angle [14]

Azimuth angle is the angle the sun moves through the sky from east direction to west direction over the day which is calculated from the south. The angle is planar angle.

Zenith angle is the angle of the sun looking up from the horizon. The angle of the sun varies in the form of arc with the sun reaching its maximum elevation over the day. The angle is 3 dimensional. To get more advantage from the sun, the PV module is oriented according to azimuth and zenith angle as they are dependent on the sun movement. Both angles will be calculated further in the report.

Tilt angle is the angle between horizon and PV module. At the equator (means at lower latitude), sun rays hit directly therefore there is no requirement of larger tilt angle of a module and with increase in latitude sun rays hit angularly to the surface which needed more tilt angle. In conclusion, Tilt angle depends on the latitude. As latitude increases tilt angle should be increased to use more or capture more amount of solar radiance.

The optimum tilt angle is 90° for the East-West direction of a module and calculation is needed to find out optimum tilt angle for the direction North-south. Which will be done further in this report.

3.3.6 Effect of other climatic conditions

There are other climatic conditions which affect the power output of the bifacial PV module, one of them is clearness index. The clearness index is the ratio of global horizontal radiance to the corresponding irradiance available of the atmosphere.

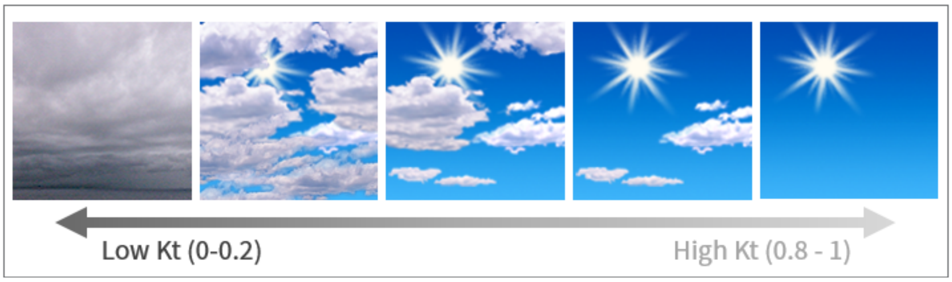


Figure: 3.3.6. Clearness Index (Kt) [15]

The clearness index depends on the geographic location, its value changes with location.The value of the clearness index lies between 0 and 1. Higher the value of the clearness index more the sky is clear.

CHAPTER 4. EVALUATION METHODOLOGY

4.1 Specification of Bifacial Module

For our study we took specifications of ELAN Series N-type PERT Bifacial Photovoltaic module which is commercially available in the market by Adani Solar company. Specifications in the Data Sheet [16] provided by the manufacturer for this particular bifacial module is mentioned in table 4.1.1,

Table: 4.1.1 Specification of ELAN Series N-type PERT Bifacial Module [16]

Electrical Characteristics with 30% ground reflectance on rear side	
Maximum Voltage, Vmp (V)	38.33
Maximum Current, Imp (A)	12.4
Open Circuit Voltage, Voc (V)	46.72
Short Circuit Current, Isc (A)	13.05

Temperature co-efficients (TC)	
TC of open circuit voltage (β)	-0.31% /°C
TC of short circuit current (α)	0.065 % /°C

Mechanical data	
Length	1998 mm
Width	1010 mm
Height	40 mm
Weight	23 kg

4.2 Procuring Meteorological Data

To analyze the feasibility of a bifacial Photovoltaic module in Ahmedabad, there is a need of the climatic data of our site i.e. Ahmedabad. Indian Meteorological Center, Ministry of Earth Sciences at Ahmedabad helped us by providing the daily Meteorological data i.e. Ambient Temperature, Wind Speed, Global Irradiance and Humidity for a period of one year (2020).

4.2.1. Data Filtering

Procured raw meteorological data was unstructured and too messy to process and analyze. Therefore sortation is done for the data of each month and did the proper data filtering to the entire dataset. Data entries which had the global irradiance of less than 200W/m^2 were removed, because those hours had the least amount of contribution in power production during the entire day. Blank and unwanted data entries were also removed which resulted from equipment error during data collection by the IMC organization because it would have potentially caused an error in our findings. Lastly, a tabulation was done for the data of Ambient Temperature, Wind Speed and Global Irradiance for each month and also calculated their averages from 06:00HRS to 20:00HRS.

4.3 DNI & DHI

After properly filtering the Global Horizontal Irradiance (GHI), there is a need to calculate two other components Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). To obtain DHI from GHI, empirical correlation given by Orgill and Holland's [17] is used. This relationship is a function of sky clearness index (Kt), which is as follows,

Table: 4.3.1. Orgill and Hollands Correlation

DHI/GHI = 0.177	Kt > 0.75
DHI/GHI = 1.577 - 1.84 * Kt	0.35 < Kt < 0.75
DHI/GHI = 1 - 0.249 * Kt	0 < Kt < 0.35

To calculate DHI, we used the sky clearness index (Kt) values for Ahmedabad from the study done by R. C. Srivastava and Harsha Pandey [18]. As GHI and DHI are already calculated, in order to calculate DNI, there is a relation among these three parameters which is expressed in [3] as,

$$I_{GHI} = I_{DNI} \times \mathrm{Cos}(\theta_Z) + I_{DHI} \qquad \text{Eq. (1)}$$

Here, $\mathrm{Cos}(\theta_Z)$ is the angle between the sun rays and the vertical, known as Zenith angle. For calculating zenith angle, there is a need to find a couple of other angles, that is Declination angle, Hour Angle, and Solar Azimuth Angle. Declination angle is a function of the 'Day of the Year', which is expressed in [19] as,

$$\delta = 23.45^{\circ} sin[\frac{360(d_n + 284)}{365}] \quad \text{Eq. (2)}$$

As the declination angle changes every day, and to analyze the data for each month with different albedo and orientation, it would be tedious work to calculate the angle for each and every day for a period of one year. Therefore, a particular day of each month is used based on the principle given by Klein [20]. According to Klein, the monthly average daily global radiation is equal to that of the specific day of each month.

