Performance Analysis of Building Integrated Photovoltaic (BIPV) for Commercial Buildings in Urban Area

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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
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Declaration

It is hereby declared that

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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.
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Abstract

The objective of this work is to carry out a performance analysis of building integrated photovoltaic systems. The proposed system will occupy the majority of the unused space of vertical walls and harness more solar energy that can be used as the back up electrical energy resources for daily usage in urban areas. Here mono-facial solar panel is considered that harnesses energy from the front side of the panel. A special parameter i.e. cloud shadow effect is taken into consideration throughout the study. Results show that, proposed system mounted in the rooftop gives 30% less electrical energy in the cloudy days where as the vertically mounted system can generate 26% less electrical energy. The system is more recommendable for the vertical space than rooftop installation.

Keywords: BIPV, Solar, Photovoltaic, Cloud, Vertical, Energy.

Dedication

To our parents who nurtured us & the teachers who tried their best for our betterment from the very beginning because without their support up to this it would not be possible for us to complete our graduation.

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List of Acronyms

BIPV	Building Integrated Photovoltaic
GHG	Green House Gas
RES	Renewable Energy Resources
SREDA	Sustainable and Renewable Energy Development Authority
UNDP	United Nations Development Programme
BAPV	Building Attached Photovoltaic

Chapter 1

Introduction

1.1 Why to Use Solar Energy

In this modern era, renewable energy has become a talk of the world and the fascination of using renewable energy has grown high. The majority of the developed countries as well as the developing nations are focusing to be more dependent on renewable energy not only to fight against the rapidly changing climate but also to cope with the continuously rising prices of conventional energy sources in the international market. The main energy generation sources in the world are fossil fuels like oil, coal, and gas together with nuclear energy sources. World's most of the Green House Gas (GHG) emission is happening due to the use of fossil fuels to generate electricity whereas nuclear energy sources are responsible for emitting radioactive waste.

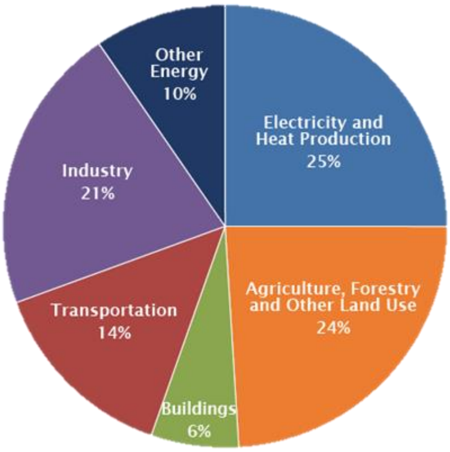

Figure 1: Green House Gas Emission by Economic Sectors [1]

Moreover, conventional energy source reserves are decreasing with time which will lead the whole world to a serious energy crisis in the near future. To minimize the effect of climate change around the world and to reduce dependency on conventional energy sources, usage of Renewable Energy Sources (RES) is increasing worldwide. The renewable energy sources consist of Solar, Wind, Hydro, Tidal, Geothermal and Bioenergy; among these all, Solar Energy is considered as the most reliable and adaptable renewable energy source to produce electricity.

The demand for electric energy is rising extremely in Bangladesh as the economy of Bangladesh is booming rapidly. According to the World Bank report of 2019, Bangladesh is among the top 6 global economies by annual GDP growth [2], and to maintain this growth of economy, Bangladesh needs to expand the production of renewable energy as Bangladesh mainly relies on natural gas and biofuels for power generation. Bangladesh has the possibility to generate 40,000 MW of electricity from solar energy according to the study of 'National Solar Energy Action Plan 2021-2041', which was conducted by the Sustainable and Renewable Energy Development Authority (SREDA) in collaboration with the United Nations Development Programme (UNDP) [3]. At present, Bangladesh has 1500 high rise buildings and many more are under construction, we can utilize all the spaces available like roofs and all four sides for generating solar power. Building-integrated Photovoltaic (BIPV) can be a great option to generate the required energy which will be both cost effective and eco-friendly.

Solar energy is a type of energy that is generated by the sun, harnessed through using technologies. Considering availability, solar energy is the most obtainable and untroublesome as sunlight can reach everywhere in the world. Solar energy from sunbeams can be converted into electrical energy which is appropriate to use on both smaller and larger scales. Proper utilization of solar energy results in less reliability on non-renewable energy sources as well as ensuring green and GHG-emission-free environmental conditions.

1.2 Potential of Solar Energy

The sun is the solitary source of solar energy. According to some studies the earth receives almost 3.85 million EJ (1 ExaJoule = 10^18 Joules) [4] [5] which is equal to 174 PW (1 PetaWatt = 10^{15} Watts) of solar irradiation. But a significant amount of the irradiation, almost 30% of total irradiation is reflected by the earth. The amount of remaining solar energy absorbed by the earth is much higher than the energy that is being consumed every year. Solar energy can be used in different forms such as Solar Photovoltaic Energy and Solar Thermal Energy. Systematic use of solar energy can be an alternative to conventional energy sources. Solar energy has significant potential in the upcoming world if the rapid decrease of fossil fuel and the effect of climate change are considered.

1.3 Photovoltaic System

1.3.1 Solar Cell, Solar Panel and Solar Array

Solar Cell: A solar cell or well known as a photovoltaic cell is an electric device which converts the light energy into electrical energy through the photovoltaic effect. A solar cell is basically a p-n junction diode. Most commonly used materials for solar cells are Silicon, GaAs, $CuInSe_2$ and CdTe.

Solar Panel: Solar panel is an assembly of solar cells mounted in a framework for installation to convert sun rays into electricity.

Solar Array: Solar Array is the combination of several solar panels. Solar Array can be of different sizes and is part of the solar system

1.3.2 Solar Cell Working Principle

A solar cell is an electric device which converts light energy into electrical energy through the photovoltaic effect. It is basically a p-n junction diode and light photons can easily enter in the junction through the very thin layer of p type junction. The photons carry such energy that it creates electron-hole pairs on the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction and the holes in the depletion can quickly come to the p-type side of the junction. Once the free electron comes to the n-type side, the electrons cannot go further due to the potential barrier of the junction. Same thing happens with holes, when the holes come to the p-side of the junction they cannot move further because of the potential barrier. As a result, the concentration of electrons becomes higher in one side (n-type side), concentration of holes becomes higher in another side (p-type side) and it behaves like a battery cell. A photo voltage is set up and if we connect a load across the junction there will be current.

1.3.3 Available types of Solar Modules and their Efficiency

There are 3 types of solar panels that are currently available and each one of them is made in different ways.

Monocrystalline (Mono-SI) - Monocrystalline solar panels are made from almost 40 of the Monocrystalline solar cells and these cells are made of pure silicon. Monocrystalline solar panels are the oldest and most developed type of solar panels.

Polycrystalline (Poly-SI) - Polycrystalline solar panels are made of melting raw silicon. Polycrystalline solar panels are a newer type of developed solar cells and their production cost is lower.

Thin-film - Thin-film solar panels can be made from cadmium telluride (CdTe), amorphous silicon (a-Si), and Copper Indium Gallium Selenide (CIGS). Thin-film solar panels are the easiest to produce and they are less expensive.

Differences of the 3 types of solar panels is given below:

Monocrystalline (Mono-Si)	**Polycrystalline (Poly-Si)**	**Thin-film**
Monocrystalline solar panels can reach up to 20% efficiency.	Polycrystalline can reach up to 15-17% efficiency.	Thin-film solar panels can reach up to 11% efficiency.
Most expensive type of panel.	Newer development approach.	These are the cheapest type of panels.
Made of pure silicon.	Made of melting raw silicon.	Can be made from various photovoltaic materials.

Table 1: Differences between Various types of Solar Panels

1.3.4 Photovoltaic Modules as BIPV and BAPV System

BIPV: Building Integrated Photovoltaics (BIPV) is the integration of photovoltaics (PV) into the building envelope such as the roof or the facade. BIPV is a great solution for urban high buildings to generate electricity with almost zero maintenance and zero environmental pollution.

BAPV: Building Attached Photovoltaics (BAPV) are the type of photo-electric modules which consist of fitting modules to existing surfaces via superimposition once construction has been completed. These types of photovoltaics can be dismantled at any moment without any damage to the building.

1.4 Literature Review: Previous Works on Building Integrated Photovoltaics

There are many more research done with solar PV cell and BIPV based on their performance and optimum tilt angle for maximum power generation and monthly or yearly demand would be met the maximum. An Egyptian group [6] of student research on the different type of BIPV and the photovoltaic technologies and architecture form of a building to implementation of BIPV. A research paper was published based on the performance of building integrated photovoltaic applications with respect to tilt angle and azimuth. It is recommended to perform this work to optimize the inclination and azimuth to achieve maximum energy efficiency. The analysis [7] shows that as the tilt angle is reduced from 50° to 10°, the performance of the proposed array is improved by 26.154%. When the azimuth angle is reduced from 160° to 20°, the power increases by 8.93%. NREL has provided the data [8] for the optimum default tilt angle 23.5° which is equal to the latitude of Bangladesh by observing eight different locations of Bangladesh these are Bogura, Chittagong, Cox's Bazar, Dhaka, Ishwardi, Jessore, Rangpur and Sylhet. A group of student study [26] on the tilt angle optimization by using to methods one default tilt angle used for the whole year which varies (20.20° to 23.30°) for different division of Bangladesh the other method was the two tilt angle for two halves of a year system for April to September tilt angle varies (7.20° – 10.70°) for different division and for October to March its varies (36.40° - 39.80°). Another team of BUET [27] works on an average tilt angle optimization of a PV panel for meeting the maximum demand over the year. Their findings are at 23° tilt angle they get the maximum power generation 63,158 kWh yearly and second maximum power generation get at 12° tilt angle 61,705 kWh over the year. They found 12° tilt angle met the maximum demand for a remote area. Another study [9] was taking place by the student of University of Palermo, Italy about the comparison on the use of PV systems in the vertical walls. They used three different methods are a Dye Sensitized Solar Cell (DSSC), grey and blue caved silicon panels these systems can be placed behind the window or glass walls. The efficiency of DSSC and silicon panel is accordingly 5% and 15% in the vertical orientation its 2.5% and 7.5%, experimentally they got for DSSC 0.31% and for both grey and blue caved silicon panel got 1.31% efficiency.

1.5 Motivation: Why to Install Building Integrated Photovoltaic (BIPV)

Buildings are one of the main sources of global energy consumption around the world and according to studies, buildings consume around 40% of the global energy [10]. In this modern world, the numbers of high-rise buildings are increasing every single day and with the numbers of buildings the demand for electric energy is also increasing. Buildings are also responsible for high amounts of CO2 emissions which cause a threat to the ecosystem such as global warming. From the Kyoto Protocol of 1997 to the Paris Agreement of 2015, various policy directions have been motivated to mitigate international environmental pollution [11] [12]. Building Integrated Photovoltaics (BIPV) is an option for the future building designers to generate clean electric energy without creating any damage to the ecosystem.

Building Integrated Photovoltaic (BIPV) is a multifunctional design which can be applied to the facade of the buildings. The fundamental purpose of BIPV is to generate electricity but installing BIPV to the facade can have multiple advantages like solar and glare protection.

Moreover, as solar energy is free of cost and abundant, installation of building integrated PV system maximizes the rate of energy collection. Integration of BIPV enlarges the scope of utilizing the facades of building in different ways. Use of transparent PV panels can be applied as the safety glass as well as eco-friendly heat protection system for the building. By reducing expenditure of electric bills, BIPV also can reduce the space requirement for additional power generation stations that relies on fossil fuels.

Along with harnessing more energy, installing BIPV on Curtain Wall or on windows can perform as thermal insulator and sunshade as well.

1.6 Application of Building Integrated Photovoltaic in Bangladesh

Use of solar panels has increased in every area of Bangladesh as the solar panels are more affordable now. But there is no single application of BIPV in the commercial high-rise buildings of Bangladesh.

