การจำลองและวิเคราะห์ผลของมุมเอียงและมุมอะซิมุทสำหรับอาเรย์ผลิตไฟฟ้าเซลล์แสงอาทิตย์ประเภทบนหลังคา

นายผาพิทูน ปันยาดา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2558

Modeling and Effect Analysis of Tilt and Azimuth Angles for Rooftop Photovoltaic Arrays

Mr. Phaphithoun Pangnada

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2015

Thesis Title	Modeling and Effect Analysis of Tilt and Azimuth Angles for Rooftop Photovoltaic Arrays
By	Mr. Phaphithoun Pangnada
Field of Study	Electrical Engineering
Thesis Advisor	Assistant Professor Surachai Chaitusaney, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Engineering
(Associate Professor Supot Teachavorasinskun, Ph.D.)

THESIS COMMITTEE

....Chairman
(Assistant Professor Sotdhipong Phichaisawat, Ph.D.)

....Thesis Advisor
(Assistant Professor Surachai Chaitusaney, Ph.D.)

....External Examiner
(Att Phayomhom, Ph.D.)

ผาพิทูน ปันยาดา : การจำลองและวิเคราะห์ผลของมุมเอียงและมุมอะซิมุทสำหรับอาเรย์ผลิตไฟฟ้าเซลล์แสงอาทิตย์ประเภทบนหลังคา (Modeling and Effect Analysis of Tilt and Azimuth Angles for Rooftop Photovoltaic Arrays) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร.สุรชัย ชัยทัศนีย์, 81 หน้า.

ไฟฟ้าเป็นสิ่งสำคัญที่มนุษย์เราใช้ในด้านต่างๆ ของกิจกรรมในชีวิตประจำวัน อันที่จริงเราไม่สามารถแม้แต่จะขาดการใช้ชีวิตในกรณีที่ไม่มีไฟฟ้าในยุคปัจจุบัน และการใช้ไฟฟ้า ก็มีการเพิ่มขึ้นเรื่อยๆ ในแต่ละวันการใช้พลังงานแสงอาทิตย์ในทั่วโลกมี ศักยภาพที่จะตอบสนองทุกความต้องการพลังงานของเรา และอัตราการเจริญเติบโตในการติดตั้งเซลล์แสงอาทิตย์ที่ผ่านมามีการขยายตัวอย่างต่อเนื่อง

หนึ่งในตัวแปรที่สำคัญที่สุดที่มีผลกระทบต่อเซลล์แสงอาทิตย์คือ ความสามารถในการได้รับพลังงานแสงอาทิตย์ของแผงเซลล์ ตำแหน่งที่ตั้ง และมุมของแผงเซลล์แสงอาทิตย์ เป็นปัจจัยที่สำคัญมากในการออกแบบระบบเซลล์แสงอาทิตย์

การตรวจสอบมุมที่เหมาะสมของแผงเซลล์แสงอาทิตย์โดยใช้วิธีการทางคณิตศาสตร์ การคาดการณ์ รังสีดวงอาทิตย์ ในการติดตั้งแผง เซลล์แสงอาทิตย์ในมุมต่างๆ บนพื้นฐานของข้อมูลจากดาวเทียมของรังสีดวงอาทิตย์เฉลี่ยรายเดือนประจำวัน และการกระจายรังสีแสงอาทิตย์บนพื้นผิวแนวนอนเป็นเวลา 10 ปี โดยการใช้มุมเอียง รายเดือนเฉลี่ยรายวันที่ดีที่สุด สามารถเพิ่มพลังงานที่ได้รับมากกว่าการใช้มุมเอียงที่เหมาะสมรายปี อย่างไรก็ตามสำหรับการติดตั้งแผงเซลล์แสงอาทิตย์บนหลังคาระบบการติดตั้งโมดูลที่เลือกขึ้นอยู่กับประเภทของหลังคา และลักษณะโครงสร้างของอาคาร การเพิ่มประสิทธิภาพโดยระบบการติดตามดวงอาทิตย์ สามารภใช้ได้ แต่การติดตั้งแบบนี้มักจะใช้ในการติดตั้งบนพื้นดิน และก็จะมีค่าใช้จ่ายที่มากขึ้น ต้องใช้เทคนิคที่ซับซ้อน และต้องการการบำรุงรักษาเพิ่มขึ้น

ภาควิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2558		

5770523421 : MAJOR ELECTRICAL ENGINEERING
KEYWORDS: SOLAR RADIATION / TILTED AND AZIMUTH ANGLE / SOLAR ROOFTOP

PHAPHITHOUN PANGNADA: Modeling and Effect Analysis of Tilt and Azimuth Angles for Rooftop Photovoltaic Arrays. ADVISOR: ASST. PROF. SURACHAI CHAITUSANEY, Ph.D., 81 pp.

Electricity is so important that we use it in various fields of human activity every day. Indeed, we cannot even dream of living in absence of electricity in modern times and the use of electricity is increasing day by day. Global solar radiation has the potential to meet all of our energy requirements and the recent installation growth rates in the PV sector have demonstrated the potential benefit.

One of the most important parameters that affects Photovoltaic (PV) panel system is solar radiation received from the Sun. Because both position and angle of a PV panel are important factors in PV system design, they are considered in many numerical analyses in this thesis.

Investigation the optimal tilt angle of PV panels in this thesis uses a mathematical method, the forecasted solar radiation in different tiled and azimuth angles, and the satellite data of monthly average daily solar radiation and diffuse solar radiation on horizontal surface of 10 years. Using monthly average daily optimal tilt angle can increase the received energy than using the optimal yearly tilt angle. However, for rooftop installations, the module mounting system selected is dependent on the roof type and the structural characteristics of the building. Sun tracking systems are also possible, but these are more common in the ground mounted installations. They are typically more expensive and technically complicated and require additional maintenance.

Department:	Electrical Engineering	Student's Signature	....
Field of Study:	Electrical Engineering	Advisor's Signature	....
Academic Year:	2015		

ACKNOWLEDGEMENTS

My deepest gratitude goes to my principal advisor, Assistant Professor Dr. Surachai Chaitusaney, for his constant guidance, helpful advice, and constructive suggestions on my research.

I would like to thank to all committee members of my research: Assistant Professor. Dr. Sotdhipong Phichaisawat for his fruitful comments on my work, and for being one of the committees of this thesis; and Dr. Att Phayomhom for his willingness to serve on the thesis committee.

I gratefully acknowledge the JICA AUN/SEED-Net for the full financial support throughout my master’s study.

I would like to thank to Dr. Tu Van Dao for his fruitful thesis revisions.

Finally, I would like to thank my family for their support during my study abroad. Thanks are also given to all members of Power Systems Research Laboratory, Chulalongkorn University for their encouragement and friendship.

CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

Chapter 1 Introduction

1.1. Problem statement

Electricity is so important that we use it in various fields of human activity every day. For example, large machines are mainly powered by electricity and essential items like food, cloth, paper and many other things are manufactured by using electricity. Indeed, we cannot even dream of living in the absence of electricity in modern times and the use of electricity is increasing day by day.

There are many different sources of energy that are naturally available throughout the world in different forms for generating electricity. Two main different sources are renewable and non-renewable sources. Some of non-renewable sources are unsafe for humans and the environment (nuclear power), not last for the long future (fossil thermal power). Renewable sources of energy are obtained from different natural sources. The most common sources are sunlight, wind, water and geothermal. One advantage of this form of energy is that it can be replaced and used continuously without becoming depleted. Renewable sources of energy are mostly used in three different areas including electricity generation, heating by use of solar hot water and motor fuels through the use of renewable bio-fuels.

Renewable energies represent a cornerstone to steer our energy system in the direction of sustainability and supply security and the global potential of photovoltaic (PV) energy as an indication of long term availability of the resource (1, 2). The power generated by a solar panel is dependent on the angle at which it is tilted, the prevailing weather condition and the orientation of the solar panel. Improper orientation of the solar panel would eventually lead to a loss in power and poor return on investment.

1.2. Objective

- To calculate the monthly and yearly solar radiation on the tilted surface.
- To increase the efficiency of receiving the sun's energy to solar panel by adjusting the tilted angle towards the sun.

1.3. Expected benefits

- The results of this research are a basis for PV panel installation in Thailand.
- The model of the average solar radiation energy can be used for rooftop PV installation.

Chapter 2 Installation of PV panel

2.1. Literature review

Many papers have presented models to predict solar radiation on tilt surfaces and employed the method proposed by Liu and Jordan(3, 4). Normally, the tilted surfaces that get high solar radiation is not the same at all places and it depends on the interested location. Some models have been made and led to different recommendations based on the latitude. Many researchers have found that the tilted surfaces facing toward the equator (zero azimuth surface) could help a PV panel get high solar radiation. Moreover, some researchers also proposed methods for estimating solar radiation on the surfaces that faced toward the equator (non-zero azimuth surface) and the vertical surfaces. Solar panels are generally oriented toward the equator (5-8). In the northern hemisphere, solar panels are oriented towards the south. But in the southern hemisphere, solar panels are oriented towards the north.

The value of the optimal tilted angle has been given by many researchers. During the winter months in Baghdad city, that angle is about 54° which means latitude+20^0. The maximum incident insolation on a collector nearly horizontal surface in the summer months is about 12^0 which means latitude-20^0. The maximum radiation energy of the tilted angle collector in the winter is latitude +21^0 and -19^0 in the summer (9-11). The efficiency of solar energy conversion by photovoltaic (PV) panels is one-problem which is constantly a focus of attention of scientists and technologists in the field. One of its many aspects is the concentration of solar radiation and/or tracking of the Sun to increase the total energy collected by a panel for conversion. Photovoltaic (PV) system that has a one-axis and two-axis tracking (12-16).

Measurements of solar radiation are not often available, attempts have been made by many researchers to establish a relationship between values of radiation with sunshine hours, cloud cover and precipitation. In this paper, we use the method of Erbs et al (17) that could be related to the amount of solar radiation by linear relation of the clearness index K_{T}.

2.2. Introduction of solar energy

Solar energy is the most widespread renewable energy. The amount of sunlight falling on the earth contains offers far more energy than we could ever use. Solar energy is easier accessible than other energy resources. The initial cost is the main disadvantage of installing a solar energy system, largely because of the high cost of the semi-conducting materials used in building one. But after the initial investment has been recovered, the energy from the sun is practically free. Solar energy is sure and the yearly yield is fairly constant. At any given time during the day, the sun is usually shining somewhere and solar electricity can be distributed from a region where the sun is shining to the one where it is shining less.

Solar radiation is the energy emitted from the sun that travels through the space to the surface of the earth. A radiation can be diffuse or direct (Figure 2.1). When a radiation is scattered, reflected, or absorbed by atmospheric constituents such as clouds, water vapour and dust, we talk about diffuse radiation. On the other hand, it is direct radiation on clear days where the sun prevails. Solar radiation is the power of solar radiation per unit area. It is commonly expressed in units of watts per square meter or kilowatts per square meter. The solar energy that constantly arrives the atmosphere is around 1,370 W/m² and is called solar constant. The absorption of radiation by air, clouds and water vapour reduces the radiation energy on earth. The standard value for the maximum radiation on earth is 1,000 W/m² (4-6).

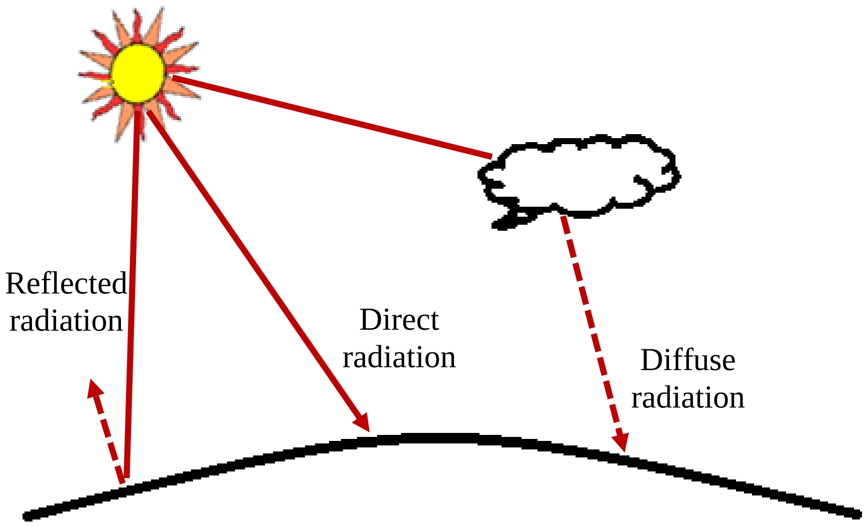


Figure 2. 1. The schematic diagram of solar radiation through the atmosphere to the earth's surface

2.3. Solar radiation in space

The sun emits only a fraction of the total power, impinges on an object in space which is some distance from the sun. The solar radiation (H_0 in W/m^2) is the power density incident on an object due to illumination from the sun. However, at some distance from the sun, the total power from the sun is now spread out over a much larger surface area and therefore the solar irradiance on an object in space decreases as the object moves further away from the sun (1, 2).

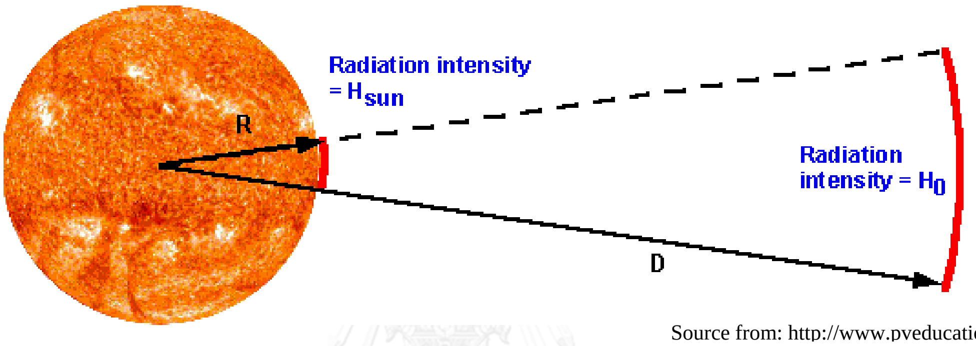
The solar irradiance on an object some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls. The total solar radiation emitted by the sun is given by σT^4 multiplied by the surface area of the sun ($4\pi R^2_{sun}$) where R_{sun} is the radius of the sun. The surface area over which the power from the sun falls will be $4\pi D^2$. Where D is the distance of the object from the sun. Therefore, the solar radiation intensity, H_0 in (W/m^2), incident on an object is:

$$H_0=\frac{R_{sun}^2}{D^2}H_{sun} \qquad (2.1)$$

where:

H_{sun} is the power density at the sun's surface (in W/m^2) as determined by Stefan-Boltzmann's blackbody equation

R_{sun} is the radius of the sun in meters as shown in the figure below; and
D is the distance from the sun in meters as shown in the figure below.



Source from: http://www.pveducation.org/

Figure 2. 2. At a distance, D, from the sun the same amount of power is spread over a much wider area so the solar radiation power intensity is reduced

The table below gives standard values for the radiation at each of the planets but by entering the distance you can obtain an approximation.

Table 2. 1 Standard values for the radiation at each of the planets

Planet	**Distance ($\times 10^9$ m)**	**Mean Solar Irradiance (W/m^2)**
Mercury	57	9116.4
Venus	108	2611
Earth	150	1366.1
Mars	227	588.6
Jupiter	778	50.5
Saturn	1426	15.04
Uranus	2868	3.72
Neptune	4497	1.51
Pluto	5806	0.878

2.4. Solar radiation outside the earth's atmosphere

The solar radiation outside the earth's atmosphere is calculated using the radiant power density (H_{sun}) at the sun's surface ($5.961 \times 10^7 W/m^2$), the radius of the sun (R_{sun}), and the distance between the earth and the sun. The calculated solar irradiance at the Earth's atmosphere is about 1.36 kW/m^2. The geometrical constants used in the calculation of the solar irradiance incident on the Earth are shown in the figure below.

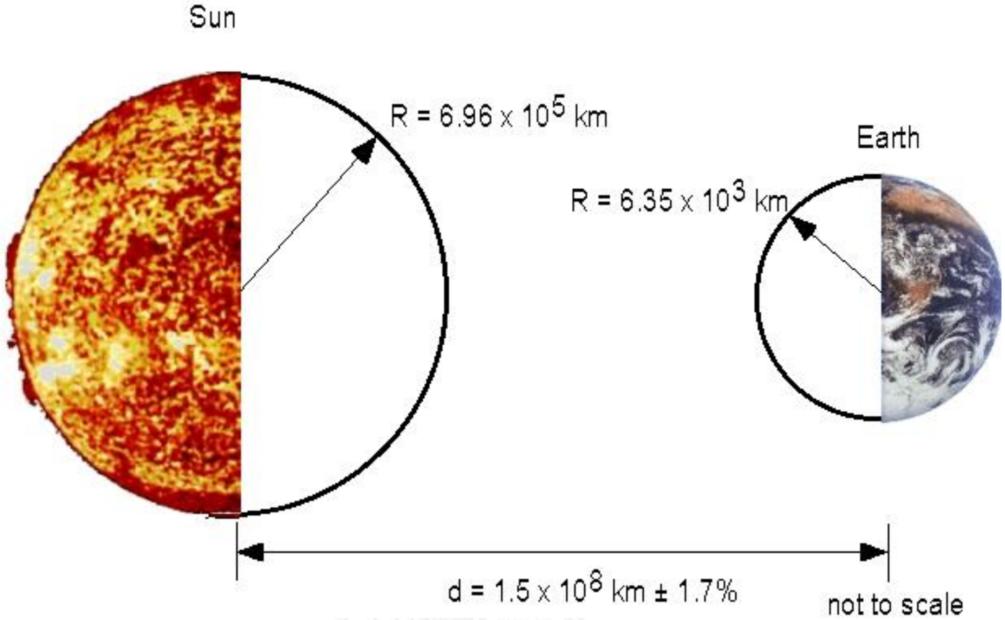


Figure 2. 3. Geometrical constants for finding the Earth's solar radiation

The actual power density varies slightly since the Earth-Sun distance changes as the Earth moves in its elliptical orbit around the sun, and because the sun's emitted power is not constant. The power variation due to the elliptical orbit is about 3.4%, with the largest solar irradiance in January and the smallest solar irradiance in July. An equation (2.2) which describes the variation throughout the year just outside the earth's atmosphere is:

$$\frac{H}{H_{constant}} = \frac{H}{I_0} = \mathrm{E}_0 = 1 + 0.033 \times \cos\left(\frac{360 \times \mathrm{n}}{365}\right) \tag{2.2}$$

where:
H is the radiant power density outside the Earth's atmosphere (in W/m^2);
$H_{constant}$ is the value of the solar constant, 1.367 kW/m^2; and
n is the day of the year.

These variations are typically small and for photovoltaic applications the solar irradiance can be considered constant. The value of the solar constant and its spectrum have been defined as a standard value called air mass zero (AM0) and takes a value of 1.367 kW/m^2.

2.5. Declination angle

The declination angle, denoted by δ, varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. If the Earth were not tilted on its axis of rotation, the declination would always be 0°. However, the Earth is tilted by 23.45° and the declination angle varies plus or minus this amount. Only in the spring and fall equinoxes is the declination angle equal to 0°. The rotation of the Earth around the sun and the change in the declination angle is shown in the animation below.

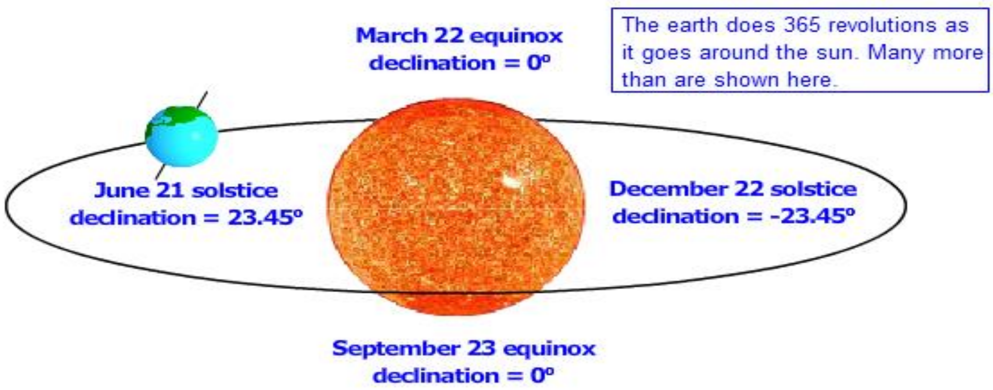
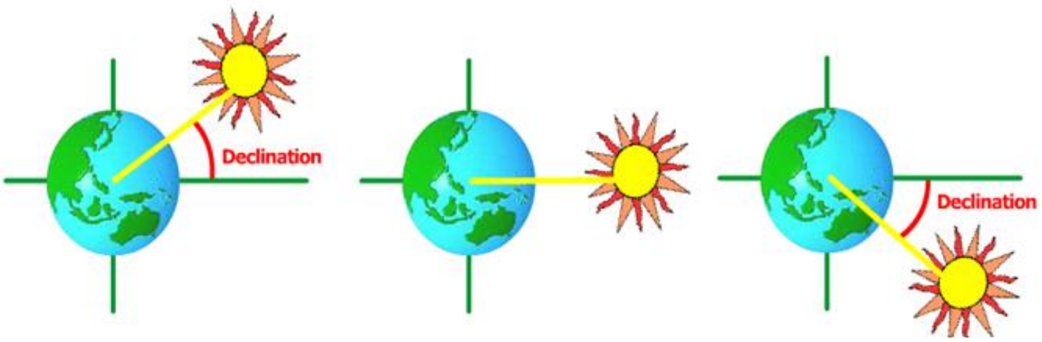


Figure 2. 4. Declination angle changes from the session of the year

The declination of the sun is the angle between the equator and a line drawn from the centre of the Earth to the centre of the sun. The seasonal variation of the declination angle is shown in the animation below. Despite the fact that the Earth revolves around the sun, it is simpler to think of the sun revolving around a stationary Earth. This requires a coordinate transformation. Under this alternative coordinate system, the sun moves around the Earth.



Summer solstice in the northern hemisphere. The declination angle (δ) is at maximum and is 23.45°

Spring equinox in the northern hemisphere and autumn equinox in the southern hemisphere. The declination angle (δ) is 0°

Winter solstice in the southern hemisphere. The declination angle (δ) is at maximum and is -23.45°

Figure 2. 5. Declination angle change in each session

The declination angle can be calculated by the equation:

$$\delta = \begin{pmatrix} 0.006918 - 0.399912 \times \cos D + 0.070257 \times \sin D - 0.006758 \times \cos 2D \\ +0.000970 \times \sin 2D - 0.002697 \times \cos 3D + 0.00148 \times \sin 3D \end{pmatrix} \times \frac{180}{\pi}$$

(2.3)

δ is the declination angle (degree)

D is day angle (degree), many computational purposes, it is customary to express the time of year in term of n, the day of the year, that as an integer from 1 is the first day of the year till 365 is the last day of the year

$$D = \frac{360^\circ (n-1)}{365}$$

(2.4)

where D is the day of the year with Jan 1 as D = 1

The declination is zero at the equinoxes (March 22 and September 22), positive during the northern hemisphere summer and negative during the northern hemisphere winter. The declination reaches a maximum of 23.45° on June 22 (summer solstice in the northern hemisphere) and a minimum of -23.45° on December 22 (winter solstice in the northern hemisphere).

2.6. Effect from improper installation angle of PV panel

2.6.1. Types of solar PV system

Photovoltaic-based systems are generally classified according to their functional and operational requirements, their component configuration, and how the equipment is connected to the other power sources and electrical loads (appliances). The two principal classifications are Grid-Connected and Stand Alone Systems.

Grid connected PV

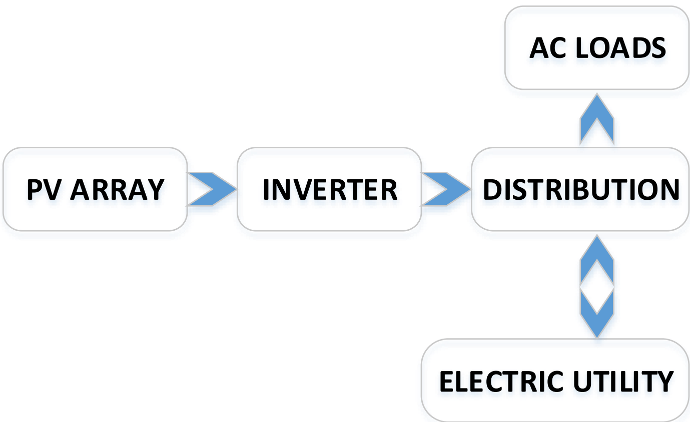


Figure 2. 6. Grid connected system

Grid-connected or utility-intertie PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component is the inverter, or power conditioning unit (PCU). The inverter converts the DC power produced by the PV array into AC power consistent with the voltage and power quality required by the utility grid. The inverter automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the power produced by the PV system to either supply on-site electrical loads, or to back feed the grid when the PV system output is greater than the on-site load demand. During periods when the electrical demand is greater than the PV system output (night-time), the balance of power required is received from the electric utility This safety feature is required in all grid-connected PV systems, it also ensures that the PV system will not continue to operate and feed back onto the utility grid when the grid is down for service or repair.

Stand-alone system

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. Stand-alone systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as a backup power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load.

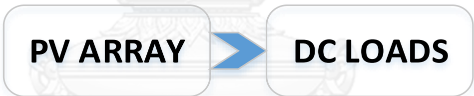


Figure 2. 7. Direct-coupled stand-alone system

Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT) is used between the array and load to help better utilize the available array maximum power output.

In many stand-alone PV systems, batteries are used for energy storage. Below is a diagram of a typical stand-alone PV system with battery storage powering DC and AC loads.

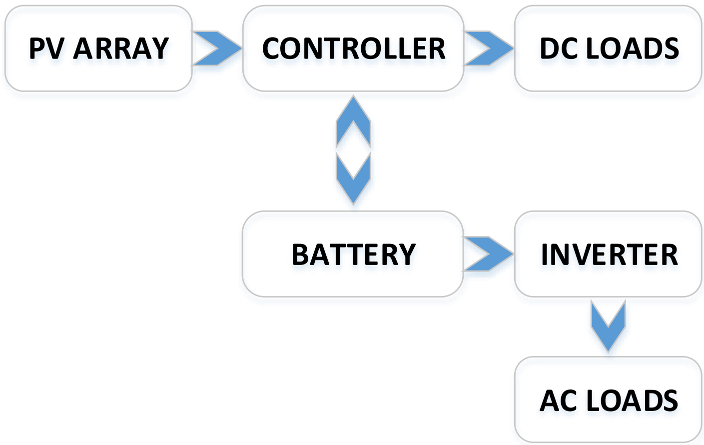


Figure 2. 8. Stand-alone system with battery

Below is a diagram of a Photovoltaic Hybrid System with battery storage powering DC and AC loads and using a using a backup power source (wind, engine-generator or utility power).

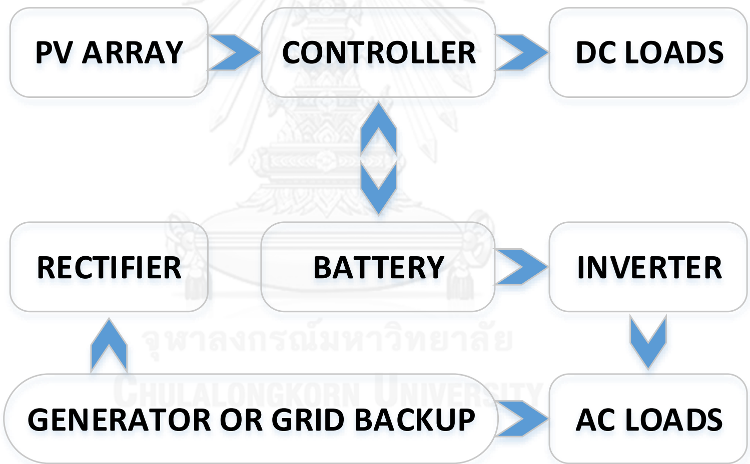


Figure 2. 9. Stand-alone hybrid system

2.6.2. Effect from not optimized angle

Pv installations for normal houses are usually installed on the roof. The roof of them may be angle facing to the sun not throughout the year well. So, It receives the solar radiation not full efficiency. The common roof for modern house there tilt angle of about 35 degrees and is divided into 3 types:

Lean-to roof

Lean-to roof is focused on creating a simple roof. Popular for building temporary shelters in the garden on a farm. The roof is flat, but raised the front higher than the back to allow for drainage of rain. Generally, we may see a lean-to roof of Modern house and may have more detail such as in the stacked roof. But No side vents necessary to vent from the roof floor.

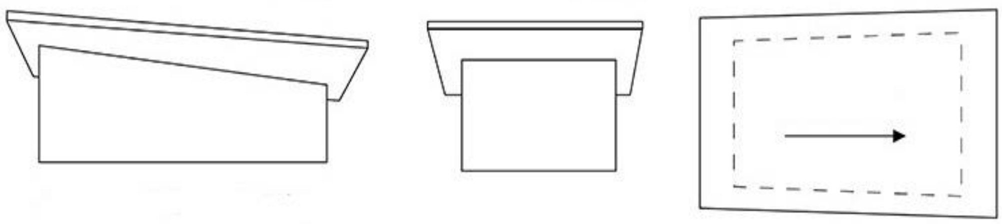


Figure 2. 10. Type of rooftop (Lean-to roof)

Gable Roof

Gable roof is sloped 2 sides collide at the top of the roof. This roof is commonly used. Suitable for tropical climate like Thailand. Because there will be more air under the roof as well as insulation. Construction was easy, but protect the sunlight and rain well. It is the format used in the roof that houses ancient Thailand. In the past may have been designed the height of roof top to increase the slope of the roof. This will allow rain water to flow down easily. Reduce the fracture of roofing material from wind, rain, hail or branches of tree.

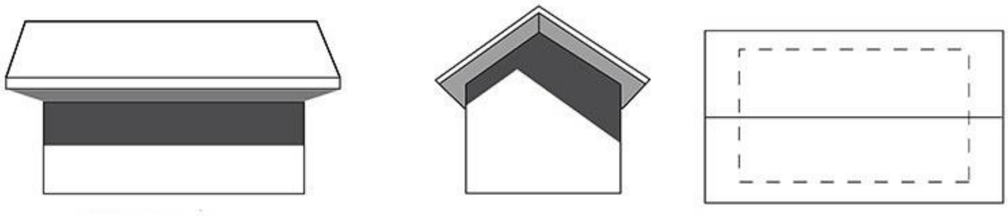


Figure 2. 11. Type of rooftop (Gable roof)

Hip Roof

This model has a sloping roof top four side collision similar to a pyramid. Has been popular in the past to the present. Can be protect the sunlight and rain from all sides and withstand the impact of wind well. But No side vents necessary to vent from the roof floor.

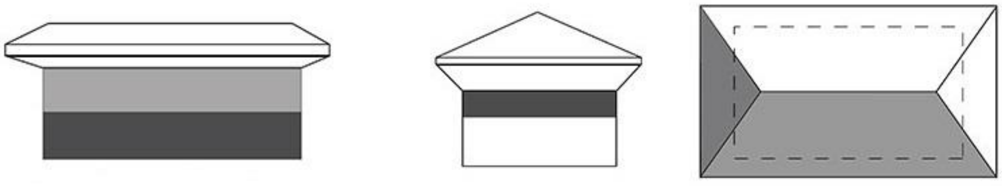


Figure 2. 12. Type of rooftop (Hip roof)

Each type of rooftop will be facing in any direction depends on the area of the house toward the front and the type of roof will determine whether to install the solar panel facing into. Such as, Lean-to roof there is a panel, Gable Roof there are 2 panels and Hip Roof There are 4 panels can receive the solar radiation. In some cases, the panels installed on the rooftop facing the direction in any way not perpendicular to the sun, that receives energy should be any less than the optimum installation panel.

2.7. Tracking to increase the efficiency

Tracker is a generic term used to describe devices that orient various payloads toward the sun. In the case of photovoltaic (PV) systems, the payload is the PV module. There is no other single balance-of-system (BOS) component that can increase a PV system’s performance like a tracker. By maintaining consistent direct exposure from the sun to the module, trackers can improve a PV system’s output by up to 40 percent over a fixed-tilt array. The increment of production improvement over a fixed system depends on the project’s latitude and the type of tracker. The benefits of trackers vary between the different categories of trackers (one-axis, 1.5-axis, and dual-axis).

Chapter 3 Mathematical Model of Solar Radiation

3.1. Solar radiation model on tilted surface

Monthly average daily radiation on tilted angle H_T consists of three components: beam radiation H_B, diffuse radiation H_D and reflected radiation H_R calculate in (3.1) and (3.2) respectively.

$$H_T = H_B + H_D + H_R \tag{3.1}$$

$$\overline{H}_T = \left(\overline{H} - \overline{H}_d\right) R_b + 0.5\overline{H}_d\left(1 + \cos\beta\right) + 0.5\rho\overline{H}\left(1 - \cos\beta\right) \tag{3.2}$$

Where $\overline{H}$ is the monthly average daily solar radiation on horizontal by satellite data (Mj/m^2-day), $\overline{H}_d$ is the monthly average daily diffuse solar radiation on horizontal (Mj/m^2-day), ρ is ground reflectivity, which is assumed to be equal to 0.2 as mentioned in much literature for no snow flat surfaces and R_b is the ratio of the average daily beam radiation on horizontal calculate in (3.3).

Thus this thesis proposals used a monthly average daily solar radiation on horizontal surface of 15 years satellite data (18, 19), to estimate the monthly and yearly average daily solar radiation on tilted surface in table 3.1.