Table: 4.3.2. Recommended days by Klein for each month

Month	**Date**	**Day of the year**
January	17 January	17
February	16 February	47
March	16 March	75
April	15 April	105
May	15 May	135
June	11 June	162
July	17 July	198
August	16 August	228
September	15 September	258
October	15 October	288
November	14 November	318
December	10 December	344

Next step is to calculate the Hour Angle. This angle is dependent on the 'Time of the Day'. Once we have selected a particular day for every month, we have our Irradiance data from 6:00HRS to 20:00HRS. Therefore, we calculated the hour angle for every hour for which we have the Irradiance data for each month. The equation to calculate Hour Angle [19] is as follows,

$$\omega = (720 \text{ min} - \text{LST in min from midnight}) / 4 \text{ min} / \text{deg} \quad \text{Eq. (3)}$$

Where, LST = Standard Time ± 4 (Standard Time Reference longitude – Longitude of location) + Time Correction factor

Here, Standard Time Reference Longitude for our location Ahmedabad (72.5 degrees East) is Mirzapur (82.5 degrees East). And just for the simplicity of calculation, there is not a consideration of the Equation of Time correction factor. Now that required angles are calculated, using these a calculation is done for the zenith angle ($Cos(\theta_Z)$) which goes by the expression[19],

$$cos\theta_{ZS} = sin\delta sin\varnothing + cos\delta cos\varnothing cos\omega \quad \text{Eq. (4)}$$

4.4 Front Side Irradiance

For calculating the front irradiance, an isotropic diffuse model given by Liu and Jordan[21] has been used. Isotropic diffuse model assumes that the intensity of diffuse irradiation is uniform all across the sky. The correlation to calculate the irradiation on a tilted photovoltaic module is divided in three components: Direct, Diffuse and Reflected Irradiation.

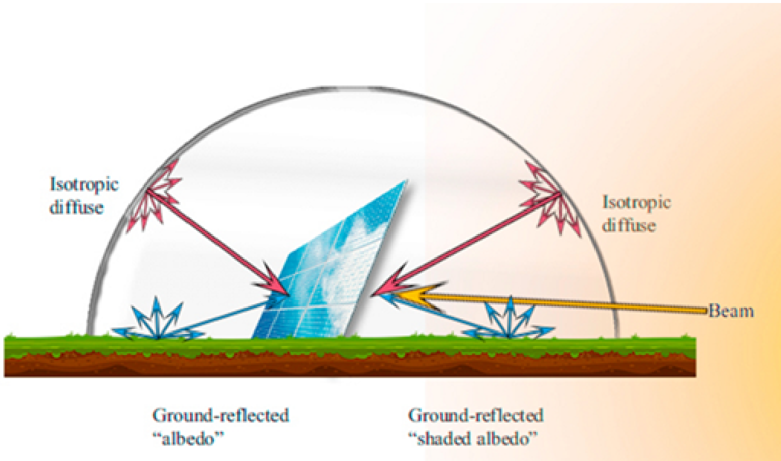


Figure: 4.4.1. Components of Solar Irradiation on Bifacial PV Module [21]

Direct component calculates the irradiation coming from the sun reaching the module without scattering through the atmosphere. Diffuse irradiation is the amount of irradiation reaching the module after scattering through the sky. It is difficult to predict this component as it is dependent on cloud density and sky clearness index (Kt). Lastly, the reflected component includes the irradiation reflected from the ground and surrounding nearby objects.

Reflectivity of irradiation depends on the albedo value of the surface and the surface material. Figure: 4.4.1 represents all the three components of solar Irradiation. Using all these three components, Liu and Jordan proposed a correlation to calculate the total solar irradiation on a tilted surface, which is expressed as follows,

$$I_t = I_b R_b + I_d\left(\frac{1+cos\beta}{2}\right) + I\rho_g\left(\frac{1-cos\beta}{2}\right) \qquad \text{Eq. (5)}$$

Where, β is the tilt angle of the PV module. ρ_g is the albedo value of the ground surface. '*I'* is the total solar Irradiation on a horizontal surface. I_d is the hourly diffuse solar Irradiation on a horizontal surface. I_b is the hourly beam radiation on a horizontal surface. R_b is the ratio of hourly beam radiation on a horizontal surface to that on a tilted surface.

4.5 Rear Side Irradiance

For calculating the rear side irradiation, a modified Liu and Jordan's isotropic model proposed by Beyza, Talat and Bulent[21] is used. Same as the model given by Liu and Jordan, it has all the three solar irradiation components i.e. Direct, Diffuse and Reflected; However, the modifications are, instead of tilt angle, complementary angle of β is used. The reason for this is, the rear side is treated as the front side, as a result the tilt angle becomes (π-β). Another modification is in the component of reflected solar irradiation. As the bifacial module is tilted, therefore different parts of the module will have different elevation heights from the ground. As a result, different parts of the module will receive different amounts of reflected irradiation. To account for these differences, a correction factor is multiplied in the component of reflected solar irradiation. Thus, the modified model to calculate rear side irradiance is expressed as,

$$I_{t,back} = I_b R_{b,back} + I_d\left(\frac{1-cos\beta}{2}\right) + I\rho f(h)\left(\frac{1+cos\beta}{2}\right) \qquad \text{Eq. (6)}$$

Here, the correction factor i.e. the function of height f(h) is integrated over the range of minimum and maximum height of the module from the ground. This function can be expressed as,

$$f(h) = 1 - e^{-l/l_c} \qquad \text{Eq. (7)}$$

Where l_c is the critical length constant and can be calculated at mid-length height. Also, the $R_{b,back}$ value is taken as the ratio of beam irradiation on the front surface $R_{b,front}$, for Angle of Incidence(AOI) greater than 90 degrees. It means that when Angle of incidence (AOI) is greater than 90 degrees, the sun is on the rear side of the module and $R_{b,back}$ is the same as $R_{b,front.}$

4.6 Bifacial gain

The main aim of this feasibility study is to analyze how much additional power is generated due to the bifacial module compared to the monofacial module. And the metric used to calculate this is known as Bifacial Gain. For the simplicity of calculation Bifacial gain can also be calculated considering the optical parameter, that is the front and rear irradiance G_{front} and G_{rear}[5]

$$BG_E\,[\%] = \varphi_{\mathrm{Pmp}} \times \frac{G_{\mathrm{rear}}}{G_{\mathrm{front}}}(1 - \eta_{\mathrm{loss}}) \qquad \text{Eq. (8)}$$

Here, η_{loss} is the losses due to non-uniformity in the irradiance on the rear side of the module or the shading. Φ_{pmp} is the bifaciality factor; every bifacial module is characterized by its bifaciality factor, which is provided by the manufacturers in their PV module datasheet. Typically, bifaciality value in commercially available modules ranges from 60-90%[5]. In this study, for the simplicity of calculation, we have considered Φ_{pmp} = 100% and $\eta_{loss} = 0$.