But a Bangladeshi company named “Sustainable & Renewable Energy Ltd. (SREL)”, has announced plans to build the first ever BIPV enabled commercial building in Bangladesh. The project of building the first ever BIPV enabled commercial building is expected to be completed by Mid-2022. The power generation capacity of the system is expected to be 1.2 MWh [13].

Chapter 2

System Details

In the system design and analysis, for integrating photovoltaic modules into buildings, mono facial solar panel is considered to accumulate solar irradiance. Rear part of the photovoltaic modules are attached to the vertical walls of building for which solar irradiation can be absorbed only from one side. Moreover, to harness maximum incident energy from solar irradiation, panels need to attached without any space-gap. Solar geometric angles are also considered to harness irradiation effectively.

2.1 Theoretical Background

Mono-facial Solar Panel: Mono-facial solar panels are made of solar cells placed only on the front surface of the panel. In mono-facial solar panels, light only enters through the front side of the cells so that it can harness the majority of the direct solar irradiance and a little amount of diffuse and reflected irradiance from the sun. This type of solar panels is widely used because of the cheap price rate and easily available. In the BIPV system, Mono-facial Solar Panels are suitable as the backward side of the panels are attached to the building's wall.

While designing the system, some solar geometric angles and properties have been observed. The properties are interrelated with one another which is described later in the next chapter.

Solar Declination Angle: The angle between the Sun and the earth's equatorial plane is called the solar declination (δ). The value of declination angle depends on the day of the year and it determines the seasons. The solar declination angle value rises to a maximum 23.45° at the summer solstice and the minimum value we can get from the winter solstice - 23. 45°.

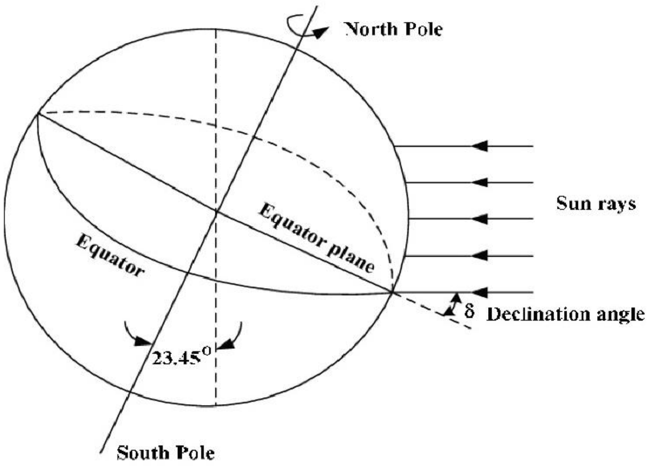

Figure 2: Diagram of Declination Angle

Hour Angle: The hour angle (ω) of a point on the surface of the earth is the angle at which the earth rotates, so the meridian of this point is directly below the sun. The earth rotates, so angular displacement represents time. When observing the sun from the earth, the solar hour angle is a representation of time, expressed in angle units, usually the angle between degrees and solar noon.

Air Mass: Air mass (AM) is a function of solar elevation. Air mass is the path length which is measured in degrees relative to the vertical axis of earth from where we measure the zenith angle. The vertical axis is the shortest path for the Sun light to reach the earth known as solar noon zenith angle is zero. The Air Mass properties are the reason of the loss of Sun light intensity (solar radiation) as it travels into the earth atmosphere and the light intensity varies by the power or light absorption of air and dust which carry out through the atmosphere.

Solar Elevation Angle: Solar elevation angle (α) is the angle between the Sun relative to the earth's horizon. It varies based on the other facts such as day of the year whether it is summer or winter, time of the day whether it is solar noon or other time of the day and also depends on the latitude of the place. The solar noon of a summer day has had the maximum solar elevation.

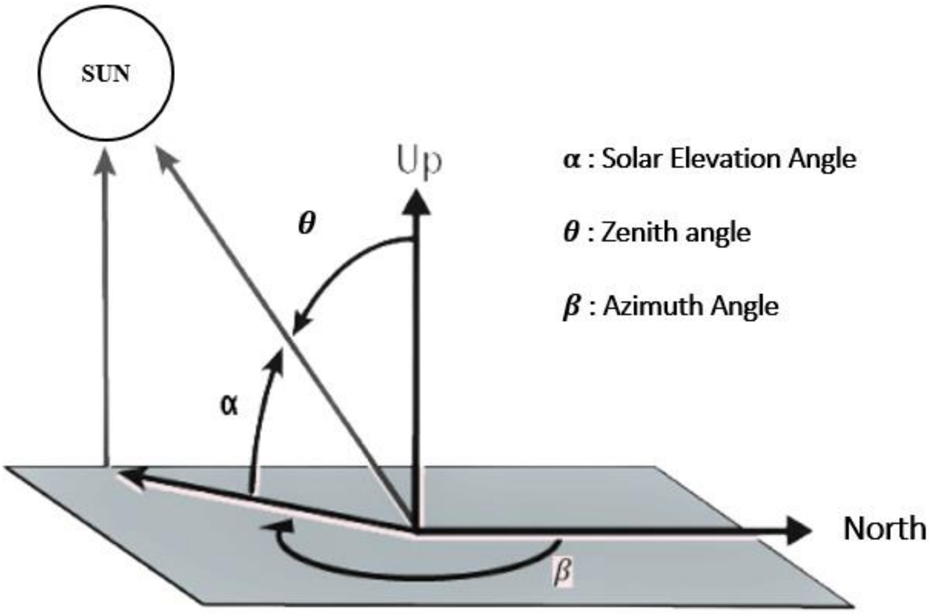

Figure 3: Diagram of Solar Geometric Angles

Zenith Angle: Zenith angle (θ) is the angle between the Sun and the vertical axis of the earth. It has a correlation with the solar elevation. The solar radiation layer is intended to be used on flat terrain, but we often need to calculate the radiation at different angles to the sun's rays. For this we need to know the zenith angle, which is the incident angle of the sun relative to the sun.

Azimuth Angle: Azimuth Angle (β) is introducing a location or position of a body object on the Earth which basically describes the angular position of an object on the earth horizon from north to south and vice versa. It is the compass direction of earth. The horizontal coordinate defines the relative direction of the sun along the local horizon, and the sun's zenith angle or its complementary sun height defines the apparent height. Azimuth, however, is traditionally defined as the angle between the southern line and the shadow cast on the earth by the vertical bar.

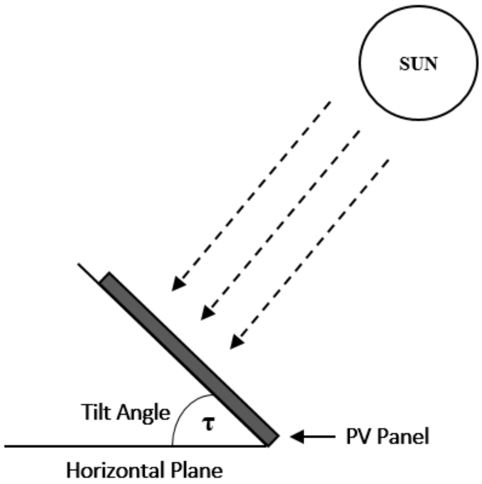

Figure 4: Diagram of Tilt Angle for PV Panel Installation

Tilt angle: An angle between the Earth’s horizontal surface line and the PV panel installation line is called panel’s tilt angle (τ). A panel efficiency and panel radiation depends on tilt angle. A different segment of a day's tilt angle can be varied with the sun position tracking for ensuring to capture the maximum solar radiation through the PV panel. We can also use a fixed panel for every single time for a day and also find the panel radiation for the fixed tile angle. The performance of a PV cell notably depends on the tilt angle.

2.2 Design Assumptions and Parameters

To analyze the study, some parameters are assumed -

1. Solar Panel Type: Mono Facial Fixed Axis
2. Solar Panel Efficiency: 20%
3. Area per Solar Panel: 1 m^2
4. Panel Facing: Towards the South
5. Diffuse Irradiance: 10% of Direct Irradiance

Chapter 3

System Design

The study of performance analysis on BIPV is a systematic approach to analyze the installation and outcome of the harnessing solar incident energy by installing photovoltaic panel on the rooftop as well as on the vertical walls. Thus environmental issue like cloud shadow plays vital role while harnessing solar incident energy. Cloud shadow effect is also taken into consideration while analyzing the study. The overall system design approach can be graphically represented in a workflow diagram that is depicted below in figure 5 –

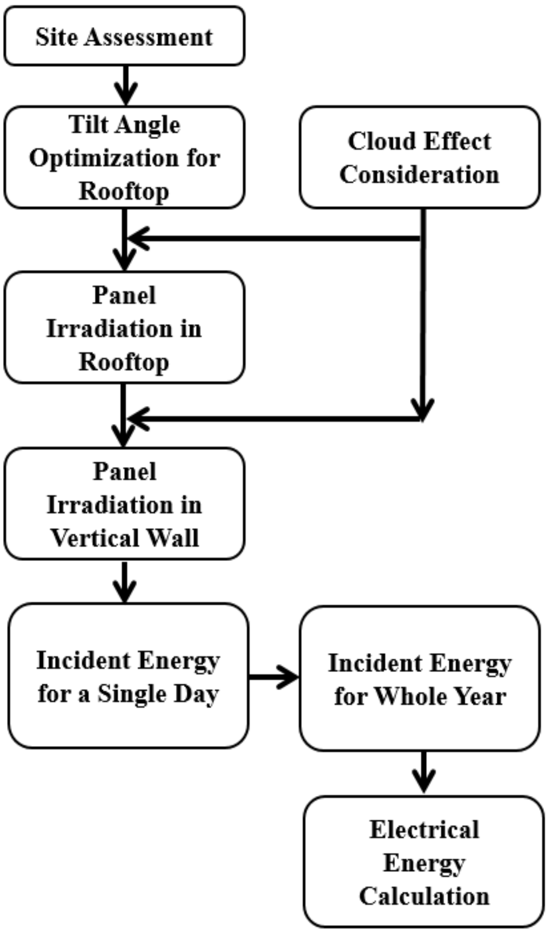

Figure 5: Workflow Diagram for Overall System Design

3.1 Tilt Angle Optimization for PV Panels of Rooftop

The output of building integrated photovoltaic (BIPV) predominantly depends on the tilt angle of the PV module. Thus, to determine the optimized tilt angle for a certain location and to calculate received panel irradiation, solar geometric equations are used. To mention the standardized equations that are used in brief -

To begin with, the Sun's Declination Angle (δ) is determined from the equation [14] -

$$\delta = sin^{-1}[\sin(23.45)\ \sin(\frac{360}{365}\ (d\text{-}81)]$$

Here, d is the n-th number of day for a year such as for 1st January d = 1, for 31st December d = 365 and so on. Along with the declination angle, Hour Angle (ω) and Elevation Angle (α) is also calculated while the formula [15] is -

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

Here, ϕ is the latitude of a specific location. Determining the declination angle (δ), the next approach is measuring the amount of daytime for a specific day of 24 hours' timeline through calculation of Sun Rise and Sun Set time in Standard Time. The daytime is calculated using the equation -

Daytime = Sun Set Time - Sun Rise Time

where the equations to determine the Sun Rise Time and the Sun Set Time are -

$$Sun\ Rise\ Time = 12 - \frac{cos^{-1}(-tan\ \phi\ tan\ \delta)}{15°} - \frac{TC}{60}$$

$$Sun\ Set\ Time = 12 + \frac{cos^{-1}(-tan\ \phi\ tan\ \delta)}{15°} - \frac{TC}{60}$$

Here. TC is Time Correction factor that is used to adjust the longitude position within the local time zone.

Afterward, Zenith Angle (θ) calculation from the equation below [16] -

$$\theta = (90^\circ - \alpha)$$

Air Mass (*AM*) depends on Zenith Angle (θ) and Elevation Angle (α). Both of the angles are taken into consideration to specify Air Mass (*AM*), while the used formula [17] [18] is -

$$AM = 1 / [\,cos\,(90^\circ - \alpha) + 0.5057\,(6.0799 + \alpha)^{-1.6364}]$$

After specifying air mass for a particular day, the next approach is to calculate the Solar Intensity (I) for the particular day. In normal condition, solar intensity is calculated using the following equation [19] -

$$I = 1.353 \times 0.7^{AM^{0.678}}$$

Solar intensity is calculated in the unit of W/m^2. When the sun's rays fall upon any surface directly from the sun, it remains perpendicular to the surface. Thus solar intensity calculated using the above equation is direct solar intensity.