Table 3. 1. The monthly average solar radiation on horizontal surface of satellite data of each province (Mj/m^{2}day)

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bangkok	16.49	17.80	18.60	19.11	19.29	19.36	19.20	19.01	18.62	18.11	17.74	17.53
Krabi	18.22	19.34	19.99	20.11	19.93	19.60	19.35	18.99	18.71	18.32	17.95	17.70
Kanchanaburi	15.17	16.48	18.33	18.26	18.61	18.75	18.53	18.30	17.95	17.42	17.03	16.86
Kalasin	15.98	17.08	17.99	18.88	19.29	19.46	19.30	18.97	18.54	18.15	17.68	17.36
Kampheangphet	16.36	17.61	18.54	19.44	19.67	19.66	18.65	18.92	18.54	17.90	17.41	17.25
Khonkean	15.91	17.13	17.91	18.75	19.18	19.33	19.21	18.94	18.55	18.14	17.70	17.43
Chanthaburi	17.85	18.64	19.24	19.35	18.91	18.66	18.30	17.92	17.50	17.16	17.01	16.95
Chachoengsao	16.52	17.72	18.51	18.93	18.98	19.07	18.78	18.58	18.29	17.92	17.64	17.44
Chonburi	15.53	16.75	17.31	17.58	17.64	17.72	17.54	17.41	17.12	16.74	16.47	16.30
Chainat	16.27	17.34	18.22	19.26	19.61	19.63	19.49	19.26	18.91	18.42	18.06	17.91
Chaiyaphoum	15.93	17.15	17.95	18.76	19.22	19.44	19.31	19.03	18.68	18.28	17.88	17.68
Chumphon	18.16	19.23	20.11	20.54	20.56	20.30	20.01	19.75	19.45	18.97	18.49	18.28
Chiangria	14.59	15.45	16.14	17.40	18.18	18.46	18.12	17.80	17.48	17.08	16.53	16.22
Chiangmai	14.52	15.31	16.41	17.78	18.41	18.62	18.39	18.14	17.76	17.28	16.76	16.44
Trang	19.76	20.53	20.79	21.04	20.83	20.41	20.05	19.74	19.41	18.99	18.51	18.25
Trat	18.09	18.96	19.61	19.78	19.50	19.13	18.71	18.33	17.89	17.58	17.49	17.46
Tak	15.58	16.75	17.80	18.67	18.81	18.87	18.47	18.12	17.77	17.28	16.83	16.61
Nakhom nayok	15.77	16.94	17.66	18.20	18.42	18.45	18.12	17.88	17.54	17.20	16.89	16.63
Nakhon Pathom	15.96	17.40	18.36	19.15	19.28	19.34	19.14	18.88	18.51	17.99	17.60	17.43
Nakhon Panom	16.12	17.00	17.73	18.57	18.85	18.76	18.34	17.95	17.55	17.30	17.03	16.76

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nakhom Ratchasima	16.16	17.19	17.91	18.61	16.29	19.18	19.03	18.81	18.39	19.55	17.54	17.34
Nakhon Sithammarat	16.79	18.10	37.72	19.84	20.32	20.02	19.93	19.79	19.65	19.22	18.61	18.12
Nakhon Savanh	16.11	17.43	18.31	19.12	19.59	19.68	19.58	19.29	18.90	18.38	17.98	17.56
Nonthaburi	15.88	17.19	18.03	18.65	18.79	18.84	18.66	18.44	18.10	17.65	17.29	17.09
Narathiwat	18.29	19.66	20.86	21.70	21.82	21.79	21.64	21.53	21.40	21.10	20.45	19.84
Nan	14.19	15.21	16.03	17.22	17.90	18.09	17.79	17.48	17.10	16.73	16.25	15.99
Buriram	15.86	16.97	17.85	18.58	19.08	19.40	19.36	19.24	19.07	18.34	17.86	17.59
Pathum Thani	15.60	17.03	17.69	18.32	18.56	18.66	18.49	18.29	17.96	17.54	17.19	17.00
Prachuap Khirikhan	17.04	18.43	19.05	19.49	19.79	19.72	19.49	19.21	18.98	18.60	18.22	18.01
Prajinburi	16.26	16.54	18.28	18.80	18.84	18.81	18.46	18.12	17.77	17.45	17.15	16.93
Pattani	18.74	20.15	21.20	21.63	21.59	21.44	21.28	21.16	20.90	20.55	19.82	19.34
Ayutthaya	16.22	17.38	18.15	18.77	19.10	19.28	19.10	18.87	18.52	18.10	17.72	17.55
Phayao	13.03	14.17	15.45	16.57	16.96	17.26	17.08	16.81	16.45	15.95	15.44	15.15
Phang Nga	19.89	20.69	21.24	21.21	20.86	20.40	20.01	19.65	19.25	18.86	18.49	18.34
Phattalung	17.16	18.51	19.79	20.11	20.85	20.76	20.64	20.47	20.26	19.84	18.60	18.70
Phichit	15.79	17.01	17.95	19.11	19.60	19.66	18.36	18.07	18.65	18.15	17.85	17.58
PhitSanulok	15.42	16.51	17.46	18.70	19.18	19.35	19.08	18.72	18.28	17.77	17.37	17.18
Phetchabun	16.13	16.10	17.98	17.51	18.22	19.26	18.91	18.44	18.05	17.67	17.32	17.16
Phetchaburi	17.19	18.77	19.65	20.41	20.53	20.52	20.16	19.90	19.50	18.95	18.59	18.44
Phrae	13.67	14.19	16.33	17.79	17.55	18.00	17.94	17.76	17.39	16.99	16.48	16.24
Phuket	19.41	20.22	20.83	20.53	20.21	19.88	19.59	19.19	18.84	18.47	18.17	18.05
Mahasarakham	16.05	17.23	18.00	18.86	19.29	19.46	19.37	19.08	18.69	18.26	17.80	17.54
Mukdahan	16.48	17.28	18.13	18.94	19.22	19.29	18.98	18.64	18.19	17.85	17.48	17.20
MaeHongson	16.79	17.53	68.03	18.66	19.18	19.18	18.72	18.36	18.03	17.65	17.25	17.01
Yasothon	16.60	17.42	18.16	18.83	19.30	16.79	19.48	19.19	18.75	18.30	17.85	17.55
Yala	17.80	19.14	20.23	20.82	20.99	20.98	20.85	20.78	20.61	20.20	19.60	19.02
Roiet	15.85	16.78	17.48	18.40	18.90	19.13	19.04	18.83	18.46	18.10	17.68	17.43
Ranong	18.00	19.22	20.08	20.21	19.75	19.24	18.75	18.29	17.84	17.42	17.01	16.91
Rayong	17.05	18.16	18.90	19.32	19.16	19.07	18.80	18.57	18.17	17.75	17.47	17.36
Ratchaburi	16.10	17.50	18.48	19.42	19.63	19.62	19.36	19.09	18.71	18.13	17.68	17.48
Lopburi	16.42	17.63	18.60	19.31	19.64	19.70	19.56	19.35	18.95	18.49	18.12	17.91
Lampang	14.12	14.89	15.95	17.40	18.21	18.73	18.55	18.33	17.88	17.32	16.74	16.42
Lumphun	14.16	14.95	16.14	17.55	18.28	18.67	18.50	18.24	17.82	17.33	16.72	16.40
Loei	15.69	16.54	17.32	18.00	18.39	18.74	18.53	18.22	17.74	17.35	16.94	16.74
Sisaket	16.64	17.55	18.34	18.91	19.16	19.28	19.20	19.03	18.64	18.20	17.80	17.54
Sakhon Nakhon	16.18	16.93	17.65	18.51	18.67	18.68	18.43	18.15	17.90	17.55	17.22	16.95
Songkhla	18.89	20.16	20.80	21.20	21.22	20.96	20.75	20.53	20.26	19.89	19.28	18.81
Satun	18.70	19.87	20.41	20.56	20.46	20.22	30.03	19.74	19.41	19.07	18.70	18.41
Samutprakan	15.94	17.29	18.33	18.80	18.89	18.97	18.76	18.66	18.37	17.98	17.61	17.36
Samut songkhram	16.25	17.94	18.84	19.62	19.77	19.80	19.55	19.32	18.93	18.43	17.99	17.81
Samut sakhon	16.15	17.69	18.77	19.41	19.54	19.59	19.33	19.10	18.76	18.22	17.79	17.57
Sakaeo	16.67	17.49	18.28	19.00	19.15	19.06	18.77	18.47	17.56	17.77	17.45	17.25
Saraburi	15.96	16.30	17.02	17.75	18.06	18.20	18.88	18.61	18.24	17.81	17.45	17.27
Sing buri	16.65	17.63	18.41	19.44	19.84	19.92	19.78	19.61	19.24	18.81	18.42	18.21
Sukhothai	15.93	17.20	17.99	18.95	19.55	19.66	19.23	18.91	18.57	18.11	17.63	17.41
Suphanburi	15.76	16.75	17.59	18.53	18.84	19.07	18.84	18.66	18.39	17.99	17.68	17.41

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Suratthani	17.77	19.36	20.13	20.59	20.51	20.27	20.06	19.79	19.59	19.08	18.47	18.07
Surin	16.07	17.07	17.85	18.88	19.16	19.42	19.40	19.25	18.85	18.38	17.95	17.66
Nong khai	16.06	17.11	18.03	18.98	19.32	19.50	19.21	18.85	18.46	18.09	17.60	17.39
Nong bualamphu	16.20	16.96	17.71	18.48	18.87	19.10	18.89	18.57	18.16	17.76	17.34	17.11
Ag thong	16.41	17.59	18.44	19.13	19.45	19.56	19.36	19.20	18.84	18.40	18.08	17.85
Amnat charoen	16.23	17.22	18.05	18.82	19.09	19.17	19.04	18.76	18.33	17.93	17.54	17.24
Udon thani	16.21	17.20	18.07	18.99	19.28	19.41	19.11	18.78	18.29	17.95	17.55	17.30
Uttaradit	13.85	14.84	16.15	17.72	18.38	18.74	18.50	18.28	17.90	17.51	17.04	16.80
Uthaithani	16.33	17.58	18.36	19.31	19.78	19.65	19.45	19.18	18.82	18.30	17.88	17.75
Ubon ratchathani	17.23	17.05	17.91	19.44	19.47	19.43	19.29	19.02	18.50	18.02	17.65	17.37

$$R_b = \frac{\cos(L-\beta)\cos\delta\sin\omega + \frac{\pi}{180}\omega\sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin\omega + \frac{\pi}{180}\omega\sin L\sin\delta} \tag{3.3}$$

Where L is the latitude of the location (degree), β is the titled angle (degree), δ is the declination angle (degree) can be calculated in (3.4) and ω is sunrise or sunset hour angle (degree) calculate in (3.5).

$$\begin{aligned}\delta = (&0.006918 - 0.399912\cos D + 0.070257\sin D - 0.006758\cos 2D \\ &+0.000907\sin 2D - 0.002697\cos 3D + 0.00148\sin 3D)(180/\pi)\end{aligned} \tag{3.4}$$

$$\omega = \min\{a\cos(-\tan L \times \tan\delta),\ a\cos(-\tan(L-\beta)\tan\delta)\} \tag{3.5}$$

Hour angle ω, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon positive. D is day angle (degree), many computational purposes, it is customary to express the time of year in term of n, the day of the year, that as an integer from 1 is the first day of the year till 365 is the last day of the year.

where D is day angle (degree) and can calculated in (4.6).

$$D = \frac{360°(n-1)}{365} \tag{3.6}$$

where n is the day number in a year with the 1st January equal to 1.

The monthly average daily beam radiation on horizontal surface can be calculated in (3.7)

$$H_b = \bar{H} - \bar{H}_d \tag{3.7}$$

where $\overline{H}$ is the monthly average daily solar radiation on horizontal surface by satellite data for 15 years (MJ/m^2-day), $\overline{H_d}$ is the monthly average daily diffuse solar radiation on horizontal surface (MJ/m^2-day), ρ is ground reflectance (ρ =0.2), β is the tilted surfaces (degree), $\overline{R_b}$ is the ratio of monthly average daily beam solar radiation on the tilted surface to horizontal surface, and $\overline{R_d}$ is the ratio of the monthly average daily diffuse solar radiation on the tilted surface to horizontal surface.
The ratio of monthly average daily beam solar radiation on the tilted to horizontal surface is divided into two cases: azimuth surface is equal to zero and not equal to zero and it can be calculated in (3.8), and (3.9) respectively.

$$\overline{R}_d = (1+\cos\beta)/2 \quad (3.8)$$

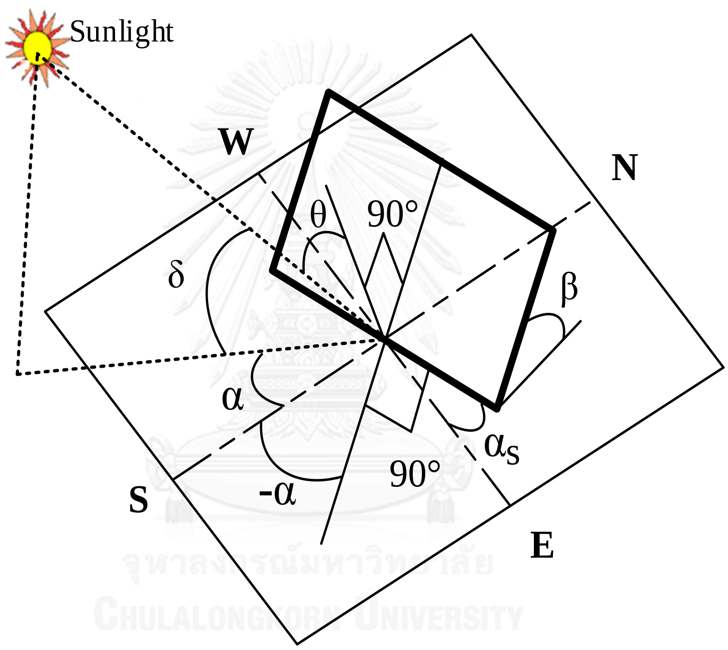


Figure 3. 1. Solar radiation with tracking both tilted angle surface and azimuth angle surface through the atmosphere to the panel

For Azimuth non Zero

$$\begin{aligned}\overline{R}_b = {} & [(\cos\beta\sin\delta\sin L)(\pi/180)(H_{SS}-H_{SR}) \\ & -(\sin\delta\cos L\sin\beta\cos\alpha)(\pi/180)(H_{SS}-H_{SR}) \\ & +(\cos L\cos\delta\cos\beta)(\sin H_{SS}-\sin H_{SR}) \\ & +(\cos\delta\cos\alpha\sin L\sin\beta)(\sin H_{SS}-\sin H_{SR}) \\ & -(\cos\delta\sin\beta\sin\alpha)(\cos H_{SS}-\cos H_{SR})] \\ & /[2(\cos L\cos\delta\sin H_S+(\pi/180)H_S\sin L\sin\delta)]\end{aligned} \quad (3.9)$$

where H_s is sunset hour angle on horizontal surface (degree) and can be calculated in (3.10), H_S' is sunset hour on the tilted surface (degree) and can be calculated in (3.11), L is location latitude (degree), α is azimuth surface (local meridian is zero, the east-south is negative and west-south is positive) (degree), H_{SS} and H_{SR} are the sunset and sunrise hour angle on the tilted surfaces for the case of non-zero azimuth surface and can be calculated in equations respectively.

$$H_s = ar\cos\left(-\tan L \tan\delta\right) \tag{3.10}$$

$$H_s' = \min\{H_s,\ ar\cos[-\tan(L-\beta)\tan\delta]\} \tag{3.11}$$

If : $\alpha < 0$

$$H_{SS} = \min\{H_S, ar\cos[(XY - \sqrt{X^2 - Y^2 + 1}) / (X^2 + 1)]\} \tag{3.12}$$

$$H_{SR} = -\min\{H_S, ar\cos[(XY + \sqrt{X^2 - Y^2 + 1}) / (X^2 + 1)]\}$$

If : $\alpha > 0$

$$H_{SS} = \min\{H_S, ar\cos[(XY + \sqrt{X^2 - Y^2 + 1}) / (X^2 + 1)]\} \tag{3.13}$$

$$H_{SR} = -\min\{H_S, ar\cos[(XY - \sqrt{X^2 - Y^2 + 1}) / (X^2 + 1)]\}$$

$$X = [\cos L / (\sin\alpha \tan\beta)] + \sin L / \tan\alpha \tag{3.14}$$

$$Y = \tan\delta[(\cos L / \tan\alpha) - \sin L / \sin\alpha \tan\beta] \tag{3.15}$$

3.2. Solar radiation model on horizontal surface

The monthly average daily clearness ratio $\bar{K}_T$ can be estimated from the ratio of extraterrestrial global radiation on the horizontal surface to the radiation on the horizontal surface by using the method proposed from Erbs et al as follows equations following.

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \tag{3.16}$$

Erbs et all

For $\omega \le 81.4$ and $0.3 \le \bar{K}_T \le 0.8$

$$\bar{H}_d = \bar{H}\left(1.391 - 3.56\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3\right) \tag{3.17}$$

For $\omega > 81.4$ and $0.3 \le \bar{K}_T \le 0.8$

$$\bar{H}_d = \bar{H}\left(1.311 - 3.022\bar{K}_T + 3.4427\bar{K}_T^2 - 1.821\bar{K}_T^3\right) \tag{3.18}$$

H_0 is the average daily extraterrestrial solar radiation can calculate in (3.19) and $\overline{H}_0$ is the monthly average daily extraterrestrial solar radiation can calculate in (3.20).

$$H_0 = \frac{24 \times 3600}{\pi} \times I_{sc} \times E_0 \left(\cos\delta \cos L \sin\omega + \frac{\pi\omega}{180} \times \sin\delta \sin L \right) \quad (3.19)$$

$$\overline{H}_0 = \frac{1}{n' - m + 1} \sum_{i=m}^{n'} H_{0(i)} \quad (3.20)$$

Where i is considered number of days, m is first day of each month and n' is last day of each month. I_{SC} is the solar constant which is equal to 1367 (W/m^2), and E_0 is the extraterrestrial solar radiation (Mj/m^2-day) calculated outside of atmosphere on the horizontal surface of the day number of the year which represents the relative distance between Earth and Sun.

$$E_0 = 1 + 0.033 \times \cos\left(\frac{360 \times n}{365}\right) \quad (3.21)$$

Table 3. 2. The monthly average daily extraterrestial solar radiation on horizontal surface of some province in Thailand (Mj/m^2day)

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lampang	27.87	29.29	35.27	37.98	39.03	39.16	38.98	38.26	36.29	32.82	28.94	26.77
Khonkean	28.83	29.99	35.69	38.02	38.76	38.74	38.62	38.16	36.54	33.44	29.82	27.77
Ayutthaya	29.89	30.76	36.13	38.02	38.41	38.21	38.16	37.99	36.79	34.11	30.81	28.9
Krabi	32.88	32.83	37.17	37.74	37.07	36.38	36.54	37.22	37.24	35.83	33.53	32.08

Table 3. 3. The monthly average daily diffuse solar radiation on horizontal surface of some province in Thailand (Mj/m^2day)

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lampang	6.03	5.91	7.66	8.25	8.48	8.50	8.46	8.31	7.87	7.06	6.07	5.46
Khonkean	6.14	5.90	7.73	8.24	8.40	8.39	8.37	8.27	7.90	7.15	6.18	5.58
Ayutthaya	6.39	6.07	7.82	8.24	8.32	8.27	8.26	8.23	7.96	7.33	6.47	5.93
Krabi	6.99	6.38	7.96	8.10	7.94	7.79	7.85	8.04	8.06	7.74	7.19	7.19

Chapter 4 Estimation of Monthly and Yearly Average Solar Radiation on Tilted Surfaces

The estimated monthly and yearly solar radiation on the tiled surface is used to calculate the optimum angle for installing PV panels. This chapter estimates solar radiation in the following provinces:

- Ayutthaya: Latitude 14.36° and Longitude100.57°.
- Lampang: Latitude 18.30° and Longitude 99.50°.
- Khonkaen: Latitude 16.47° and Longitude102.48°.
- Krabi: Latitude 8.07 ° and Longitude 98.91°.

4.1. Monthly Average solar radiation on the tilted surface

In each province, the solar radiation is calculated by the method of Erbs et al when changing the tilted angle each month from -25^0 to 50^0. It can be seen that the monthly average daily solar radiation in each month has different values, depending on the tested tilted angle.

4.1.1. Ayutthaya

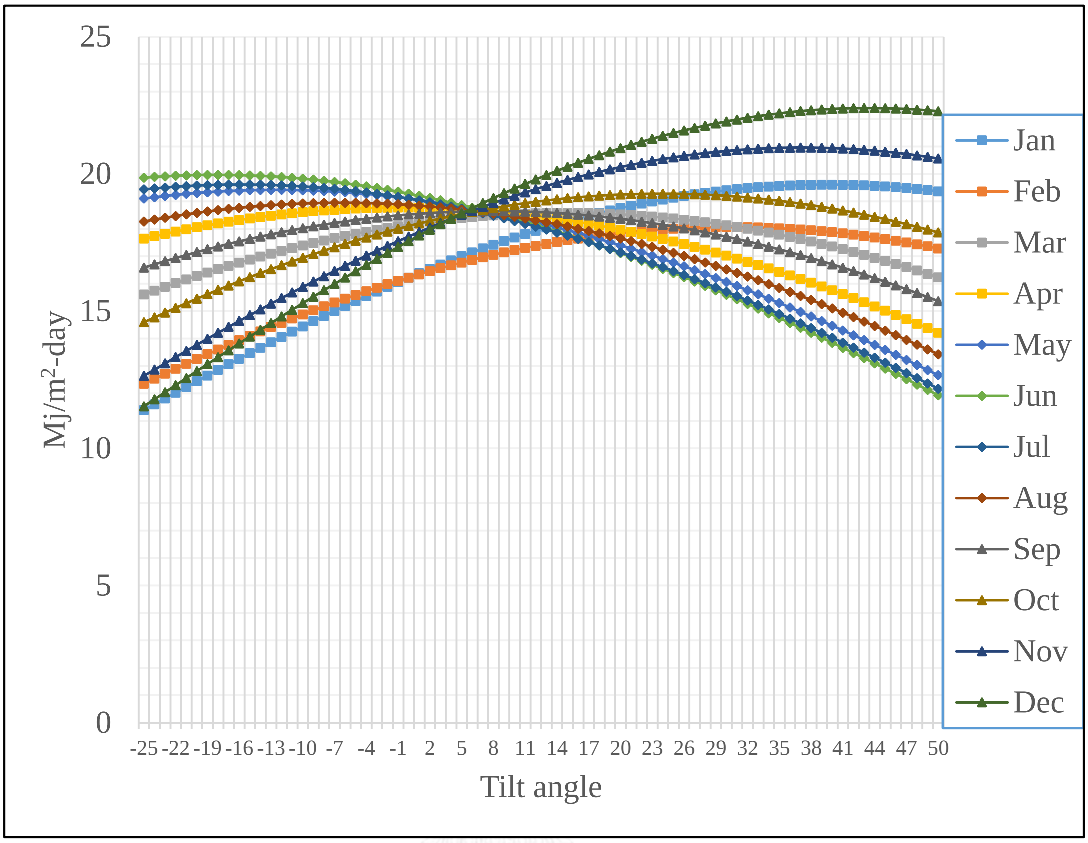


Figure 4. 1. The monthly average daily solar radiation on the tilted angles in Ayutthaya

Figure 4. 1 shows the tilt angles for each month of the year when the collector panel is tilted at the optimum angle in Ayutthaya. It is clear that the optimal tilt angle is very sensitive to the collector place which represents the latitude of the station. In other words, as the collector is oriented away from the equator plane towards the north pole, the sun appears close to the horizon even at solar noon. Moreover, in Winter (December, January, and February) the collector needs to be set at high tilt angles approximately due to the low altitude of sun across the sky, while it needs to be adjusted at low angles for Summer (May, June, and July) till face to the north pole (Monthly angle are minus), due to the high elevation of the sun in these months as Table 4.1.

Table 4. 1. Optimum tilted angles for monthly average daily in Ayutthaya

Tilt setting	Jan	Feb	Mar	Apr	Ma y	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	19.6 1	18.0 6	18.5 8	18.7 7	19.4 2	19.9 6	19.6 1	18.9 5	18.6 4	19.2 8	20.9 6	22.4 0
Monthly Angles	40 °	30 °	15 °	-1 °	-13 °	-18 °	-16 °	-6 °	8 °	24 °	37 °	43 °

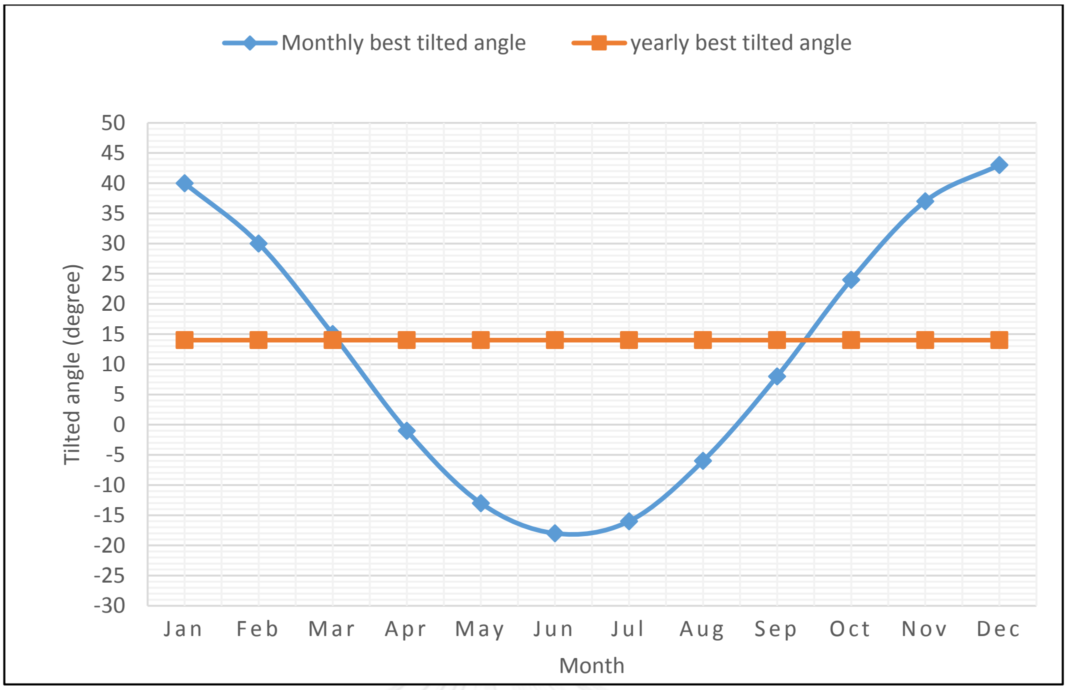


Figure 4. 2. Monthly and yearly best tilted angles at Ayutthaya

Figure 4.2. demonstrates the behavior of total radiation values with the months of year at different collector settings.

The daily variation of optimum slope has been extended to evaluate the yearly optimum tilt angle. The yearly optimum tilt angle is a fixed value for any solar collector throughout the course of a year. It is 14° for Ayutthaya and oriented towards the south. The amount of solar radiation received by the solar collector tilted at yearly optimum angle facing south was computed and results in Table 4.2. The yearly average tilt angle was found to be close to latitude of each station.

Table 4. 2. Optimum tilted angles for yearly average daily in Ayutthaya

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/m^2-day)	18.16	17.52	18.58	18.36	18.05	17.90	17.86	18.16	18.57	19.08	19.67	20.11
Yearly Angles	14 °	14 °	14 °	14 °	14 °	14 °	14 °	14 °	14 °	14 °	14 °	14 °

For non-zero azimuth surface, estimation of yearly average solar radiation on best tilted surface of the year 14°, that is varied by azimuth surface of 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165° and 180° are performed and shown in figure .4.3.

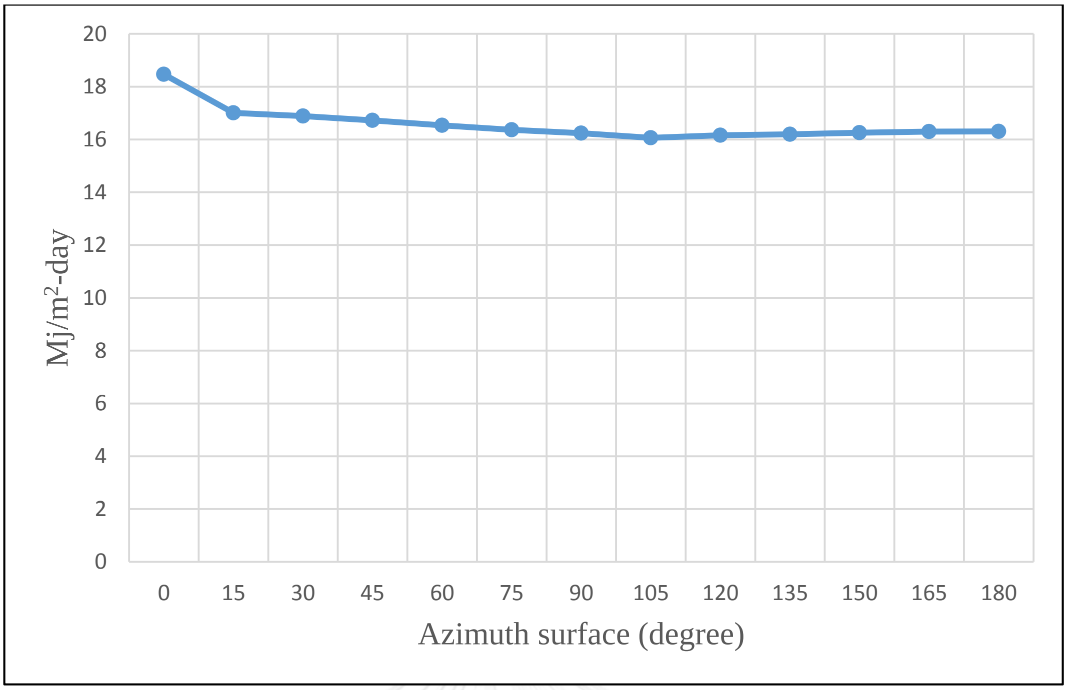


Figure 4. 3. The yearly average daily solar radiation on best tilted angle for non-zero azimuth angles at Ayutthaya

In figure 4.3, a big reduction of the yearly average solar radiation on the tilted surface observed at the azimuth surface of 105° is (16.06 Mj/m^2-day). And the best tilted surface which receives the maximum energy is facing to the south or zero azimuth angle.

The above analysis is similar to other provinces in Thailand except specific numbers. So, in other provinces, estimated results are only shown in Figures and Table format.

4.1.2. Lampang

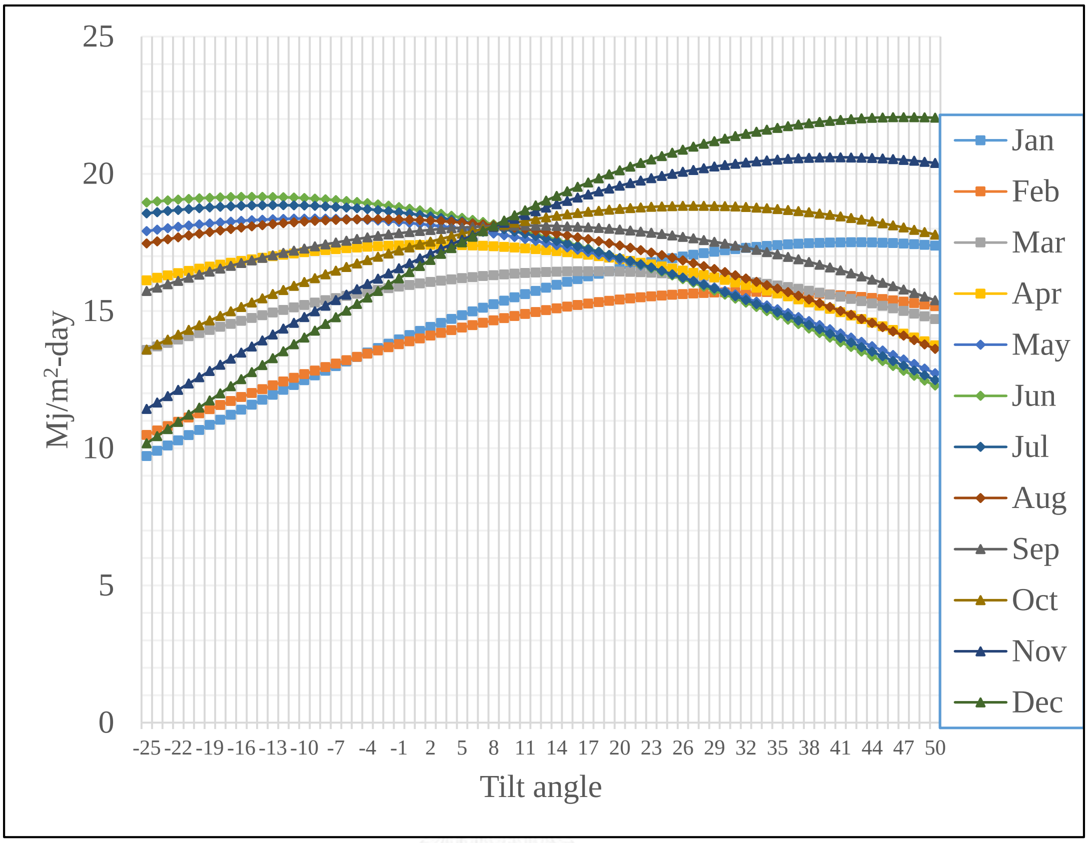


Figure 4. 4. The monthly average daily solar radiation on the tilted angles in Lampang

Table 4. 3. Optimum tilted angles for monthly average daily in Lampang

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	17.5	15.69	16.45	17.41	18.37	19.16	18.86	18.35	18.11	18.84	20.6	22.07
Monthly Angles	42 °	33 °	17 °	2 °	-9 °	-15 °	-13 °	-3 °	11 °	27 °	41 °	47 °

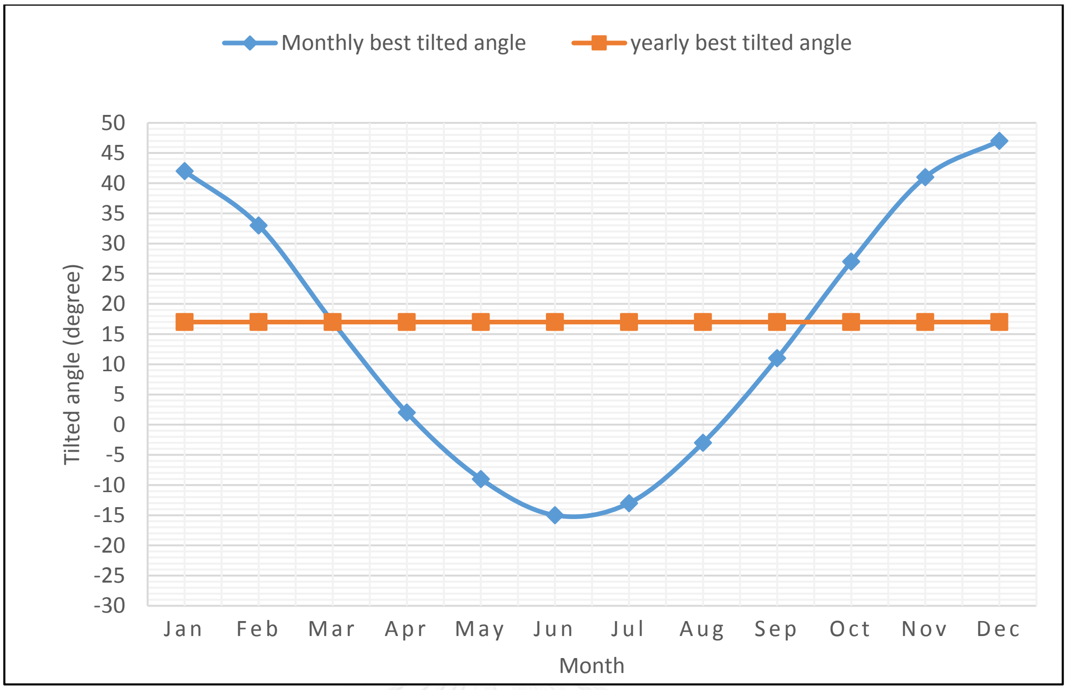


Figure 4. 5. Monthly and yearly best tilted angles at Lampang

Table 4. 4. Optimum tilted angles for yearly average daily in Lampang

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	16.26	15.27	16.45	17.05	17.15	17.28	17.26	17.62	18.05	18.62	19.25	19.68
Yearly Angles	17 °	17 °	17 °	17 °	17 °	17 °	17 °	17 °	17 °	17 °	17 °	17 °

For non-zero azimuth surface, estimation of yearly average solar radiation on best tilted surface of the year 17°, that is varied by azimuth surface of 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165° and 180° are performed and shown in figure 4.6.

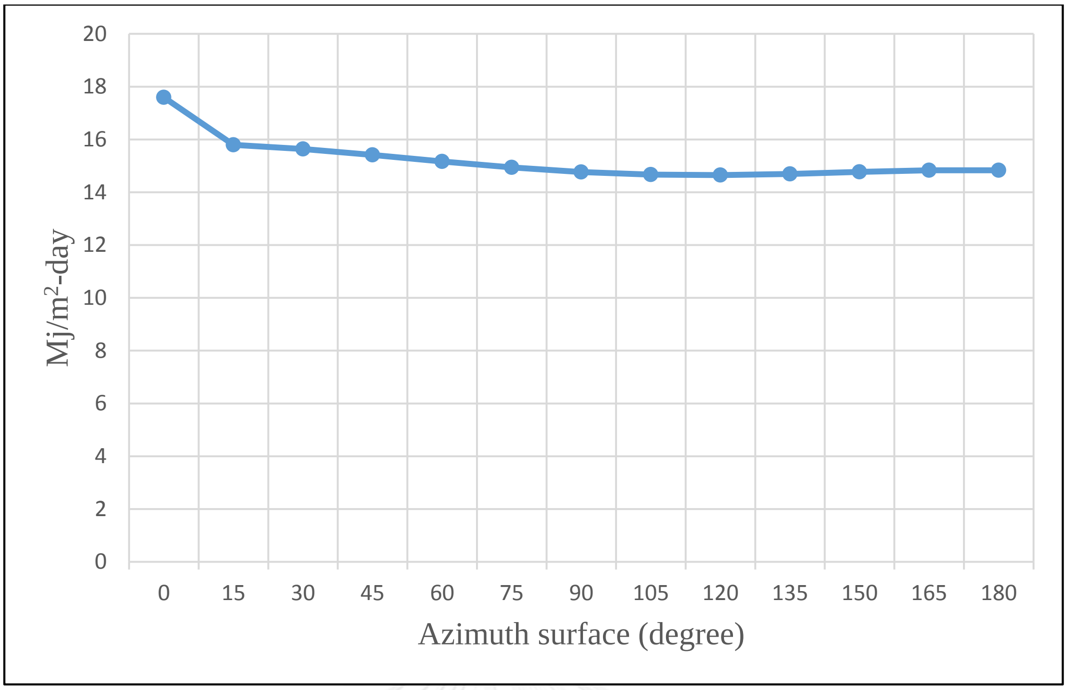


Figure 4. 6. The yearly average daily solar radiation on best tilted angle for non-zero azimuth angles at Lampang

4.1.3. Khonkaen

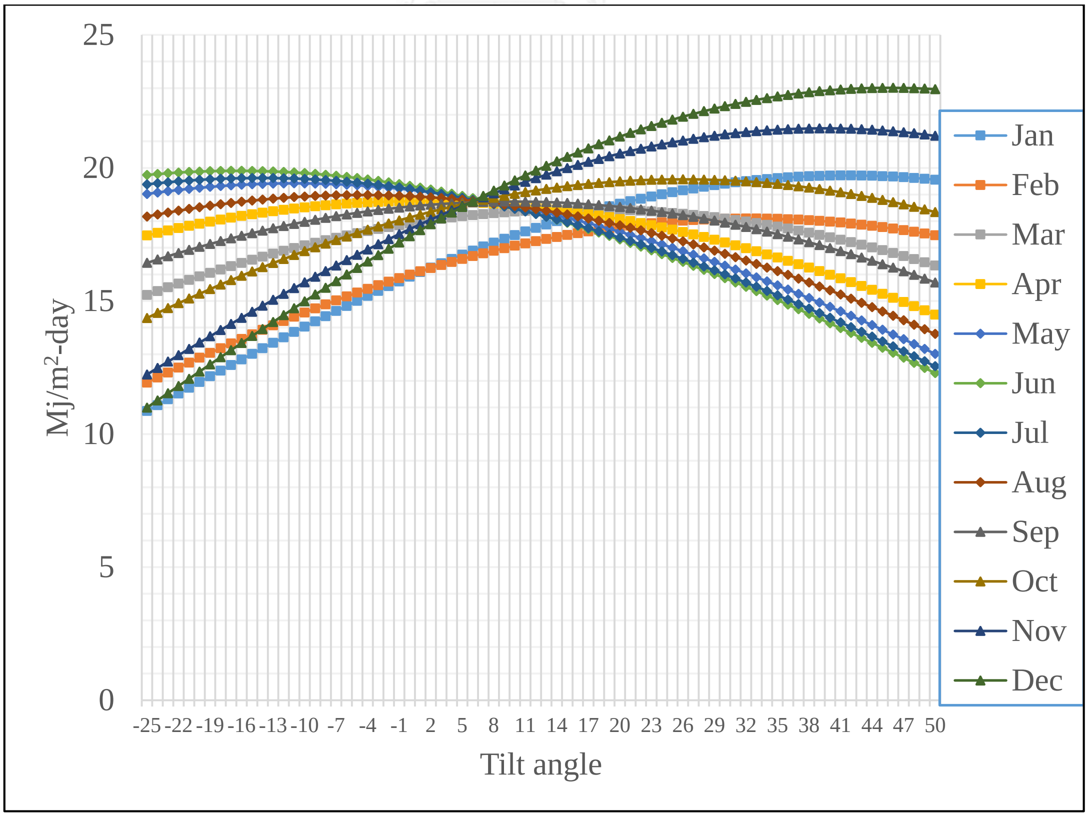


Figure 4. 7. The monthly average daily solar radiation on the tilted angles in Khonkaen

Table 4. 5. Optimum tilted angles for monthly average daily in Khonkaen

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	19.72	18.1	18.44	18.75	19.42	19.89	19.62	18.98	18.74	19.57	21.49	23.01
Monthly Angles	42 °	32 °	17 °	1 °	-11 °	-16 °	-14 °	-5 °	10 °	26 °	39 °	46 °

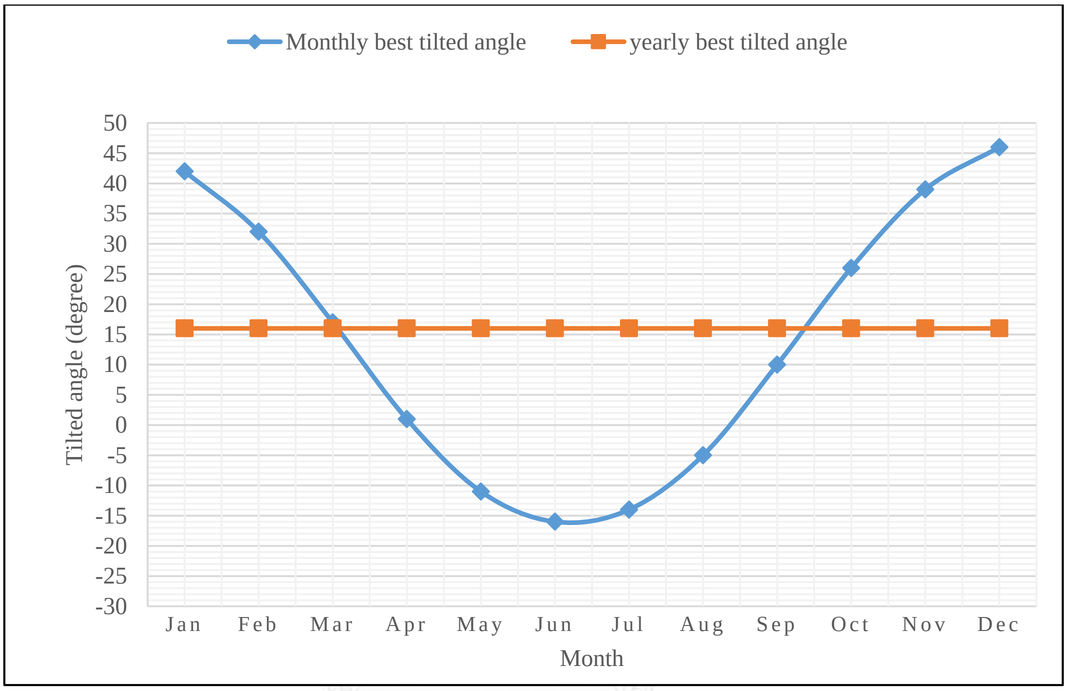


Figure 4. 8. Monthly and yearly best tilted angles Khonkaen

Table 4. 6. Optimum tilted angles for yearly average daily in Khonkaen

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	18.23	17.55	18.44	18.33	18.03	17.82	17.85	18.18	18.66	19.36	20.11	20.58
Yearly Angles	16 °	16 °	16 °	16 °	16 °	16 °	16 °	16 °	16 °	16 °	16 °	16 °

For non-zero azimuth surface, estimation of yearly average solar radiation on best tilted surface of the year 16°, that is varied by azimuth surface of 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165° and 180° are performed and shown in figure .4.9.