4.7 Module Temperature using Kurtz model

Now that calculation has been done for front and rear side irradiance, there is a need to check how the ambient temperature and wind speed at our location affects the temperature of bifacial modules and cells. Because there is an assumption that, as module temperature rises the output voltage will decrease.

Study done by the Sandia National Laboratories verified that the module temperature model for monofacial can be used for Bifacial modules too[22]. Thus, the Kurtz model to predict the bifacial module temperature which takes into consideration the ambient temperature and wind speed is used and is expressed in [22] as,

$$T_{mod} = \left(E_f + E_r\right) \times \left[e^{a+b \cdot WS}\right] + T_{amb}$$ Eq. (9)

Where, E_f and E_r are the font and rear side irradiance (W/m^2). T_{mod} is the module temperature. T_{amb} and WS are the ambient temperature and wind speed (m/s). a and b are empirical constants and its suggested values are -3.47 and -0.0594[22]. From the module temperature, cell temperature (T_c) can be calculated using the formulae,

$$T_C = T_M + \Delta T\left(E_f + E_r\right)/1000$$ Eq. (10)

Here, ΔT = 3 degree Celsius for open racking structure.

4.8 Efficiency based on Cell Temp and Irradiance

To calculate the efficiency of the module, there is a need to predict its operating voltage and current in a given climatic condition. Cell temperature has already been calculated. So, now using the Temperature coefficient of open circuit voltage (β) and Temperature coefficient of short circuit current (α), a prediction can be made for the voltage and current for each month. These values for the bifacial module used in this study can be found in table 4.1.1. There has been a use of the required equations from [23] to calculate Voc, Isc, Vmp, and Imp; which are expressed as,

$$I_{SC}(G, T_C) = I_{SCS} \cdot \frac{G}{G_S} \cdot [1 + \alpha \cdot (T_C - T_S)],$$
$$I_{MP}(G, T_C) = I_{MPS} \cdot \frac{G}{G_S} \cdot [1 + \alpha \cdot (T_C - T_S)],$$
$$V_{OC}(T_C) = V_{OCS} + \beta \cdot (T_C - T_S),$$
$$V_{MP}(T_C) = V_{MPS} + \beta \cdot (T_C - T_S).$$ Eqs. (11 - 14)

Where, Iscs, Imps, Vocs, and Vmps are obtained from the datasheet of a bifacial module provided by the manufacturer. G and Tc are the total irradiation and cell temperature. G_s and T_s are the irradiation and surrounding temperature at standard testing conditions i.e. (G = 1000 W/m^2 & T_s = 25 degree Celsius). Next, we need to calculate the fill factor and Power for the bifacial module. Its equation is expressed in [19] as,

$$Fill\ factor\ (FF) = \frac{Vmp * Imp}{Voc * Isc}$$

$$Power\ (p_m) = FF * Voc * Isc$$

Eqs. (15 - 16)

Lastly, the efficiency is calculated by the equation expressed in [19] as,

$$\eta = \left(\frac{P_m}{E * A_c}\right) * 100\%$$

Eq. (17)

Where, E is the incident irradiation at STC (1000 W/m^2) and Ac is the area of the collector (m^2).

5.1. Site Description

The site Ahmedabad - is a metropolitan city in the state of Gujarat, with Sabarmati river flowing through the heart of the city. Ahmedabad lies at 23.03° N 72.58° E in western India at 53 meters above sea-level. Being a tropical city Ahmedabad has a hot and humid climate (tropical savanna climate). Apart from the rainy season the climate is extremely dry with an annual average temperature of 27.1°C, this makes the city an ideal site for capturing solar energy. The graph below shows Ambient Temperature, Wind speed and Global Horizontal Irradiance of Ahmedabad over a year. This further supports our selection of Ahmedabad as our site of study. There have been no studies done yet discussing feasibility of bifacial modules in western part of India. Also Gujarat being the only state in India receiving maximum solar irradiation, feasibility analysis in Ahmedabad for bifacial modules creates lots of opportunities for such technology in future.

