THE EFFECT OF TEMPERATURE ON PHOTOVOLTAIC MODULE POWER PRODUCTION IN TRACKING SYSTEM UNDER THAILAND HOT CLIMATE CONDITION

PERAPHAT KAMKIRD

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by Peraphat Kamkird

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Oral Defense Committee

.... Chair

(Chatchai Sirisamphanwong, Ph.D.)

.... Advisor

(Assistant Professor Nipon Ketjoy, Dr.-Ing.)

.... Co - Advisor

(Associate Professor Wattanapong Rakwichian, Ph.D.)

.... Co - Advisor

(Sukruedee Sukchai, Ph.D.)

.... External Examiner

(Assistant Professor Boonyang Plangklang , Dr.-Ing.)

Approved

....

(Professsor Rattana Buason, Ph.D.)

Dean of Graduate School

๒๕ July 2014

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Peraphat Kamkird

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Author	Peraphat Kamkird
Advisor	Assistant Professor Nipon Ketjoy, Ph.D.
Co-Advisor	Associate Professor Wattanapong Rakwichian, Ph.D. Sukruedee Sukchai, Ph.D.
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ABSTRACT

The main aim of this research was to study the effect of temperature on power output of photovoltaic modules power production in tracking system under Thailand climate and develop the mathematical model for evaluating the module temperature and power output and develop the program to accurately estimate the power output of photovoltaic module on tracking system power plant and investment cost optimization. In this research, the three different types of PV as amorphous silicon (a-Si) mono crystalline silicon (c-Si) and Poly crystalline silicon (p-Si) on 1-axis and 2-axis photovoltaic tracking system and fixed system will be evaluated. They were installed at the Energy Park, School of Renewable Energy Technology, Naresuan University (north latitude 16°47', east longitude 100 °16').The data have been recorded since January, 2010 to December,2010. It was analyzed by linear regression technique to find the relationship between power production and Module Temperature. The mathematical model to predict the power production was also being developed.

The results indicated that the solar irradiance and ambient temperature were the main important parameters that affects to power output of PV array. The mathematical model of PV array was developed with respect to solar irradiance and ambient temperature for module temperature prediction, therefore, its respects to solar irradiance and module temperature for power production prediction.

The mathematical model could predict the power production of a-Si PV module on fixed, 1 axis and 2 axis system with simulation results which are approximately ±0.17%, ±5. 06% and ±2. 52 %,respectively. The power production of m-Si PV module on fixed, 1 axis and 2 axis system with simulation results are approximately ±0.71 %, ±0.69 %, m-Si PV and ±0.74 % respectively. The power production of p-Si PV module on fixed,1 axis and 2 axis system with simulation results which are approximately ±0.72 %, ±6.42 % and ±7.09 % respectively, This difference is based on the experimental results. These mathematical models consist of three parameters as following; solar irradiance, module temperature and ambient temperature. This study found that the solar irradiance and module temperature was the most important factors that influence to the power output of the three different PV technologies and the three system installation. For this study, the development program was used to predict the performance and economic results on a 1 MW scale and compare with the commercial program for predicting the energy output and the cost of investment for solar cell system. The results show that the energy output of the development program value is less than the commercial program approximately 2.80-13.49% and the economic analysis show result that less than the commercial program in term of COE and internal rate of return for deciding that proper in technology and economic in the future PV system installation in Thailand was developed. These results have an impact on systems design and sizing in similar climate regions. Thus, recommended that design and sizing of PV systems in Tropical climate regions of the world take due address to these results.

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CHARPTER I

INTRODUCTION

Rationale for the study and statement of problem

In the recent year, the energy crisis has more effect for human in every part of the world; the energy need and costs have increased in recent years and the nature is damaged during the process of energy production. All of these it's impact of limited fossil fuel source. It is empty in nearly future. In the same case Thailand has increased demand of electricity need it cause electricity is the main power for lifestyle of social and economic development.

Solar energy is clean, abundant and the best renewable choices in Thailand for replacing fossil fuel in electrical production. Which country has more potential for receiving solar energy all of the year. By research Thailand have increased used solar energy for electricity. In 2007, Thailand has total 32 MW [26] by solar power plant and all of this is the photovoltaic fixed system. This system has a limit in electricity generation and for defending this limit in the last month of 2008,1 MW photovoltaic tracking power plant has installed for electricity generation. The Sun tracking system is designed in a way to track follow the sun all of day for increase solar power.

In designing any power production of photovoltaic (PV) system and that incorporates there is a basic requirement to accurately estimate the output from the proposed photovoltaic array under operating conditions. The output power of photovoltaic module was measured under standard test conditions (STC: irradiation 1000, Air mass 1.5 and a module temperature of) but these conditions do not rarely occurs in outdoor condition. The power output is dependent the local climatic condition. In occur value estimate the power output on photovoltaic module must needs the actual operational data for each module and environmental data where the photovoltaic module were installed, EST. Would the solar irradiance, the temperature cell module, ambient temperature and solar spectrum of solar cell be the parameter influencing the photovoltaic module power.