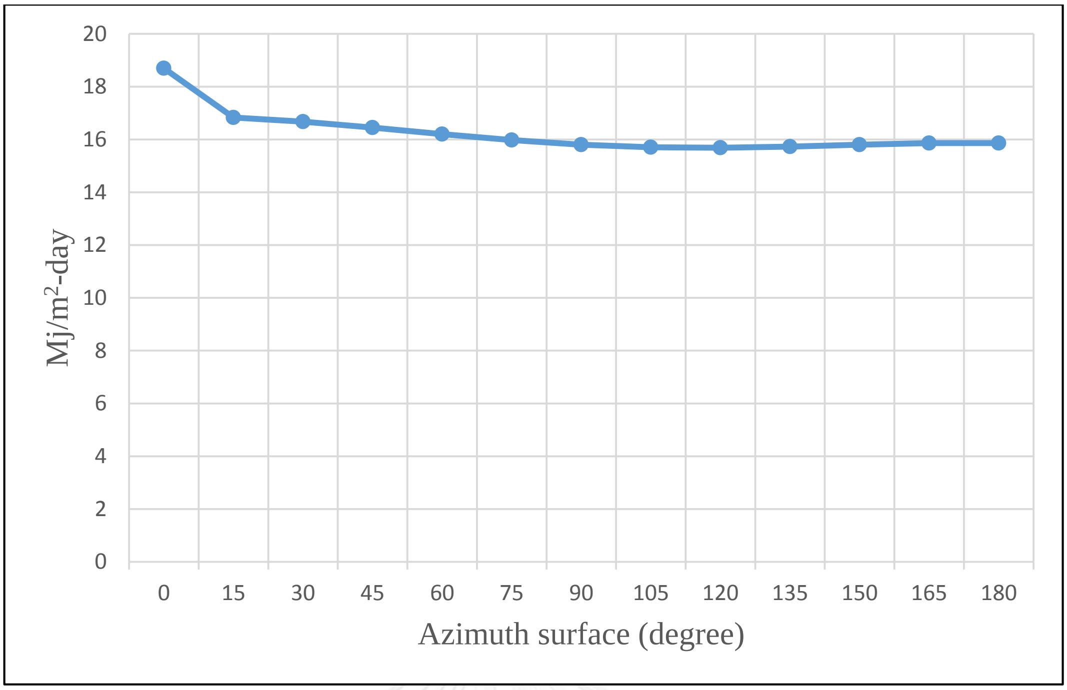


Figure 4. 9. The yearly average daily solar radiation on best tilted angle for non-zero azimuth angles at Khonkaen

4.1.4. Krabi

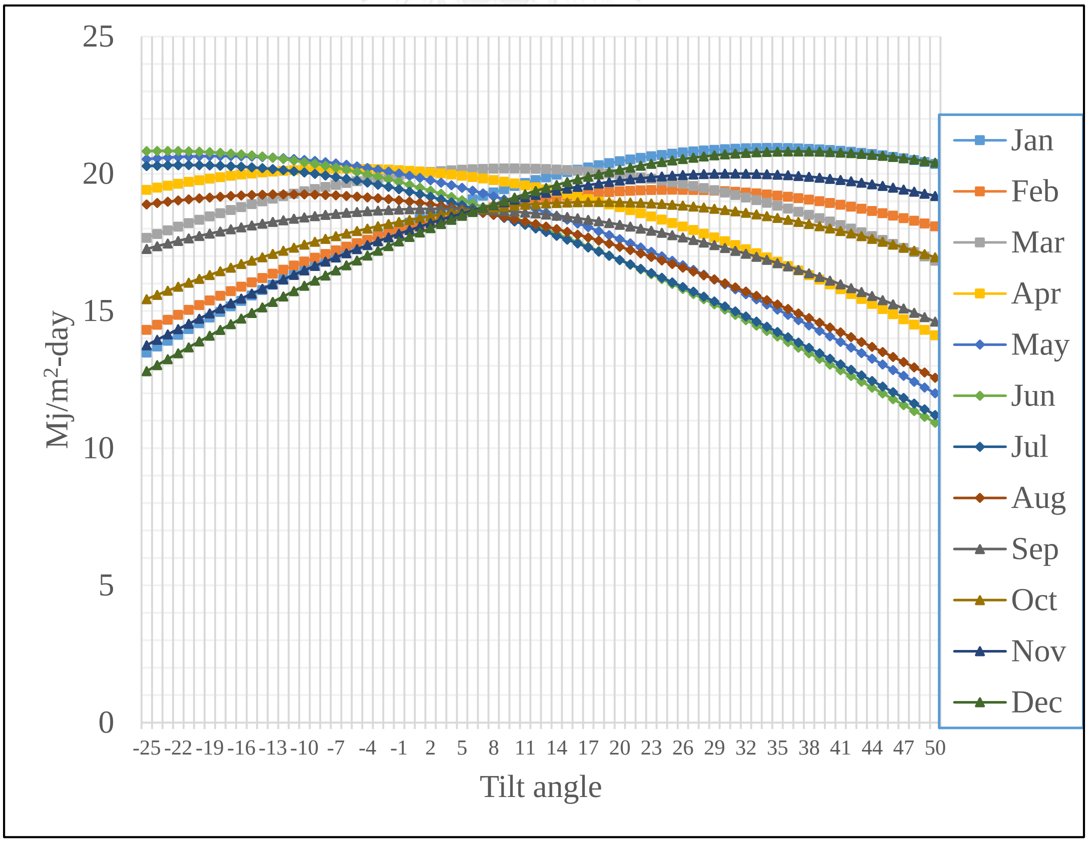


Figure 4. 10. The monthly average daily solar radiation on the tilted angles in Krabi

Table 4. 7. Optimum tilted angles for monthly average daily in Krabi

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	20.94	19.42	20.19	20.19	20.65	20.83	20.32	19.25	18.72	18.97	20.01	20.82
Monthly Angles	34 °	25 °	10 °	-6 °	-18 °	-23 °	-21 °	-11 °	3 °	18 °	31 °	37 °

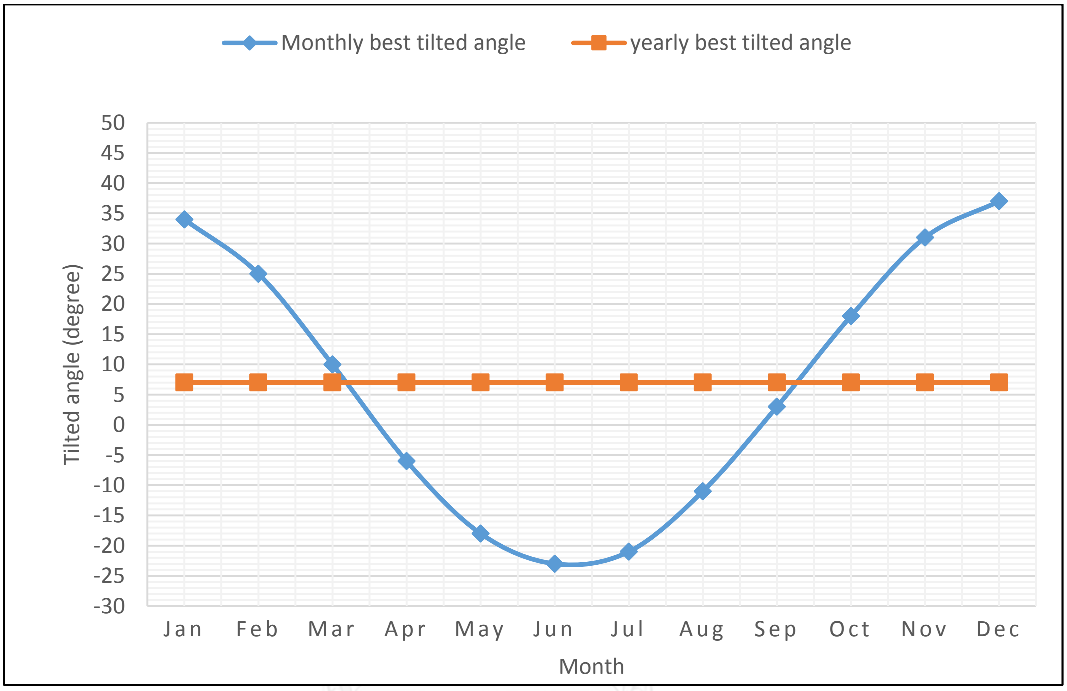


Figure 4. 11. Monthly and yearly best tilted angles at Krabi

Table 4. 8. Optimum tilted angles for yearly average daily in Krabi

Tilt setting	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radiation (MJ/ m^2-day)	19.2	18.7	20.18	19.83	19.28	18.79	18.63	18.58	18.69	18.73	18.77	18.75
Yearly Angles	7 °	7 °	7 °	7 °	7 °	7 °	7 °	7 °	7 °	7 °	7 °	7 °

For non-zero azimuth surface, estimation of yearly average solar radiation on best tilted surface of the year 7°, that is varied by azimuth surface of 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165° and 180° are performed and shown in figure 4.12.

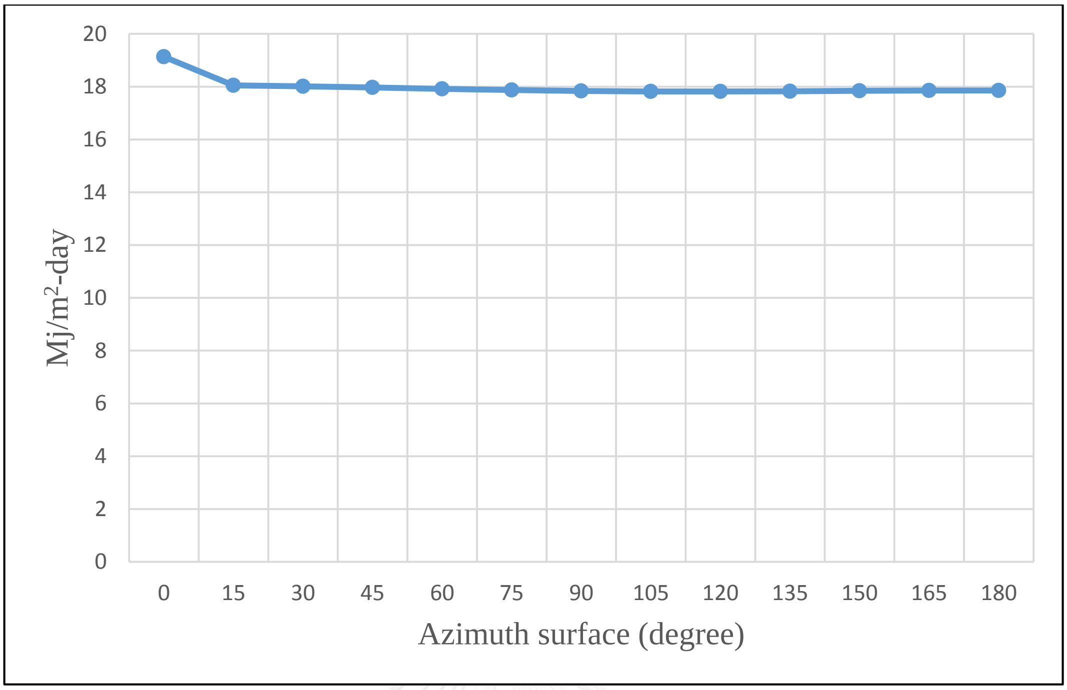


Figure 4. 12. The yearly average daily solar radiation on best tilted angle for non-zero azimuth angles at Krabi

From figure 4.12, when setting up tilted surface on the best tilted angle of the year (7°), the yearly average solar radiation is almost the same. So, when the tilted surface of the year is a small angle, the yearly average solar radiation on each azimuth surface will be the same.

Chapter 5 Comparison of the Result of Solar Radiation Data with the Satellite Measurement

The prediction of solar radiation when changing the tilt angle is compared with the satellite data in ten years (1995 - 2004) in [18]. The solar radiation is calculated by the method proposed by Erb et al. The calculation of the average daily solar radiation on tilted surface for each month uses the optimum monthly average daily tilted angle in the previous chapter.