A certain amount of solar irradiation gets diffused which is assumed to be almost 10% of the direct irradiation. Thus considering the diffused irradiation, calculation of solar intensity changes as follows -

$$I = 1.1 \times 1.353 \times 0.7^{AM^{0.678}}$$

Later, irradiation that a panel receives on a particular day for the whole daytime is calculated from the solar intensity. The formula that relates solar irradiation and Panel Irradiation (P) for a particular day is -

$$P = I \times sin\,(\alpha + \tau)$$

that also can be stated as -

$$P = I \times [cos\, \alpha\, sin\, \tau + sin\, \alpha\, cos\, \tau]$$

where α is the elevation angle and τ is the tilt angle of the solar panel with respect to the horizontal plane. To calculate maximum panel irradiation for the specific tilt angle, the difference between Solar Azimuth Angle (γ) and Panel Azimuth Angle (β) need to be a consideration. For the solar panel tilted at an arbitrary angle and considering the difference, the modified equation stands as follows [19] -

$$P = I \times [cos\, \alpha\, sin\, \tau\, cos\, (\beta - \gamma) + sin\, \alpha\, cos\, \tau]$$

Here, the panel azimuth angle (β) is the azimuth angle that the module faces. While the module is on the horizontal plane of ground lying flat, then the tilt angle, $\tau = 0°$.Similarly while it is on the vertical plane with respect to the ground, then the tilt angle, $\tau = 90°$. In general, the Sunlight falls upon the equator directly over the year.

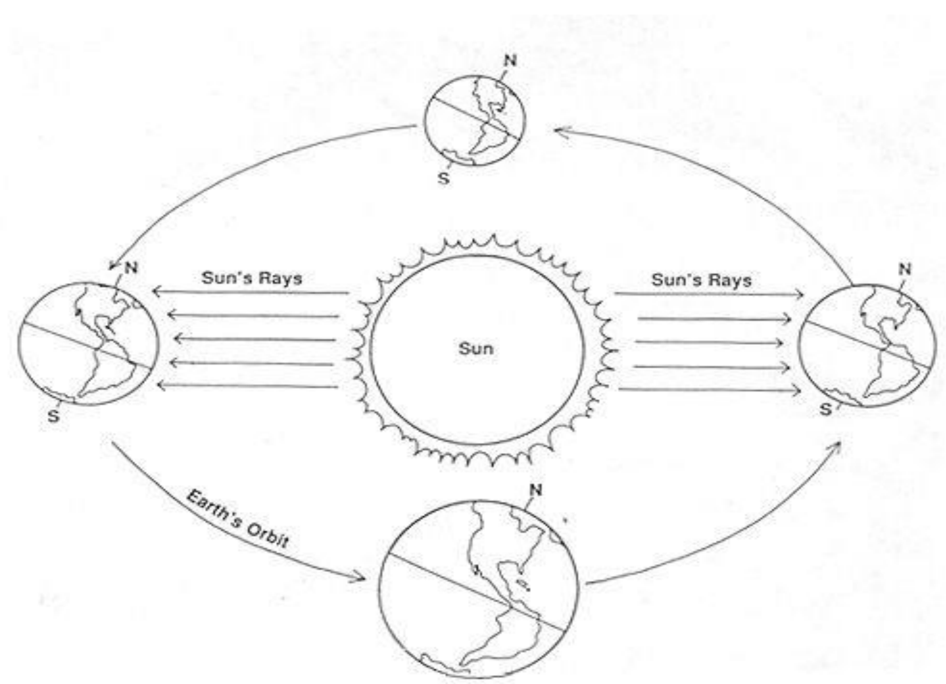

Figure 6: Sun - Earth Diagram showing Earth's Rotation Axis [20]

Thus, solar modules need to be faced to the south to get the maximum of the converted energy for all over the year. The solar panel azimuth depends on the site location where the panel is installed. However, the solar panel azimuth angle is considered as follows -

1. For the solar panel in Southern Hemisphere, the panel will be facing toward the North while the panel azimuth angle, β = 0°
2. For the solar panel in Northern Hemisphere, the panel will be facing toward the South while the panel azimuth angle, $\beta = 180°$

As Bangladesh is situated in Northern Hemisphere, Coordinates 23.8103° N, 90.4125° E, thus it needs to be faced to the South.

In addition, Sun's azimuth angle (γ) is calculated using the following formulas [21] -

$$\text{For Solar Time} \leq 12,\ \gamma \ = \ [COS^{-1}(\frac{\sin\delta\cos\phi - \cos\delta\sin\phi\cos\omega}{\cos\alpha})]$$

$$\text{For Solar Time} > 12,\ \gamma \ = \ [360° \ - COS^{-1}(\frac{\sin\delta\cos\phi - \cos\delta\sin\phi\cos\omega}{\cos\alpha})]$$

After calculating Solar Azimuth Angle and Panel Azimuth Angle for the site location, Panel Irradiation is calculated using the modified panel intensity equation that is mentioned before.

3.2 Tilt Angle for Vertically Mounted PV Panels

For vertically mounted Photovoltaic Panels, the tilt angle is considered as $\tau = 90°$ with respect to the ground which is the horizontal plane. The vertically mounted panels are attached to the building's outer surface at a 0° angle. That is the most commonly used system for BIPV applications.

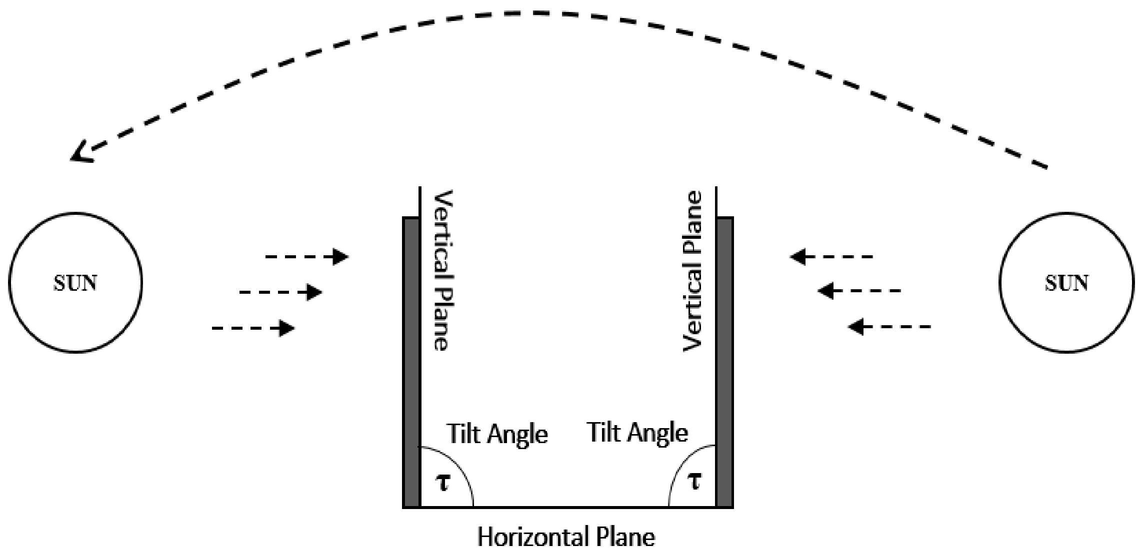

Figure 7: Diagram of Vertically Mounted Mono-facial Panel getting Solar Irradiance

Usually, this system of vertically mounted panels requires fewer monitoring approaches. As Solar Radiation is the highest at noon, generally between 12:00:00 PM - 01:00:00 PM, thus vertically mounted panels get less amount of direct irradiation for a certain period of time during the daytime. Though the vertically mounted panels get diffused irradiance for that fewer period of time, the system can gather a lower amount of incident energy than the Mono Facial Module. But in the BIPV system, the vertically mounted panels are capable of absorbing irradiation from direct solar beam early in the morning, which can be considered from the Sun Rise Time to 09:00:00 AM and at the eve of sunset, generally from 03:00:00 PM to the Sun Set Time. In that system, the vertically mounted panels can harness solar power from direct solar beam for a few periods of time whereas the panels get diffused irradiation for the remaining daytime of the day.

Moreover, for the vertically mounted panels, the panel azimuth angle needs to be optimized. As the azimuth angle changes with the orientation of panels and also depends on facing towards the sun, thus azimuth angle changes for every orientation of the solar panel.

3.3 Cloud Shadow Effect Consideration

Cloud is a significant determinant that has a consequential effect on electrical energy production from solar energy. The sun's exposure on the earth's plane for a period of time importantly relies on the sun's position as well as cloud presence on the sky. Cloud shadow condition changes by time and consequently the energy conversion process also gets notably changed. Most of the cloud shadow effect studies are observed practically in various previous studies [22]. For this study, monthly solar irradiation for a particular year is considered from this study [23]. Furthermore, energy received from a normal day is considered as Sunny Day's Energy whereas Cloudy Day's Energy is indicating 20% energy of the sunny day's energy. The equations that are used here to determine energies from the sunny and cloudy days are [24] -

$$E_{Sunny} = \int_{T_{SR}}^{T_{SS}} (Isin\alpha \; + \; 0.1I) \; dx$$

$$E_{Cloudy} = \int_{T_{SR}}^{T_{SS}} (0.2I) \; dx$$

Here, T_{SR} and T_{SS} denotes the Sun Rise Time and the Sun Set Time, respectively. Subsequently the number and percentage of Sunny and Cloudy days for a year in the context of Bangladesh is depicted here [24]. To determine the approximate number of sunny and cloudy days, the used formulas are:

$$E_{Total} = (x \times \; E_{Sunny}) + (y \; \times E_{Cloudy})$$

$$x \; + \; y \; = \; Total \; Days_{Particular \; Month}$$

Month	**Number of Sunny Days**	**Number of Cloudy Days**	**Total Days**
January	28	3	31
February	23	5	28
March	25	6	31
April	20	10	30
May	18	13	31
June	12	18	30
July	9	22	31
August	11	20	31
September	13	17	30
October	21	10	31
November	25	5	30
December	26	5	31
Total	231	134	365