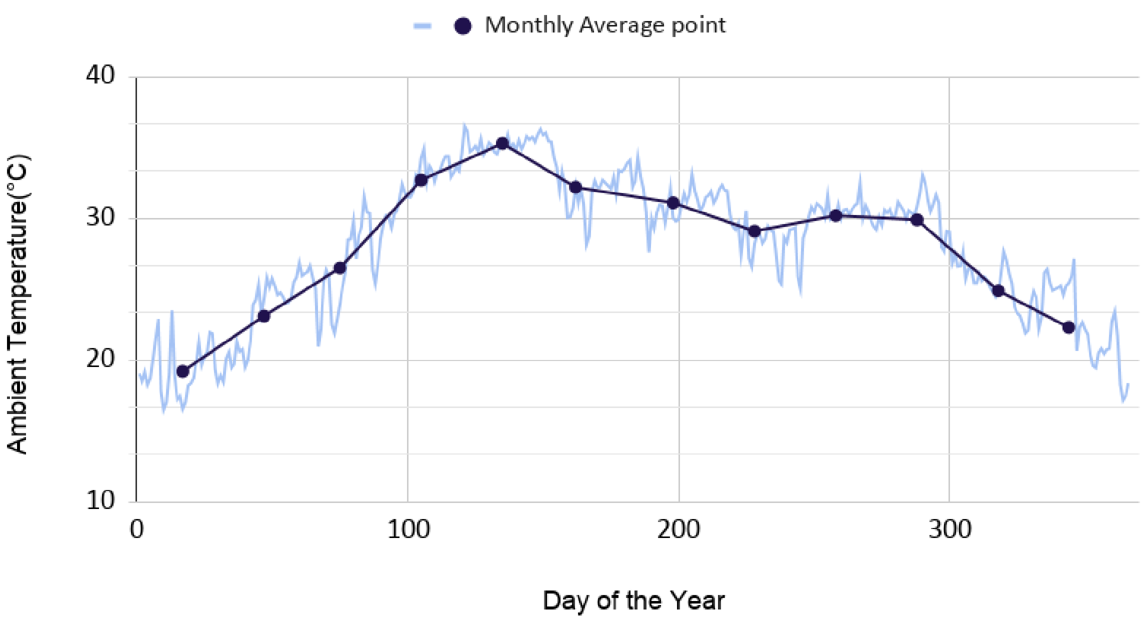


Figure: 5.1.1 Profile of Ambient Temperature over a year in Ahmedabad

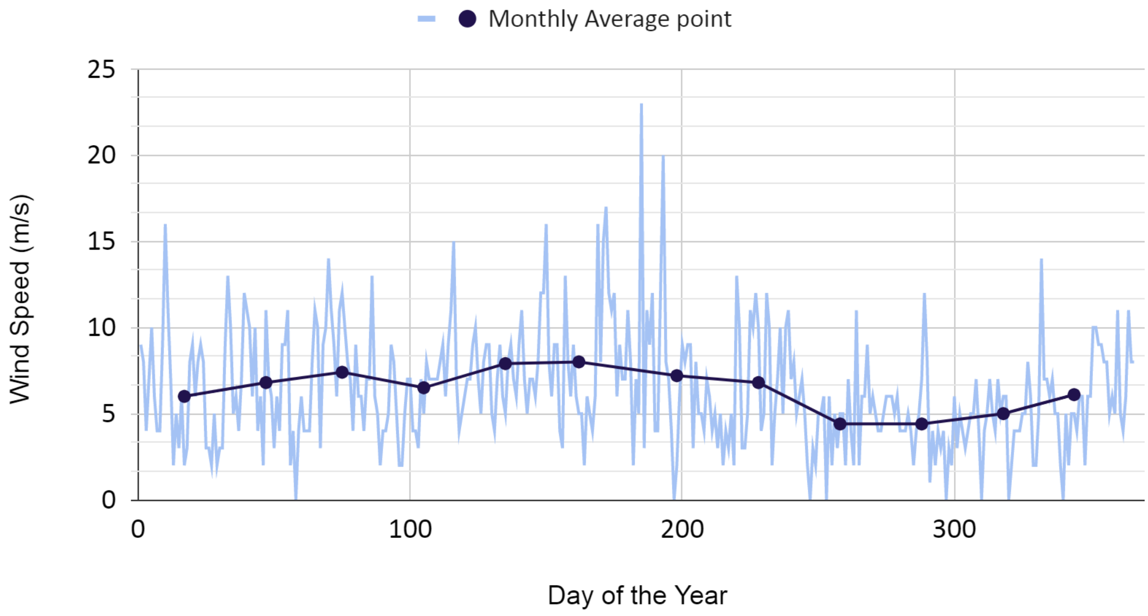


Figure: 5.1.2 Profile of Wind Speed over a year in Ahmedabad

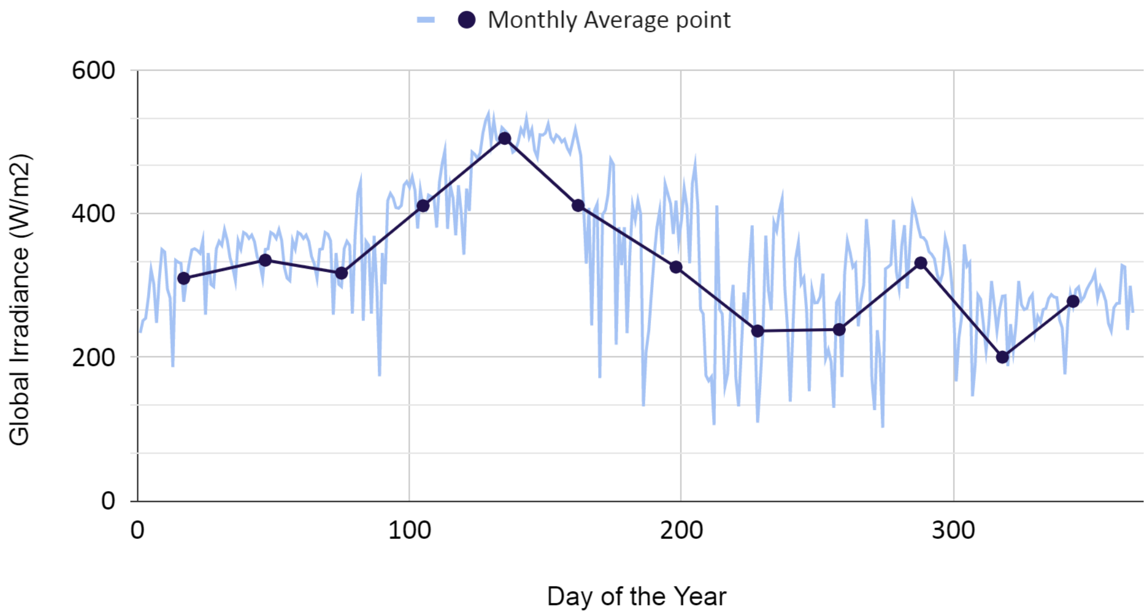
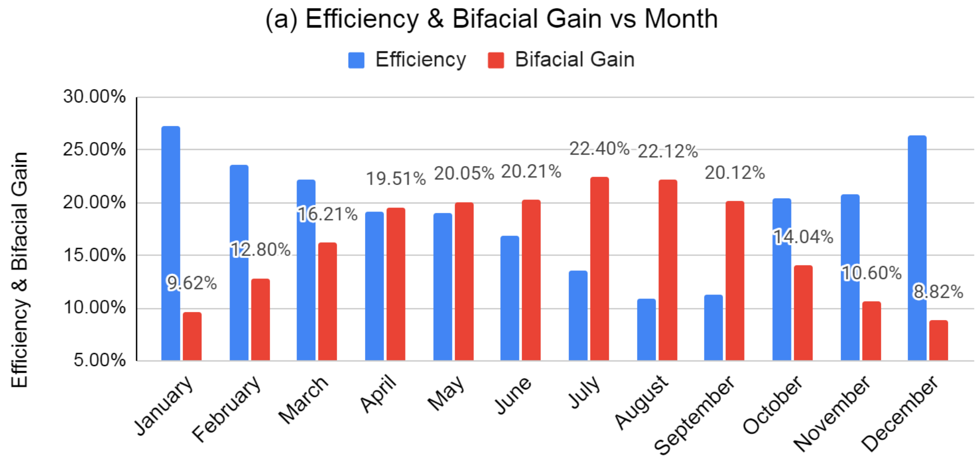