5.1. Monthly comparing results in Ayutthaya

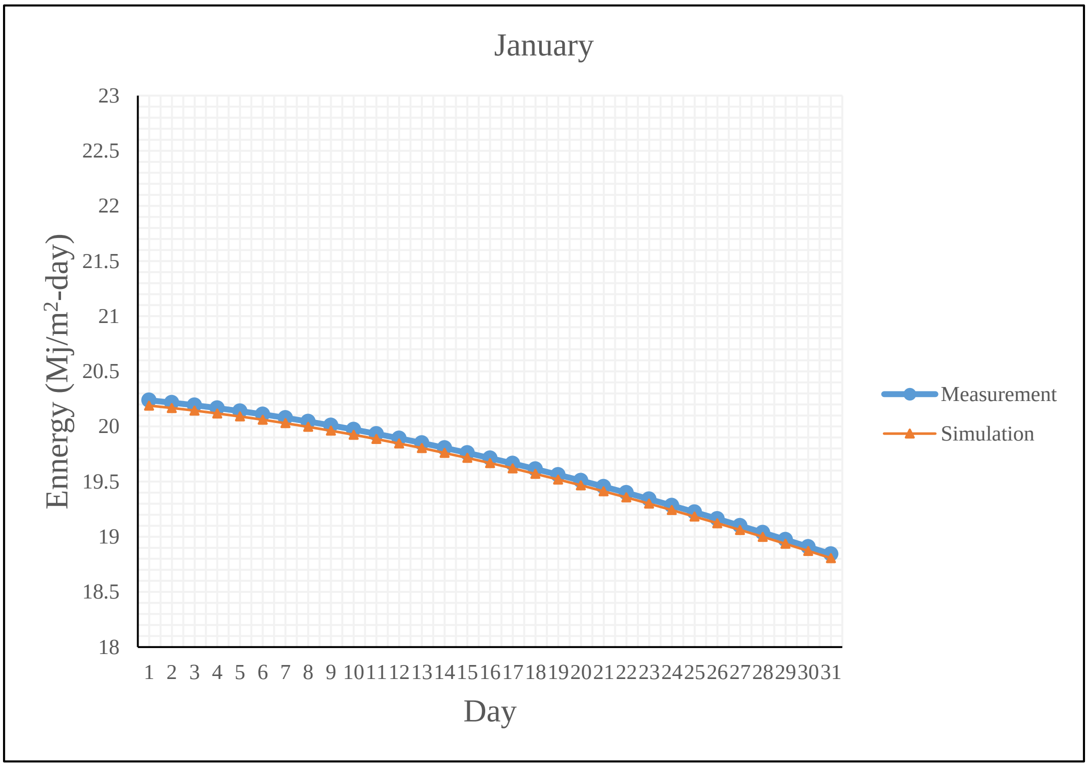


Figure 5. 1. Comparison in January

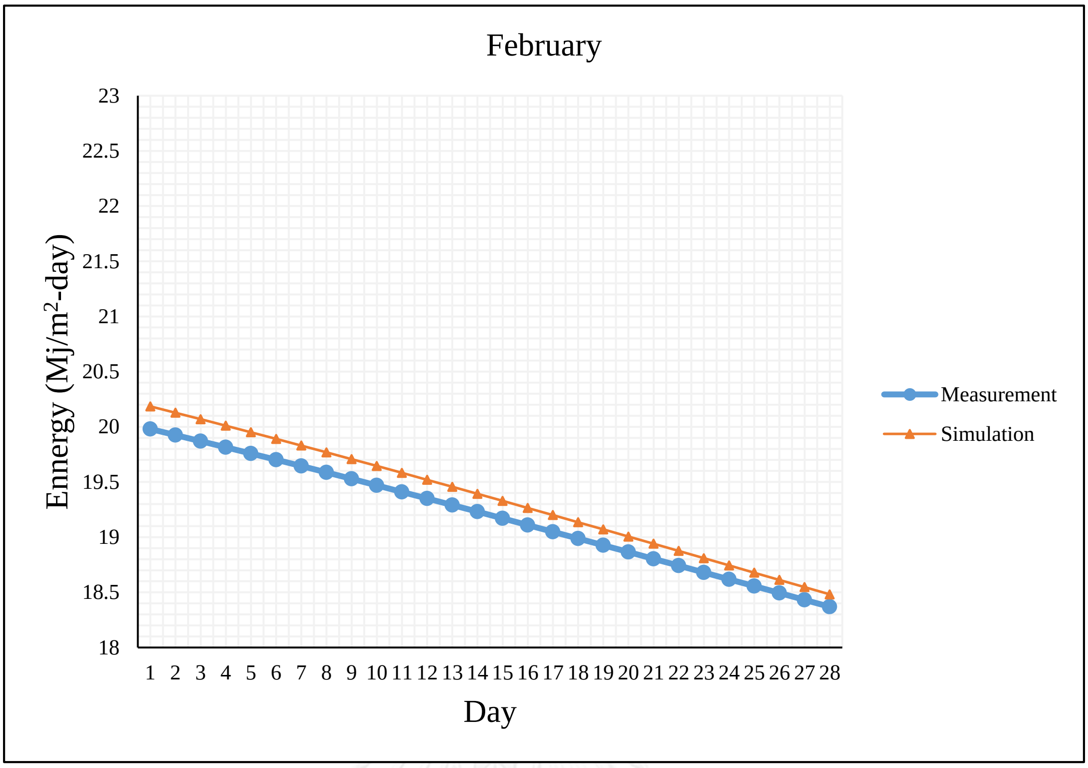


Figure 5. 2. Comparison in February

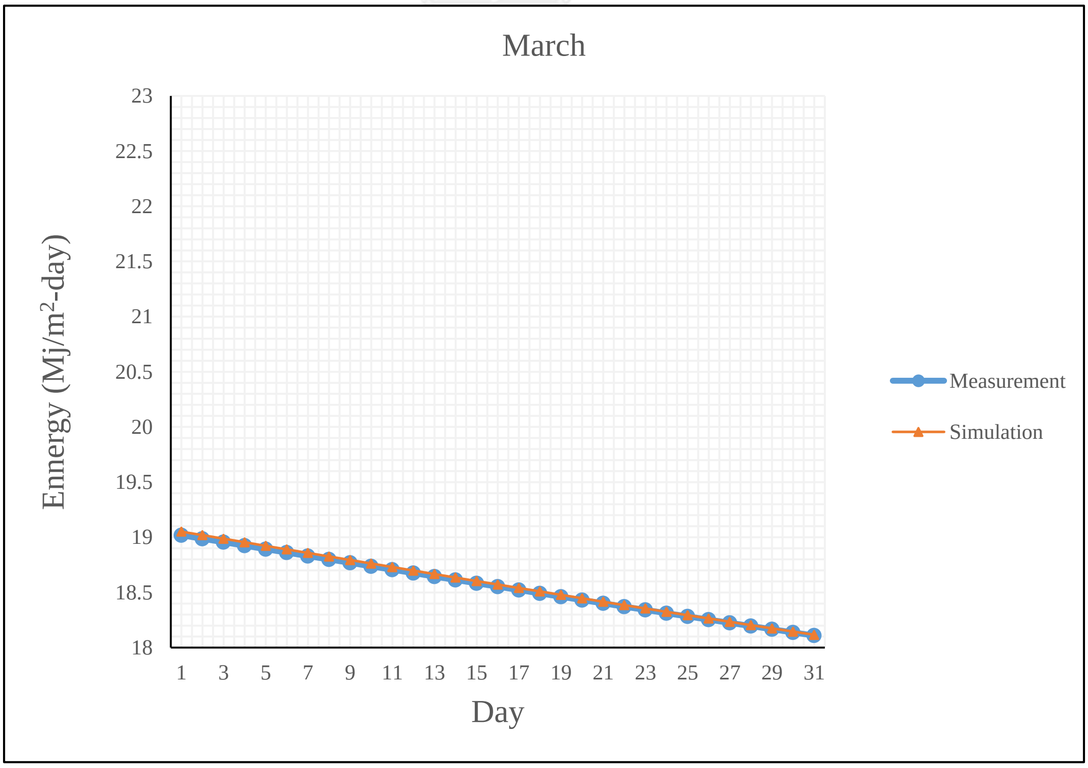


Figure 5. 3. Comparison in March

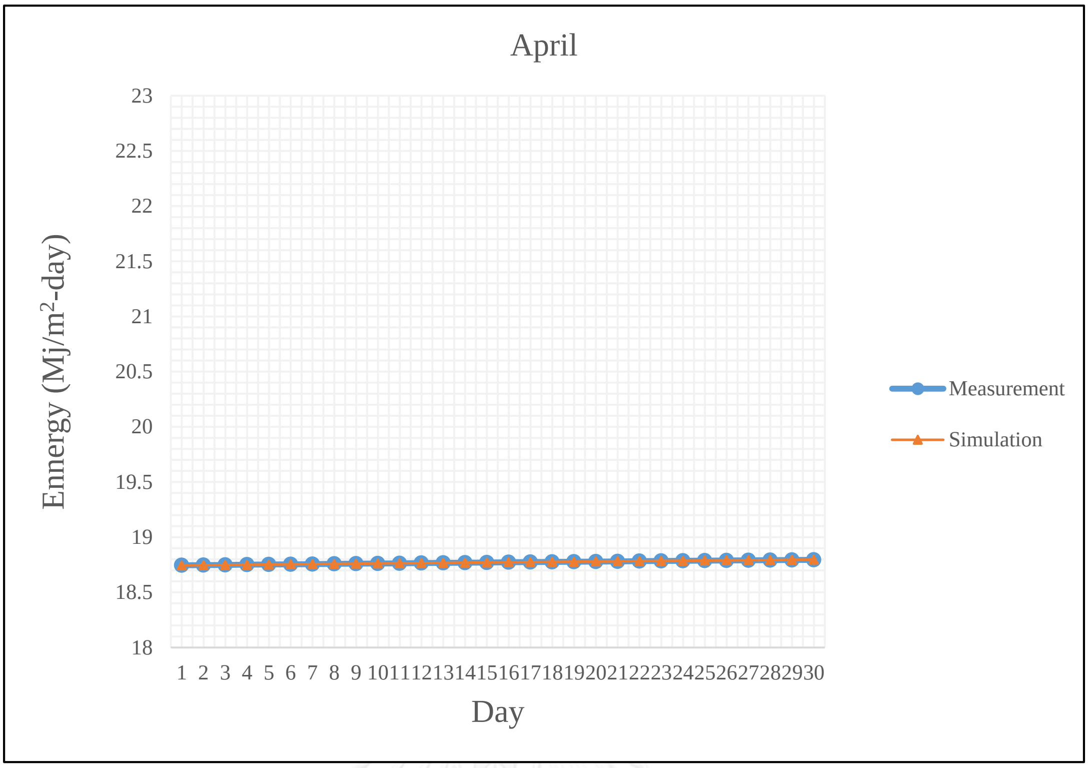


Figure 5. 4. Comparison in April

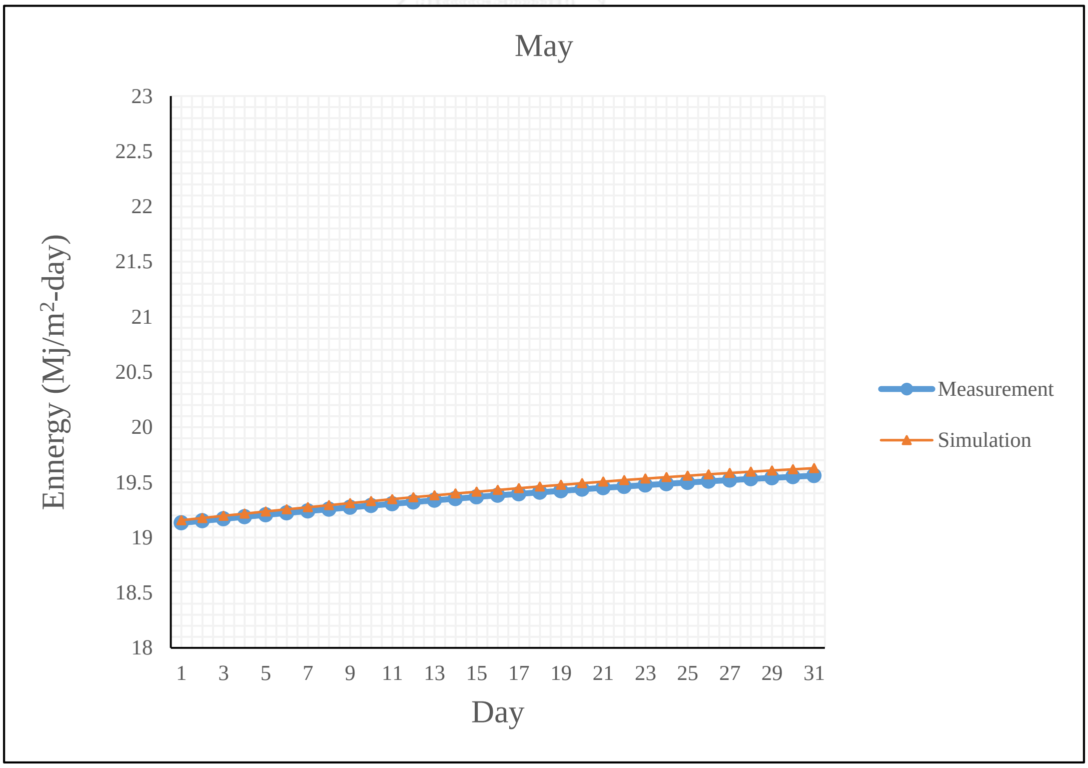


Figure 5. 5. Comparison in May

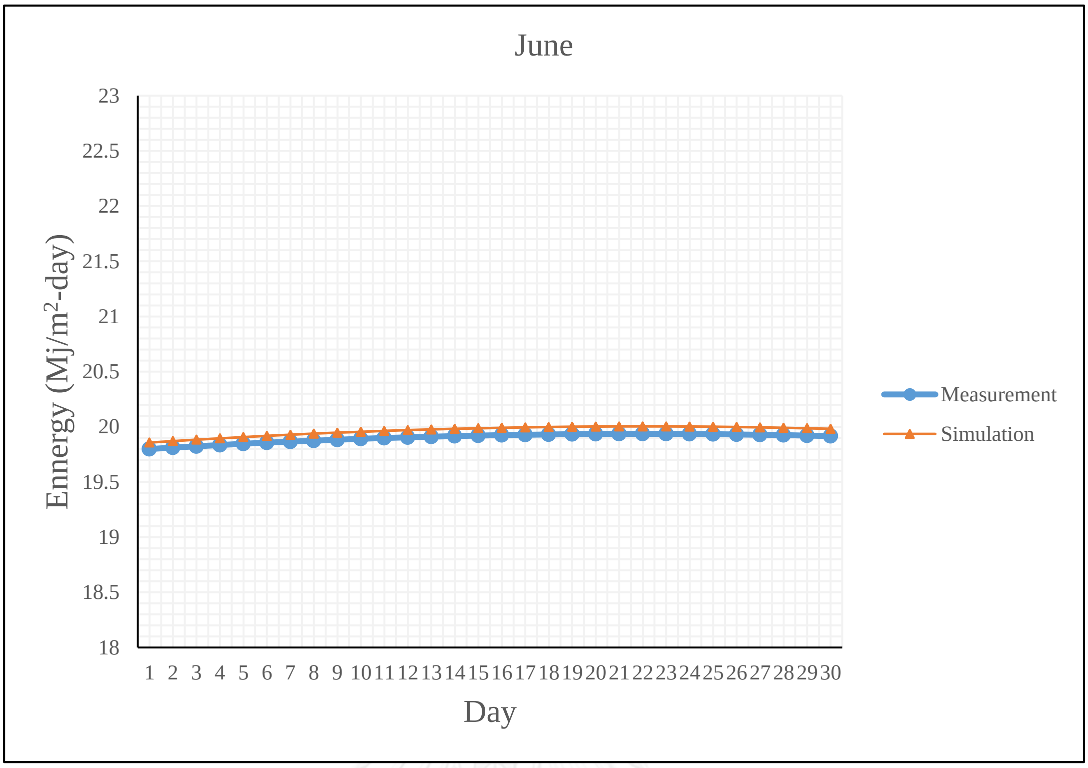


Figure 5. 6. Comparison in June

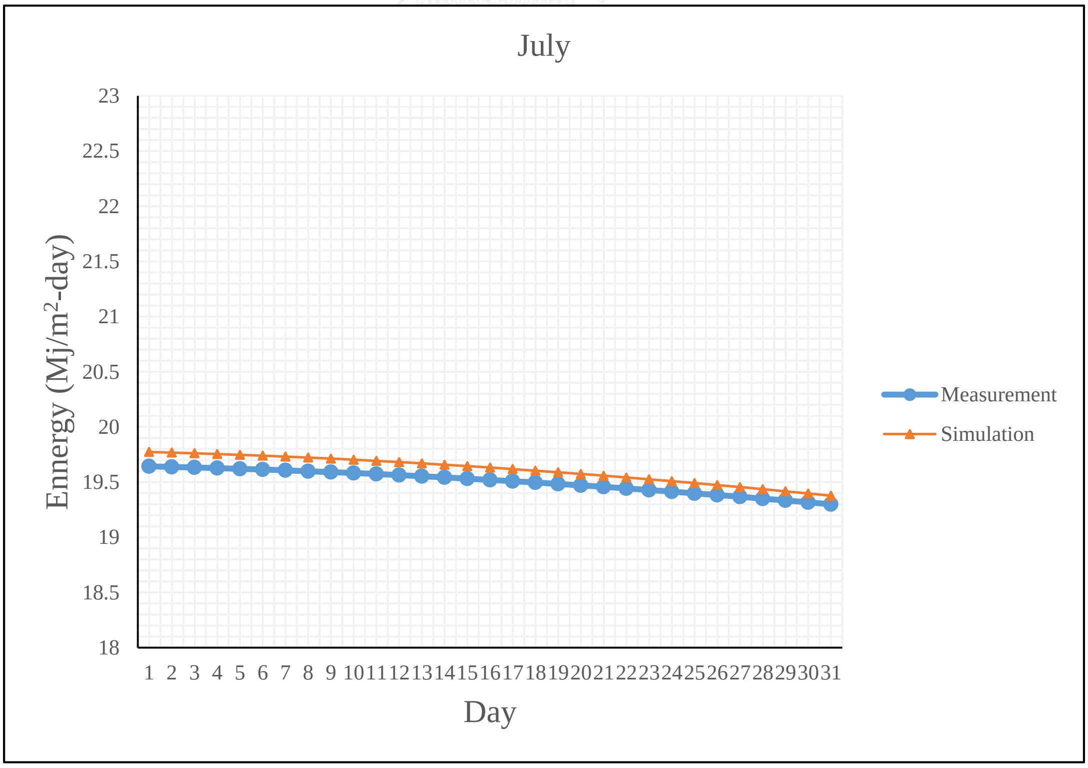


Figure 5. 7. Comparison in July

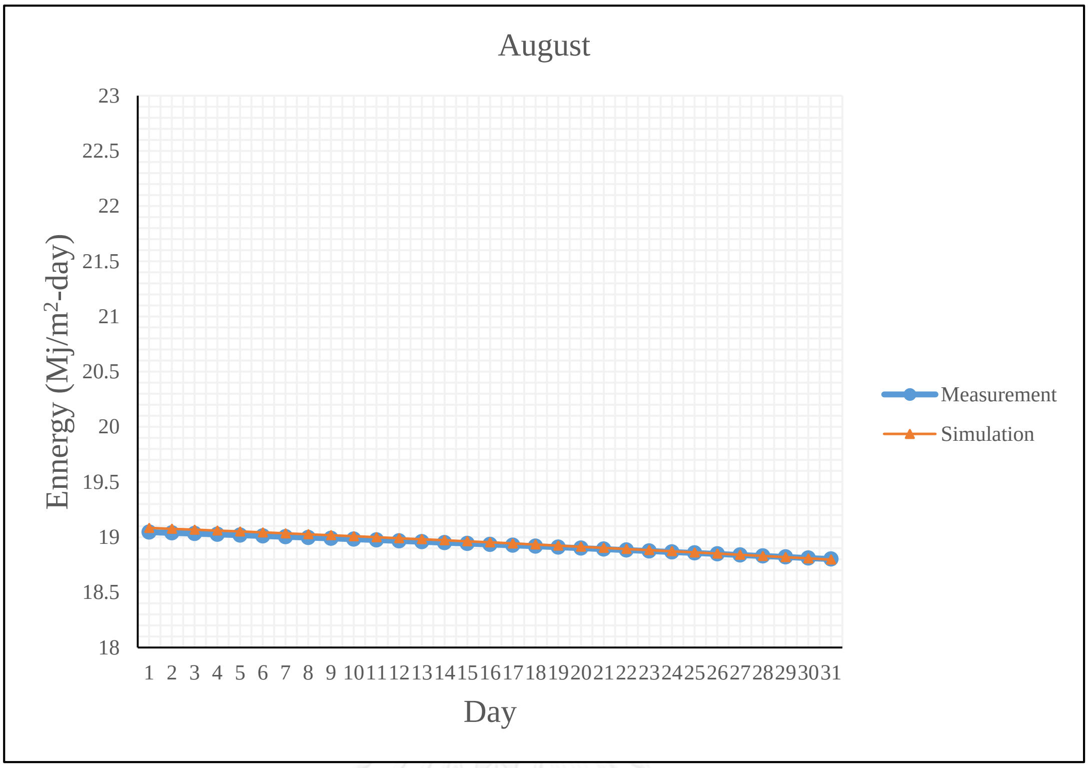


Figure 5. 8. Comparison in August

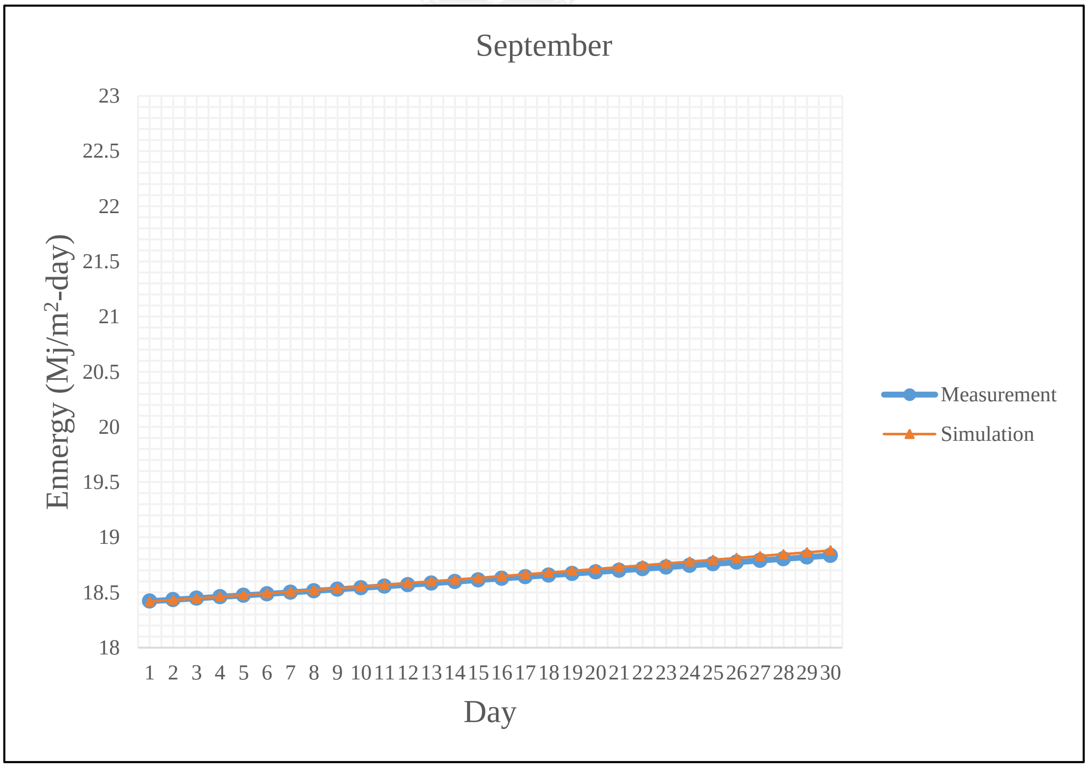


Figure 5. 9. Comparison in September

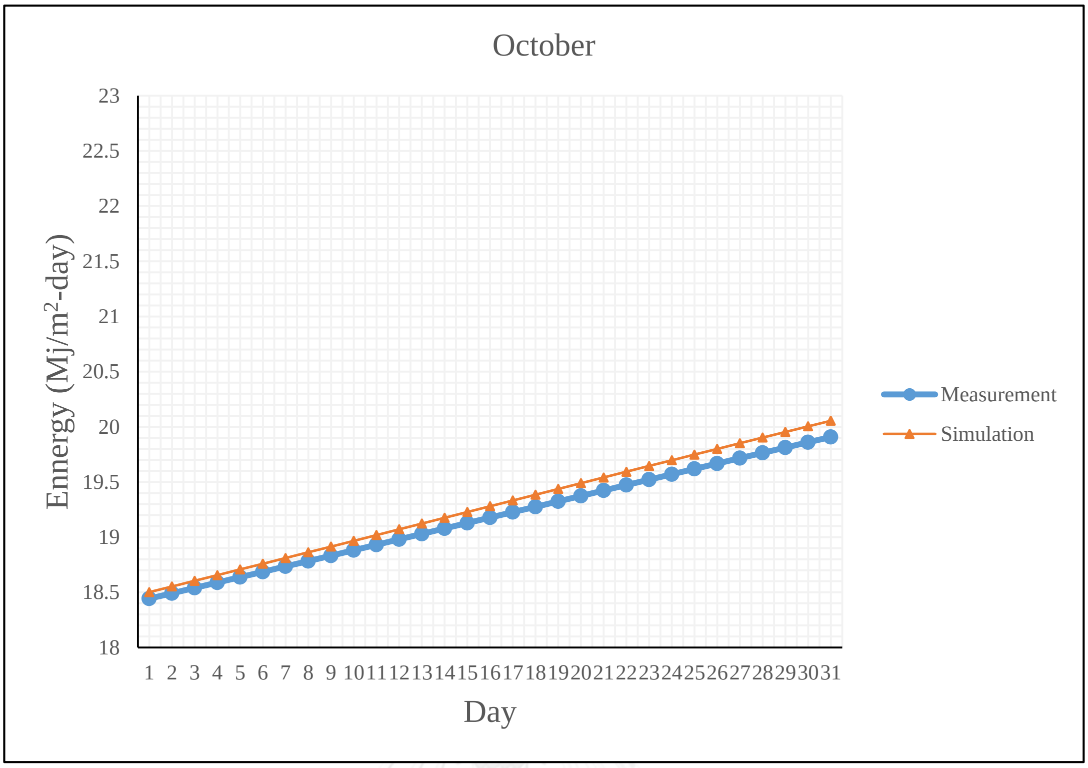


Figure 5. 10. Comparison in October

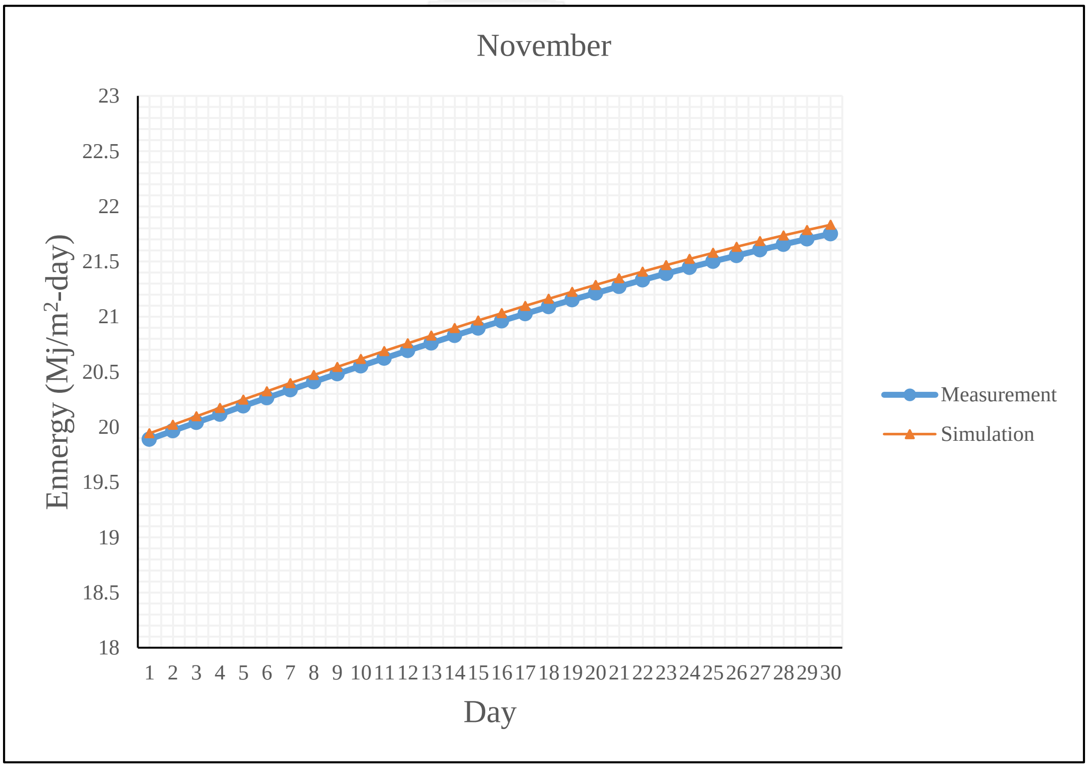


Figure 5. 11. Comparison in November

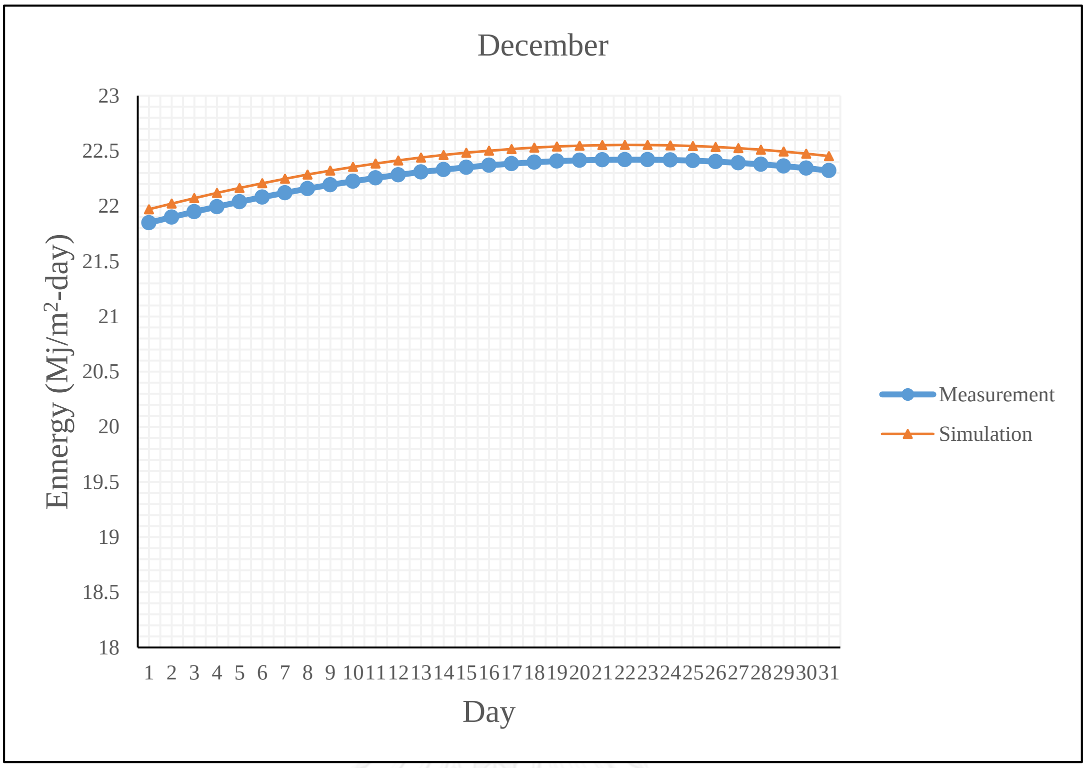


Figure 5. 12. Comparison in December

Table 5.1 illustrates the error between the Measurement and the simulation solar radiation during the whole year by using optimal tilted angle of each month.

Table 5. 1. Evaluation of Comparison error in Ayutthaya

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Measurement Radiation (MJ/sq.m-day)	19.65	19.19	18.56	18.77	19.37	19.90	19.50	18.93	18.62	19.18	20.89	22.27	19.57
Simulation Radiation (MJ/sq.m-day)	19.61	19.35	18.58	18.77	19.42	19.96	19.61	18.95	18.64	19.28	20.96	22.40	19.63
Error value (%)	-0.20	0.82	0.11	0.00	0.25	0.33	0.55	0.09	0.11	0.53	0.33	0.58	0.30

The solar radiation average error is 0.3 %, the negative error values indicate the measurement solar radiation is higher than simulation radiation. In majority, simulated solar radiation is higher than the measured values. In February, July, October and December, the monthly average daily values are quite different. But it can be seen that the error between measurement and simulation is not greater than 2 %. Thus, the simulation model is close to measurement data.

In the following calculation in other provinces, errors in twelve months are also detailed in an accompanied table.

5.2. Monthly comparing results in Lampang

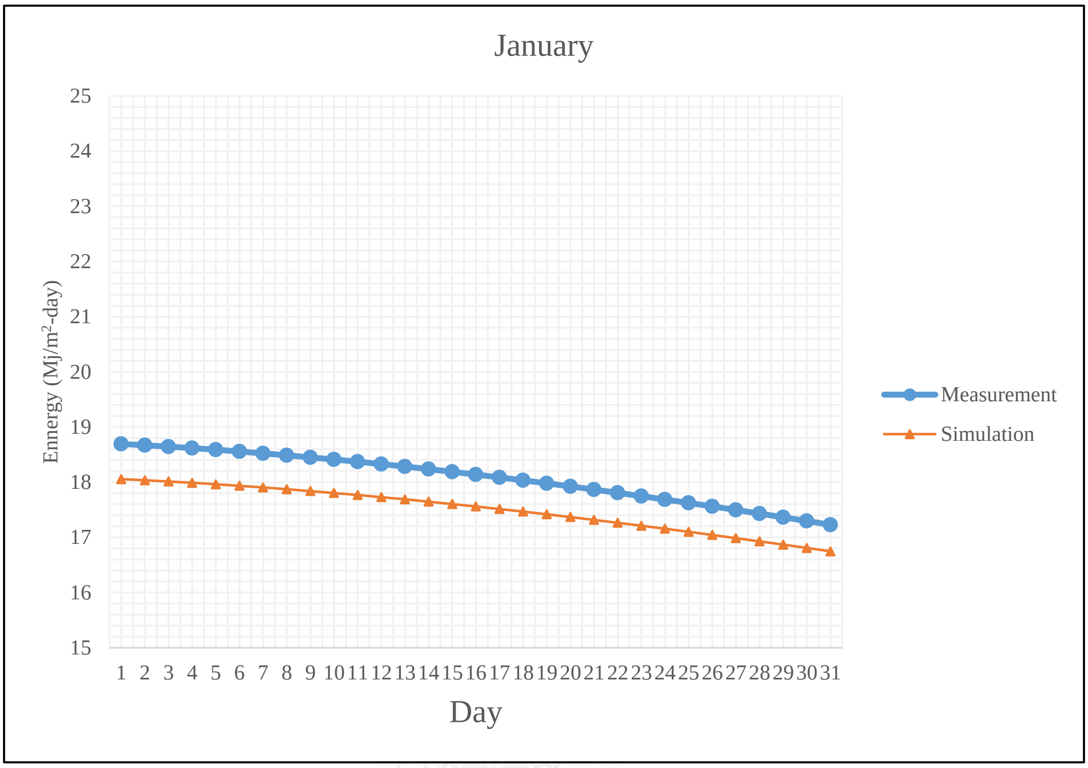


Figure 5. 13. Comparison in January

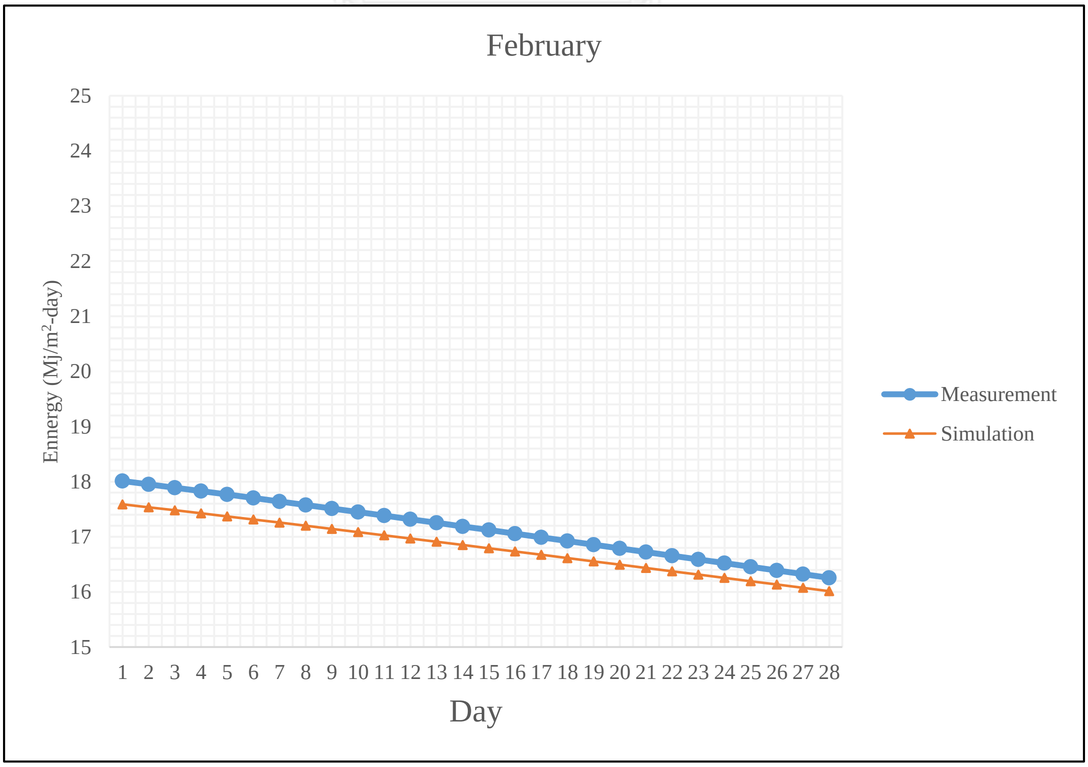


Figure 5. 14. Comparison in February

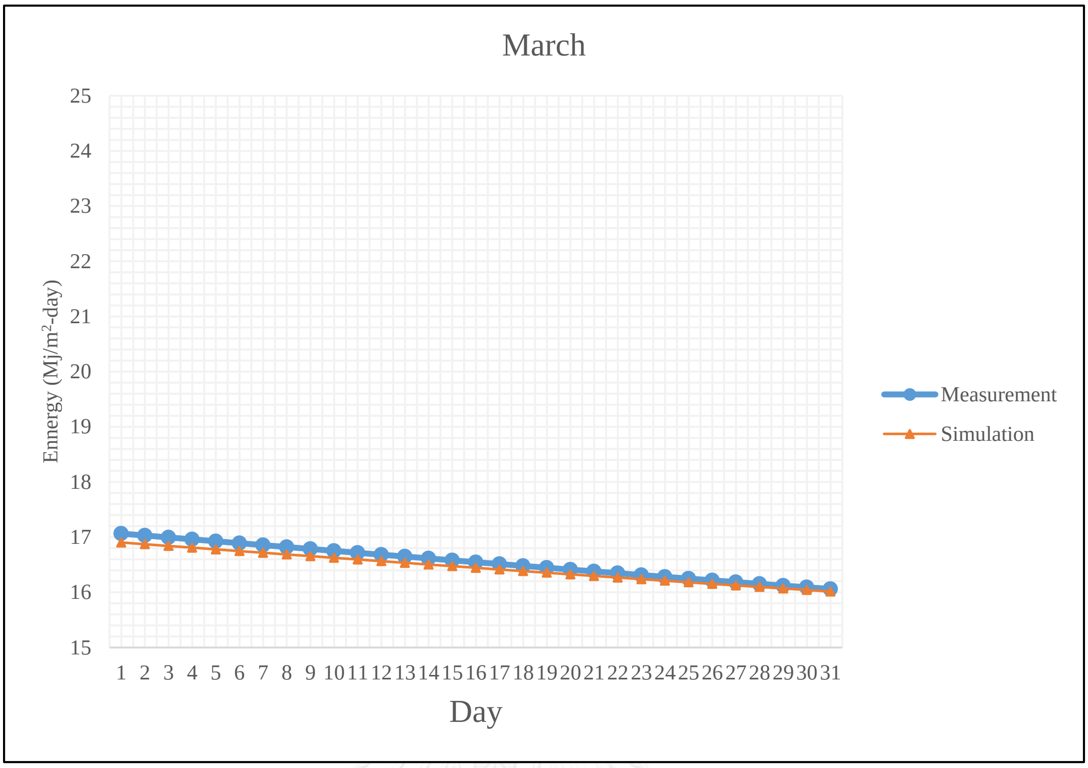


Figure 5. 15. Comparison in March

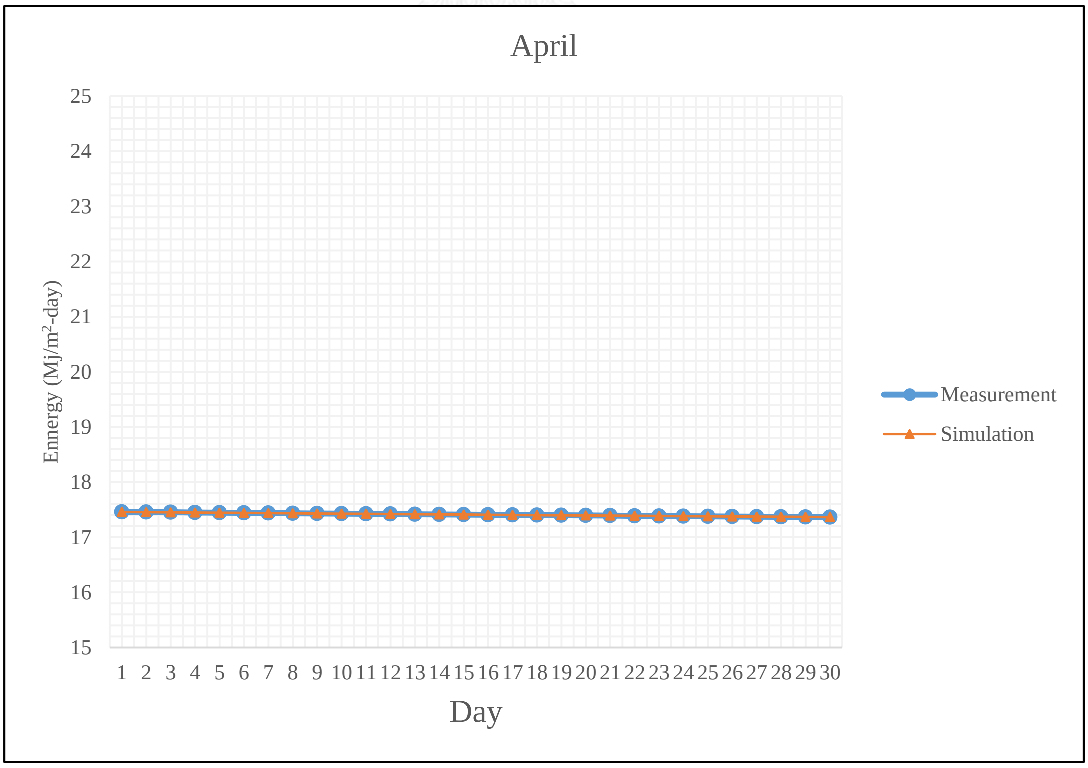


Figure 5. 16. Comparison in April

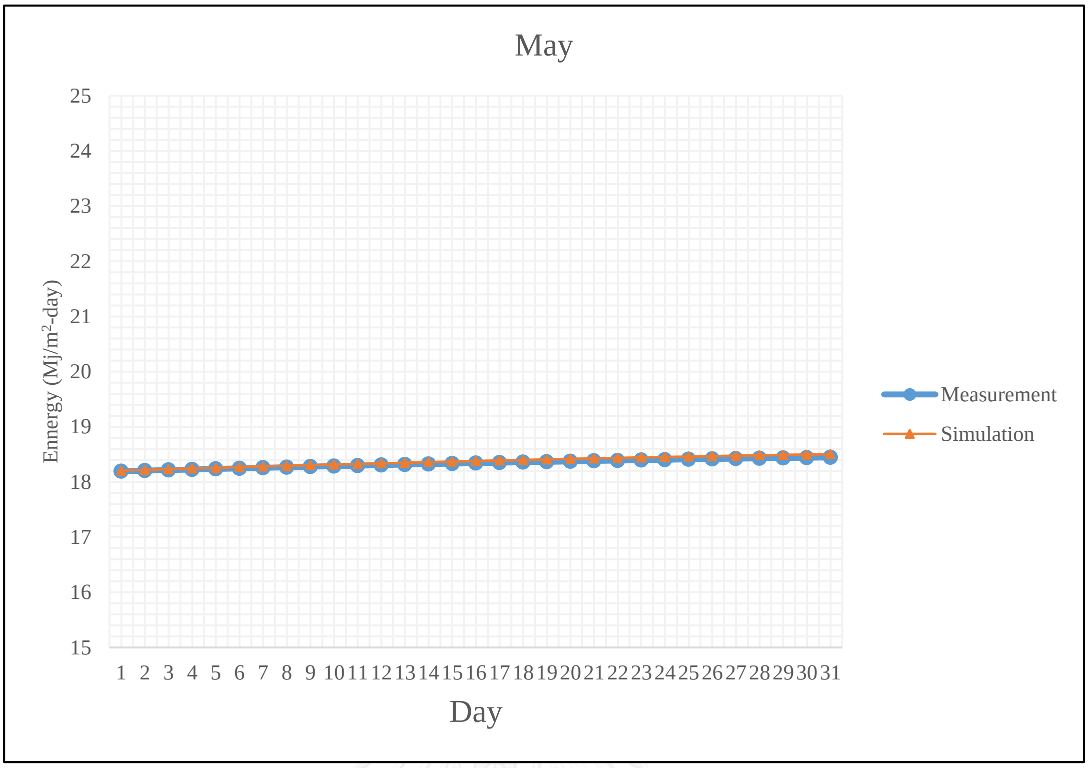


Figure 5. 17. Comparison in May

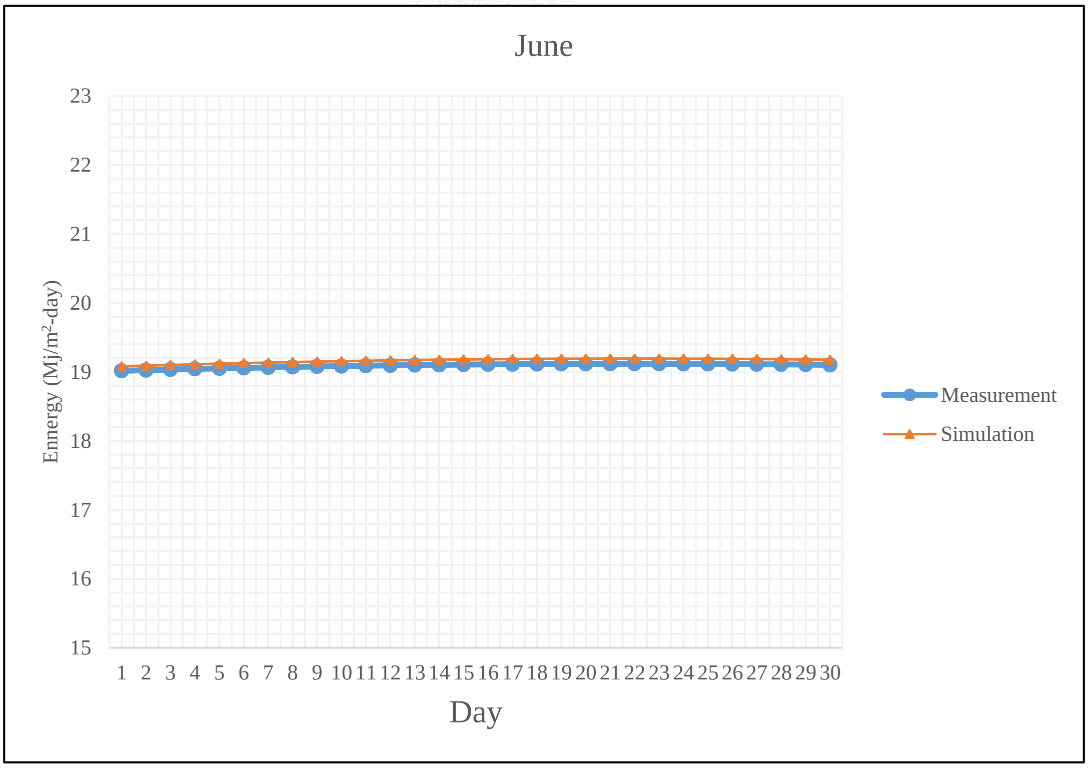


Figure 5. 18. Comparison in June

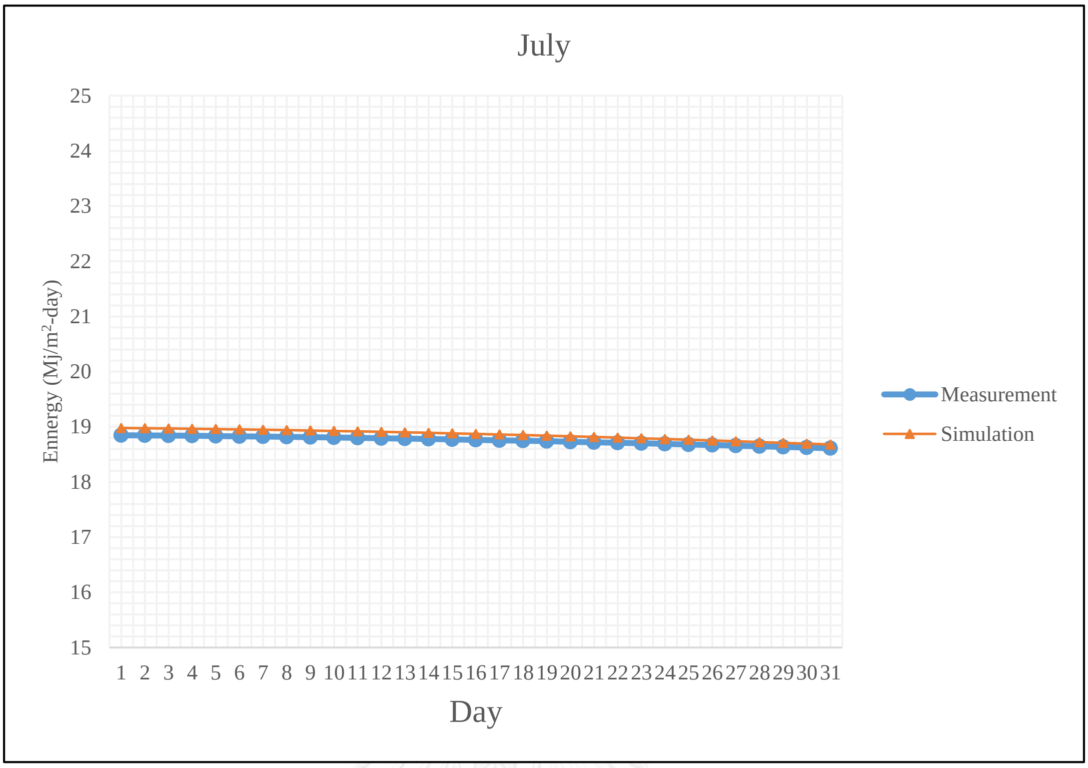


Figure 5. 19. Comparison in July

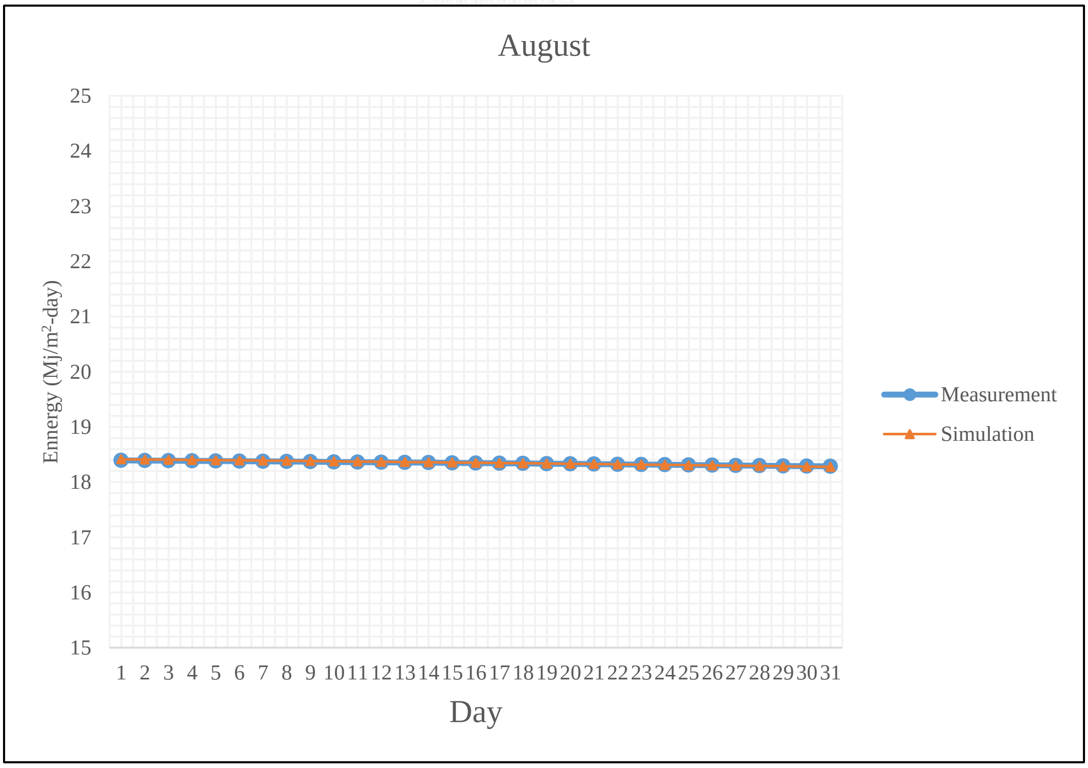


Figure 5. 20. Comparison in August

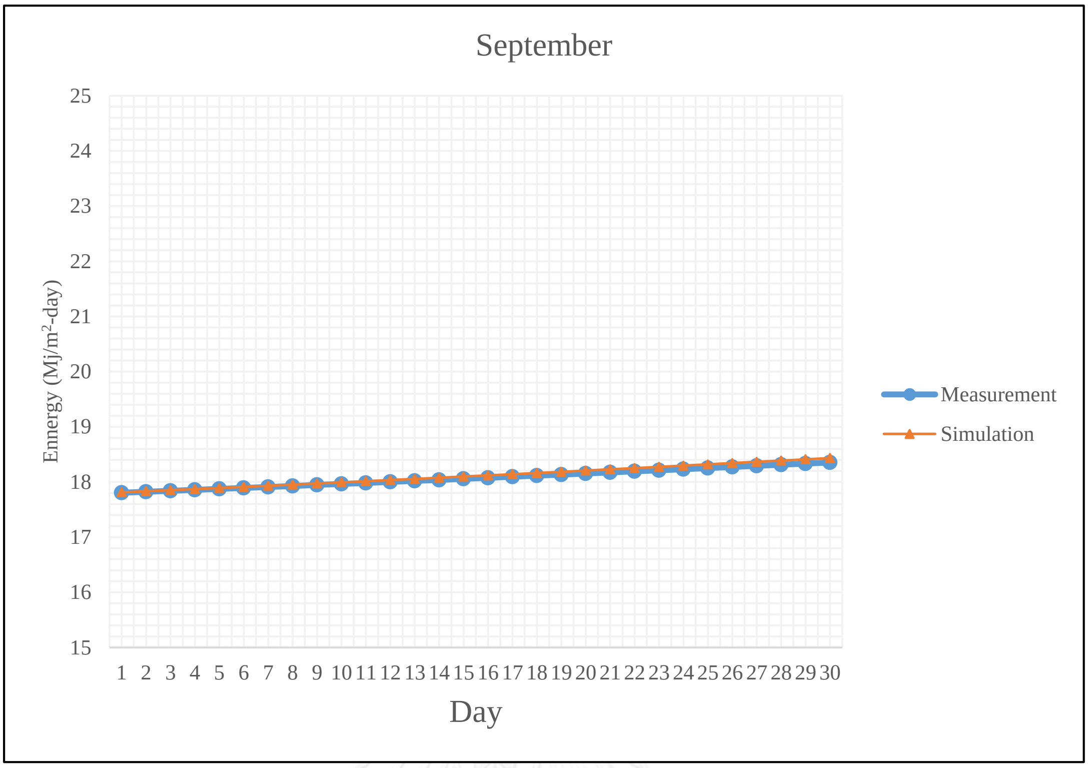


Figure 5. 21. Comparison in September

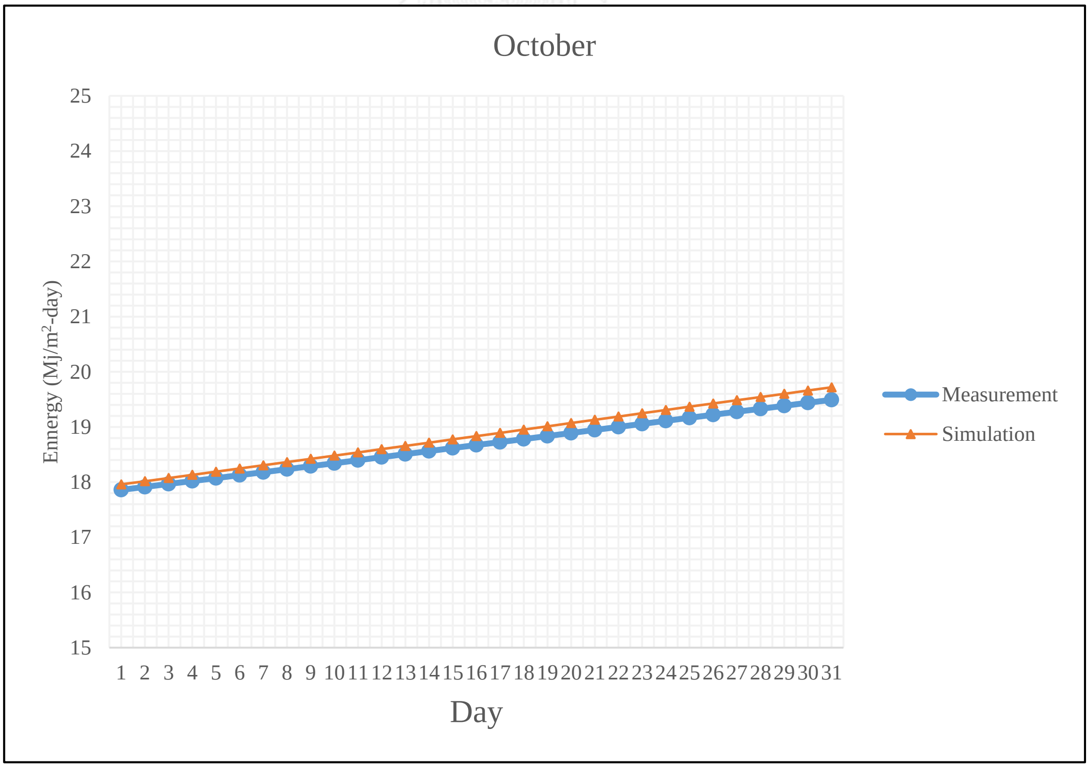


Figure 5. 22. Comparison in October

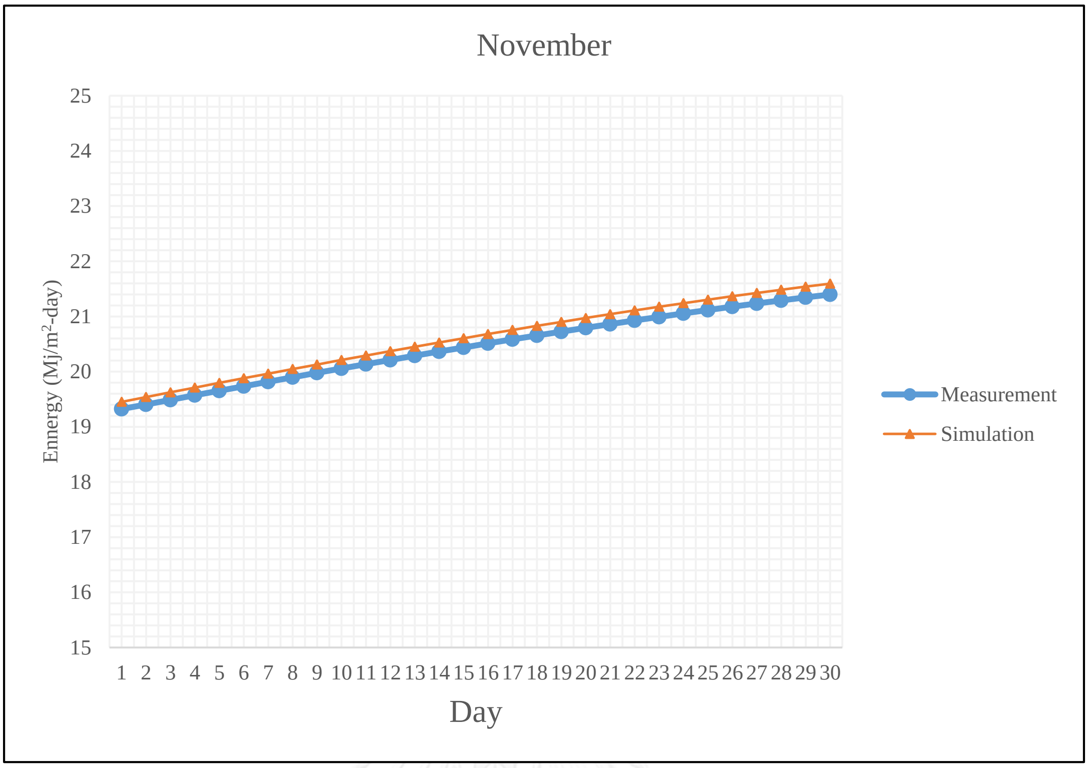


Figure 5. 23. Comparison in November

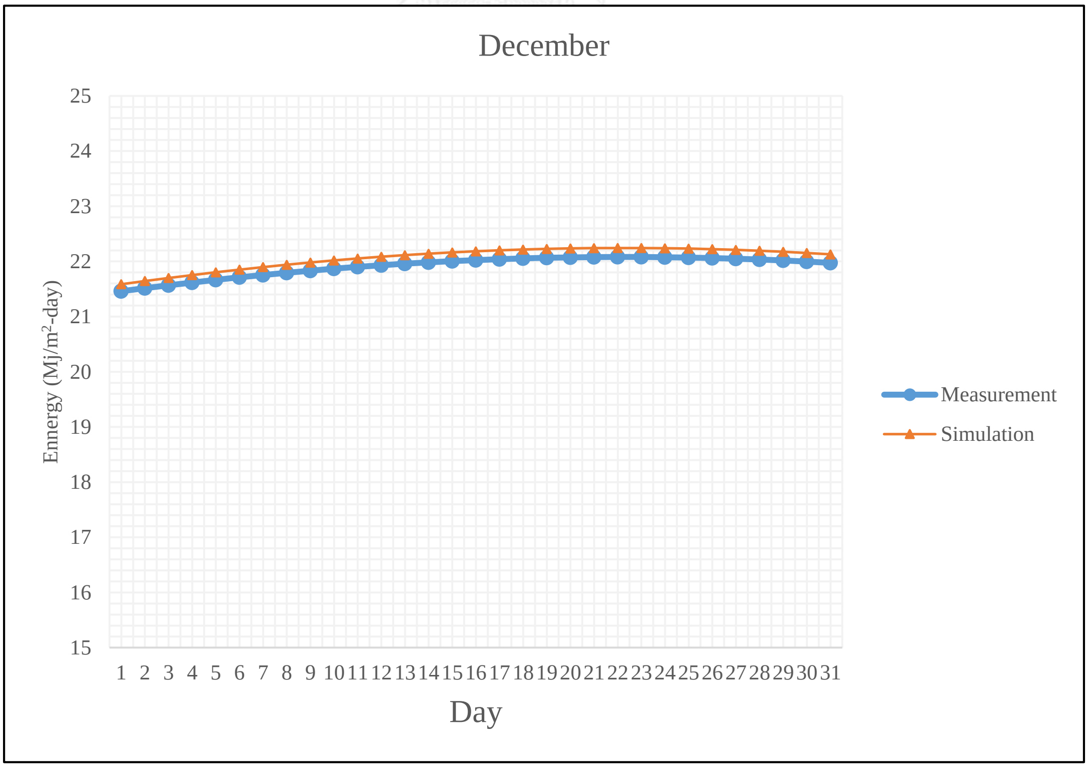


Figure 5. 24. Comparison in December

Comparison error between the Measurement and the simulation solar radiation during the whole year by using optimal tilted angle of each month.