Table 2: Number of Sunny and Cloudy Days of Each Month

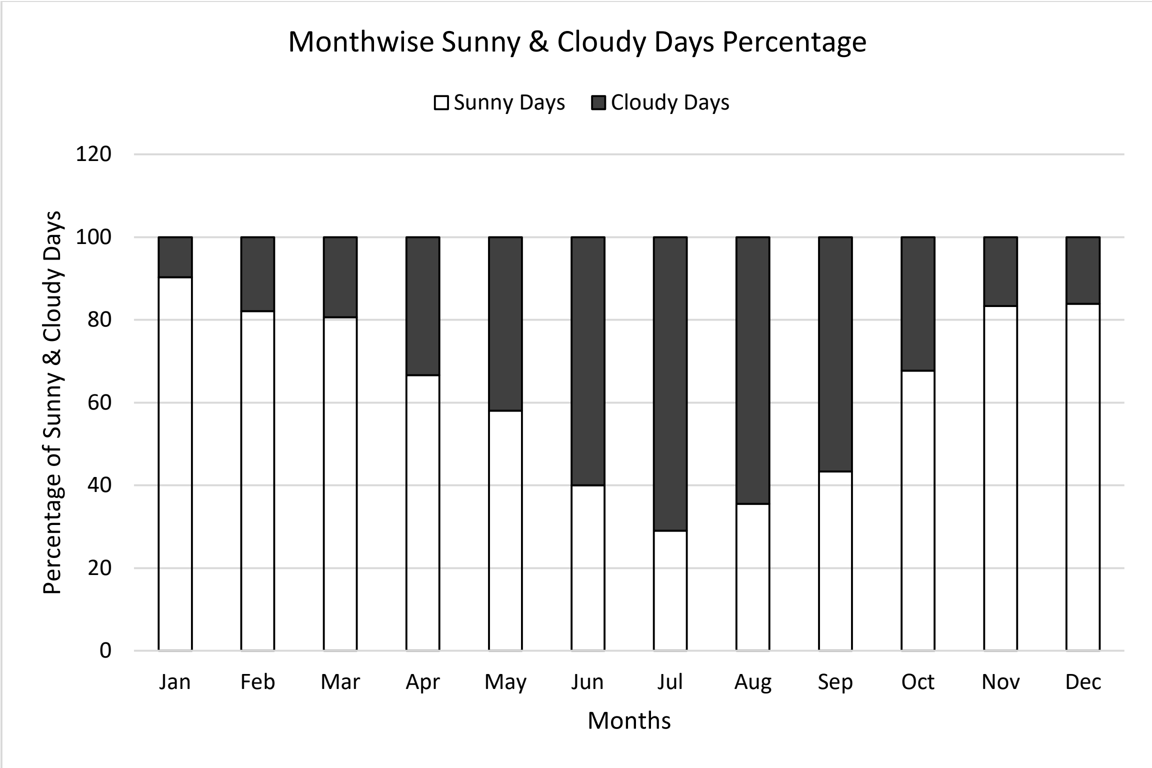

Figure 8: Percentage of Sunny & Cloudy Days in the context of Bangladesh

From the above calculation and data, total direct energy from solar irradiation for a particular month is calculated by applying the formula -

$$E_{Direct} = Total\ Days_{Particular\ Month} \times E_{Irradiation}$$

3.4 Electrical Energy Calculation

After getting all the data, electrical energy converted from the harnessed solar irradiation by a panel for a particular day is calculated using the formula [25] -

$$Electrical\ Energy_{Particular\ Day} = \eta_{Panel} \times Area_{Panel} \times E_{Direct}$$

In the above formula, η_{Panel} and $Area_{Panel}$ denotes the efficiency of the panel and size covered by the panel, respectively. Efficiency of solar panels as well as panel size varies from panel to panel because of panel materials and manufacturer. Electrical energy is calculated in the unit of $kiloWatt - hour\ per\ square\ meter$.

Chapter 4

System Outcome and Analysis

In this section, overall system outcome is analyzed briefly and comparatively. The system outcome is depicted in figures and analysis of the figures are studied along with the figures. As the system is designed for building integrated photovoltaics (BIPV) on fixed axis, the result that are presented here show monthly energy calculation in both ways - without considering cloud shadow effect and considering cloud shadow effect. Afterwards, yearly analysis has also been done in both of the ways. Finally, the proposed system is analyzed for applying to a model. For this study, the University Building no. 02 (UB02) of Brac University (BracU) has been taken into consideration as a model.

4.1 Optimization of Tilt Angle for Rooftop Mounted Photovoltaic Panels

A simulation work has been done to observe the change of solar irradiation on the photovoltaic panels that are mounted on the rooftop. As the sun path changes daily from the east to west, for Bangladesh which is Southern East to Southern West in Summer and Northern East to Northern West in Winter, thus tilt angle also changes accordingly. Solar radiation significantly depends on the panel's tilt angle as the sun path changes throughout a day. Optimization of tilt angle determines a fixed angle for the whole year that is applicable for the horizontally mounted solar panels to harness maximum of the energy from solar irradiation.

Applying the basic equations that are mentioned in the previous chapter, a simulation has been done where the optimized tilt angle is determined for the fixed axis solar panels. The outcome is shown in the figure 9 below.

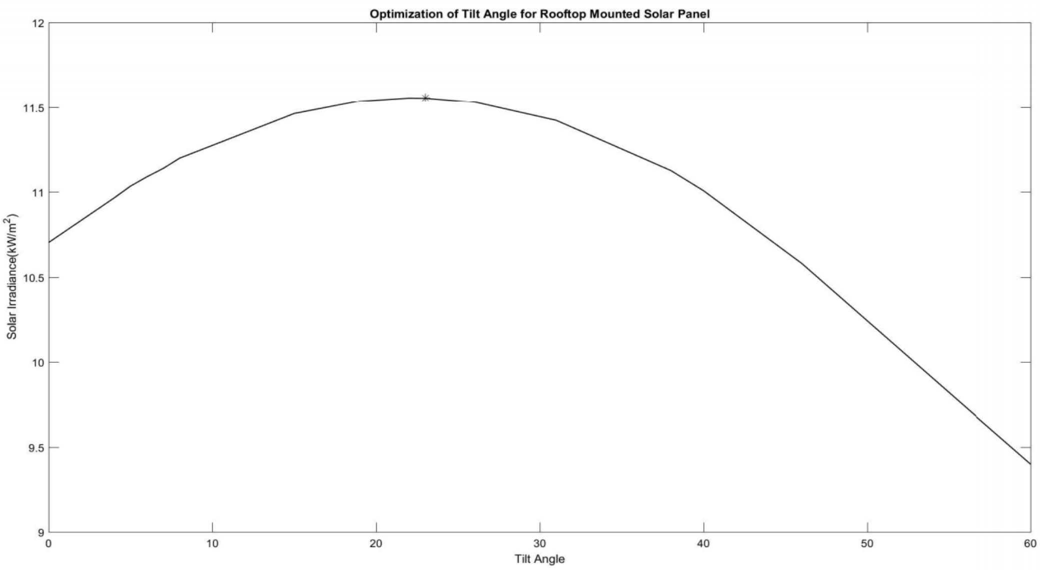

Figure 9: Total Solar Irradiation variation throughout the month with the Tilt Angle

Analyzing the outcome, the result is found that the optimized tilt angle is 23.5° considering the location Dhaka, Bangladesh (23.8103° N, 90.4125° E). One of the previous studies [26] shows the optimization procedure of tilt angle in the perspective of Bangladesh where their outcome is close to our outcome and another study [27] shows that in Bangladesh default tilt angle is considered close to its latitude (23.8103°). Thus our outcome is close enough to the latitude. Both of the studies offer an optimized and default tilt angle for solar panels which are very close to our simulated outcome which verifies our work.

Moreover, the optimization of tilt angle also offers two different tilt angles for two seasons where fixed axis solar panels are not being used. As we are considering fixed axis solar panels, thus two seasonal tilt angles are not observed here. But to mention two seasonal tilt angle will be more convenient to harness more solar energy in two different seasons effectively.

4.2 Daily Energy Calculation

4.2.1 Daily Energy Calculation for Rooftop Mounted PV Panel

In this study analysis, only single day data has been explained for untroublesome interpretation of the system. The fixed day of 15th January data is explained briefly for various approaches throughout the analysis. The study is analyzed for fixed axis mono facial solar panel to minimize mechanical loss of using single axis or dual axis. Application of optimized tilt angle which is $\tau = 23.5°$ for rooftop mounted PV panel shows that, for the particular day of 15th January, fixed axis mono facial solar panel incident energy is $6.7691\ kWh/m^2$. The figure 10 shows the variation of solar direct irradiance and diffuse irradiance for mono facial fixed axis solar panels mounted on the rooftop. The study is done without considering the cloud shadow effect for the day.

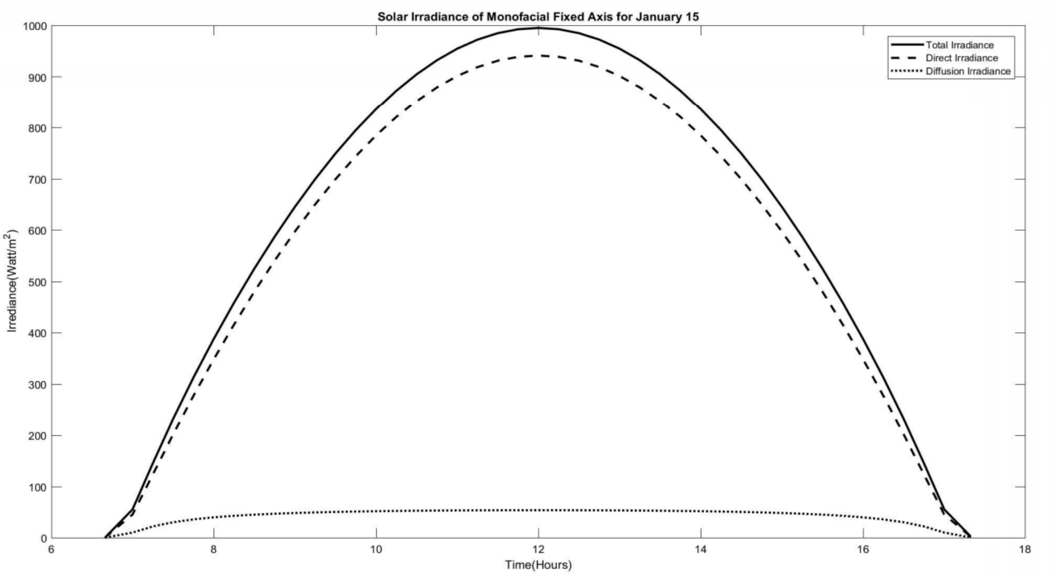

Figure 10: Solar Irradiance on the Rooftop Mounted Photovoltaic Panels for a specific day of 15th January

4.2.2 Daily Energy Calculation for Vertically Mounted PV Panel

The vertically mounted panels can be classified into two different representations which are -

1. North and South Sided Vertically Mounted PV Panel
2. East and West Sided Vertically Mounted PV Panel

The vertically mounted PV panels that are attached to the building's South side get maximum irradiation for the day of 15th January. That happens because on that day, the sun rises in the South-East side and sets in the South-West side [28]. Most common approach is considered to attach the PV panels as building integrated photovoltaic. The figure 11 shows the change of daily irradiation of a vertically mounted solar panel facing towards the north and south.

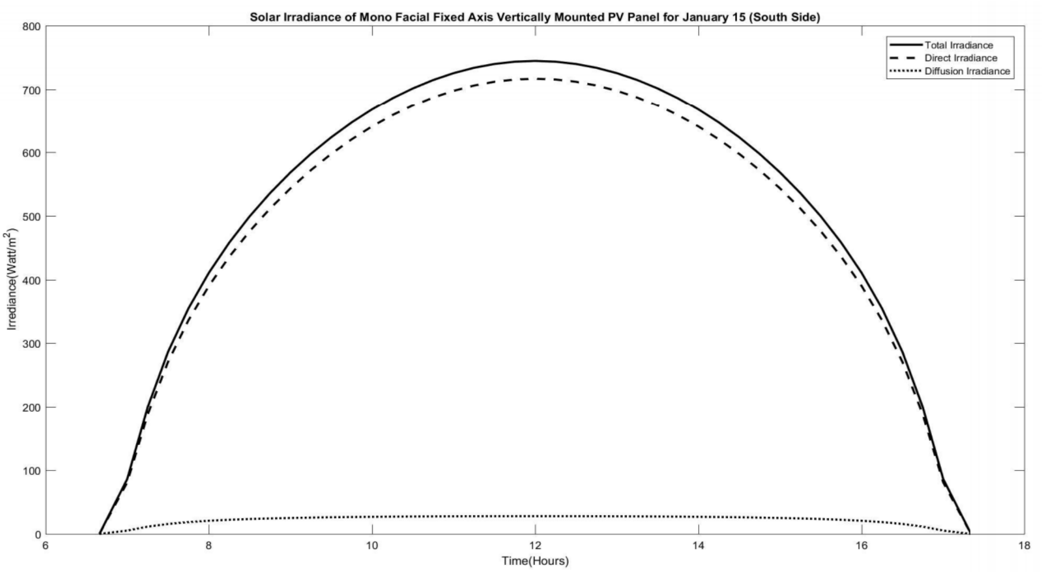

Figure 11: Solar Irradiance on the South Sided Vertically Mounted Photovoltaic Panels for a specific day of 15th January

As solar irradiation directly falls upon the solar panel for a short period of time, the North and South sided panels combined can convert a significant amount of solar energy into electrical energy than the rooftop mounted panels. The study shows total converted incident energy by the North or South sided panel is $5.6765\ kWh/m^2$ for the particular day. This study is done ignoring the cloud shadow effect as well.