Figure: 5.1.3 Profile of Global Irradiance over a year in Ahmedabad

From the mentioned methodology, the power output, bifacial gain and the efficiency of the bifacial photovoltaic module are calculated in MS Excel and results are presented in graphs. The calculation has been done depending on the affecting parameters which were seen in the report, then those parameters are optimised to get more power output and efficiency for the particular selected site Ahmedabad. There have been some data points to optimize affecting parameters and plot them in graphs to understand how they are playing a major or minor role in the output of bifacial photovoltaic.

5.2. Comparing Efficiency and Bifacial Gain



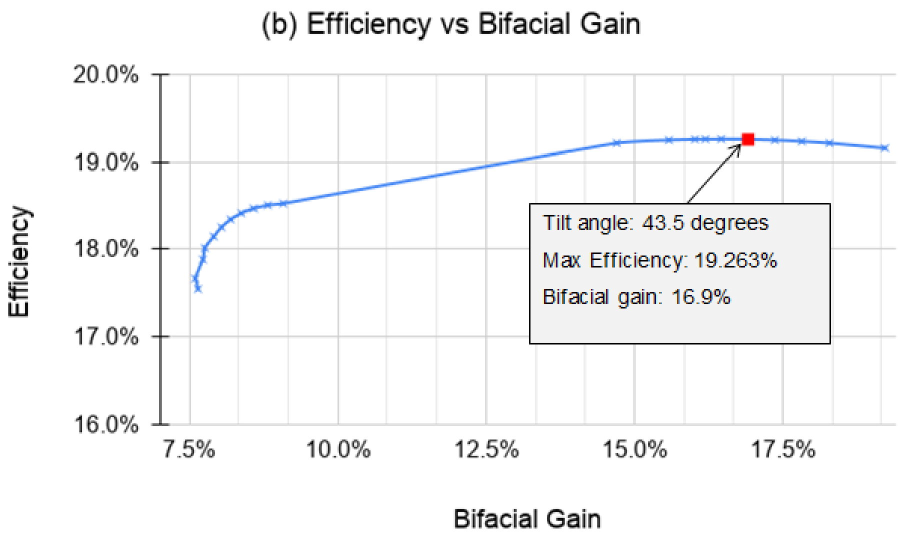


Figure: 5.2.1 (a)Comparing Efficiency and Bifacial Gain throughout the year; (b)Relationship between Efficiency and Bifacial Gain for various Tilt angle

Efficiency and Bifacial Gain are the main factors to observe the output of a Bifacial Module. We have observed that Efficiency varies according to cell temperature and ambient temperature. During the monsoon season and in cloudy sky this relationship is not satisfied because there are other parameters which have a dominating effect on efficiency like solar irradiance, sky clearness index and humidity.

The bifacial gain is dependent on irradiance. It has been deduced that reduction in front irradiance causes Bifacial Gain to rise in the monsoon season. Optimized tilt angle for the site is obtained when plotting these two as shown in figure(b).

5.3. Effect of tilt angle on efficiency and bifacial gain

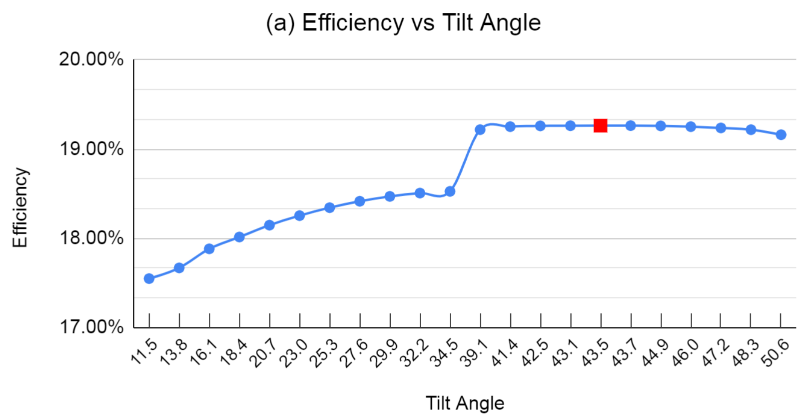


Figure: 5.3.1 (a) Relationship between Efficiency & Tilt angle

The tilt angle of a module is optimized from the efficiency. As tilt angle increases, the efficiency of a module also increases till the particular tilt angle (which has been shown in the figure(a) with red squared point), then becomes constant and then decreases. The highest value of efficiency is obtained when tilt angle is approximately 43.5° which is taken as the optimum tilt angle for our site.

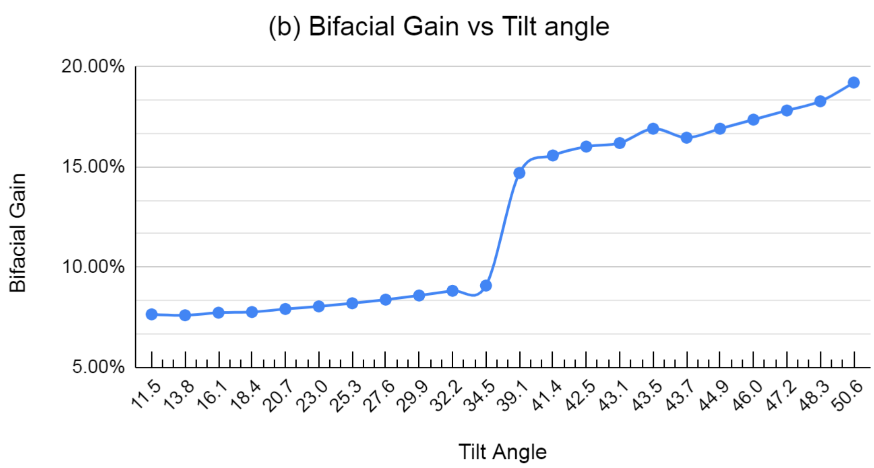


Figure: 5.3.1 (b) Relationship between Bifacial Gain & Tilt angle.