Table 5. 2. Evaluation of Comparison error in Lampang

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Measurement Radiation (MJ/sq.m-day)	18.07	17.15	16.55	17.41	18.33	19.09	18.75	18.34	18.07	18.67	20.43	21.91	18.57
Simulation Radiation (MJ/sq.m-day)	17.50	16.82	16.45	17.41	18.37	19.16	18.86	18.35	18.11	18.84	20.60	22.07	18.54
Error value (%)	-3.26	-1.98	-0.63	0.00	0.20	0.38	0.55	0.03	0.24	0.86	0.81	0.69	-0.12

The negative error values in Table 5.2 indicates the measurement solar radiation is higher than the simulated radiation. However, the simulated solar radiation is higher than the measured values for most of the months. In January, simulated solar radiation is quite smaller than the measured, at about -3.26 %. In addition, the error between measurement and simulation is not greater than 4 %. Thus, the simulation model is close to measurement data.

In the following calculation in other provinces, errors in twelve months are also detailed in an accompanied table.

5.3. Monthly comparing results in Khonkaen

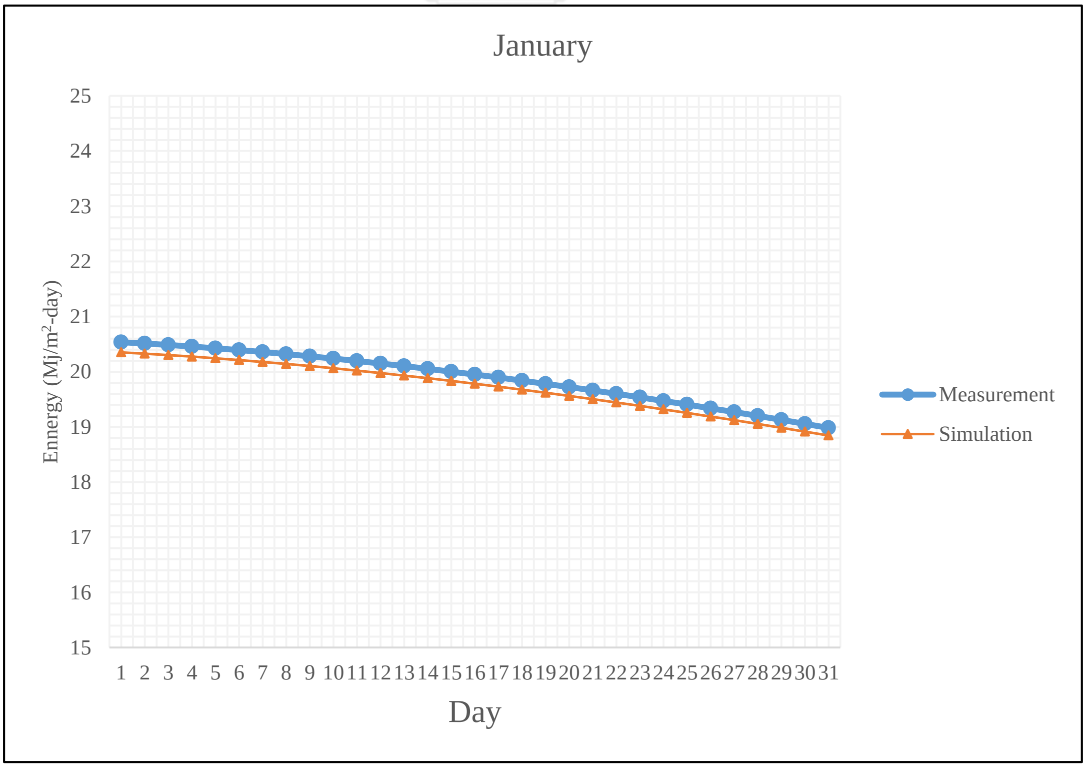


Figure 5. 25. Comparison in January

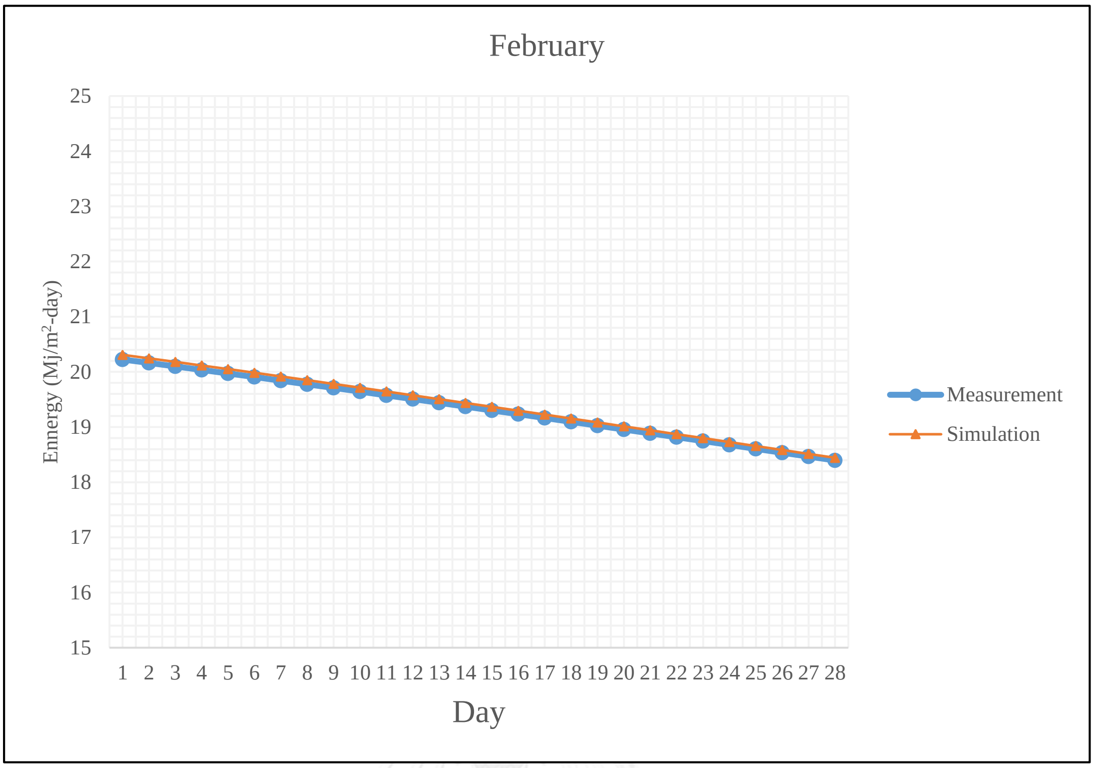


Figure 5. 26. Comparison in February

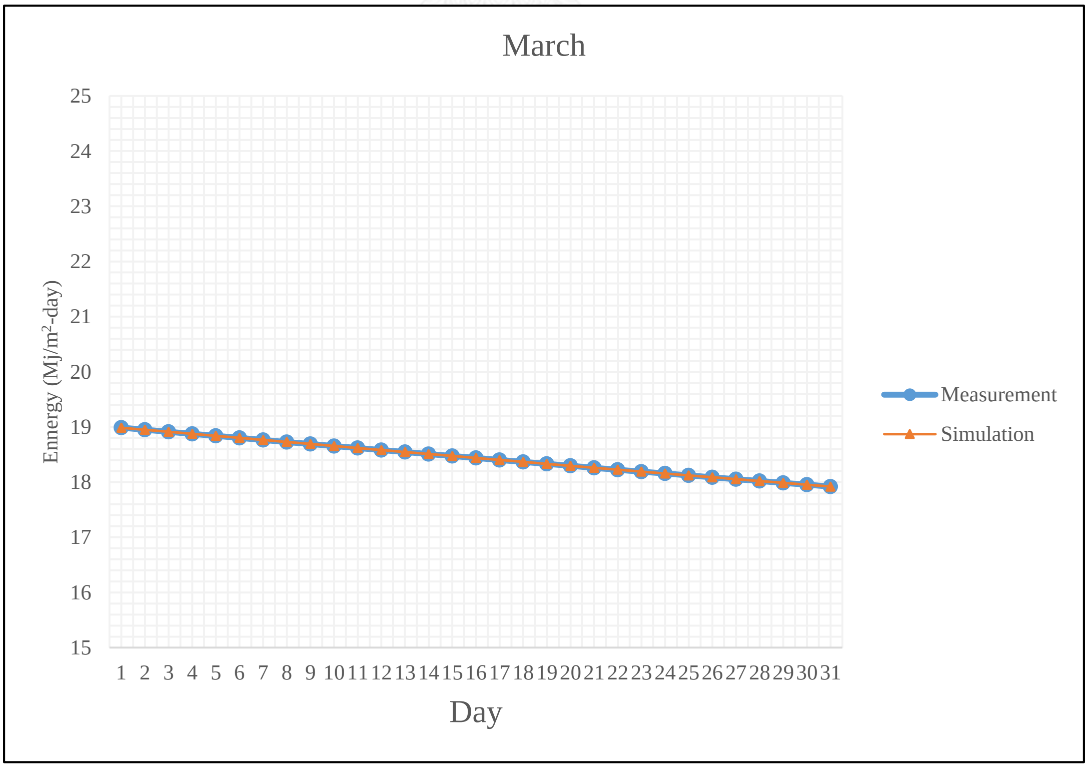


Figure 5. 27. Comparison in March

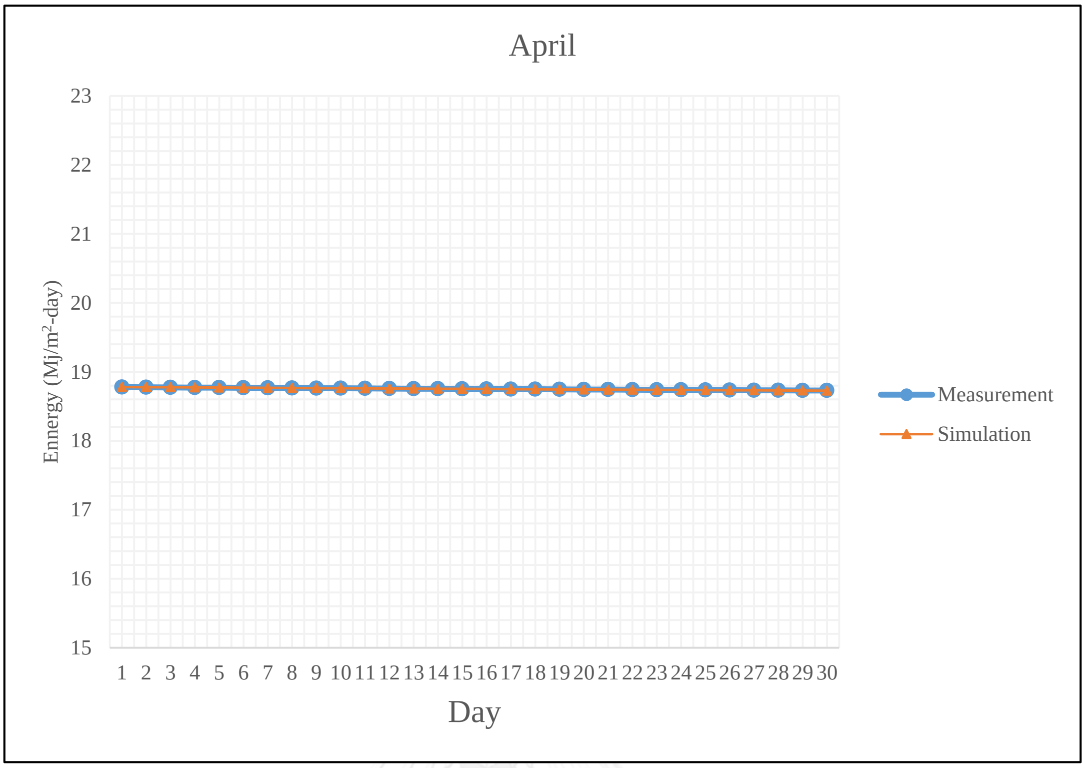


Figure 5. 28. Comparison in April

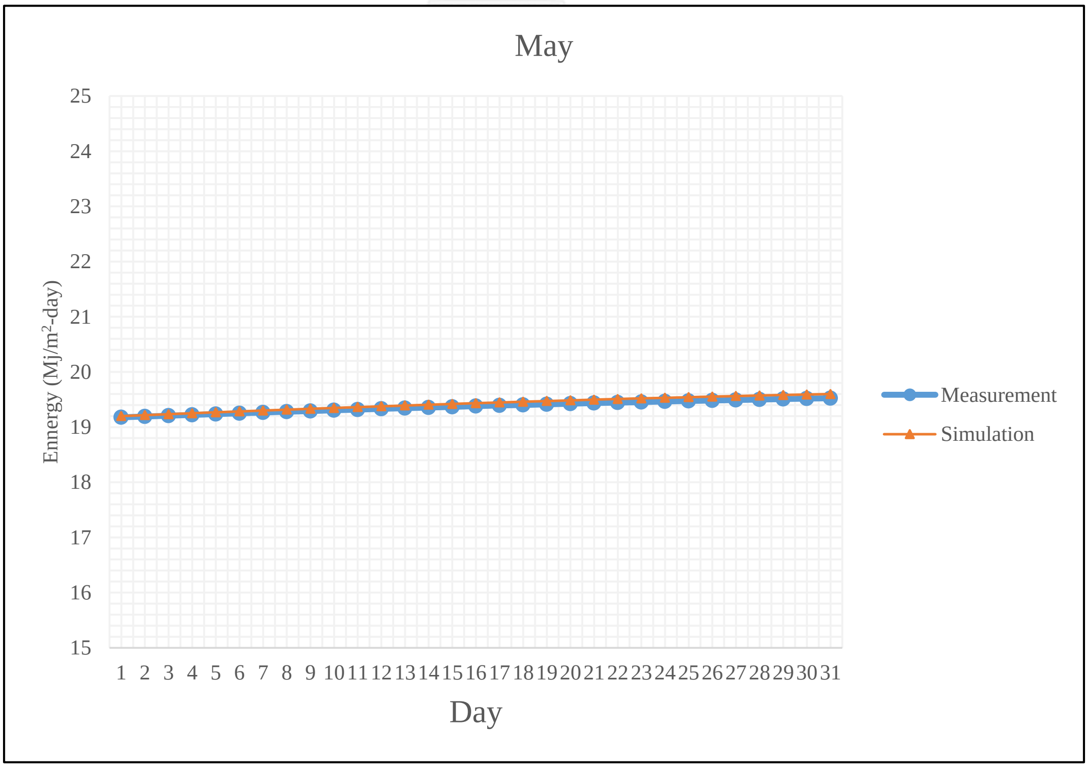


Figure 5. 29. Comparison in May

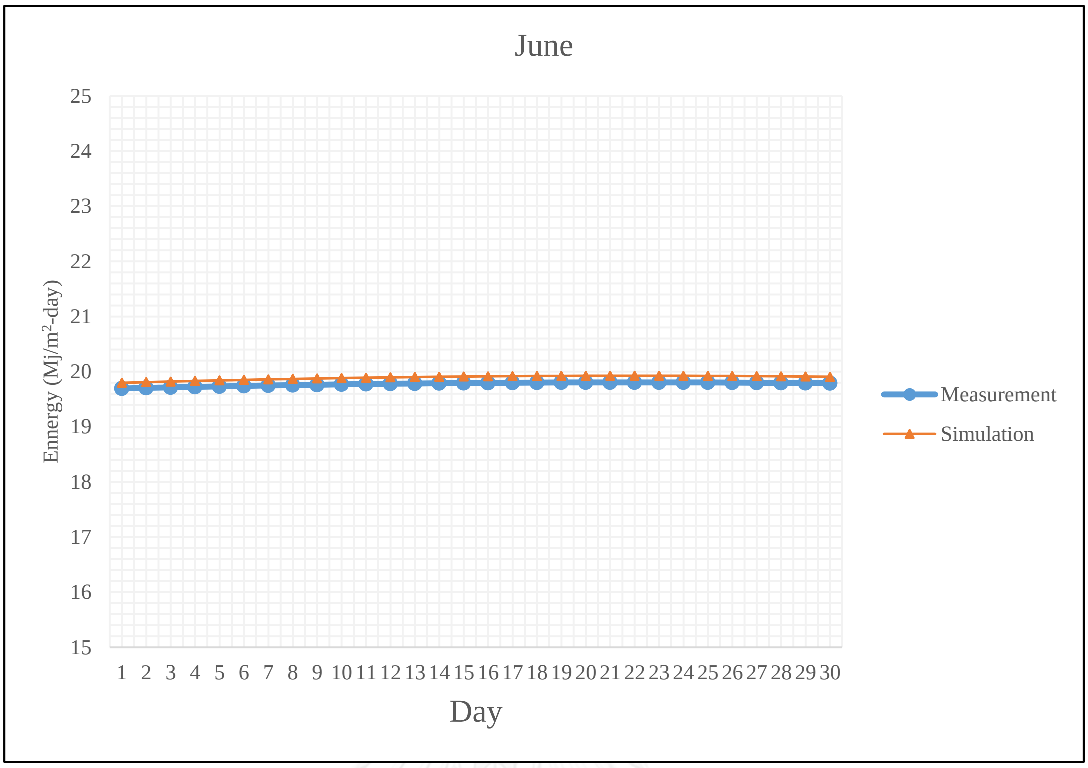


Figure 5. 30. Comparison in June

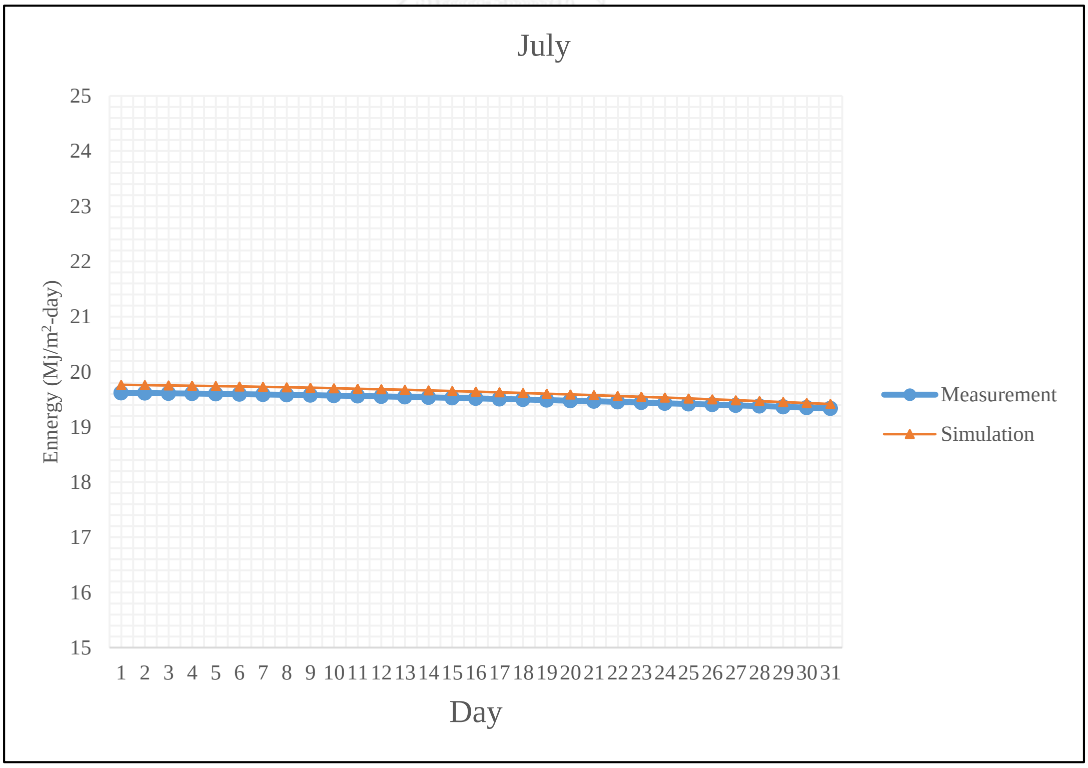


Figure 5. 31. Comparison in July

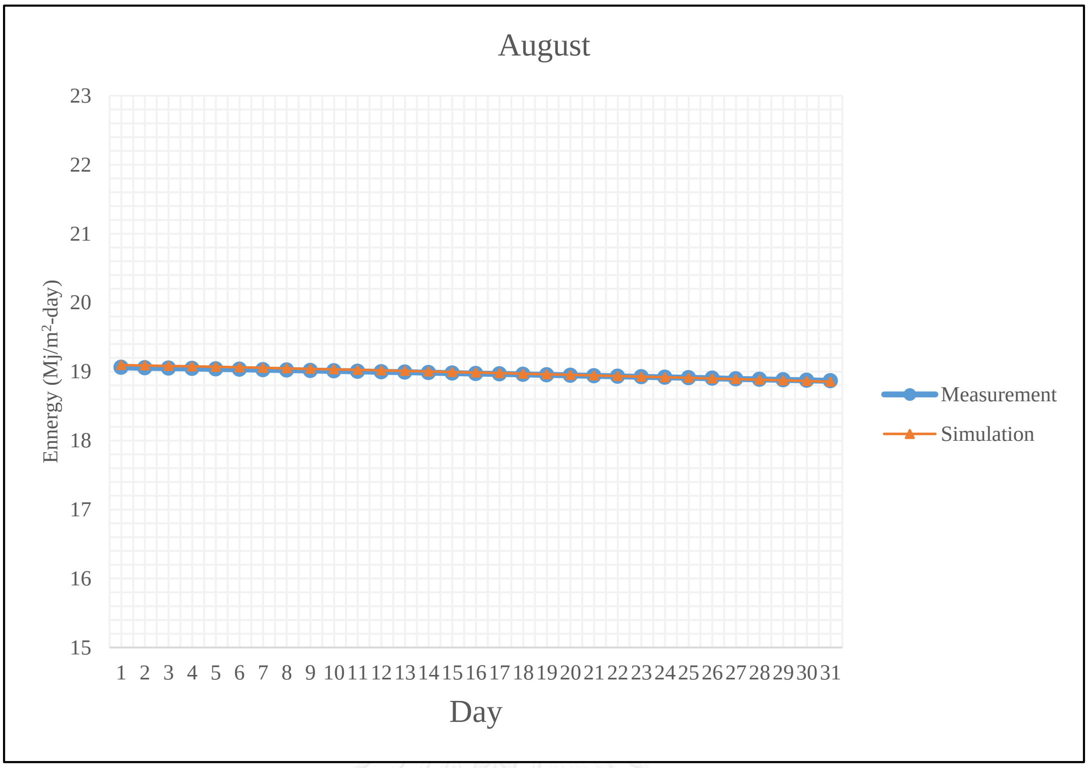


Figure 5. 32. Comparison in August

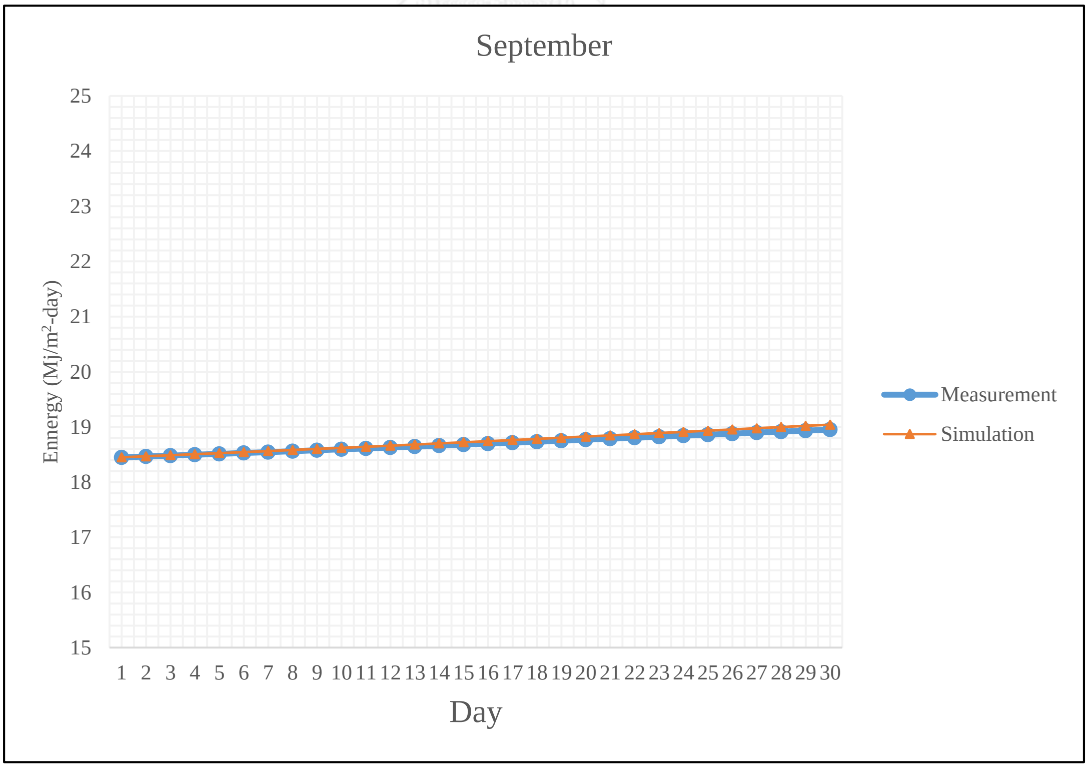


Figure 5. 33. Comparison in September

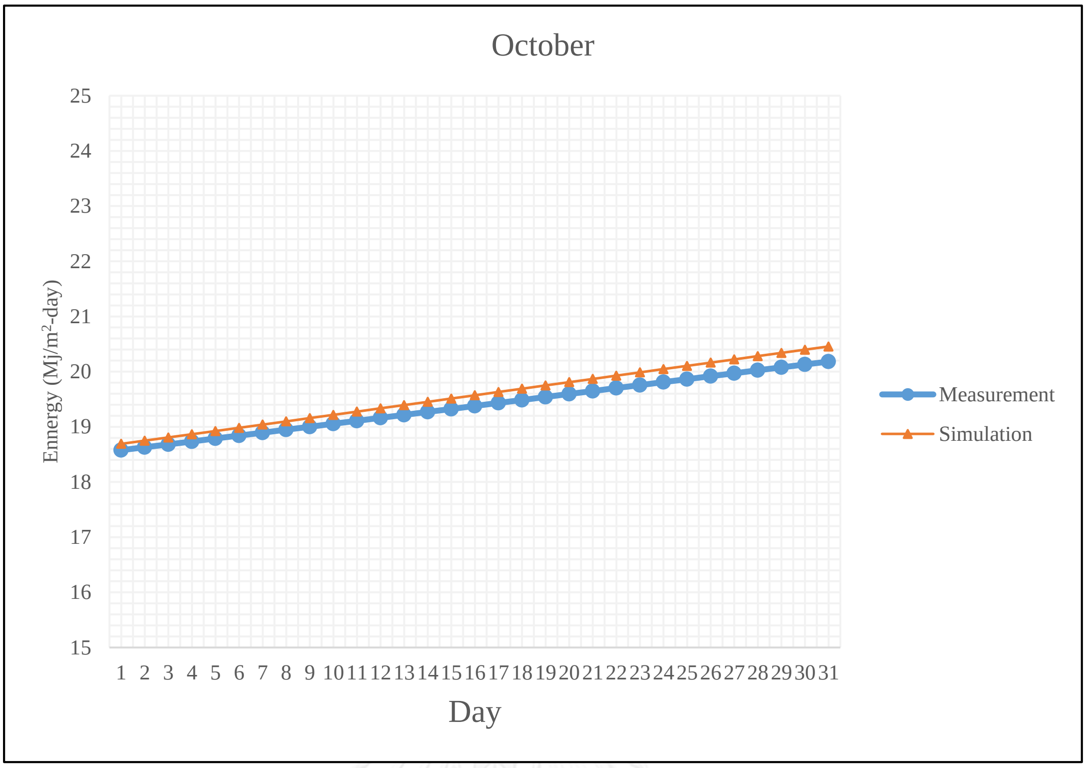


Figure 5. 34. Comparison in October

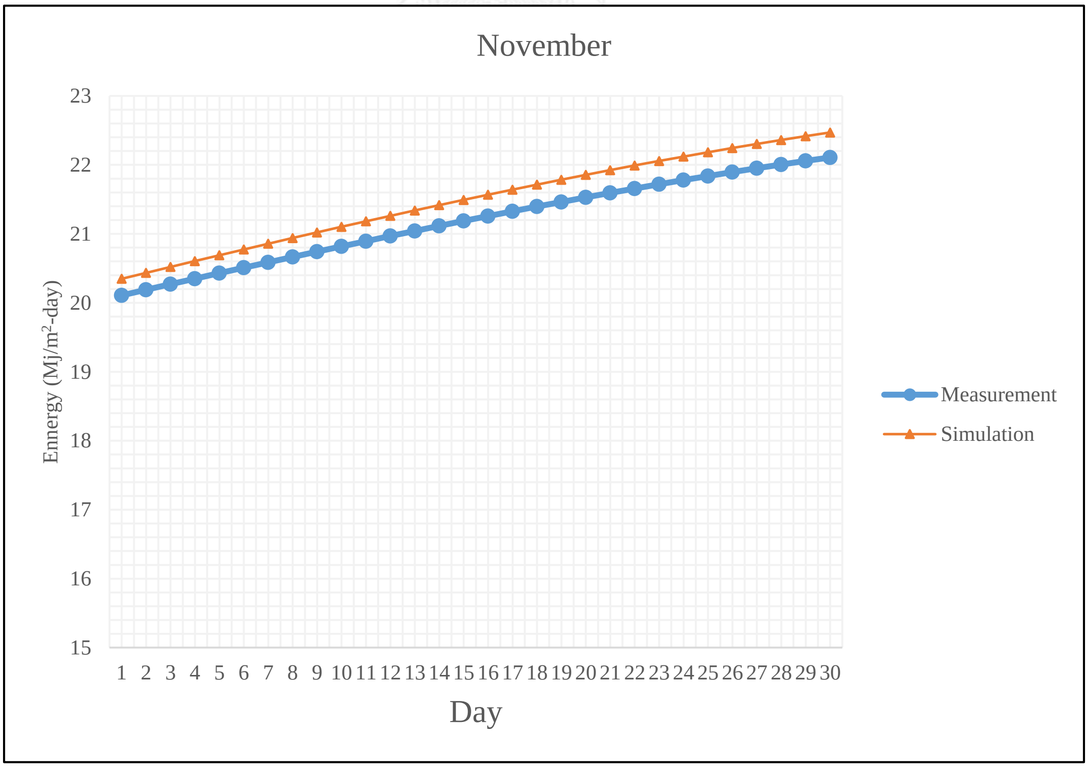


Figure 5. 35. Comparison in November

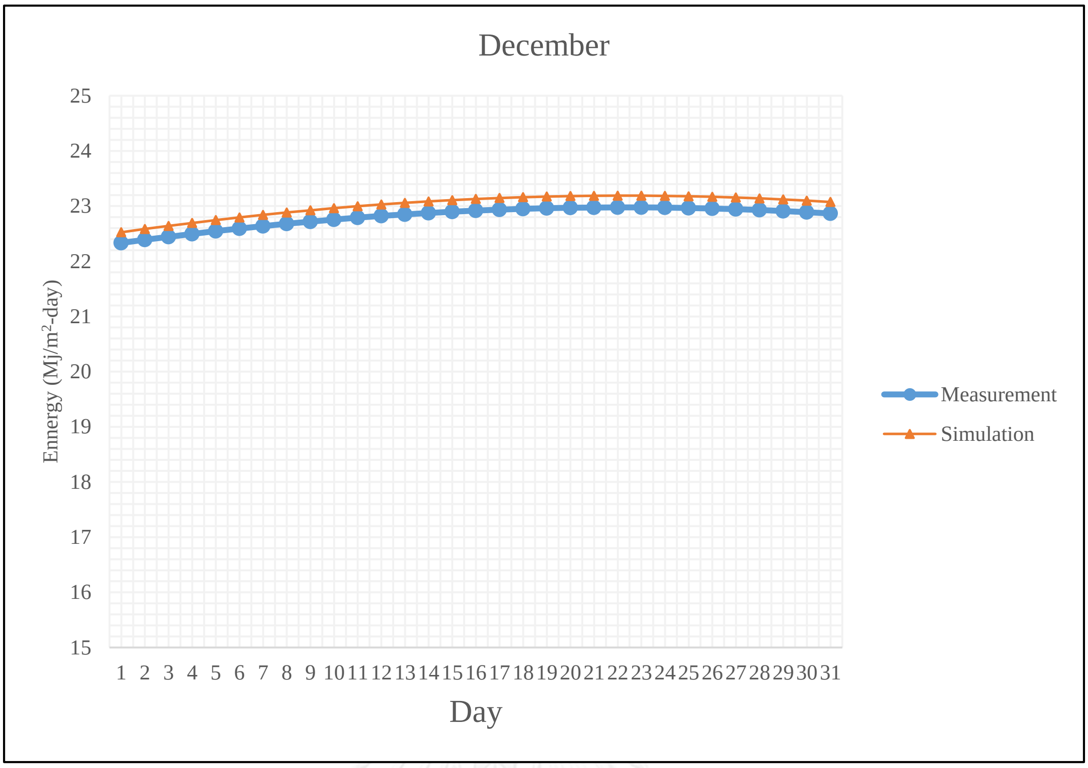


Figure 5. 36. Comparison in December

Comparison error between the Measurement and the simulation solar radiation during the whole year by using optimal tilted angle of each month.

Table 5. 3. Evaluation of Comparison error in Khonkaen

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Measurement Radiation (MJ/sq.m-day)	19.88	19.33	18.44	18.75	19.37	19.78	19.50	18.97	18.69	19.38	21.18	22.80	19.67
Simulation Radiation (MJ/sq.m-day)	19.72	19.39	18.44	18.75	19.42	19.89	19.62	18.98	18.74	19.57	21.49	23.01	19.75
Error value (%)	-0.84	0.34	0.00	0.00	0.27	0.58	0.61	0.07	0.24	0.99	1.42	0.90	0.40

In Khonkaen, the simulated solar radiation is higher than the measured values for most of the months. The monthly average daily values are quite different in some months. In addition, the error between measurement and simulation is not greater than 2 %. Thus, the simulation model is close to measurement data.

In the following calculation in other provinces, errors in twelve months are also detailed in an accompanied table.