Furthermore, for the East and West sided vertically mounted solar panels show significant changes while converting solar energy into electrical energy. As our country is in the northern hemisphere, east and west sided panels get little amount of direct solar irradiation for a little amount of time and for a particular day the panels get diffuse irradiation for the whole daytime. Thus the east and west sided panels get solar irradiation only after the sunrise and just before sunset time respectively for a period of time. The figure 12 depicted below shows the variation of solar irradiation for the particular day without considering the cloud shadow effect.

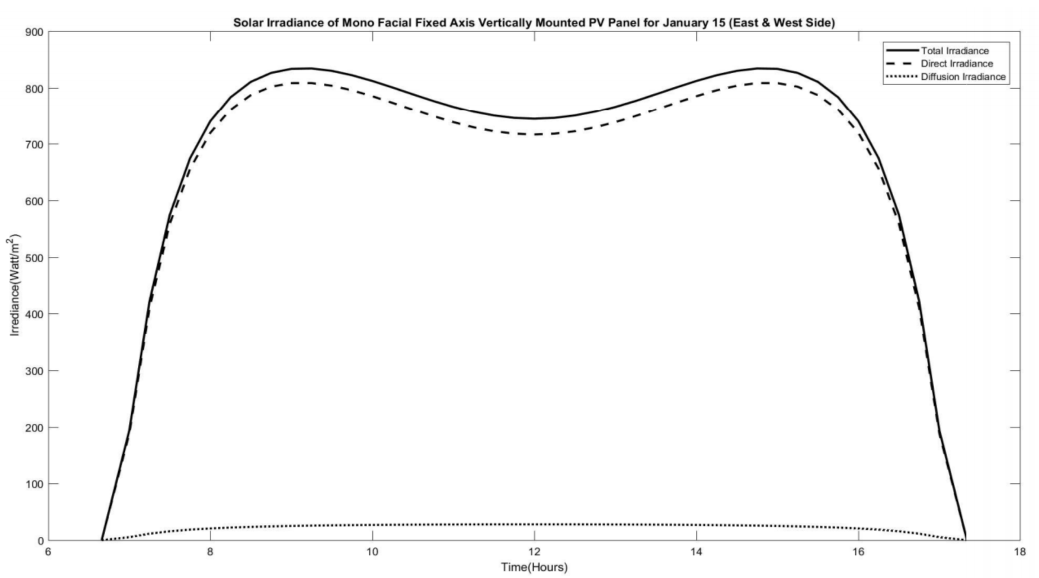

Figure 12: Solar Irradiance on the East & West Sided Vertically Mounted Photovoltaic Panels for a specific day of 15th January

The analysis shows total incident energy in the East is only $3.7278\ kWh/m^2$ for the particular day. The analysis shows an almost negligible amount of diffuse solar irradiation can be converted at noon, 12:00:00 PM and for the remaining time the panel gets considerable solar irradiation. The above figure 12 shows that for the both - east and west sided integrated panels can harness solar power on the eve of sunrise and sunset through mostly direct solar irradiation and reflected solar irradiation.

4.3 Monthly and Yearly Energy Calculation

4.3.1 Monthly Energy Calculation for Rooftop Mounted PV Panel

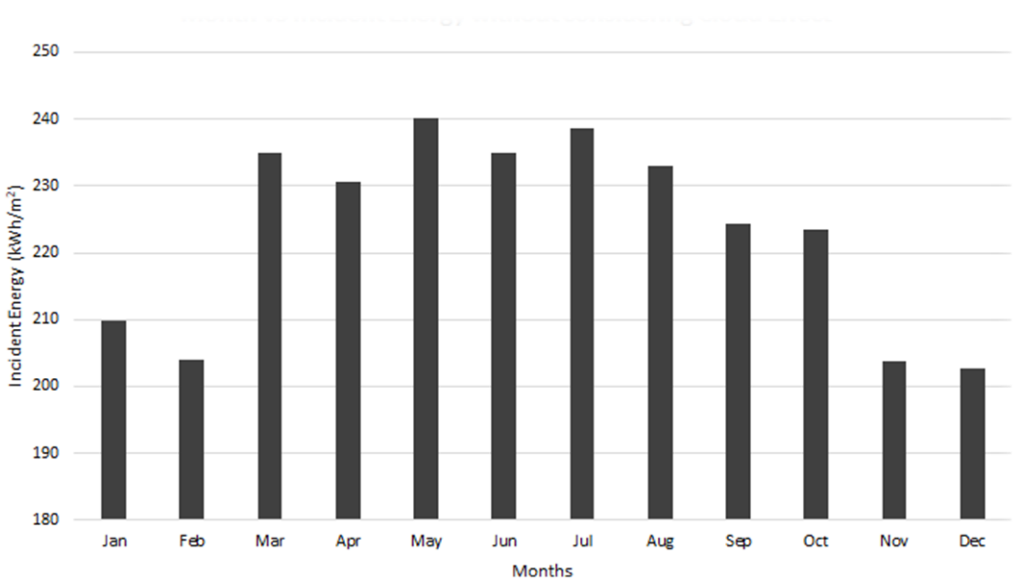

Figure 13: Month-wise Accumulated Energy without considering Cloud Shadow Effect for Rooftop Mounted Photovoltaic Panels

The above figure 13 shows the month wise accumulated incident energy at optimum tilt angle for rooftop mounted solar panels. To analyze this study, the cloud shadow effect is ignored for over the year. For the year, mono facial fixed axis solar panels can generate 2.68028 MWh/m^2 incident energy that are mounted on the rooftop.

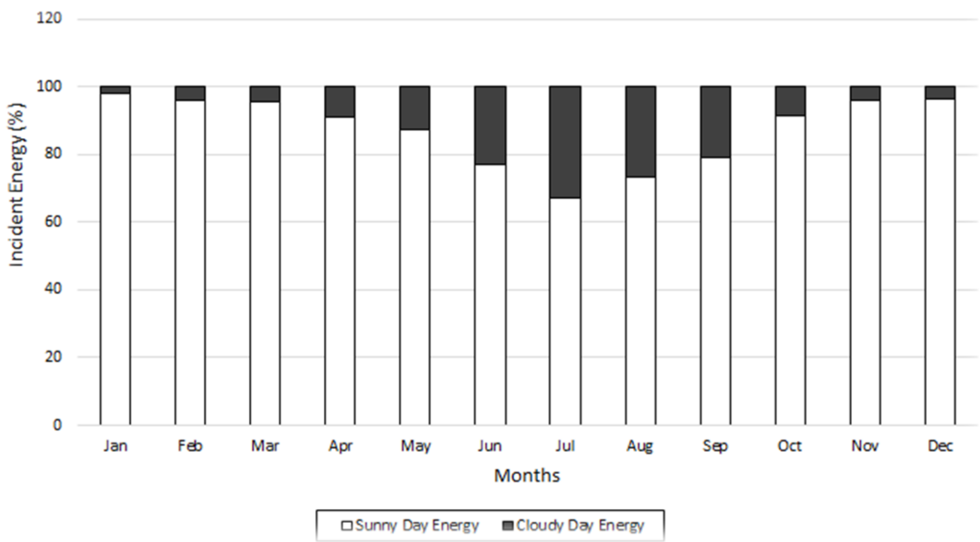

Figure 14: Month-wise Accumulated Energy considering Cloud Shadow Effect for Rooftop Mounted Photovoltaic Panels

Moreover, considering the cloud shadow effect for the rooftop panels, the month-wise energy outcome in percentage is depicted in the figure 14 above. After considering the cloud shadow effect on the rooftop, incident energy decreases significantly to $1.87525\ MWh/m^2$ for the year. According to the study, the panels can harness maximum incident energy from January to April, in the first quarter of the year whereas the other two quarters of the year can harness less energy than the first. Due to the presence of rainy season and short daytime during winter season, harnessed incident energy gets reduced for the rest of the months.

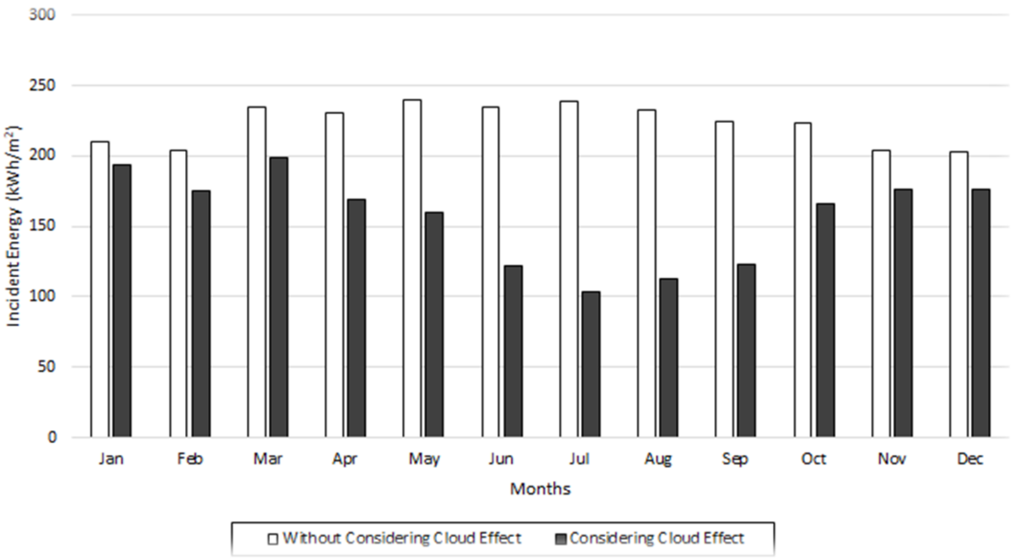

Figure 15: Month-wise Accumulated Energy Comparison for Rooftop Mounted Photovoltaic Panels

The figure 15 shows the difference of month wise accumulated incident energy between without considering cloud shadow effect and considering cloud shadow effect. Significant energy accumulation variation is seen in the second quarter of the year from the month of May to August.

4.3.2 Yearly Energy Calculation for Rooftop Mounted PV Panel

The figure 16 depicted below shows the difference of yearly incident energy between considering cloud shadow effect and without considering cloud shadow effect. For rooftop mounted solar panels, because of cloud shadow energy accumulation decreases 30% for over the year.