It has been deduced from the figure(b), Tilt angle and bifacial gain are in linear relation, meaning bifacial gain is increasing with increased tilt angle therefore it is hard to determine optimum value of tilt angle only from their relationship.

5.4. Effect of ambient temperature on efficiency

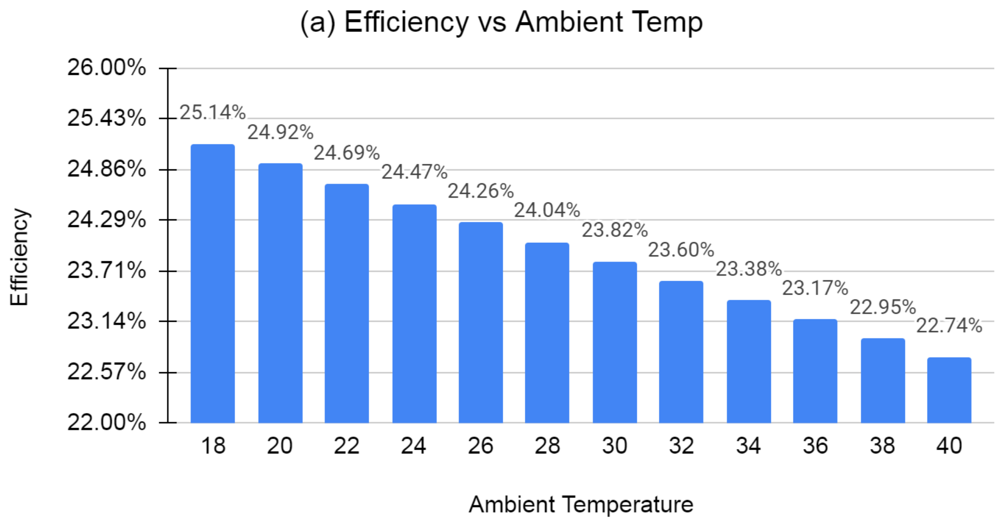


Figure: 5.4.1 (a) Relationship between Efficiency and Ambient Temperature

An observation can be made from the figure(a) that Efficiency and Ambient Temperature are inversely proportional. A reason behind this is, at higher ambient temperature solar cells of a module produce more current which results in lesser voltage because of this the efficiency decreases. Basically, Efficiency of bifacial photovoltaic modules is obtained more at lower ambient temperature compared to higher ambient temperature.

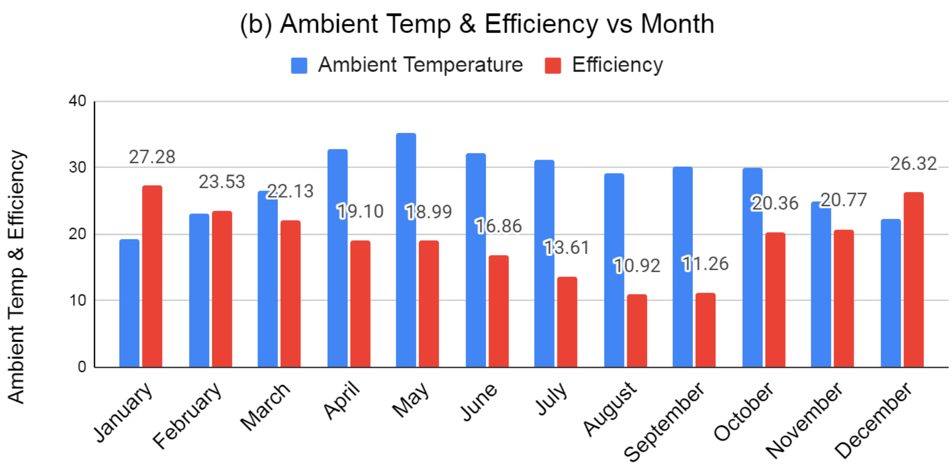


Figure: 5.4.1 (b) Comparing Efficiency and Ambient Temperature over a year

One can also observe from the above figure(b) that the efficiency of a module is higher in the winter than the summer and the monsoon, because in the winter ambient temperature is less than the other two seasons.

5.5. Effect of albedo and elevation on bifacial gain

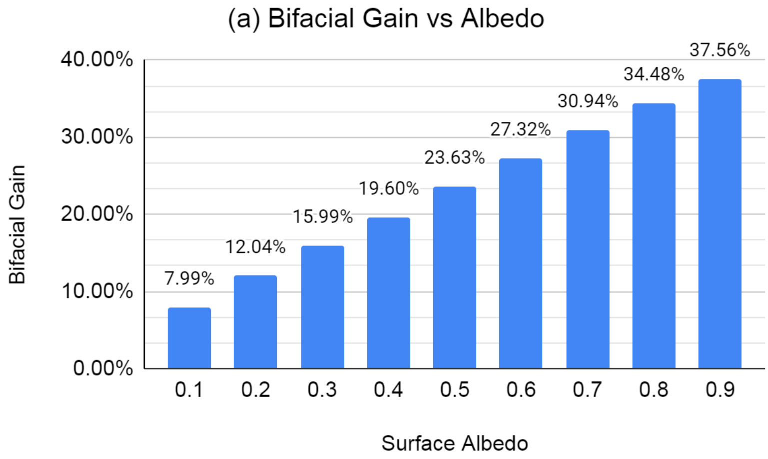


Figure: 5.5.1 (a) Relationship between Bifacial Gain & Albedo

Albedo plays a major role in bifacial photovoltaic output power and efficiency because it represents reflected irradiance, as it has seen in the methodology. A minor increase in Albedo can change Bifacial Gain positively. Clearly, Albedo and Bifacial Gain are in linear relation. To get that relation the optimum tilt angle has been kept constant and then calculated Bifacial Gain with different Albedo values. Albedo can be increased with the help of material (White roof or white paint, similar kind of light coloured surface) which can reflect more sunlight. Also, this reduces the surrounding temperature therefore one can obtain more efficiency.