5.4. Monthly comparing results in Krabi

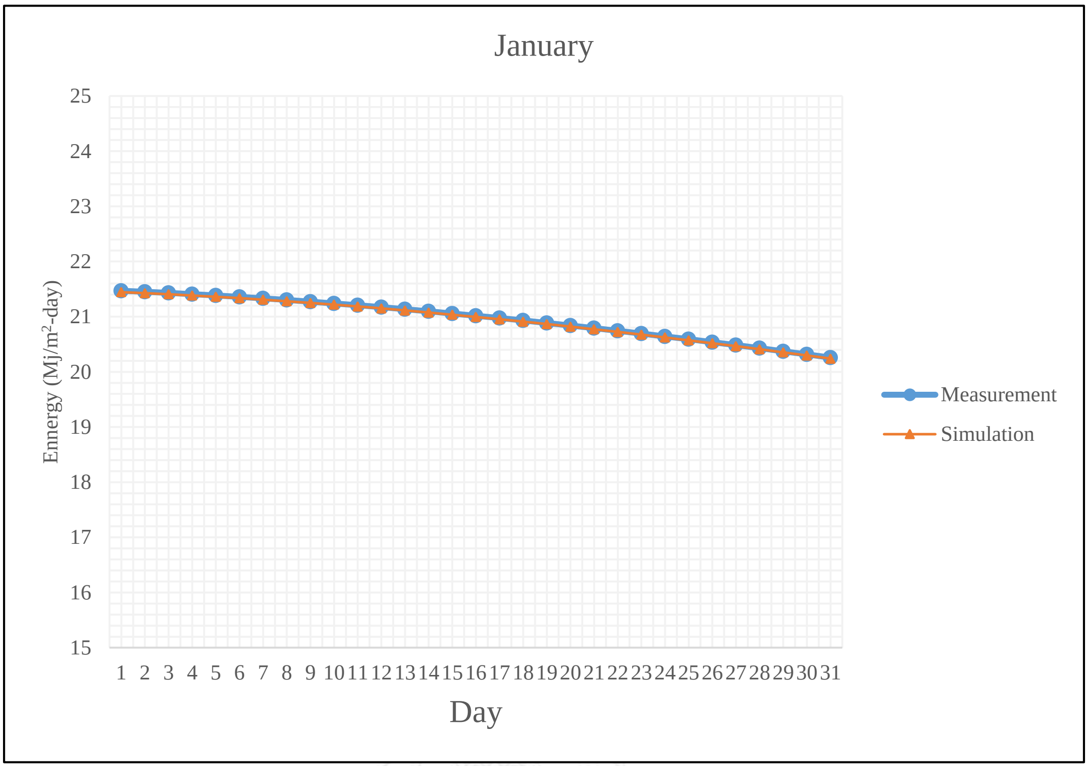


Figure 5. 37. Comparison in January

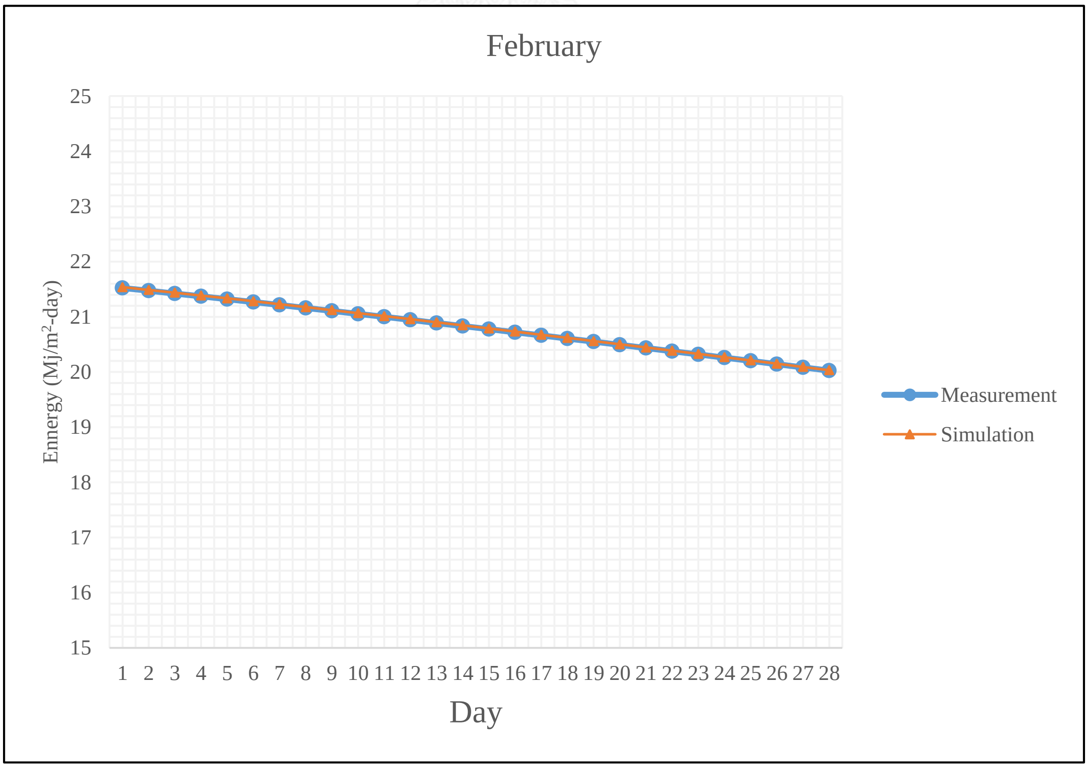


Figure 5. 38. Comparison in February

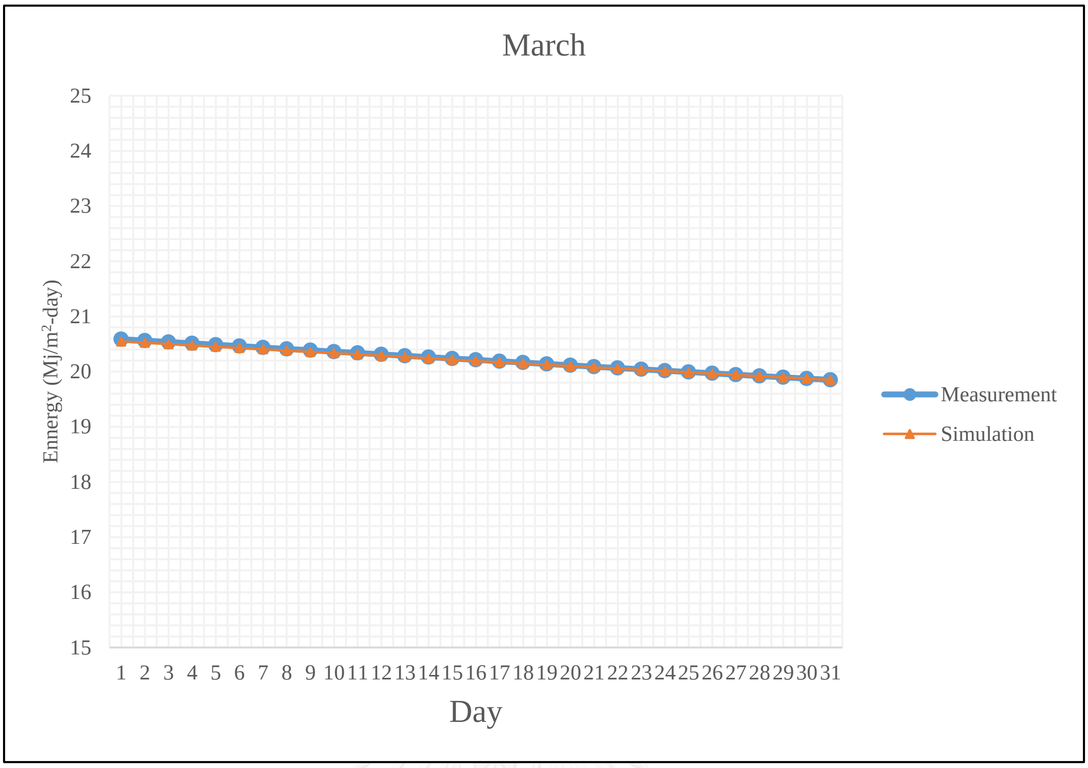


Figure 5. 39. Comparison in March

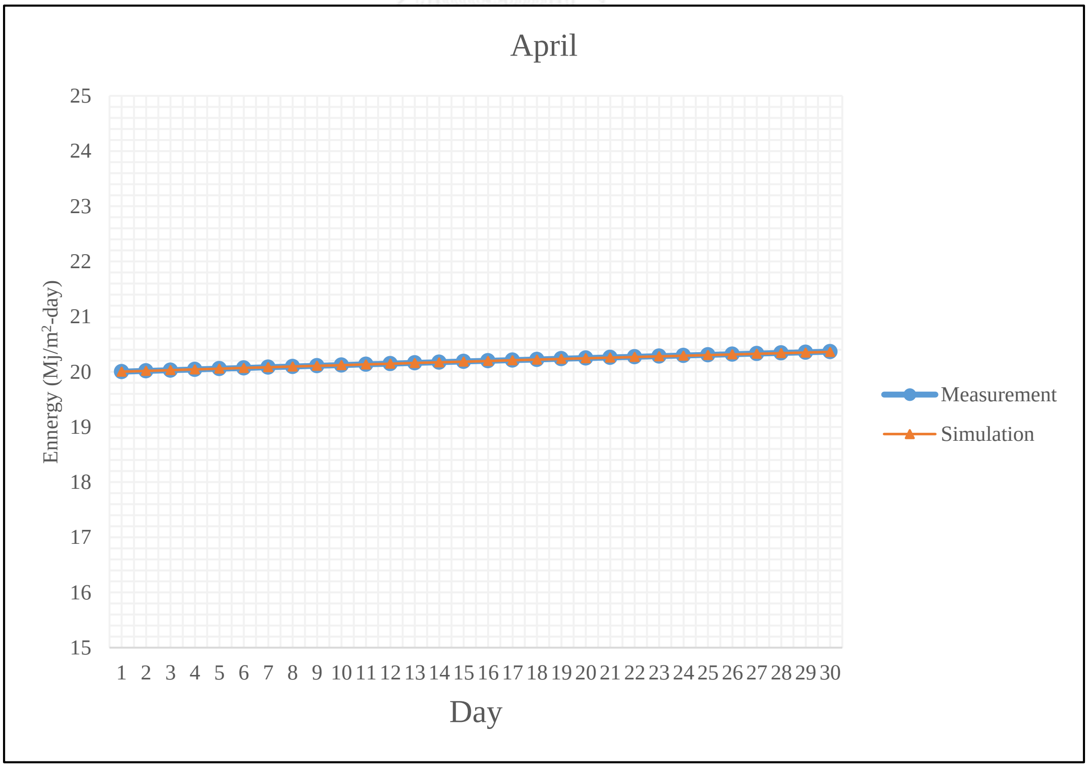


Figure 5. 40. Comparison in April

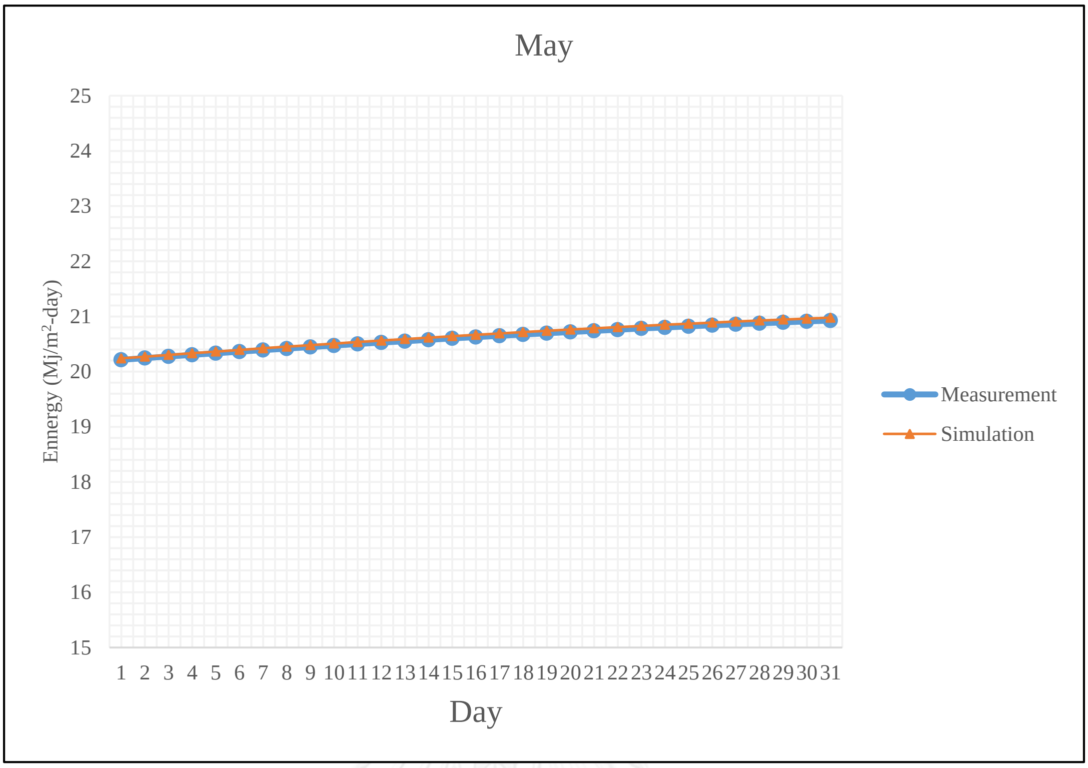


Figure 5. 41. Comparison in May

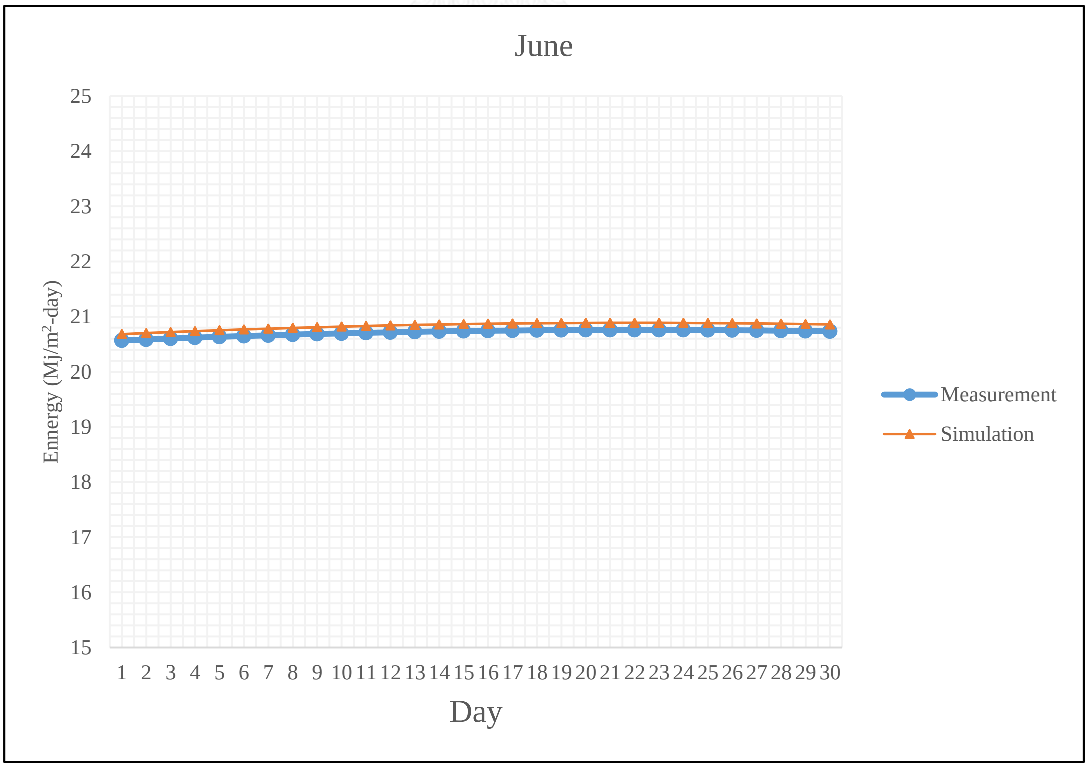


Figure 5. 42. Comparison in June

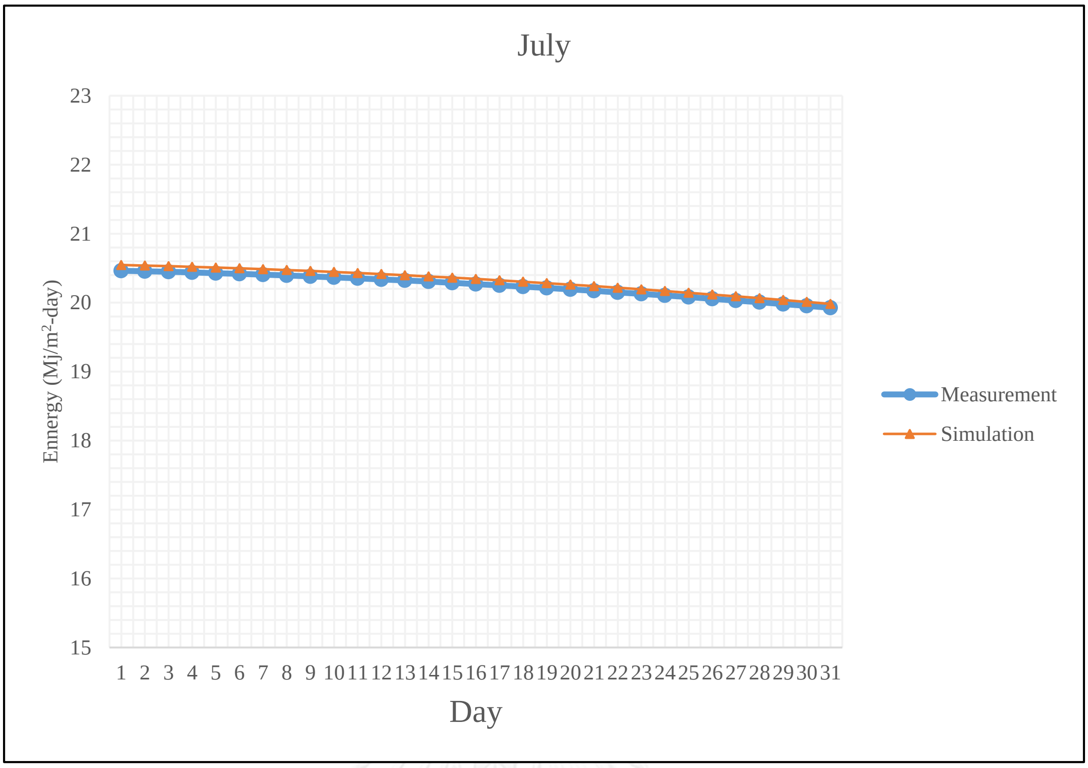


Figure 5. 43. Comparison in July

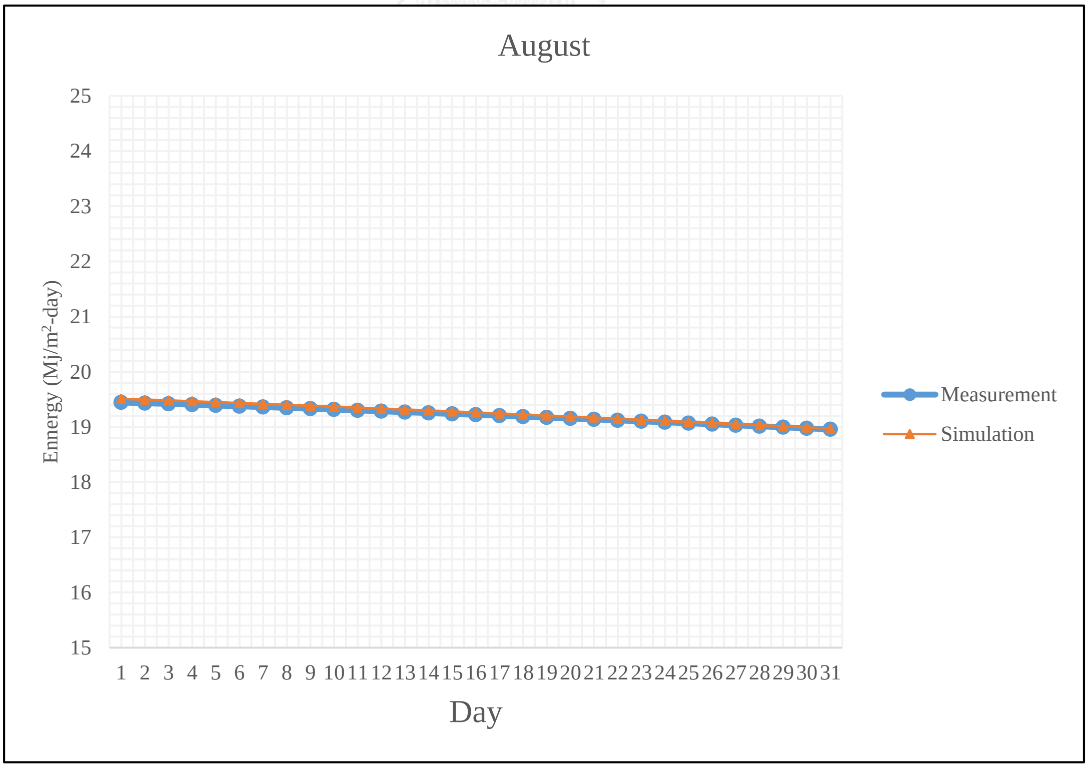


Figure 5. 44. Comparison in August

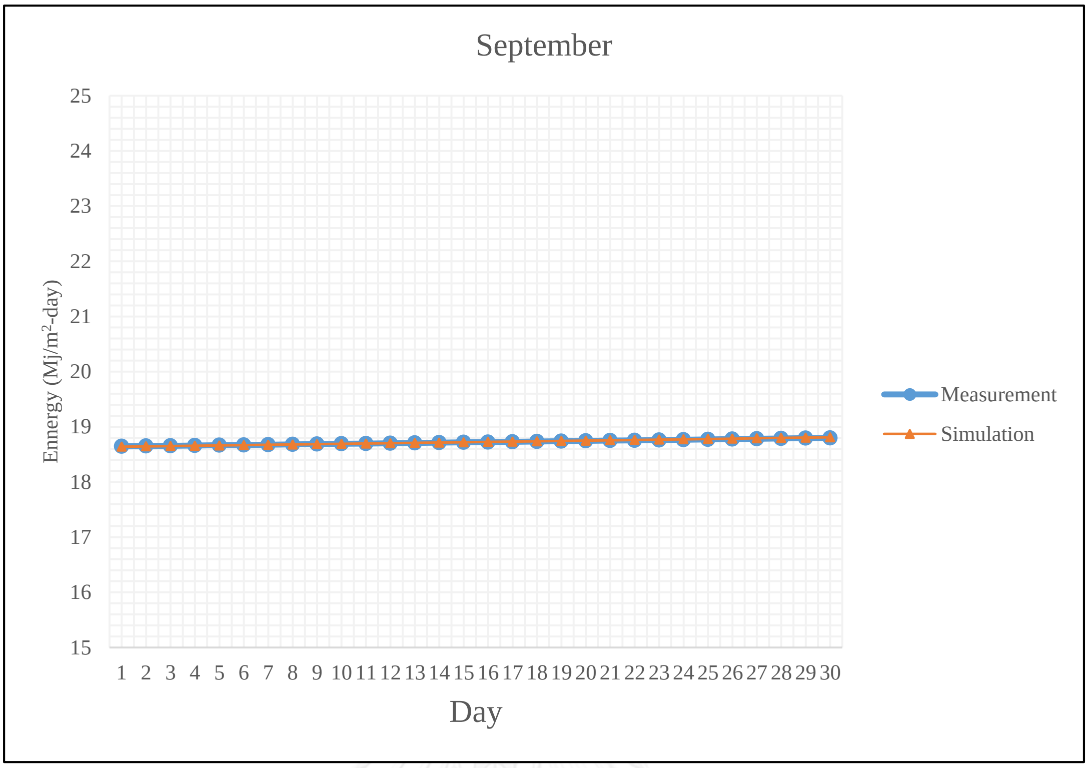


Figure 5. 45. Comparison in September

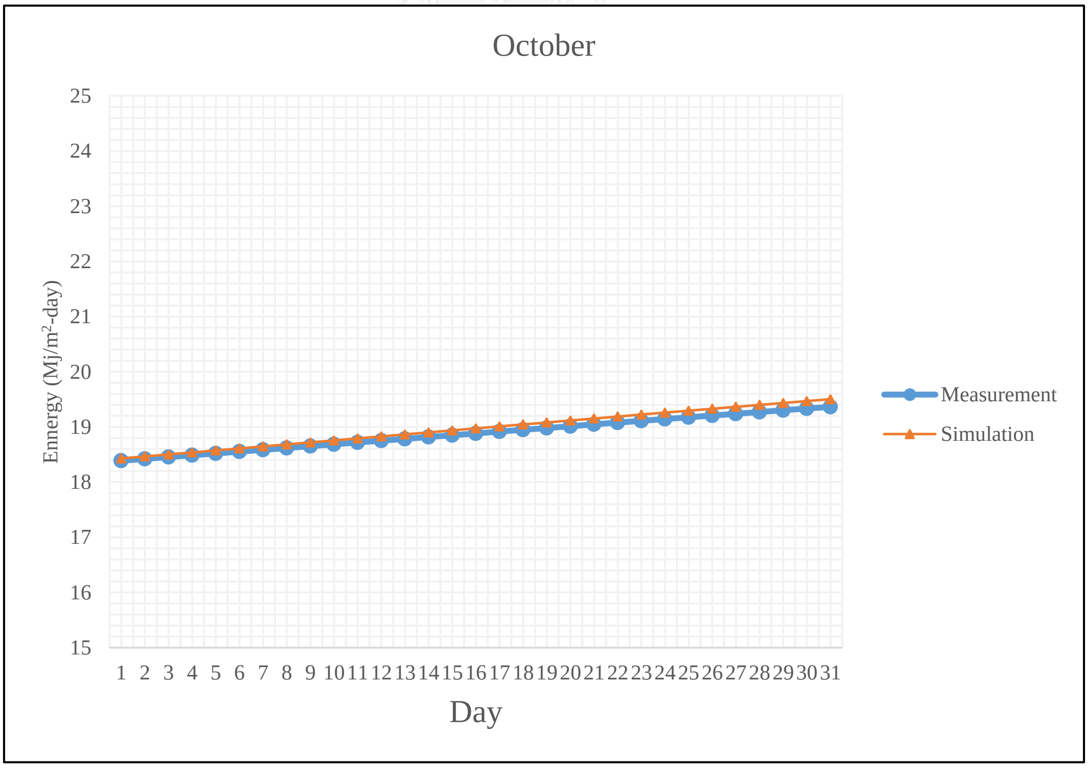


Figure 5. 46. Comparison in October

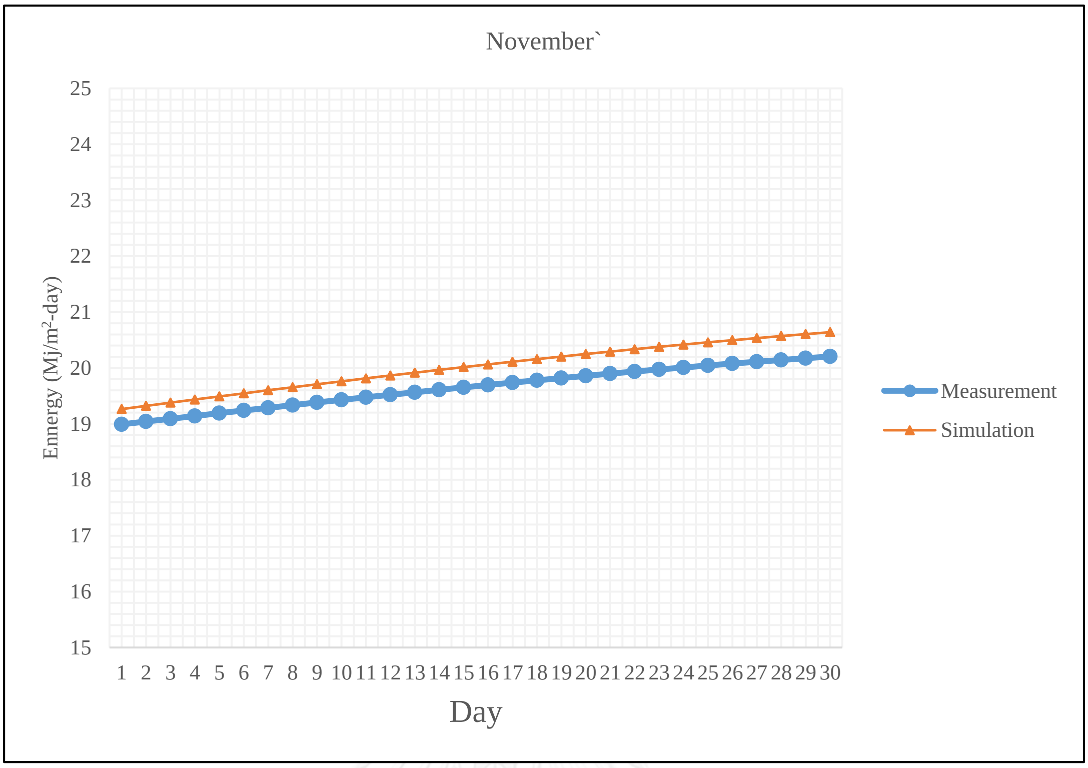


Figure 5. 47. Comparison in November

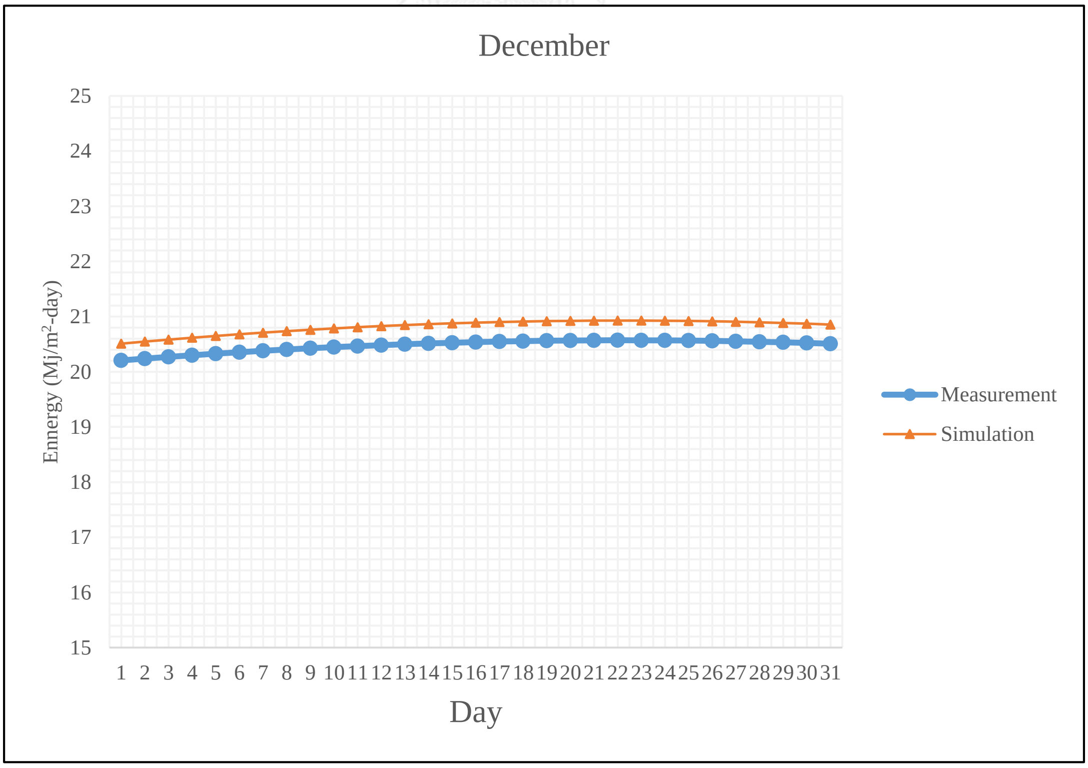


Figure 5. 48. Comparison in December

Comparison error between the Measurement and the simulation solar radiation during the whole year by using optimal tilted angle of each month.

Table 5. 4. Evaluation of Comparison error in Krabi

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Measurement Radiation (MJ/sq.m-day)	20.96	20.79	20.21	20.19	20.61	20.71	20.24	19.21	18.72	18.88	19.65	20.47	20.05
Simulation Radiation (MJ/sq.m-day)	20.94	20.81	20.19	20.19	20.65	20.83	20.32	19.25	18.72	18.97	20.01	20.82	20.14
Error value (%)	-0.10	0.06	-0.10	-0.01	0.20	0.60	0.35	0.21	0.01	0.48	1.81	1.65	0.43

In Krabi, the monthly average daily values are quite different in June, October, November and December; the error between measurement and simulation is not greater than 2 %. Thus, the simulation model is close to measurement data.

In the following calculation in other provinces, errors in twelve months are also detailed in an accompanied table.

Chapter 6 The Role of non-zero Azimuth Angle in the Installation of Rooftop PV panels in Thailand

The common tilt angle of the modern house roof is angle of about 35 degrees and rooftop can be divided into 3 types: Lean-to roof, Gable roof and Hip roof. Each type of rooftop will be facing in any direction depends on the area of the house toward the front and the roof type will determine the direction of the solar panel. In some cases, the direction of panels installed on the rooftop is not perpendicular to the sun. Consequently, the received energy is less than the amount at the optimum direction. In fact, a Thai house is facing in any direction in accordance with the Thai beliefs of 'Feng shui'. So, there are 8 directions for house facing in Thailand.

This chapter evaluates the following angles of the azimuth:
Azimuth = 0°, Tilted= 35°, Facing to South
Azimuth = 45°, Tilted= 35°, Facing to South West
Azimuth = 90°, Tilted= 35°, Facing to West
Azimuth = 135°, Tilted= 35°, Facing to North West
Azimuth = 180°, Tilted= 35°, Facing to North
Azimuth = -135°, Tilted= 35°, Facing to North East
Azimuth = -90°, Tilted= 35°, Facing to East
Azimuth = -45°, Tilted= 35°, Facing to South East

In the following evaluation, solar radiation for different angle surfaces is forecasted in some provinces of Thailand. The method is proposed by Erb et al. In each province, the simulated daily average yearly solar radiation of rooftop angle is compared with the one of the best angle.

6.1. Results of Ayutthaya

Evaluation results are summarized in Table 6.1 and graphical comparisons are illustrated from Fig.6.1 to Fig. 6.8.