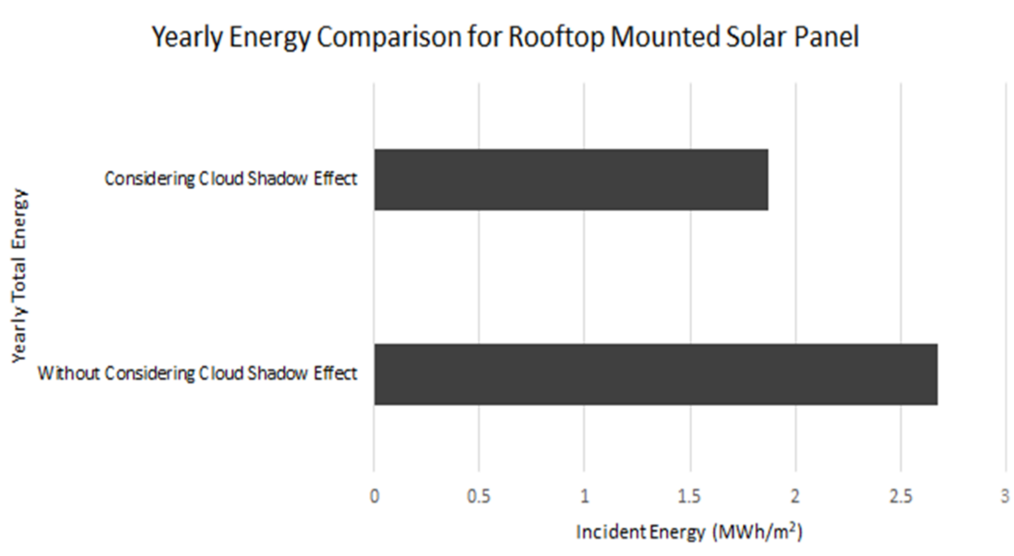

Figure 16: Comparison of Yearly Energy Accumulation on Rooftop Mounted Photovoltaic Panels considering Cloud Shadow Effect

4.3.3 Monthly Energy Calculation for Vertically Mounted PV Panel

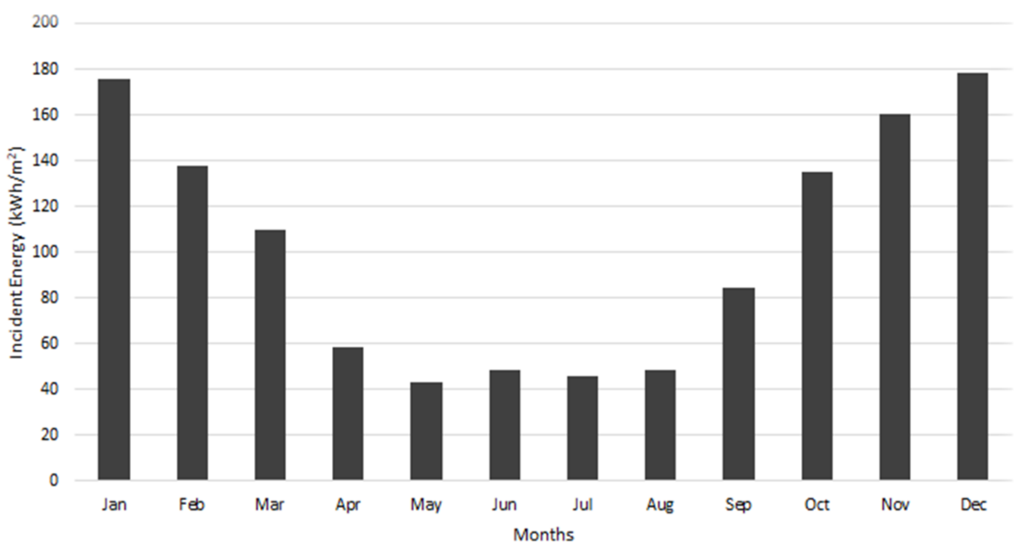

Figure 17: Month-wise Accumulated Energy without considering Cloud Shadow Effect for South Sided Vertically Mounted Photovoltaic Panels

The figure 17 illustrated above represents vertically mounted panel's month wise energy outcomes that are attached to the North and South sides of the building. The cloud shadow effect is ignored while analyzing the study. For the whole year, the South sided vertically mounted solar panel can generate 1.2276 MWh/m^2 incident energy whereas the North sided vertically mounted solar panel can accumulate only 156.882 kWh/m^2.

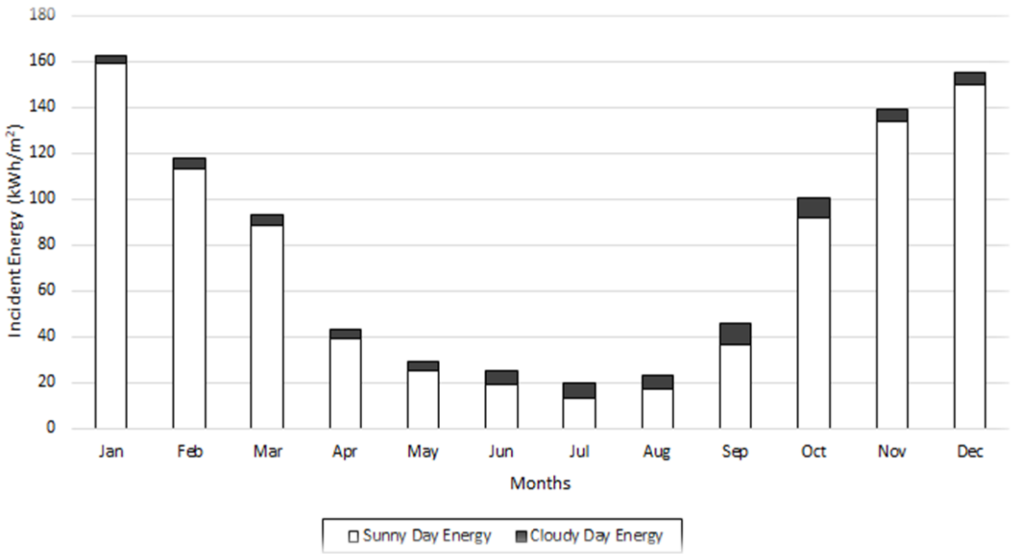

Figure 18: Month-wise Accumulated Energy considering Cloud Shadow Effect for South Sided Vertically Mounted Photovoltaic Panels

But while considered cloud shadow effect, for the South sided PV panel generated energy reduced to 954.9028 kWh/m^2 for over the year which is only 102.905 kWh/m^2. Notable change of energy accumulation is observed in the second quarter of the year from the month of May to August for the both sides. The south sided panel accumulation incident energy gradually decreases but the north sided panel accumulation gradually increases for a short period of time. That happens as in this period of time the location, Bangladesh experiences winter season when sunrise and sunset direction changes slightly.

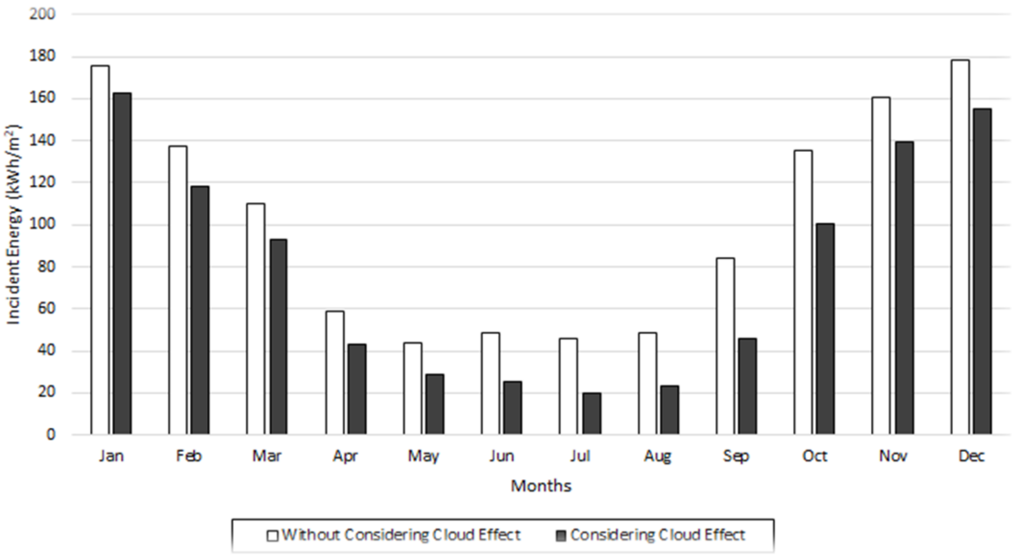

Figure 19: Month-wise Accumulated Energy Comparison considering Cloud Shadow Effect for South Sided Vertically Mounted Photovoltaic Panels

The figure 19 shows the comparison of month wise accumulated incident energy between without considering cloud shadow effect and considering cloud shadow effect. Study shows North and South sided vertical panels can accumulate more incident energy in the dry winter season than summer season which is 80% of total incident energy.

Additionally, another analysis has been done on the vertically mounted solar panels that are integrated on the East side of the building. The figure 20 below shows month wise accumulated incident energy without considering the cloud shadow effect. Yearly accumulated energy in the East without considering cloud shadow effect is $1.204\ MWh/m^2$.

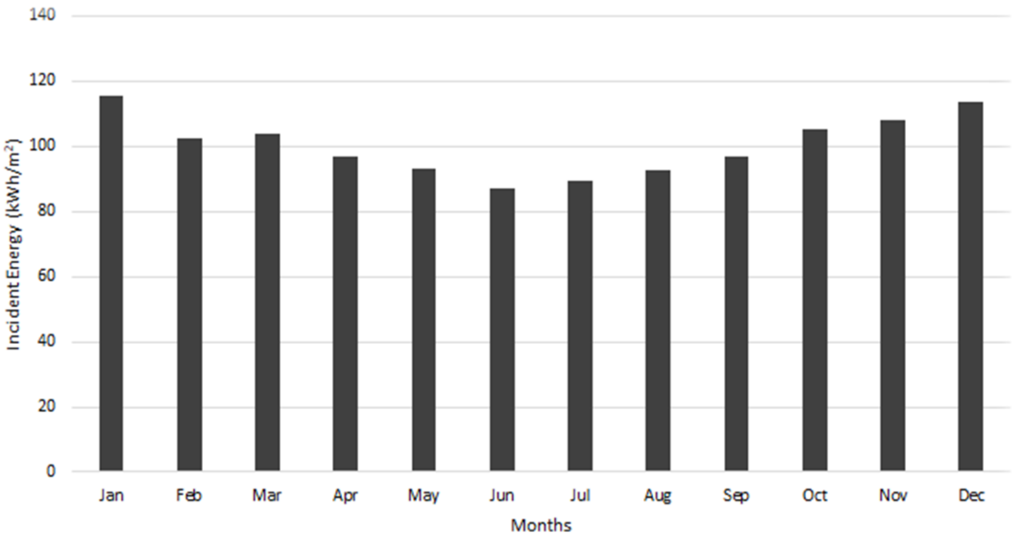

Figure 20: Month-wise Accumulated Energy without considering Cloud Shadow Effect for East Sided Vertically Mounted Photovoltaic Panels

After considering the cloud shadow effect for the East sided solar panel, the energy outcome dropped down to $867.634\ kWh/m^2$. But in this case, the East and West sided vertical panels can generate more incident energy consistently from the month of October to March as Bangladesh is in the Northern hemisphere where the sun moves from the Southern - East to Northern - East throughout the year.

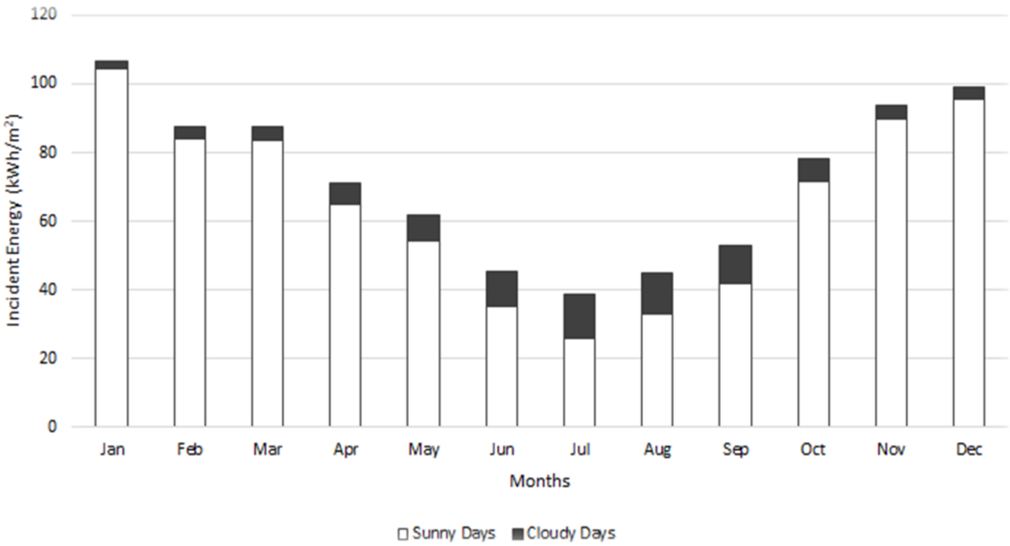

Figure 21: Month-wise Accumulated Energy considering Cloud Shadow Effect for East Sided Vertically Mounted Photovoltaic Panels

Lastly, comparison between considering cloud shadow effect and without considering cloud shadow effect on the East sided vertically mounted solar panel is illustrated in the figure 22 below.