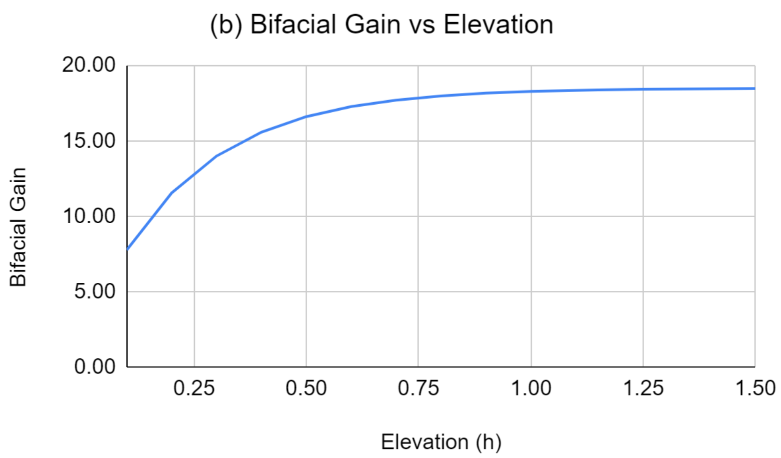


Figure: 5.5.1 (b) Relationship between Bifacial gain & Elevation

Elevation and Bifacial Gain are in linear relationship. However, maximum elevation should be around 1 m. If one keeps on increasing the elevation then it is unable to get more solar energy from the rear side because intensity of diffuse and reflected irradiance becomes lower. Here, elevation is taken 0.5 m but if we increase the elevation(up to 1 m) then it has been observed that bifacial gain will also increase.

The calculation is done for both front and rear side irradiation data of the bifacial module by taking the optimum value of Tilt angle (43.5°), Albedo of concrete (0.3), keeping elevation (0.5m) and other electrical characteristics which were mentioned in the methodology. Some of the interesting seasonal variations have been observed from the calculations which are incorporated here,

It has been seen that there is more solar irradiance during the winter season compared to other two seasons, because the sun is near to the earth's northern hemisphere in the winter season, therefore during this season efficiency of the bifacial module is more than the other two seasons. During the monsoon season, Bifacial Gain is more compared to other two seasons. Because in the monsoon season, front(direct) radiance is lower due to clouds therefore the difference between front and rear irradiance is less which results in a higher ratio of back irradiance to front irradiance. In contrast, Cell temperature, Power and Efficiency are less during the monsoon season, because overall solar radiation is lower in this season.

Thus, a bifacial photovoltaic system or a solar plant can be designed to benefit from the additional rear side output by considering atmospheric as well as weather conditions and also from the above observations and calculations which have been done for the selected site.

The solar system of 50kW is designed using bifacial panels rated at 360 W manufactured by Adani Solar company. Average power generated by a 360 W Bifacial Module during each particular month considering its climatic conditions is given in table: 6.1

Table: 6.1 Average power output for each month

Month	Bifacial Power (watt-hr)	Monofacial Power (watt-hr)
January	551.13	509.56
February	475.40	427.69
March	447.11	391.35
April	385.85	328.67
May	383.58	325.32
June	340.52	287.66
July	274.92	227.58
August	220.58	182.46
September	227.54	191.36
October	411.35	366.08
November	419.64	383.68
December	531.68	494.56
Average	**389.11**	**342.99**

a) No of bifacial Panels = System Power Requirement / Power generated by one panel

= 50,000 / 389.11

= 128.5

~ 129 Panels

Cost of one ELAN Series N-type PERT Bifacial Photovoltaic module, manufactured by Adani Solar is 11,550 INR (Including 5% GST and 1% transportation cost)[24].

b) Cost of 129 Bifacial Panel = 11000 * 129 = 14,89,950 INR

Standard rate of solar panel installation in India is approximately 7 INR per Watt[25].

c) Installation cost of system = 7 * 360 * 129 = 3,25,080 INR

Considering the benchmark from the Government and Ministry of New and Renewable Energy (MNRE), in Gujarat state, particularly for residential customers, 40% subsidy is given for a solar system upto 3kW and 20% subsidy is given for the system greater than 3kW and upto 10kW. As there is a consideration of a larger system, no subsidies are considered in our calculation.

∴ Total cost 50kw Bifacial Plant = 14,19,000 + 3,25,080 + Miscellaneous cost = 23,16,530 INR

Cost of electricity by torrent power in Gujarat is 4.3 INR / Unit [26].

d) Annual electricity Produced = 389.1W * 6 sun hours * 365 * 129 = 109.89 MW-hr

e) Total Annual cost of 109.89 MW electricity = 1,09,896 unit * 4.3 INR = 4,72,554 INR

f) Pay-back Period / Break-even point = Total initial cost of the system / Cost of total units generated annually

∴ Payback Period = 23,16,530 INR / 4,72,554 INR = 4.9 Years

6.1. Levelized Cost of Electricity (LCOE)

It is the ratio of total cost of the system in its entire lifetime period to the total number of units generated by the system in its entire lifetime. 25 years has been considered as the lifetime period of the bifacial module used in this study. For a 50 kW system, the initial cost is 17,44,080 INR and considering 3% of the initial cost as the annual maintenance cost.

The total cost of the system in 25 years = Initial installation cost + Maintenance cost for 25 years ∴ Total cost of the system = 23,16,530 + (0.03 * 23,16,530 * 25)

= 31,50,480 INR

The total unit generation by the system in 25 years = 1,09,896 units * 25 years * Derating factor (0.58) = 25,43,913 units

g) LCOE = 26,16,120 INR / 25,43,913 units = 1.23 INR/Unit

6.2. CO_2 Reduction

Average CO_2 emission factor of all power stations in the grid, weighted by net-generation for year 2017-18 is given as 0.82 tCO_2/MWh by the Central Electricity Authority (CEA) at Ministry of power in India[27]

Therefore, Carbon dioxide emissions mitigated annually is 90 tons and lifetime CO_2 reduction is approximately 2086 tons.[28] The entire system designing calculation was done for a monofacial system and the summarized results are presented in table: 6.2.1.