Table 6. 1. Comparison yearly average daily solar radiation between best angle (Azimuth=0° and Tilted= 14°) and roof top angle on each direction

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Radiation on best angle (Mj/m^2-day)	18.16	17.52	18.58	18.36	18.05	17.90	17.86	18.16	18.57	19.08	19.67	19.67	18.47
Radiation on rooftop South – facing (Mj/m^2-day)	19.56	18.02	17.79	16.43	15.30	14.75	14.90	15.85	17.25	19.02	20.95	22.21	17.67
Radiation on rooftop South West – facing (Mj/m^2-day)	12.56	13.07	15.13	15.29	14.72	14.28	14.40	15.03	15.36	14.90	13.84	13.36	14.33
Radiation on rooftop West – facing (Mj/m^2-day)	9.29	9.95	12.75	14.16	14.83	15.04	14.88	14.46	13.46	11.87	10.16	9.59	12.54

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Radiation on rooftop North West – facing (Mj/m^2-day)	7.54	8.61	12.46	15.42	17.56	18.56	18.05	16.38	13.80	10.85	8.30	7.50	12.92
Radiation on rooftop North – facing (Mj/m^2-day)	7.69	9.10	13.45	16.91	19.38	20.52	19.94	18.04	15.04	11.58	8.60	7.58	13.99
Radiation on rooftop North East –facing (Mj/m^2-day)	7.54	8.61	12.46	15.42	17.56	18.56	18.05	16.38	13.80	10.85	8.30	7.50	12.92
Radiation on rooftop East - facing	9.29	9.95	12.75	14.16	14.83	15.04	14.88	14.46	13.46	11.87	10.16	9.59	12.54
Radiation on rooftop South East – facing (Mj/m^2-day)	12.56	13.07	15.13	15.29	14.72	14.28	14.40	15.03	15.36	14.90	13.84	13.36	14.33

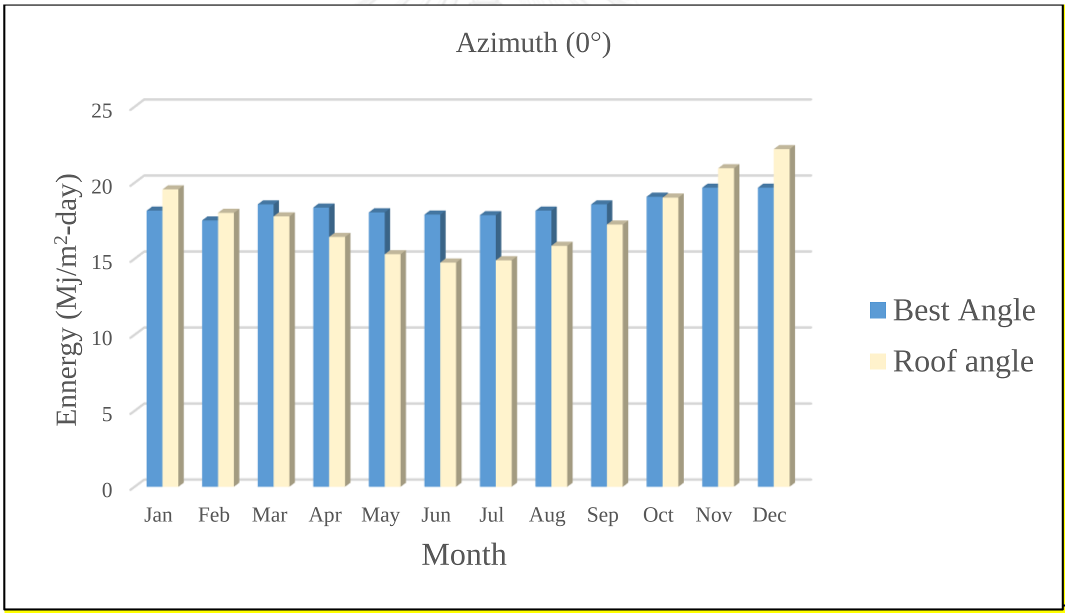


Figure 6. 1. Facing to the South

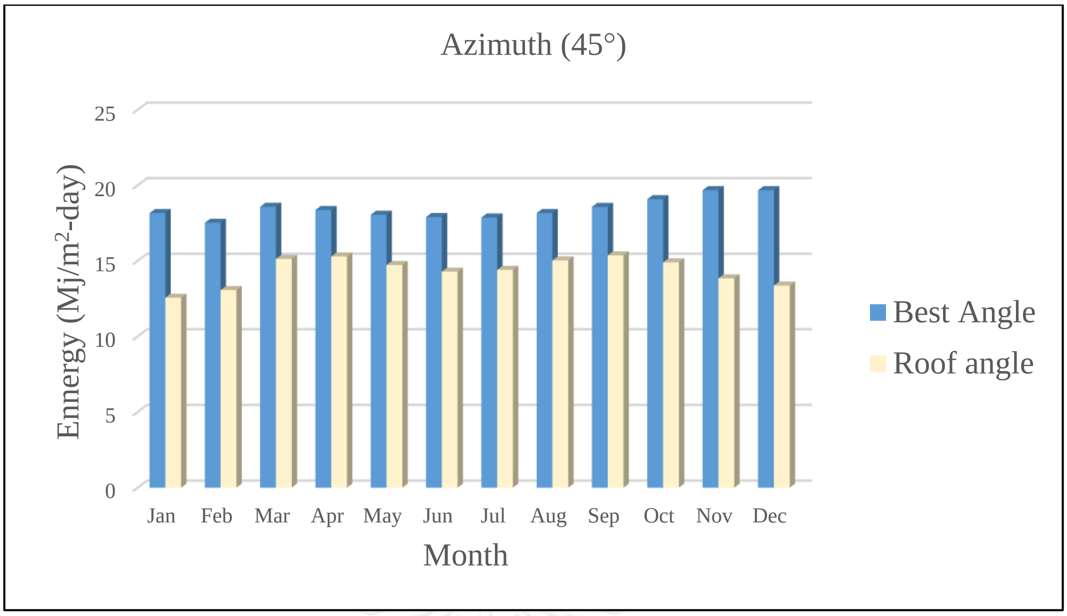


Figure 6. 2. Facing to the South West

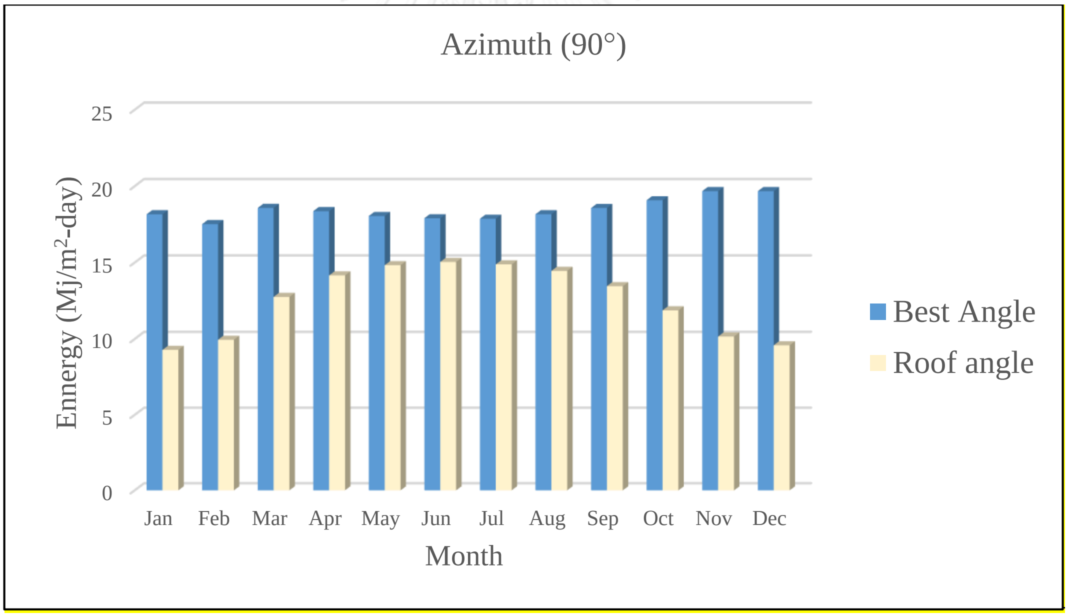


Figure 6. 3. Facing to the West

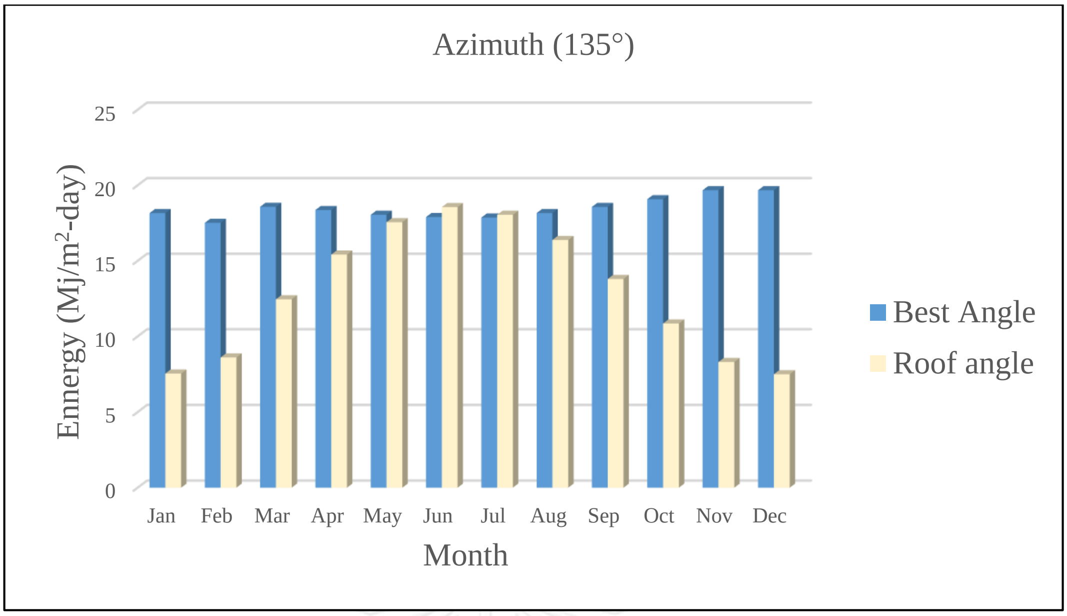


Figure 6. 4. Facing to the North West

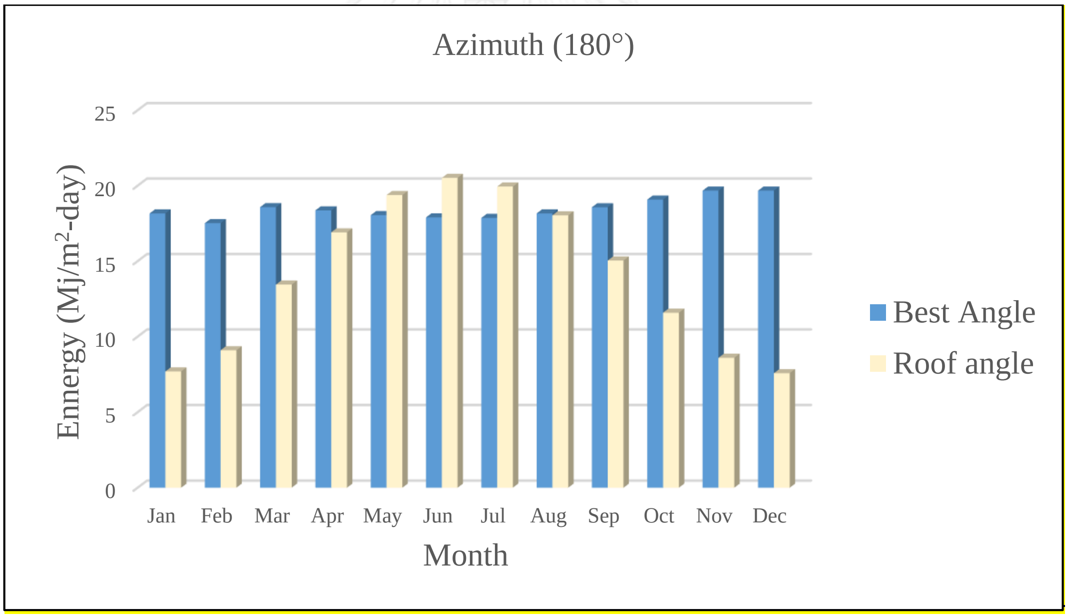


Figure 6. 5. Facing to the North

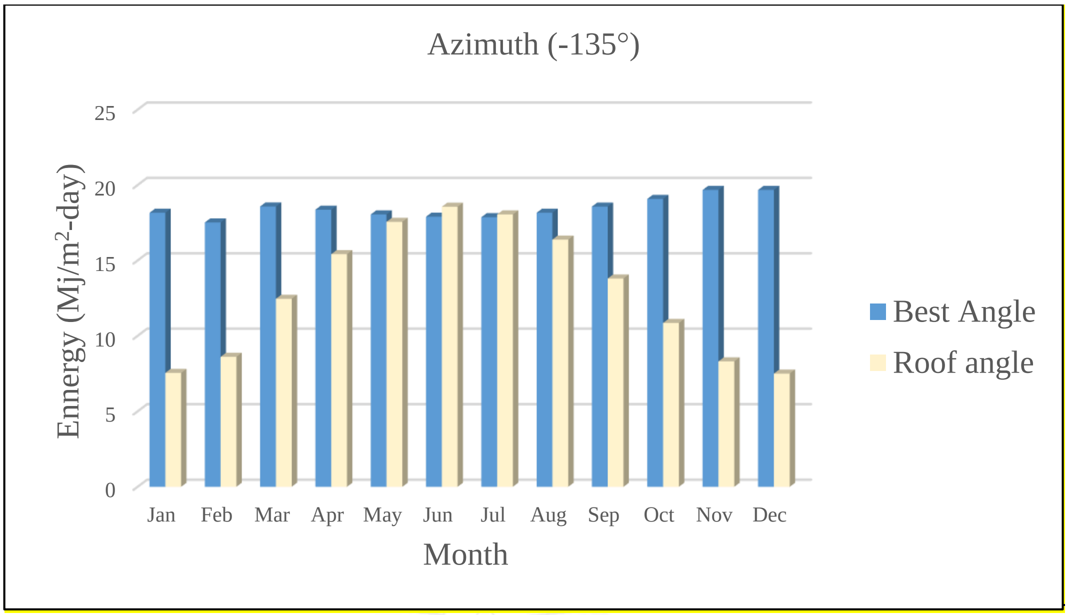


Figure 6. 6. Facing to the North East

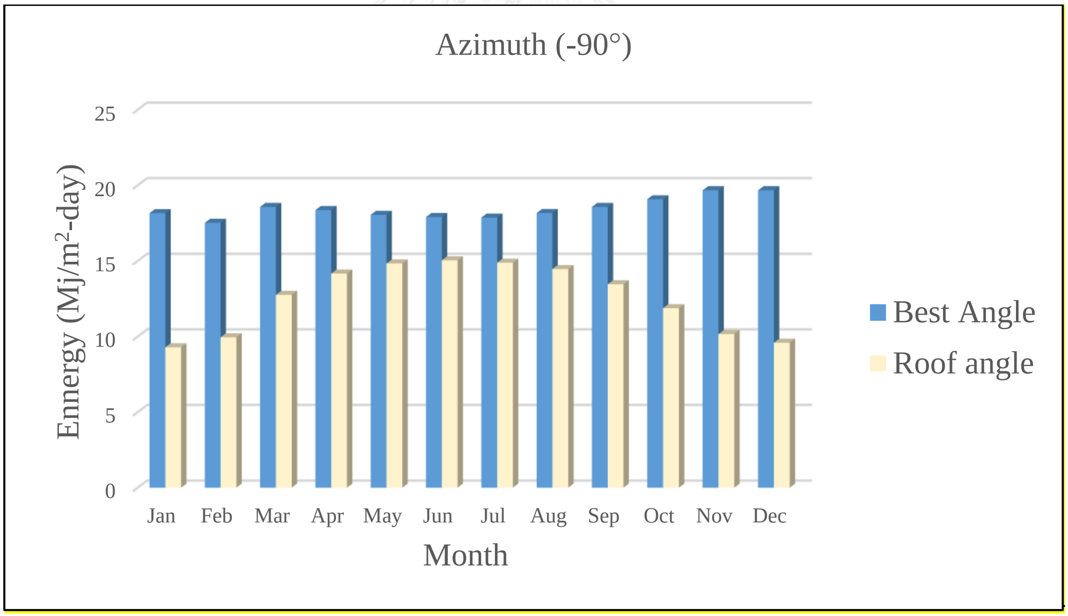


Figure 6. 7. Facing to the East

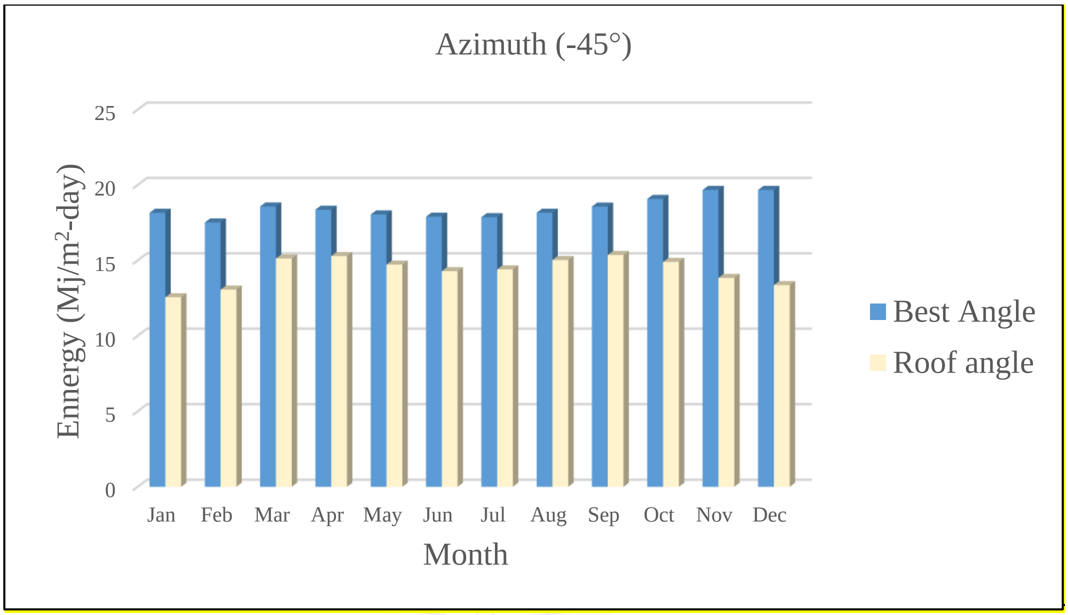


Figure 6. 8. Facing to the South East

Analysis

Results show that the highest energy is on the best angle installation. The differences of average yearly solar radiation on rooftops are 4.33%, 22.40%, 32.11%, 30.04 %, 24.26%, 30.04%, 32.11% and 22.40%, respectively.

It can be seen that the difference between the corrected angles and the following by rooftop are greater than 30% in some direction. Hence, the solar radiation receives more energy when facing to the South. If rooftop quite facing to the North will receives more energy only in the middle year. Thus, the total solar radiation for the year on rooftop tilted surface which is facing the equator (azimuth surface equal to zero) is more efficient.

In case of facing to the East or West for the same value of azimuth angle, solar radiation receives for facing to South West, Azimuth = 45° equate with facing to South East, Azimuth = -45° and (facing to West = facing to East, facing to North West = facing to North East).

6.2. Result of Lampang

Evaluation results are summarized in Table 6.2 and graphical comparisons are illustrated from Fig.6.9 to Fig. 6.16.

Table 6. 2. Comparison yearly average daily solar radiation between best angle (Azimuth=0° and Tilted= 17°) and roof top angle on each direction

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Radiation on best angle (Mj/m^2-day)	16.26	15.27	16.45	17.05	17.15	17.28	17.26	17.62	18.05	18.62	19.25	19.68	17.49
Radiation on rooftop South – facing (Mj/m^2-day)	17.40	15.69	15.93	15.64	15.07	14.84	14.96	15.82	17.06	18.71	20.52	21.67	16.94
Radiation on rooftop South West – facing (Mj/m^2-day)	10.56	11.00	13.35	14.54	14.70	14.67	14.71	15.06	14.92	13.96	12.48	11.91	13.49
Radiation on rooftop West – facing (Mj/m^2-day)	7.94	8.51	11.25	13.25	14.46	15.05	14.83	14.18	12.84	10.96	9.04	8.48	11.73
Radiation on rooftop North West – facing (Mj/m^2-day)	6.49	7.34	10.79	14.07	16.70	18.15	17.58	15.71	12.87	9.77	7.21	6.52	11.93
Radiation on rooftop North – facing (Mj/m^2-day)	6.57	7.67	11.54	15.33	18.33	19.97	19.34	17.24	13.98	10.40	7.42	6.54	12.86
Radiation on rooftop North East –facing (Mj/m^2-day)	6.49	7.34	10.79	14.07	16.70	18.15	17.58	15.71	12.87	9.77	7.21	6.52	11.93
Radiation on rooftop East – facing (Mj/m^2-day)	7.94	8.51	11.25	13.25	14.46	15.05	14.83	14.18	12.84	10.96	9.04	8.48	11.73
Radiation on rooftop South East – facing (Mj/m^2-day)	10.56	11.00	13.35	14.54	14.70	14.67	14.71	15.06	14.92	13.96	12.48	11.91	13.49

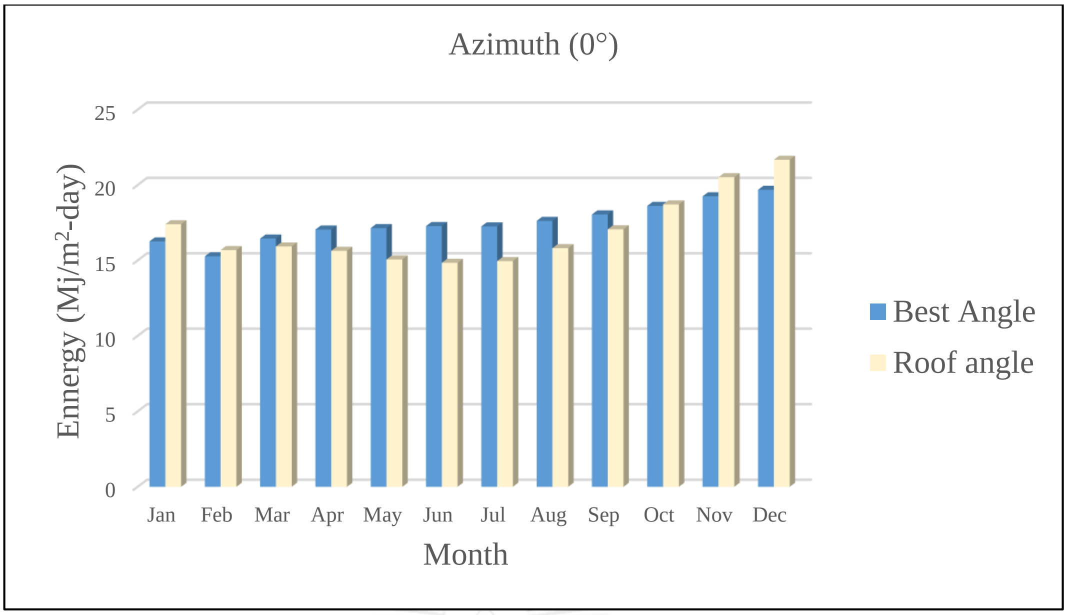


Figure 6. 9. Facing to the South

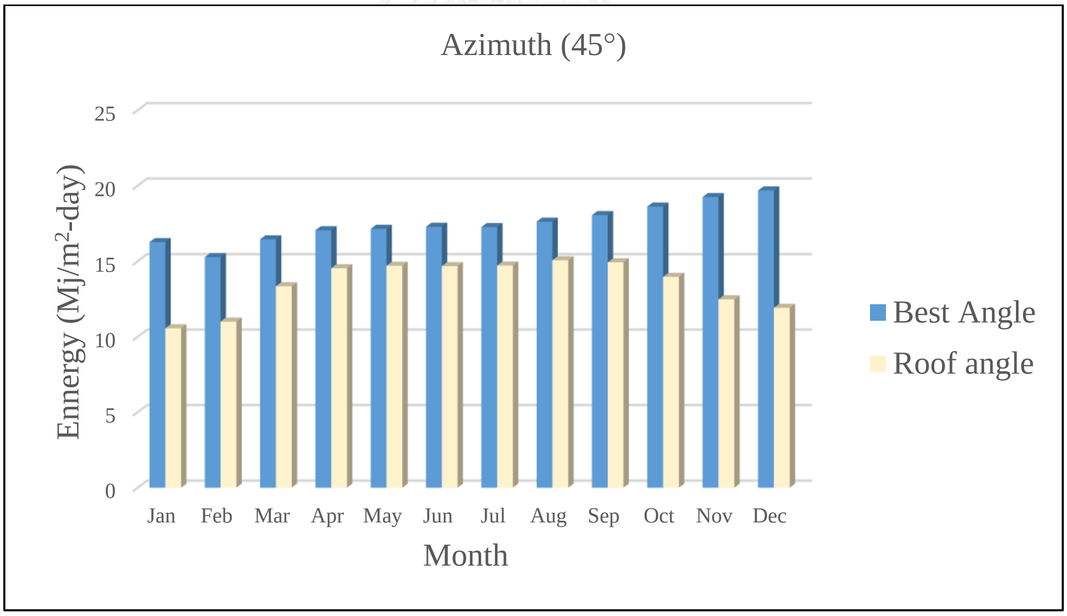


Figure 6. 10. Facing to the South West

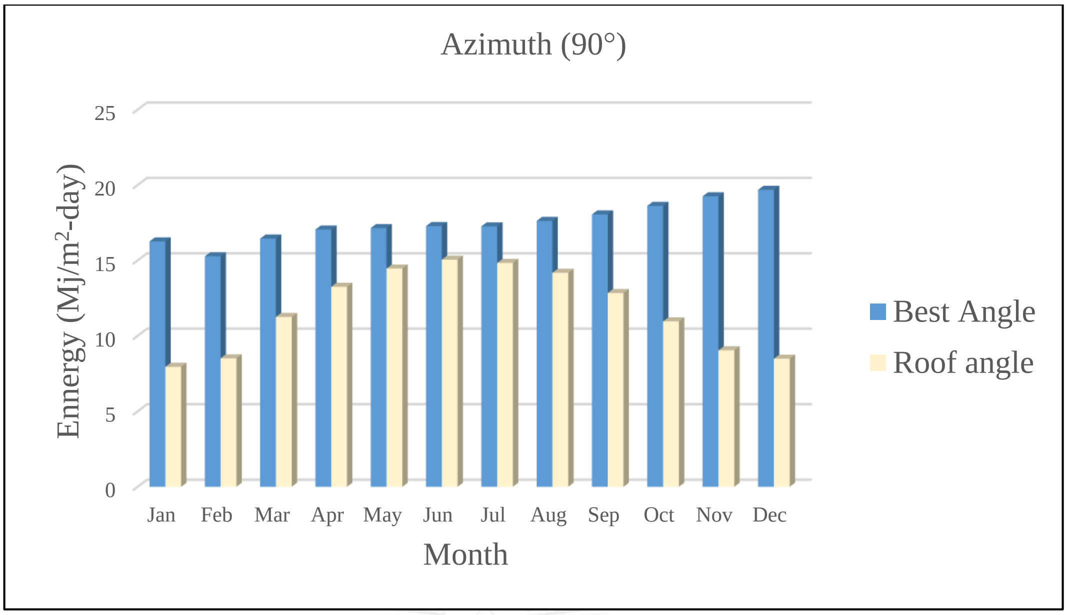


Figure 6. 11. Facing to the West

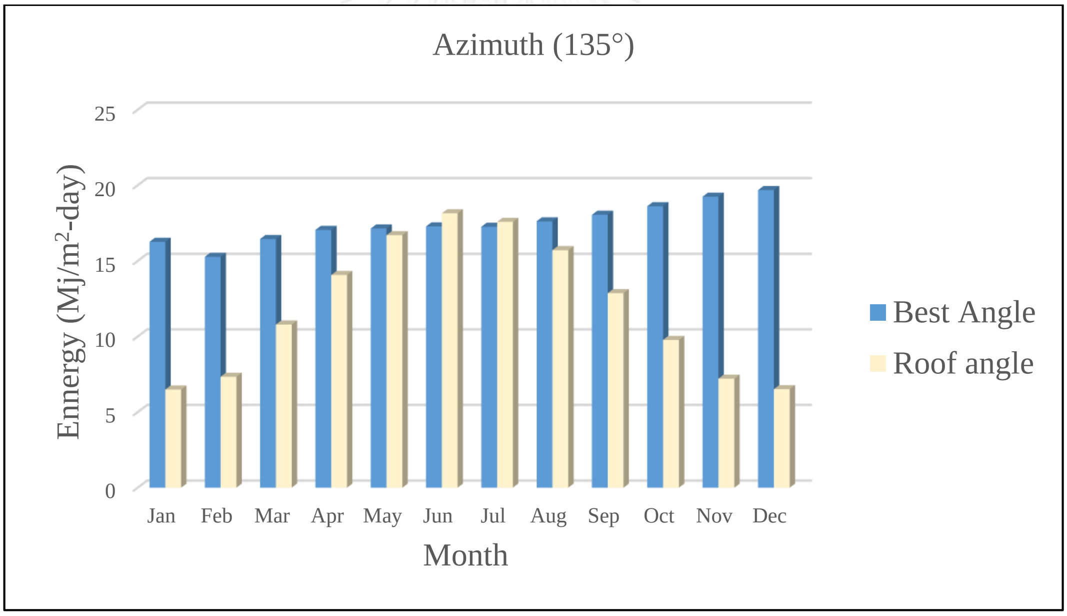


Figure 6. 12. Facing to the North West

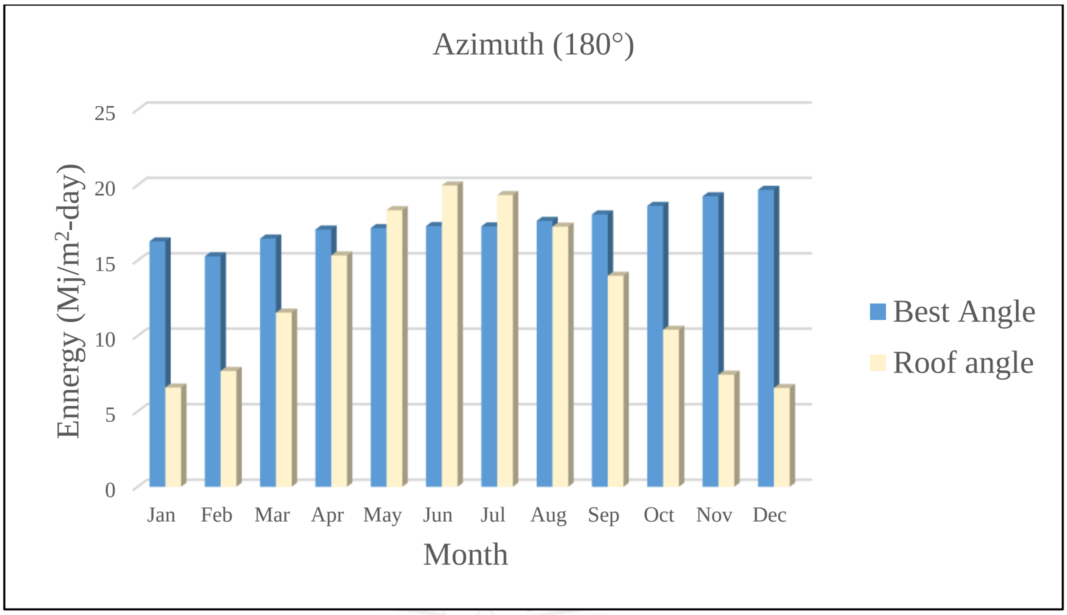


Figure 6. 13. Facing to the North

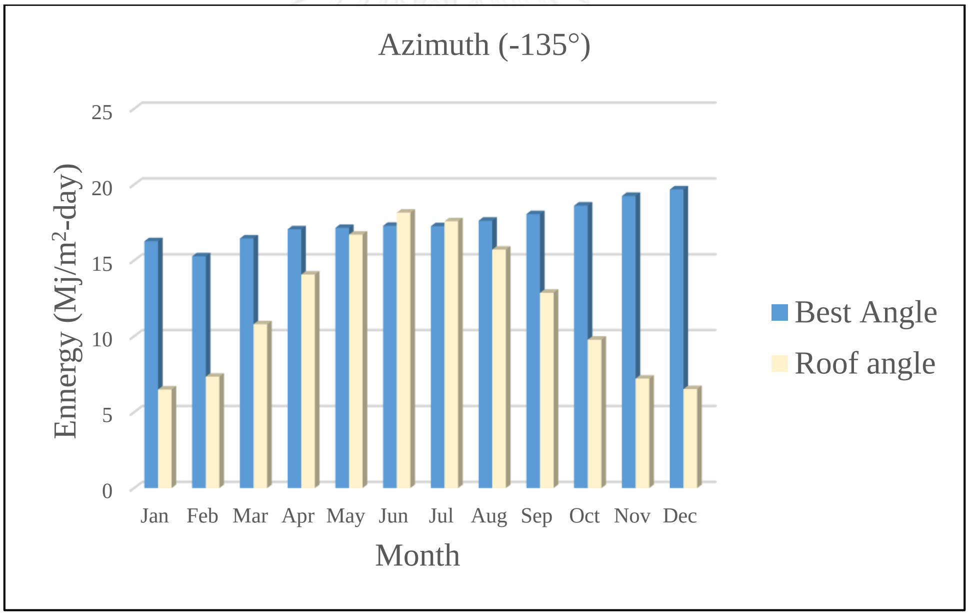


Figure 6. 14. Facing to the North East

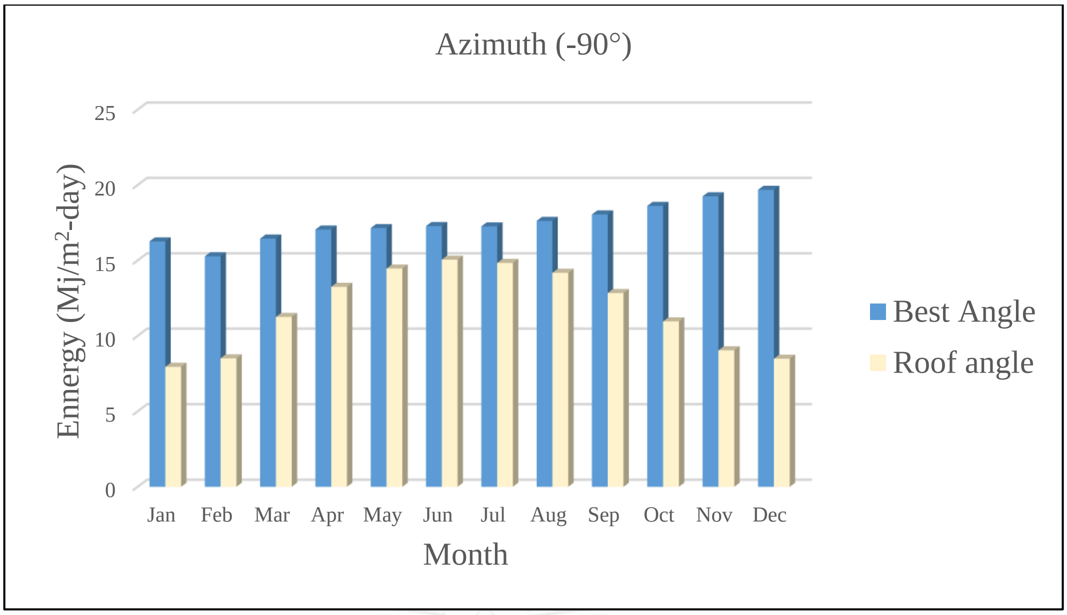


Figure 6. 15. Facing to the East

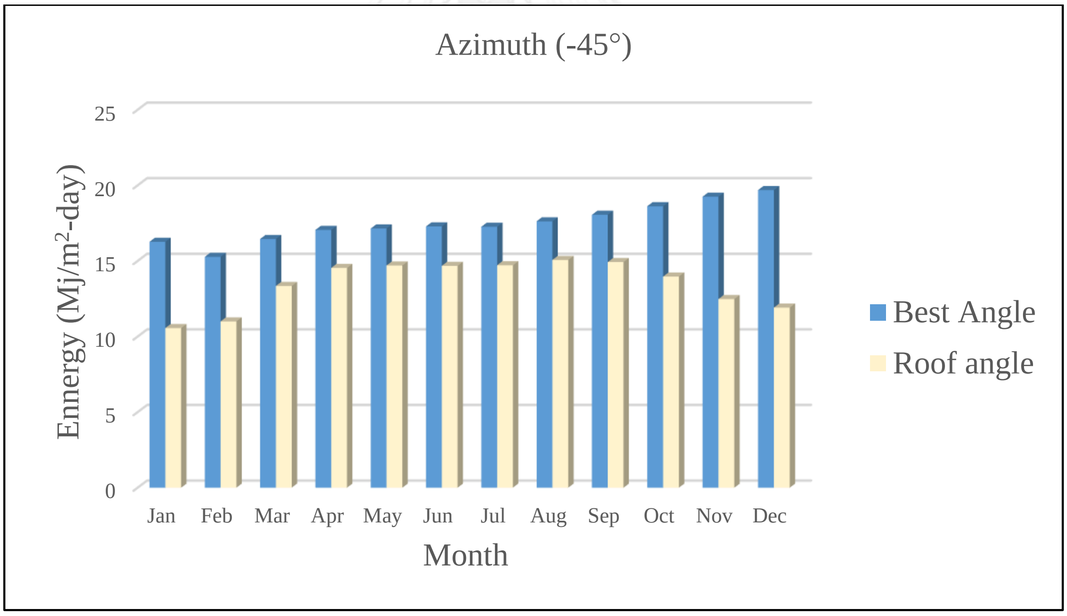


Figure 6. 16. Facing to the South East

Analysis

Results show that the highest energy is on the best angle installation. The differences of average yearly solar radiation on rooftops are 3.15%, 22.90%, 32.931%, 31.79 %, 26.49%, 31.79%, 32.93% and 22.90%, respectively.

6.3. Result of Khonkaen

Evaluation results are summarized in Table 6.3 and graphical comparisons are illustrated from Fig.6.17 to Fig. 6.24.