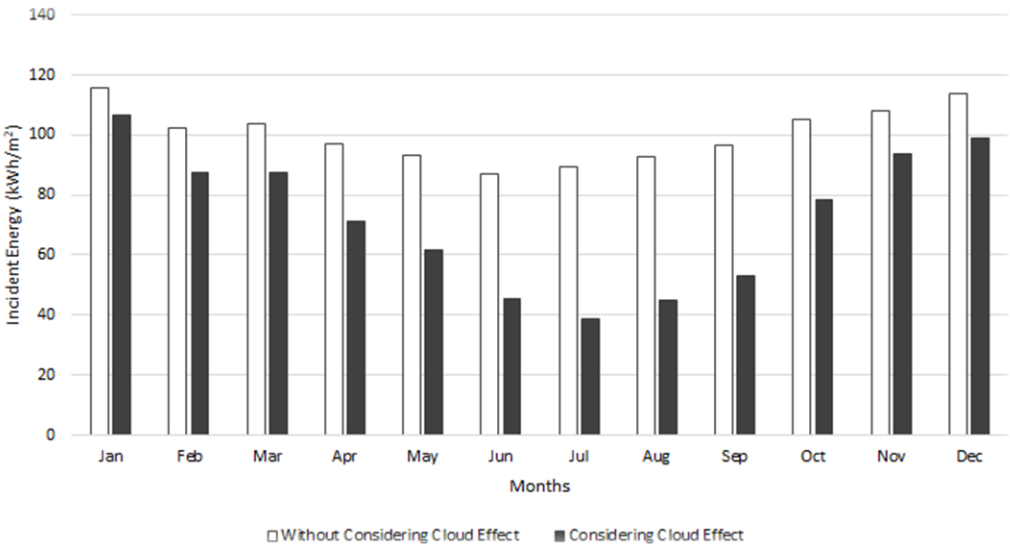

Figure 22: Month-wise Accumulated Energy Comparison considering Cloud Shadow Effect for East Sided Vertically Mounted Photovoltaic Panels

The figure 22 verifies the absorption of less solar energy in the summer season while east and west sided panels are recommendable to use almost in the dry winter season.

4.3.4 Yearly Energy Calculation for Vertically Mounted PV Panel

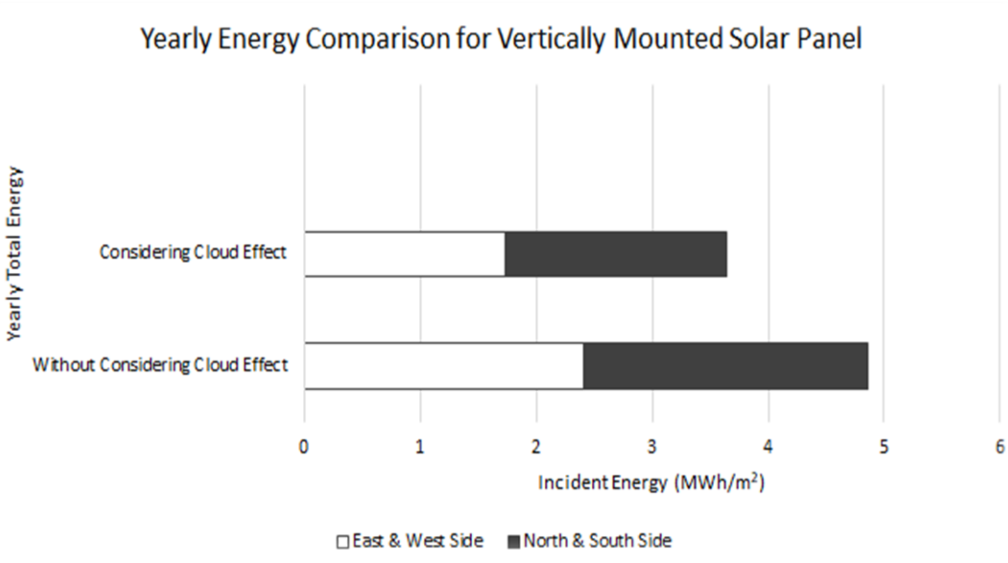

Figure 23: Comparison of Yearly Energy Accumulation on Vertically Mounted Photovoltaic Panels considering Cloud Shadow Effect

The yearly incident energy achieved from the vertically mounted panel is shown in the illustrated figure 23 defining the difference between considering cloud shadow effect and without considering cloud shadow effect. For vertically mounted solar panels, because of cloud shadow energy accumulation decreases almost 26% for over the year. More specifically, for East - West side the integrated solar panels lose almost 28% energy for cloud shadow which is 23.5% for the North - South side integrated solar panels.

4.3.5 Yearly Accumulated Incident Energy Summarization

Accumulated incident energy can be summarized like –

Systems & Considerations	Rooftop Mounted PV Panel (MWh/m^2)	North & South Side Vertically Mounted PV Panel (MWh/m^2)	East & West Side Vertically Mounted PV Panel (MWh/m^2)
Without Considering Cloud Effect	2.68028	1.38446	2.40800
Considering Cloud Effect	1.87525	1.05780	1.735268

Table 3: Yearly Incident Energy Accumulation

4.4 Yearly Output Electrical Energy

Considering panel efficiency 20% of 1 m^2 area per panel, generated yearly electrical energy is figured in the figure 24 below –

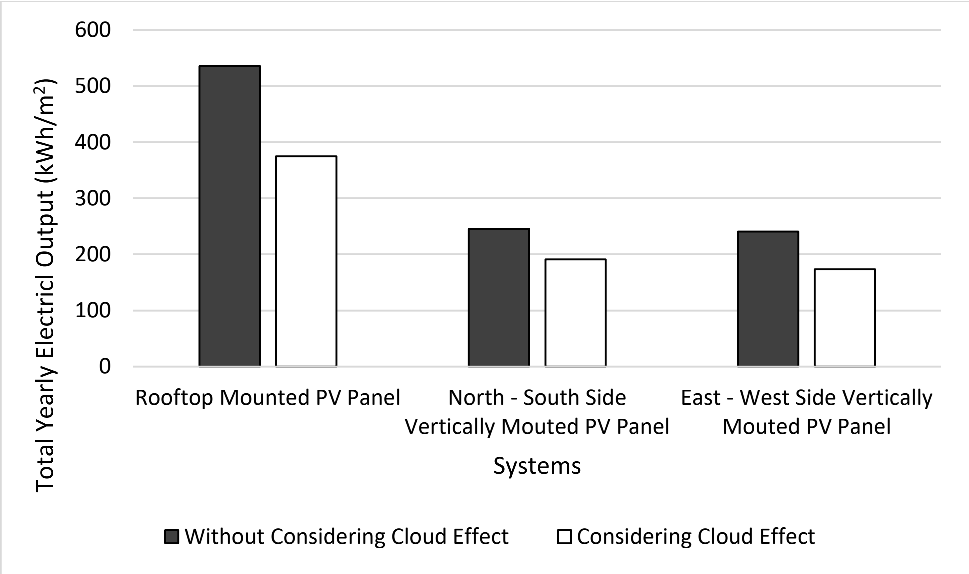

Figure 24: Yearly Electrical Energy Output Comparison

Output electrical energy is summarized below -

Systems & Considerations	**Rooftop Mounted PV Panel (kWh/m^2)**	**North & South Side Vertically Mounted PV Panel (kWh/m^2)**	**East & West Side Vertically Mounted PV Panel (kWh/m^2)**
Without Considering Cloud Effect	536.056	276.892	481.60
Considering Cloud Effect	375.050	211.560	347.0536
Difference (%)	30% Decrease	23.5% Decrease	28% Decrease

Table 4: Yearly Output Electrical Energy from Different Systems

Chapter 5

Site Survey & Output Electrical Energy Estimation

5.1 Dimensional Evaluation of Brac University Building 02

In this thesis we are considering a 20-storied structured building which is known as Brac University building 02 located in Mohakhali, Dhaka. which has 5500 sq. feet rooftop, and the structure is standing about 110 meters tall.

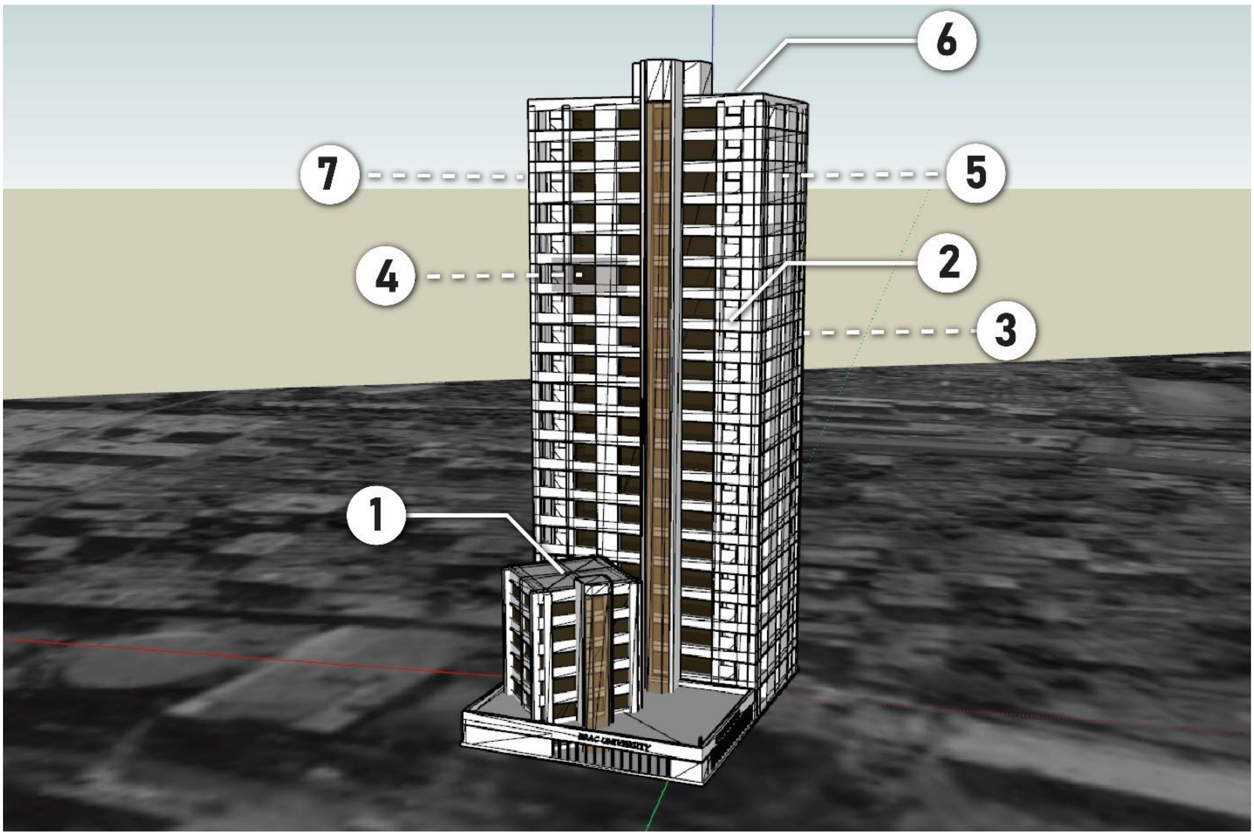

Figure 25: Brac University, Dhaka Building Dimensional View

(1- Building 01, 2- Building 02, 3- South Side of the Building, 4- North Side of the Building, 5- West Side of the Building, 6- East Side of the Building, 7- Rooftop of the Building 02)

Figure 25 above we are showing Brac University's Building 01 and Building 02. We are considering only building 02 for our analysis. According to survey, building 01 is not ideal for installing solar panels because it is five-stored structure, with a twenty-stored building standing behind it. So, the shadow of building 02 is totally covering our building 01.

Rooftop: From figure 26 we can get the proper knowledge of rooftop of the building 2. The orientation of the building is 20° with north. Where the total length is 29.55 m and the width is 17.84 m. So finally, we are getting the total area which is 527.127 m^2. In rooftop due to the 3 lift rooms, tower and other things are covering 20% of that area. If we exclude this 20%, finally we get the area 421.70 m^2.