Table: 6.2.1. Summary of System Cost-benefit and CO_2 Reduction

	Bifacial System	**Monofacial System**
Power Capacity	50kW	50kW
No of Panels	129	146
Initial Investment	23.16 Lakhs	22.68 Lakhs
Annual Electricity Produced	1,09,896 units	91,392 units
Payback Period	4.9 Years	5.7 Years
Levelized Cost of Electricity (LCOE)	1.23 Rs/Unit	1.45 Rs/Unit
Lifetime Saving	95 Lakhs	76 Lakhs
Annual CO_2 Reduction	90 tons	75 tons
Lifetime CO_2 Reduction	2086 tons	1739 tons

Thus from the above table, it can be concluded that although the initial investment of the bifacial system is 3% higher than monofacial, that too without considering the cost of land into account. However, the bifacial system generates 20% more power annually compared to the monofacial system; ultimately reducing the pay-back period and levelized cost of electricity in the long run. It is also important to note that here the calculation for bifacial gain was done based on assumption of ground albedo 0.3(concrete). If the albedo is increased by creating artificial surfaces then the bifacial system might cost less because of less number of panel requirement, in addition it will also generate more power with faster payback compared to monofacial systems.

CHAPTER 7. CONCLUSION

In summary, a comprehensive framework is developed to study the feasibility of bifacial solar modules in the context of Ahmedabad city. Several existing approaches were tested to evaluate the PV bifacial module temperature, efficiency, bifacial gain as a function of solar irradiance, ambient temperature, wind and other parameters. There is also the use of the climate data from the city of Ahmedabad located in the western region of India. It was found that using the most common approaches to evaluate the PV bifacial module outputs, the inclusion of wind cooling effects plays a fundamental role for a better estimation.

To estimate the bifacial gain and efficiency, first, weather data provided by IMD station of Ahmedabad were obtained. Subsequently, filtering and filling processes were used to determine their typical meteorological data of the year: 2020. With this data, the irradiance at the front and rear sides of the modules were estimated. Then after, cell module temperature and voltage output degradation were calculated. Afterwards, the energy generation of the 50 KW PV bifacial systems with ELAN Series N-type PERT and the total system cost during their lifetime(assumed to be 25 years) were calculated. Furthermore, total energy production, LCOE and payback period of the given technology were studied. Limitations of this work were also discussed in the above chapters in detail to help the reader to properly interpret the results presented.

The key conclusions of this work are:

1. Compared to Monofacial photovoltaic modules, Bifacial photovoltaic modules have greater power output. For producing the same degree of solar power as a typical monofacial solar array, fewer bifacial solar panels are needed and also the payback period of bifacial is less than monofacial.

2. Efficiency varies according to cell temperature. Whereas during the monsoon season and cloudy sky, i.e. June to September, due to the dominating effect of other parameters like solar irradiance, sky clearness index and humidity it has lower efficiency. Hence, August has recorded the lowest efficiency of 10.92 %, while January month has the highest efficiency of 27.28 %.

3. Bifacial gain varies inversely with efficiency of the module and is highest during the month of July at 22.40%. Also, the role of wind is relevant for the estimation of the

PV bifacial module temperature: for most technologies as it increases the efficiency to a great degree.

4. The tilt angle should be optimized in such a way that it increases the efficiency of a bifacial module. The highest value of efficiency is obtained when tilt angle is approximately 43.5° and is considered optimum for our location site.
5. Ambient temperature and efficiency are inversely related. The reason being solar bifacial modules produce more current at higher ambient temperature which in turn results in lower voltage. This ultimately reduces the efficiency of the system. At standard temperature (25° C), efficiency of approx 24% is achieved.
6. The calculations predict that elevation and bifacial gain are in linear relationship. But the maximum elevation can be upto 1 meter only. If we keep on surging the elevation then there will be lower intensity of diffuse and reflected irradiance from the rear side of the bifacial module, which will eventually diminish the bifacial gain.

Overall, the result obtained from this study indicates good correlation between theoretical outputs and different studies conducted by different groups. Thus, it will help to design a bifacial photovoltaic system to get advantageous output from the rear side of the module by considering weather conditions and also from the above calculations and observations, which has been performed for the selected site in this study.

8. Scope for Future Work

- Here in this study, there is a consideration of the data for one year. If instead of one year, if there is a procurement of last 10 years data then there would be estimation of the degradation rate of a bifacial module of a particular technology more accurately.
- It's always preferable to do physical experiments to find out the results of the theoretical study. By this approach in the future, one can verify optimization of elevation, tilt angle, getting real time data of power production, land availability, and ultimately a better cost benefit analysis and feasibility study of the location, i.e. Ahmedabad.
- The next step would be analysing the current output of the bifacial solar cells in terms of the wavelength of the sun's radiation, i.e. spectral radiation. We can measure the same with the spectral radiation meter with the correction factor to find out exact power o/p for a given location in Ahmedabad. From this data, we can also study the characteristics of different bifacial cell technology under different wavelengths.
- There are various bifacial technologies available in the indian market with the different specifications and costing. We can predict which technology will be best suited for a given location according to the local surroundings by comparing its different outputs.
- This study reviewed several different parameters, which are important to the performance of solar bifacial modules. In the future studies, the experiments can be conducted based on the concomitantly effect of these parameters. Consequently, theoretical results, correlations and simulations relying on mathematical modelling on commercially available softwares which cover different factors seem to be the possible scope of future research.

9. Notations and Abbreviations

Notations	
Vmp	Maximum Voltage (V)
Imp	Maximum Current (A)
Voc	Open Circuit Voltage (V)
Isc	Short Circuit Current (A)
Kt	Sky Clearness Index
d_n	Day of the year
θ_Z	Zenith Angle (degrees)
δ	Declination Angle (degrees)
Ꙍ	Hour Angle
ρ_g	Ground Surface Albedo
β	Tilt Angle (degrees)
Abbreviations	
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
LCOE	Levelized Cost of Electricity
LST	Local Standard Time
BG	Bifacial Gain
STC	Standard Testing Condition

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