Table 6. 3. Comparison yearly average daily solar radiation between best angle (Azimuth=0° and Tilted= 16°) and roof top angle on each direction

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Radiation on best angle (Mj/m^2-day)	18.23	17.55	18.44	18.33	18.03	17.82	17.85	18.18	18.66	19.36	20.11	20.58	18.59
Radiation on rooftop South – facing (Mj/m^2-day)	19.62	18.09	17.79	16.63	15.58	15.03	15.21	16.12	17.51	19.40	21.44	22.69	17.93
Radiation on rooftop South West – facing (Mj/m^2-day)	11.97	12.64	14.89	15.43	15.11	14.73	14.85	15.32	15.42	14.74	13.43	12.52	14.25
Radiation on rooftop West – facing (Mj/m^2-day)	8.76	9.51	12.42	14.12	15.02	15.30	15.14	14.55	13.34	11.57	9.69	8.62	12.34
Radiation on rooftop North West – facing (Mj/m^2-day)	7.01	8.10	11.98	15.20	17.62	18.70	18.20	16.32	13.51	10.40	7.74	6.43	12.60
Radiation on rooftop North – facing (Mj/m^2-day)	7.14	8.55	12.92	16.67	19.43	20.65	20.09	17.96	14.73	11.11	8.00	6.48	13.64
Radiation on rooftop North East –facing (Mj/m^2-day)	7.01	8.10	11.98	15.20	17.62	18.70	18.20	16.32	13.51	10.40	7.74	6.43	12.60
Radiation on rooftop East – facing (Mj/m^2-day)	8.76	9.51	12.42	14.12	15.02	15.30	15.14	14.55	13.34	11.57	9.69	8.62	12.34
Radiation on rooftop South East – facing (Mj/m^2-day)	11.97	12.64	14.89	15.43	15.11	14.73	14.85	15.32	15.42	14.74	13.43	12.52	14.25

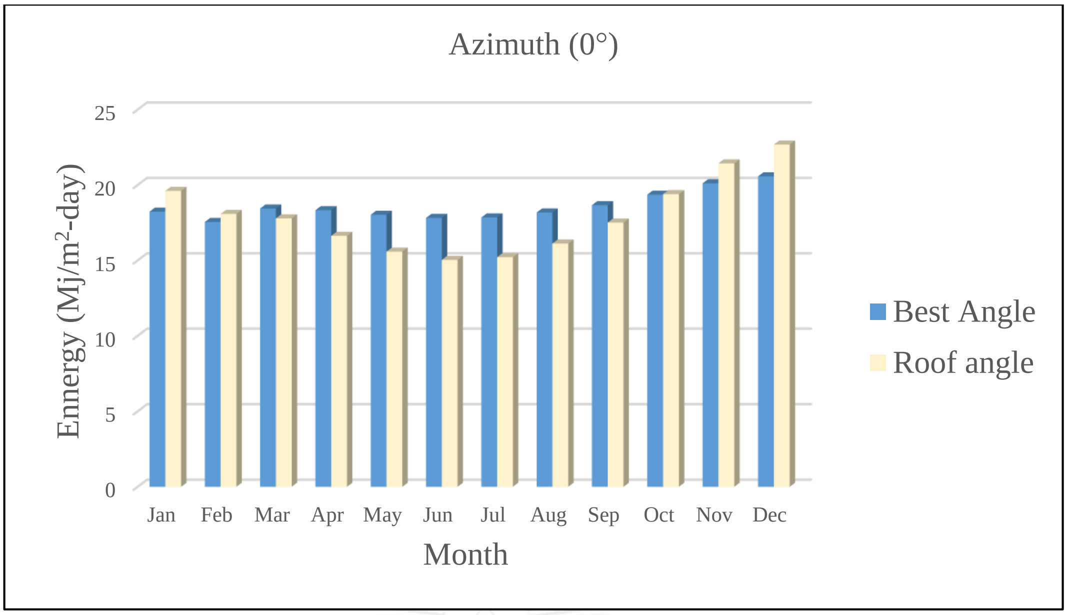


Figure 6. 17. Facing to the South

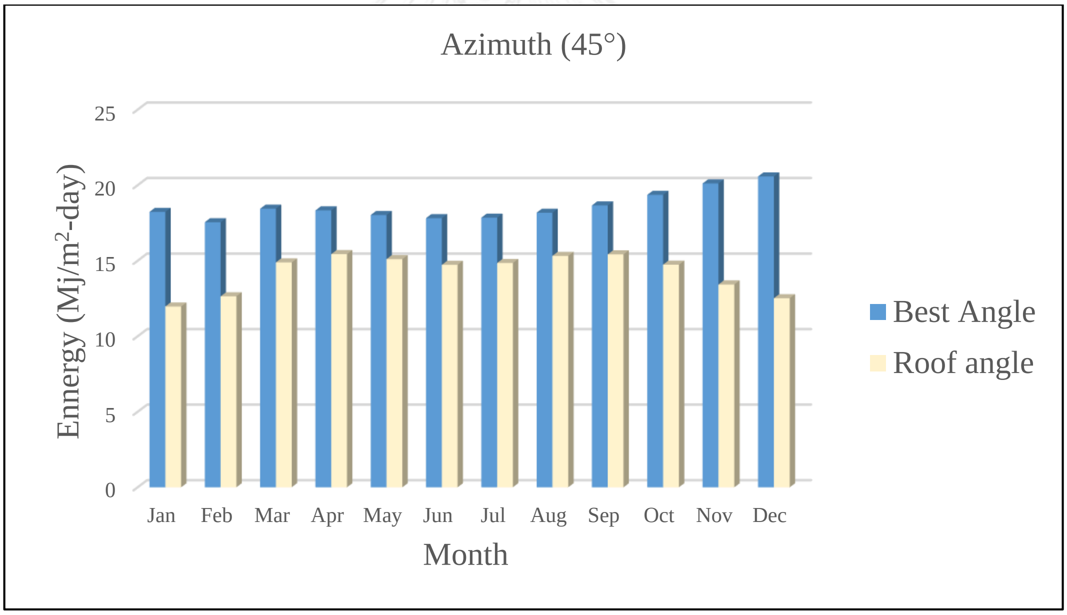


Figure 6. 18. Facing to the South West

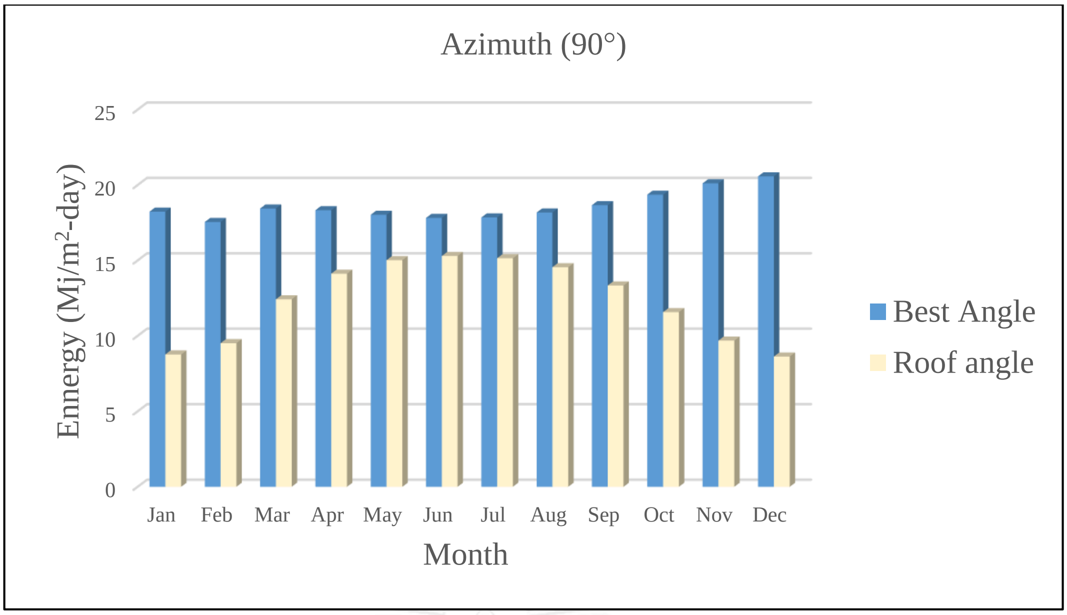


Figure 6. 19. Facing to the West

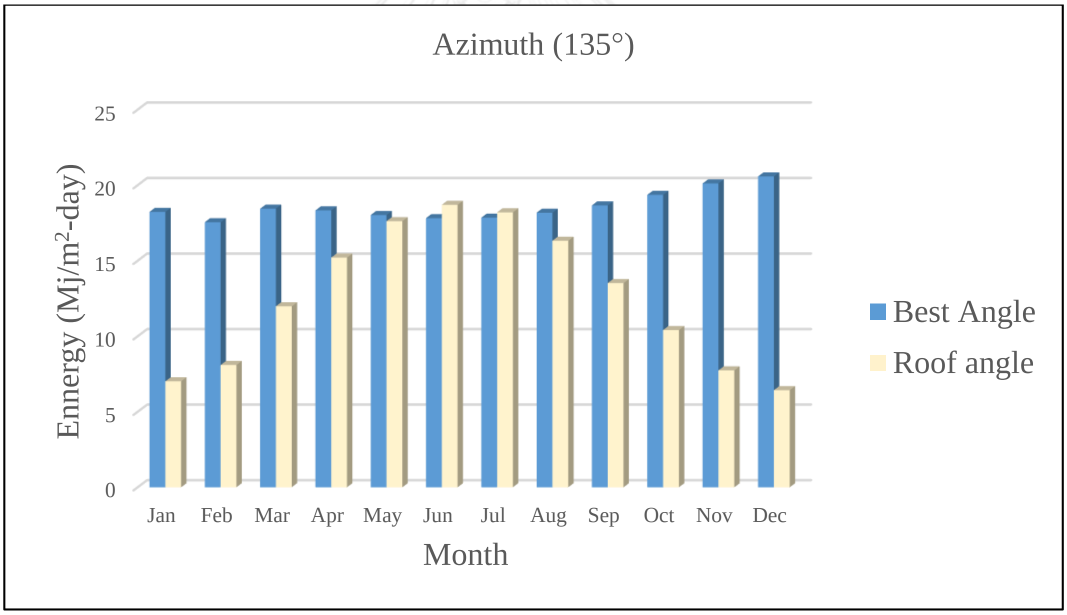


Figure 6. 20. Facing to the North West

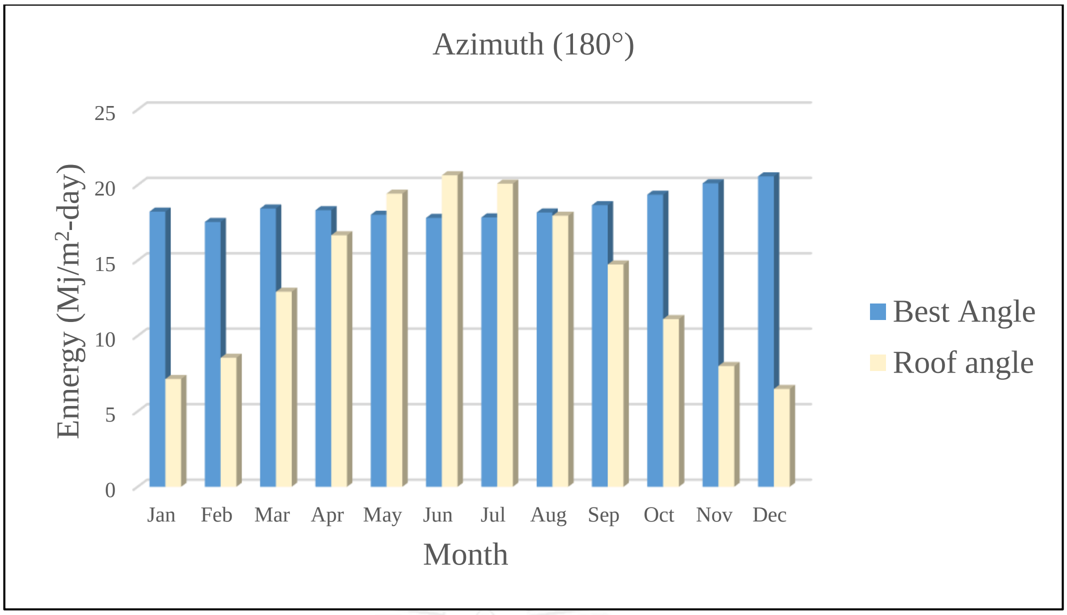


Figure 6. 21. Facing to the North

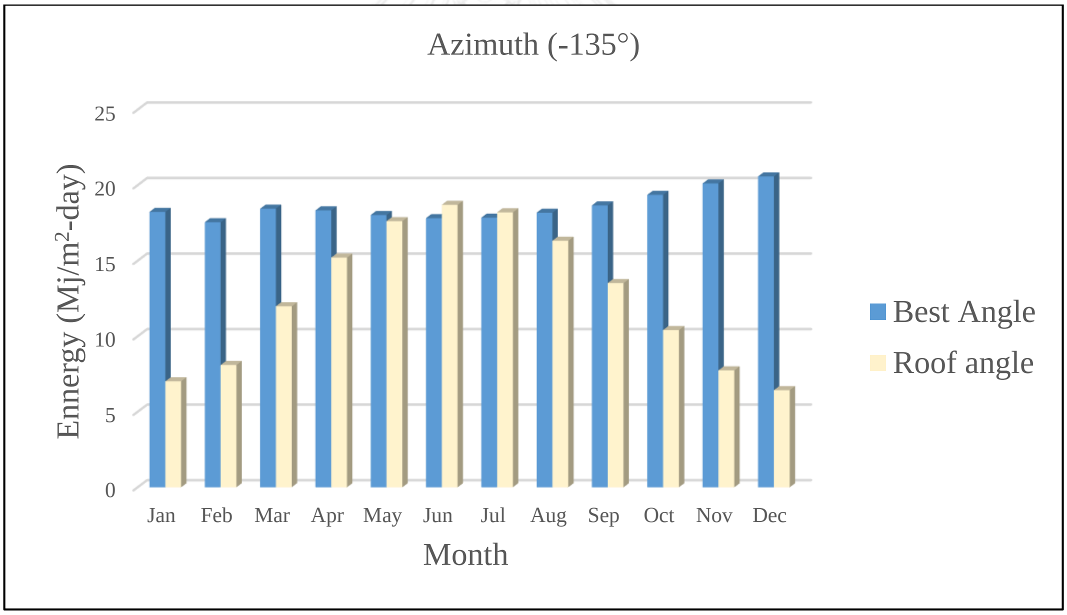


Figure 6. 22. Facing to the North East

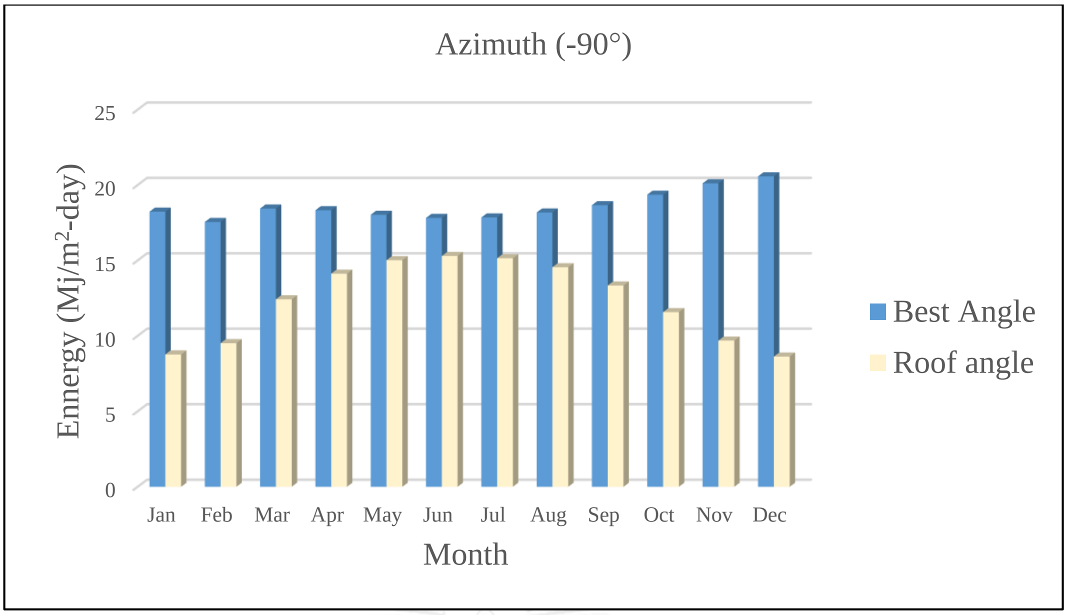


Figure 6. 23. Facing to the East

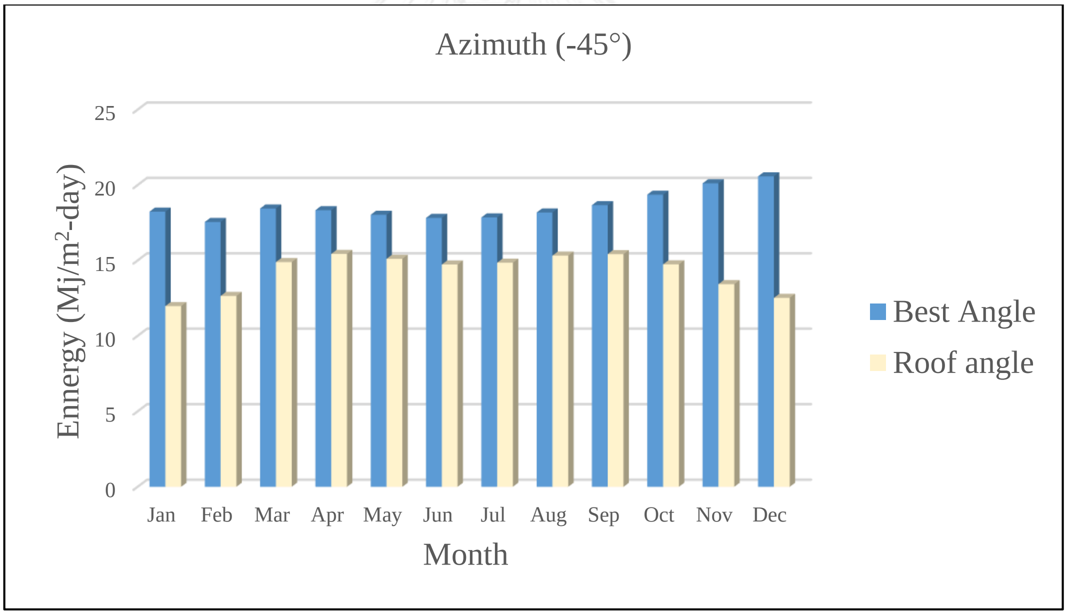


Figure 6. 24. Facing to the South East

Analysis

Results show that the highest energy is on the best angle installation. The differences of average yearly solar radiation are 3.60%, 23.35%, 33.65%, 32.23 %, 26.63%, 32.23%, 33.65% and 23.35%, respectively.

6.4. Result of Krabi

Evaluation results are summarized in Table 6.4 and graphical comparisons are illustrated from Fig.6.25 to Fig. 6.32.

Table 6. 4. Comparison yearly average daily solar radiation between best angle (Azimuth=0° and Tilted= 7°) and roof top angle on each direction

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total average
Radiation on best angle (Mj/m^2-day)	19.20	18.70	20.18	19.83	19.28	18.79	18.63	18.58	18.69	18.73	18.77	18.99	19.03
Radiation on rooftop South – facing (Mj/m^2-day)	20.94	19.21	18.84	16.79	15.05	14.07	14.24	15.24	16.75	18.39	19.97	21.00	17.54
Radiation on rooftop South West – facing (Mj/m^2-day)	15.07	15.09	16.53	15.54	14.04	13.07	13.27	14.24	15.23	15.46	15.01	14.77	14.78
Radiation on rooftop West – facing (Mj/m^2-day)	11.25	11.69	14.25	14.89	14.75	14.39	14.31	14.23	13.82	12.78	11.49	11.01	13.24
Radiation on rooftop North West – facing (Mj/m^2-day)	9.39	10.50	14.47	16.88	18.17	18.41	17.97	16.66	14.69	12.19	9.92	9.08	14.03
Radiation on rooftop North – facing (Mj/m^2-day)	9.68	11.21	15.76	18.67	20.22	20.50	19.98	18.42	16.05	13.04	10.32	9.26	15.26
Radiation on rooftop North East –facing (Mj/m^2-day)	9.39	10.50	14.47	16.88	18.17	18.41	17.97	16.66	14.69	12.19	9.92	9.08	14.03
Radiation on rooftop East – facing (Mj/m^2-day)	11.25	11.69	14.25	14.89	14.75	14.39	14.31	14.23	13.82	12.78	11.49	11.01	13.24
Radiation on rooftop South East – facing (Mj/m^2-day)	15.07	15.09	16.53	15.54	14.04	13.07	13.27	14.24	15.23	15.46	15.01	14.77	14.78

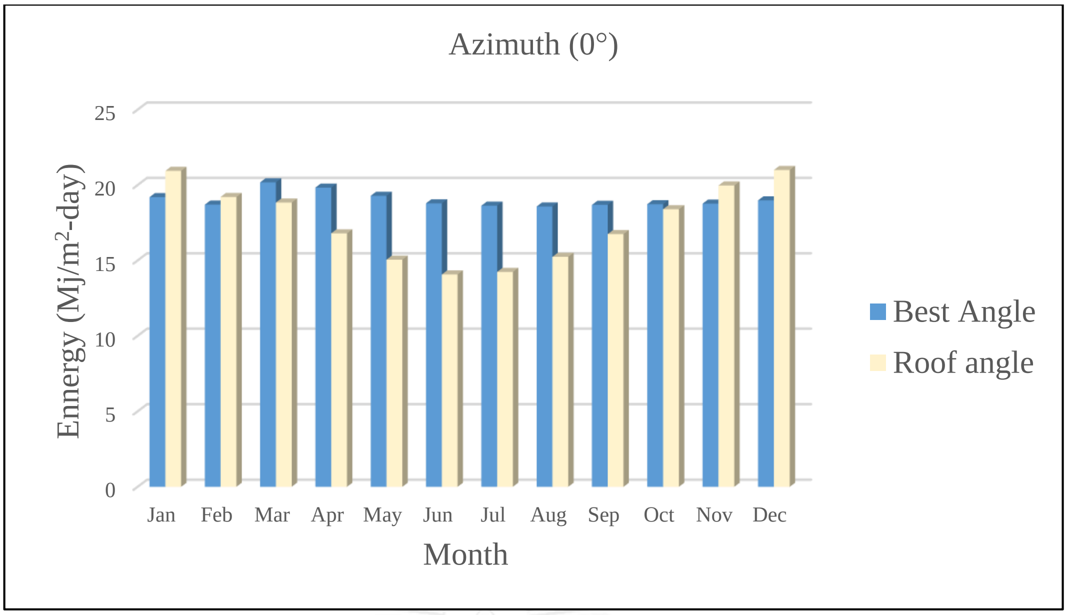


Figure 6. 25. Facing to the South

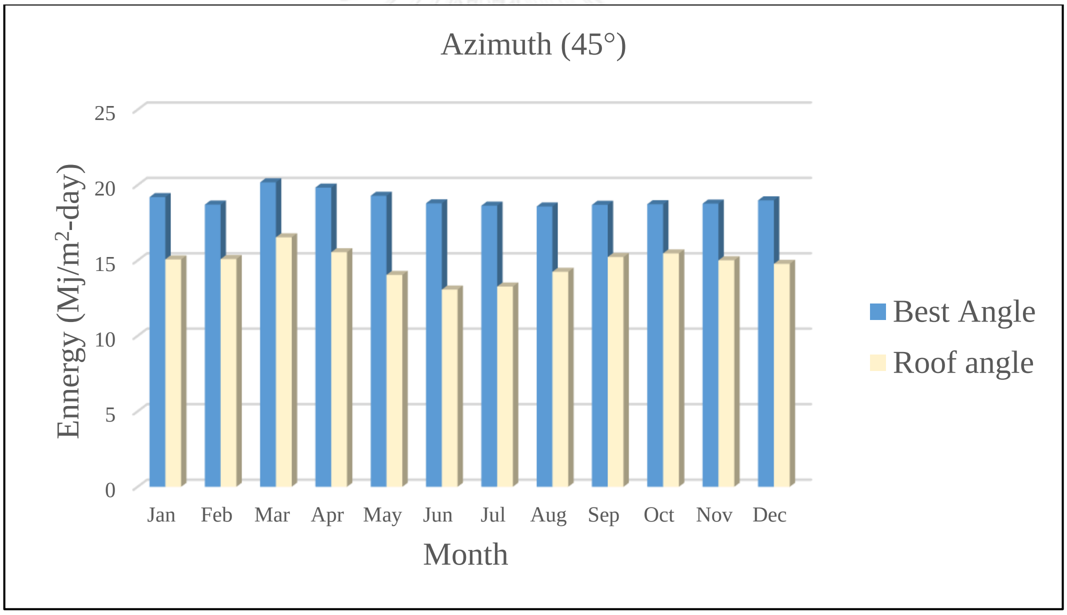


Figure 6. 26. Facing to the South West

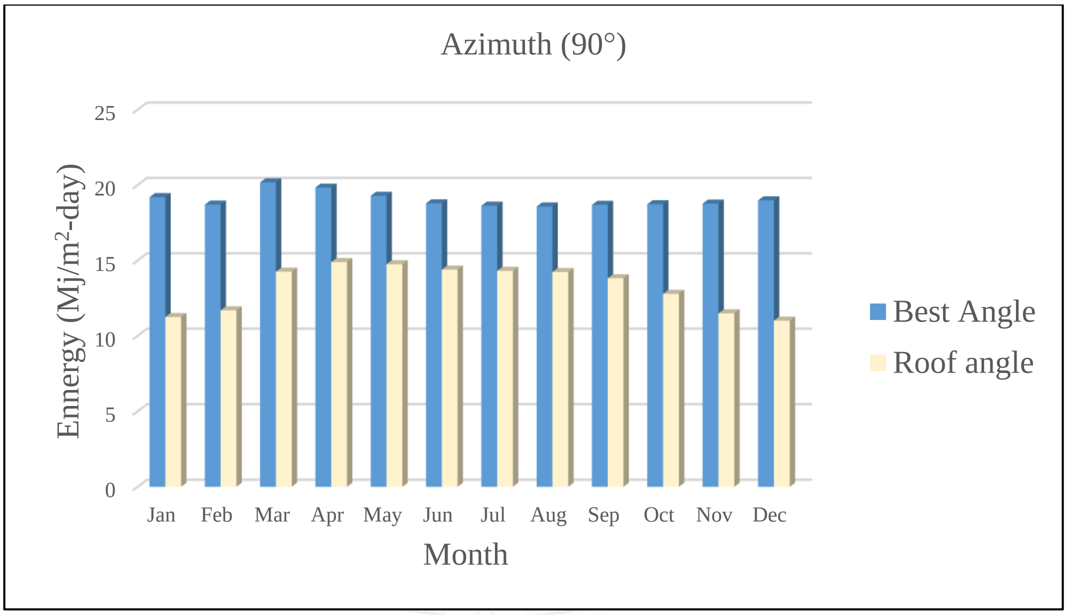


Figure 6. 27. Facing to the West

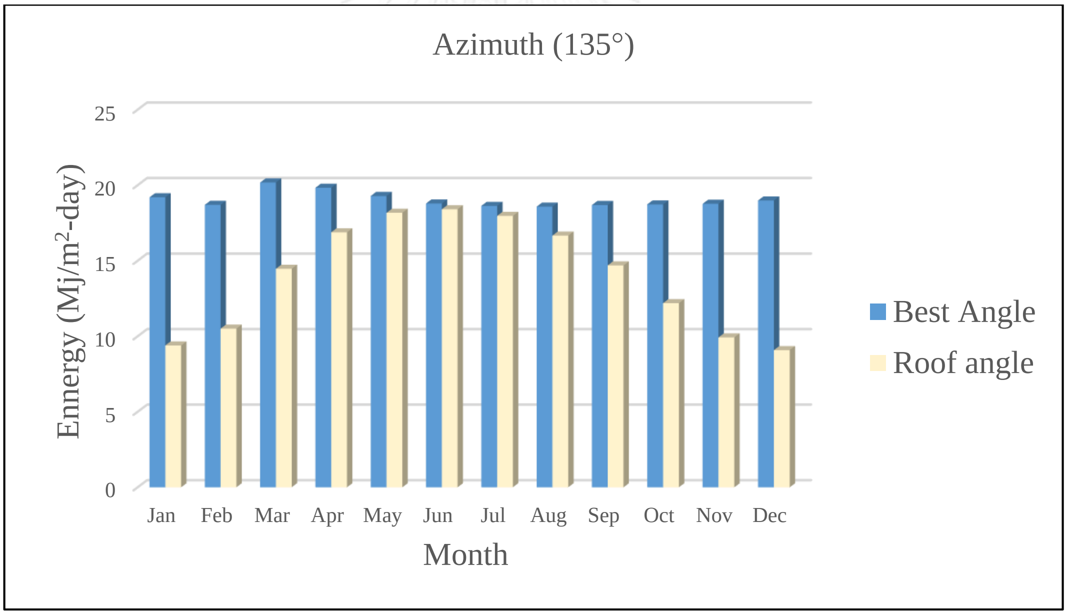


Figure 6. 28. Facing to the North West

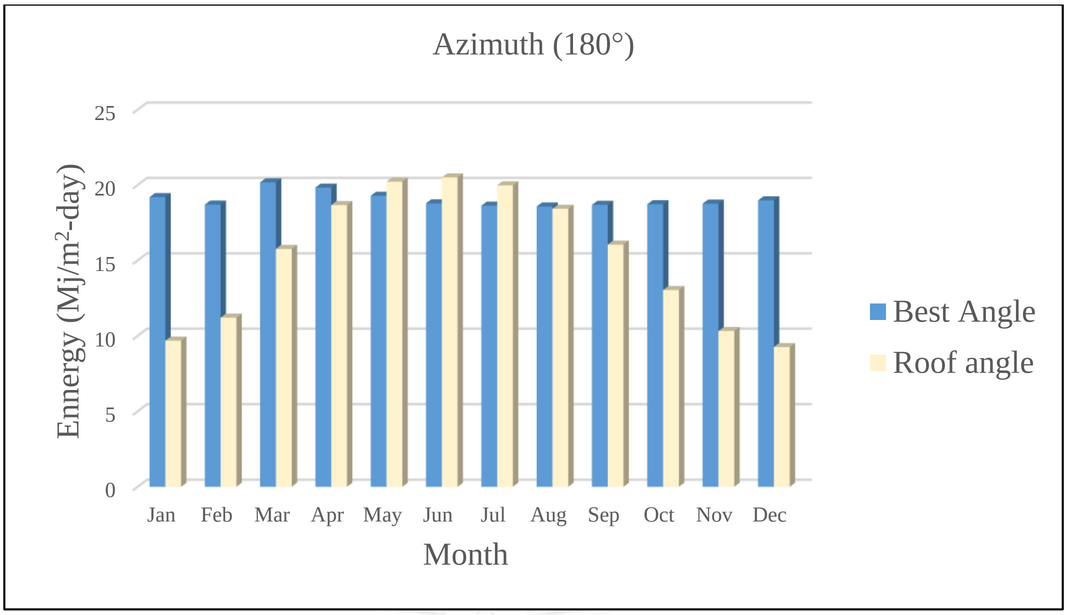


Figure 6. 29. Facing to the North

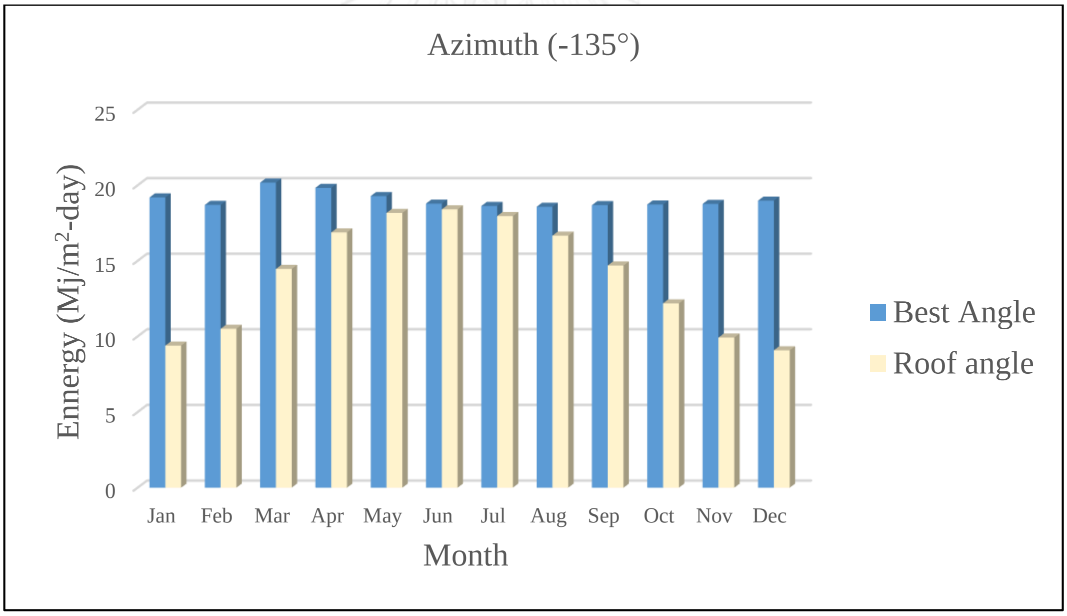


Figure 6. 30. Facing to the North East

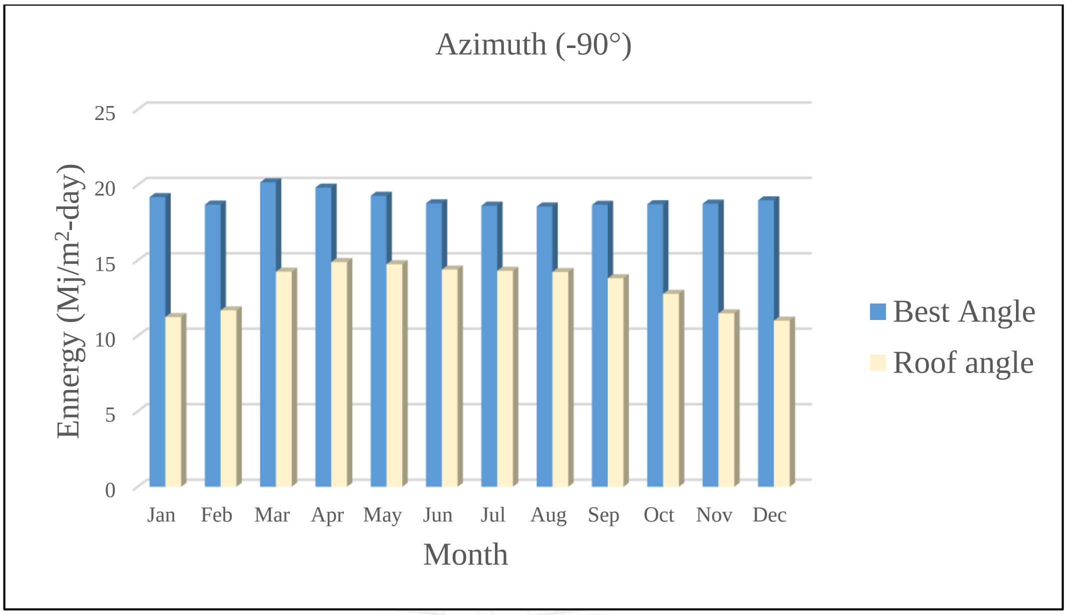


Figure 6. 31. Facing to the East

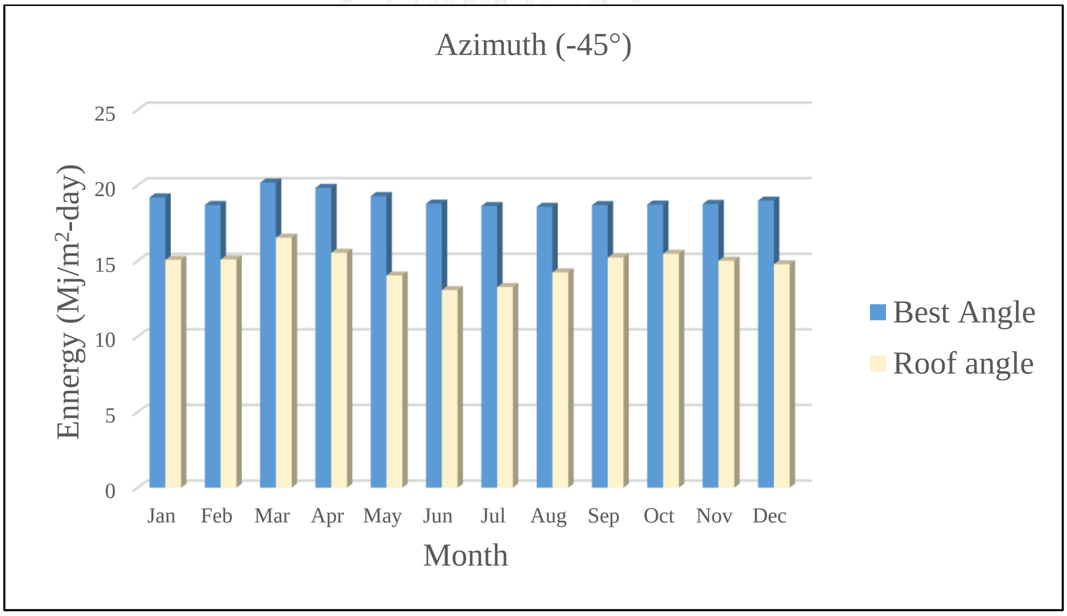


Figure 6. 32. Facing to the South East

Analysis

Results show that the highest energy is on the best angle installation. The differences of average yearly solar radiation on rooftops are 7.82%, 22.35%, 30.43%, 26.49%, 19.81%, 26.29%, 30.22% and 22.35%, respectively.

In all evaluating results above, the solar radiation receives more energy when facing to the South. Thus, the total solar radiation for a year on the rooftop tilted surface, which is facing the equator (zero azimuth surface), is more efficient. Impact of rooftop types occurs when latitude locating in the North and facing to the South receives solar radiation more than in other directions. And effect decreases when location in the South.

When facing to the North, rooftop receives more energy only in the middle year (April, May, June, July and August). Especially, the Northern region can receive more energy than using the best yearly angle. And Facing to East and West lead to the smallest energy.

Thus, the total solar radiation for the year on rooftop tilted surface which is facing the equator (azimuth surface equal to zero) is more efficient.

Chapter 7 Conclusion

This thesis proposes a model for estimating solar radiation on the horizontal surface of PV arrays. The estimation of the average daily solar radiation on surface angles is performed by using real measurements and the diffuse correlation. Results shows that the performance of a photovoltaic array is highly influenced by its orientation and its tilt angle with the horizon, due to the fact that both the orientation and tilt angle change the amount of solar radiation reaching the surface of the PV module.

The optimal value of the tilted angle and orientation for a solar panel collector are determined for some provinces in Thailand. Results are successfully verified by comparing the obtained solar radiation with the satellite data. Although error does exist, it is so small that the proposed method is acceptable and the calculated solar radiation is close to the satellite data measurement.

The research in this thesis also illustrates the impact of rooftop installation on the solar energy received on PV panels. The calculation shows that more solar energy is received if PV panels, which are installed in Thailand, face to the South. For rooftop installations, the selected module mounting system is dependent on the roof type and the structural characteristics of the building. Different roofs require different mounting solutions. Systems that track the sun are also possible, but these are more common in ground mounted installations. They are typically more expensive and technically complicated and require additional maintenance.

REFERENCES

1. Resch G, Held A, Faber T, Panzer C, Toro F, Haas R. Potentials and prospects for renewable energies at global scale. Energy Policy. 2008;36(11):4048-56.
2. Yadav AK, Chandel SS. Tilt angle optimization to maximize incident solar radiation: A review. Renewable and Sustainable Energy Reviews. 2013;23:503-13.
3. <Solar Engineering of Thermal Processes, 4th Edition - GearTeam.pdf>.
4. Liu BYH, Jordan RC. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy. 1960;4(3):1-19.
5. Yakup MAbHM, Malik AQ. Optimum tilt angle and orientation for solar collector in Brunei Darussalam. Renewable Energy. 2001;24(2):223-34.
6. <Optimization of Tilt Angle for Solar Collector to Receive Maximum Radiation.pdf>.
7. Benghanem M. Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia. Applied Energy. 2011;88(4):1427-33.
8. Gunerhan H, Hepbasli A. Determination of the optimum tilt angle of solar collectors for building applications. Building and Environment. 2007;42(2):779-83.
9. George A, Anto R, editors. Analytical and experimental analysis of optimal tilt angle of solar photovoltaic systems. Green Technologies (ICGT), 2012 International Conference on; 2012 18-20 Dec. 2012.
10. Rouholamini A, Pourgharibshahi H, Fadaeinedjad R, Moschopoulos G, editors. Optimal tilt angle determination of photovoltaic panels and comparing of their mathematical model predictions to experimental data in Kerman. Electrical and Computer Engineering (CCECE), 2013 26th Annual IEEE Canadian Conference on; 2013 5-8 May 2013.
11. Sultan DF, Ali FA, Razaq TKA. Tilt Angle Optimization of Solar Collectors for Maximum Radiation in Three Iraqi cities. International Journal of Engineering and Industries. 2012;3(4):99-107.
12. <Optimum Slope for Solar Insolation on a Surface Tilted Toward the Equator in Libya.pdf>.
13. <A Study of Solar Radiation Models for the Coastal Region of South Chaina.pdf>.
14. Mashohor S, Samsudin K, Noor AM, Rahman ARA, editors. Evaluation of Genetic Algorithm based solar tracking system for Photovoltaic panels. 2008 IEEE International Conference on Sustainable Energy Technologies; 2008 24-27 Nov. 2008.
15. Vorobiev PY, Gonzalez-Hernandez J, Vorobiev YV, editors. Optimization of the solar energy collection in tracking and non-tracking photovoltaic solar system. Electrical and Electronics Engineering, 2004 (ICEEE) 1st International Conference on; 2004 8-10 Sept. 2004.
16. Jun H, Yachi T, editors. Photovoltaic systems with solar tracking mirrors. Renewable Energy Research and Applications (ICRERA), 2013 International Conference on; 2013 20-23 Oct. 2013.
17. <Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly-Average Global Radiation.pdf>.
18. Janjai S. Handbook of Solar Radiation and Climatic Data for Renewable Energy Application. 2005.

19. Janjai S. Handbook of Solar Radiation, Silpakorn University. First Ed., Solar Energy Research. 2014.

VITA

Phaphithoun Pangnada was born in Hourxay district, Bokeo province, Laos, on June 14, 1990.He has been awarded B.Eng. degree in Electrical Engineering from National University of Laos (NUoL), in 2012. He has been receiving the scholarship to study M.Eng. degree In Electrical Engineering of Power system Research Laboratory (PSRL) at Chulalongkorn University, Thailand of year 2014.

In the year of master research, he has submitted a paper 'Estimation of Solar Radiation on the Tilted Surfaces in Songkhla, Thailand', The 13th International Conference on Electrical Engineering/Electronic, Computer, Telecommunications and Information Technology (ECTI-CON 2016), on June 28 – July 1, 2016.