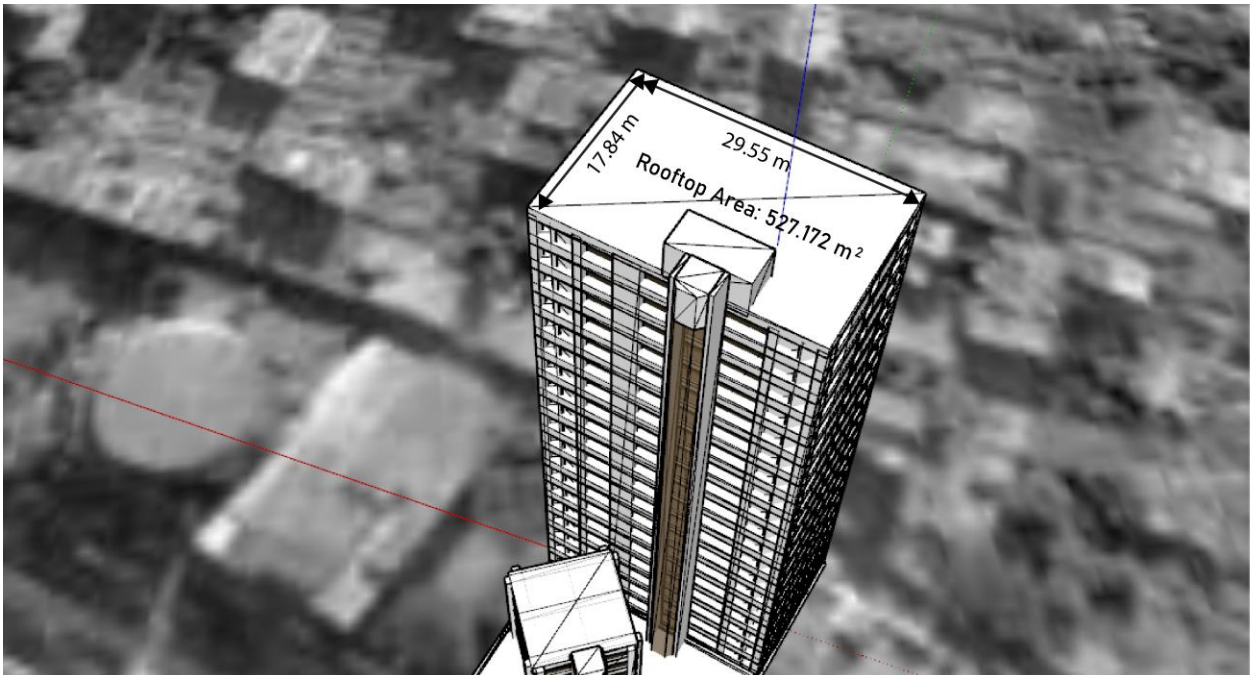

Figure 26: Rooftop of Brac University Building 2

For vertical walls, we have considered top 10 floors of BracU which is of almost 50 meters tall. But all the vertical walls are not useable. The site survey shows the North side gets shadow most of the day time and South side along with East – West side gets enough sunlight throughout the year. Thus considering the East-West and South sides which are actually Left-Right & Back sides of the building respectively, we can summarize the available area that –

East & West Side: From Top to 10th floor height 48.96 m & width 3.86 m which is in the middle of the building. Beside this, narrow pillars having height of 48.96 m but width of 0.47 m. The horizontal pillars that are constructed to connect the middle wall with the narrow pillars having height of 0.85 m and width of 4.2 m. The horizontal pillars are 9 in numbers. Figure 27 is giving us the calculation of horizontal and vertical pillar for eastern and western side.

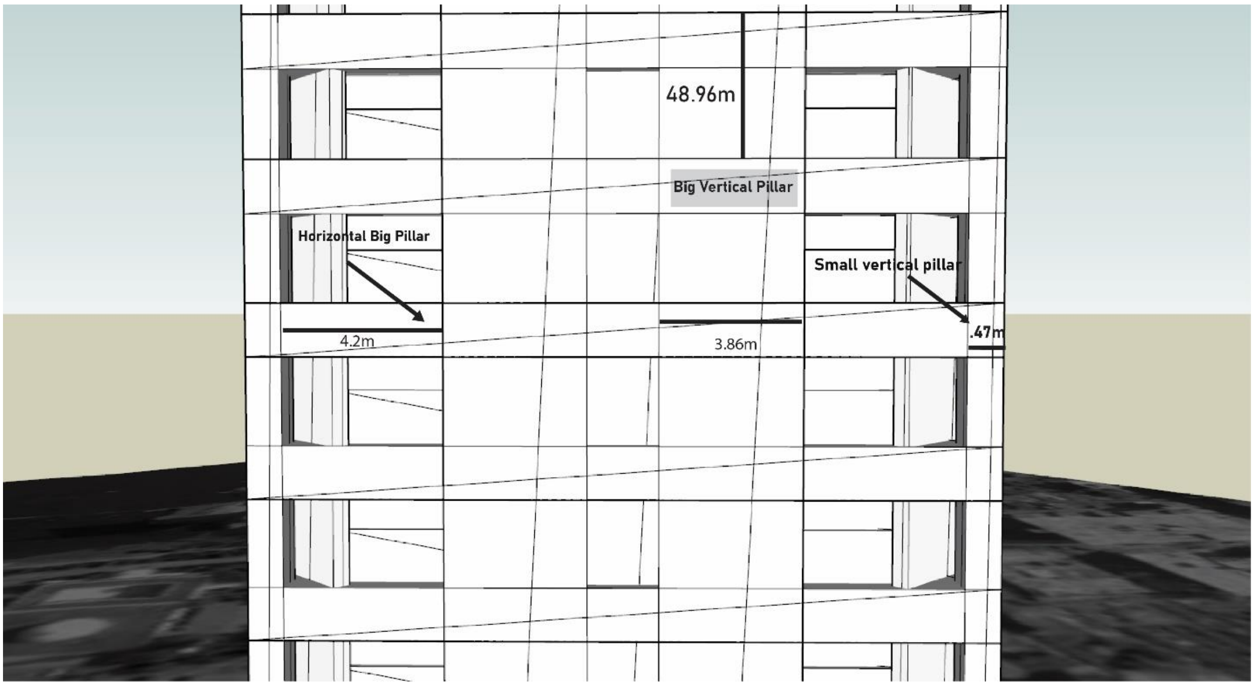

Figure 27: Vertical Dimension of East & West Side

South Side: From the figure 28 below we are getting the proper knowledge of the horizontal and vertical pillar of the back side. We can see that, the size of the one big pillar in the middle and small pillars. Here, we can calculate the total length around 48.96 m and width is 3.39 m for the middle pillar. The horizontal pillar is 0.85 m long and 4.9 m wide.

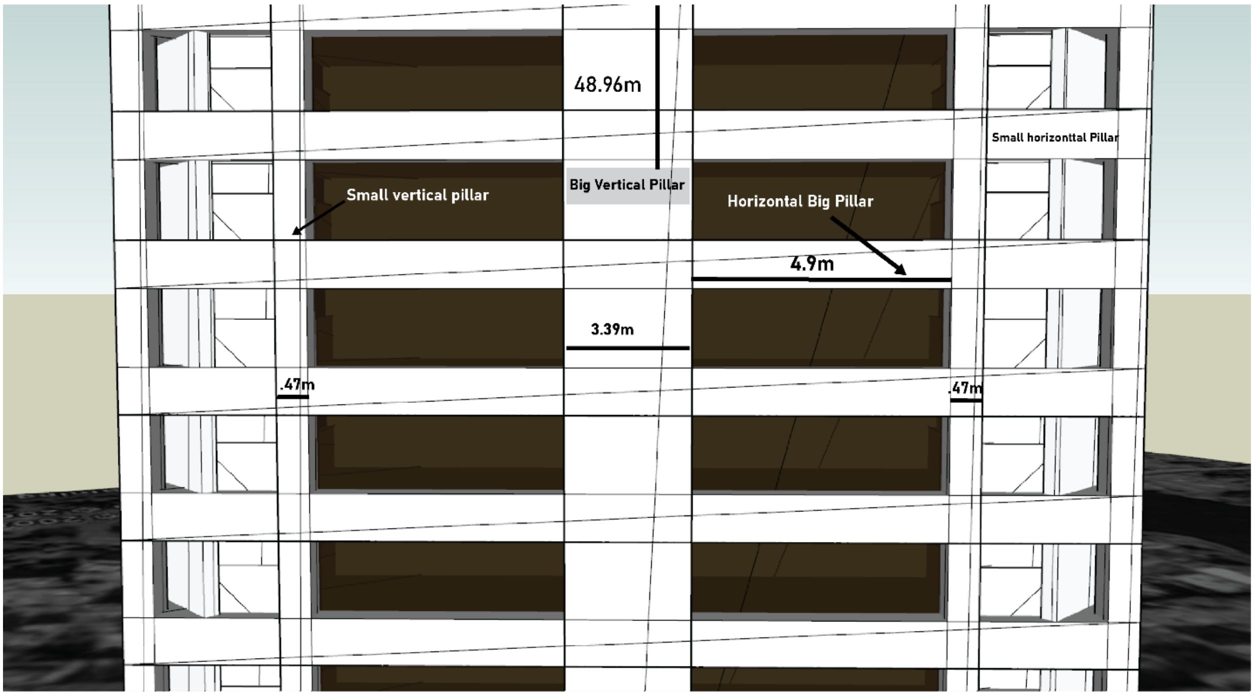

Figure 28: Vertical Dimension of South Side

Total available areas are summarized below –

System	Area (m^2)
Rooftop	421.6962
East & West Side	544.221
South Side	203.4594
Total Area	1169.3766

Table 5: Available Area for Installing PV Panel on Different Systems

5.2 Output Electrical Energy Estimation from Brac University Building 02

From the available area calculation and output electrical energy, total electrical energy after installing building integrated photovoltaic considering cloud effect is 385.886 MWh/m^2 while without considering electrical energy is 544.456 MWh/m^2. Energy estimation is summarized in the table 6 below –

System & Considerations	**Output Electrical Energy Without Considering Cloud Effect (MWh/m^2)**	**Output Electrical Energy Considering Cloud Effect (MWh/m^2)**
Rooftop	226.023	158.157
East & West Side	262.097	188.873
South Side	56.336	38.856
Total Energy	544.456	385.886

Table 6: Estimated Output Electrical Energy from Installed BIPV in BracU

Chapter 6

Future Works & Conclusion

The use of mono-facial solar panel for rooftop shows significant energy loss while considering cloud shadow effect. The above study shows loss of almost 30% of electrical energy in the rooftop because of cloud shadow while it is 26% for vertically mounted systems.

In this study mono-facial solar panel is considered for the rooftop as well as vertical panels but for rooftop mounted panels can be replaced by bi-facial modules to enlarge the accumulation of incident energy. Cloud shadow effect brings significant change in accumulating energy while dust effect as well as bird dropping deposition may also affect energy generation from solar panel installed in building's rooftop and vertical walls. In future, the factors will be considered for developing the study outcome.

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Appendix A.

%% Calculation of Solar Azimuth to Find Out Panel Radiation

```
gamma = acosd((sind(delta)*cosd(phi) - cosd(delta)*sind(phi)*cosd(omega))/cosd(alpha));
if (hour(solarTime) >= 12) && (omega >= 0)
    gamma = 360 - gamma;
end
disp(['Solar Azimuth = ' num2str(gamma)])
```

%% Calculation of Panel Radiation for Fixed Panel

```
beta = 0 ;                                  % Panel azimuth
tau = 90 ;                                      % Panel tilt
panelRad = solarRad*max(0,(cosd(alpha)*sind(tau)*cosd(beta-gamma) +
sind(alpha)*cosd(tau)));
disp(['Panel Radiation = ' num2str(panelRad) ' kW/m^2'])
```