The pronounced effect that the operating temperature of a photovoltaic cell/module has upon its electrical efficiency is well documented. There are many correlations expressing T_m, the photovoltaic module temperature T_a,as a function of weather variables such as the ambient temperature, and the local wind speed, V_w, as well as the solar radiation flux/irradiance, G_T

It is well-known that different Photovoltaic technologies have different seasonal patterns of behavior. There are differences due to the variations in spectral response, the different temperature coefficients of voltage and current. The most of the solar radiation absorbed by a photovoltaic panel is not converted to electricity, but contributes to increase the temperature of module, thus reducing the electrical efficiency. So that which this case in Thailand hot climate conditions. The fixed $40^{\circ}C$ photovoltaic system has average back of module temperature during the daylight hours are over $40^{\circ}C$ peaking at $70^{\circ}C$ in April. So that in the photovoltaic tracking system are designed in a way to move follow the sun all of day for received increase solar irradiations than the fixed system. Its effect to the high average back of module temperature to decrease the available maximum electrical power production.

So, this research presents the effect of temperature on photovoltaic module power output in tracking system under Thailand hot climate conditions by studying three types of solar cells as follow; amorphous silicon (a-Si) mono crystalline silicon (c-Si) and Poly crystalline silicon (p-Si) on 1-axis, 2-axis photovoltaic tracking system and Fixed system placed at school of renewable energy technology Naresuan University, Phitsanulok, Thailand. The reasonably for elevated power output of solar cell in each type and find the relation between photovoltaic module temperature and power output on the tracking system and to use the data for choosing and deciding solar cell system that properly in technology and economic in the future.

Objectives of the study

1. To study the effect of temperature on power output of photovoltaic module power production in tracking system under Thailand hot climate conditions.

2. To develop the mathematical model for evaluating the effect of temperature on power output of photovoltaic module in tracking system.

3. Develop the program to accurately estimate the power output of photovoltaic module on tracking system power plant in large scale and investment cost optimization.

Scope of the study

This research will evaluate three different types of PV as amorphous silicon (a-Si) mono crystalline silicon (c-Si) and Poly crystalline silicon (p-Si) on 1-axis and 2-axis photovoltaic tracking system and fixed system. This system was installed at Energy Park, School of Renewable Energy Technology, Naresuan University. The purpose of finding the effect of temperature, power production on photovoltaic module in tracking system and compare with fixed system under Thailand's climate.

Expected outcomes

1. Knowing the effect of temperature on power output of photovoltaic module power production in tracking system under Thailand hot climate conditions.

2. Knowing the relationship equation of solar irradiation, temperature and power output and performance ratio of photovoltaic module of photovoltaic module on the tracking system.

3. Attaining mathematical model for evaluation power output of the each type of photovoltaic module were installed in the tracking system.

4. Attaining program for estimate power output of photovoltaic module and investment installed on the tracking system in large scale in Thailand hot climate condition.

CHAPTER II

REVIEW OF RELATED LITERATURE AND RESEARCH

There are many publications research about the photovoltaic performance on fixing system and tracking system. I found that all most the publications talk about the relationship between solar radiation, power output and temperature coefficients of a-Si, mono-Si and poly-Si PV module on fixed system, They compare with a tracking system and fixing system in term of power output and finding methodology to increase power performance. Almost of these based on high latitude area. The Table 1 shows a summary of the most relevant papers published on the photovoltaic tracking system and compare with this dissertation.

Table 1 The publications of PV performance with fixing and tracking system

Publication	1-axis	2-axis	Fixed	Performance	Module Temperature	Economic	Latitude area
Shaari, et al. (2009)			x	x	x		Low
Kamkird, et al. (2010)			x	x	x		Low
Mattei, et al. (2006)			x	x	x		High
Carr and Pryor (2004)			x	x	x		High
Cueto (2002)			x	x	x		High
Roth, Georgiev and Boudino (2005)	x	x		x			High
Bione, Vilela and Fraidenraich (2004)	x		x	x			High
Ai, et al. (2003)		x	x	x			High
Sangani and Solanki (2007)	x	x	x	x			High
Ibrahim (1996)	x	x	x	x			High
Baltas, Tortoreli and Russell (1986)	x		x	x			High
Nann (1990)	x	x	x	x		x	High
Braun and Mitchell (1983)	x	x	x	x			High
Abdallah and Nijmeh (2004)		x	x	x			High
Mohamad (2004)	x		x	x			High
Abdallah (2004)	x	x	x	x			High

Table 1 (cont.)

Publication	1-axis	2-axis	Fixed	Performance	Module Temperature	Economic	Latitude area
Rubio, et al. (2009)		x		x			High
This Dissertation	x	x	x	x	x	x	Low

This dissertation is aim to find the relationship between module temperature and power output on photovoltaic systems as; fixed, 1-axis, 2-axis and developing the Mathematical model for predicting performance and economic installation of fixed system and tacking system in low latitude area.

Photovoltaic module temperature

Sulaiman, et al. [1] used a regression technique from temperature dependence model: The empirical relationship between current, voltage and power dependencies on temperature to find the temperature coefficient of photovoltaic module by using Malaysian field data for recommended that the design and sizing of photovoltaic systems in the hot and humid climate regions. This is achieved by studying three test stand-alone photovoltaic battery systems using 3 types of photovoltaic technology as: 62 Wp a-Si, 225 Wp multi-crystalline and 225 Wp mono-crystalline photovoltaic modules. A summary of the findings is shown in Table 2. The result show that the a-Si modules perform significantly best in the hot and humid climate, showing the highest normalized power outputs and current coefficients, whilst showing the lowest duration coefficients in voltage, power and conversion efficiency.

Table 2 Summary of temperature coefficient findings from the Malaysian field data [1]

Parameter	Unit	System I (a-Si)	System II (multi- Si)	System III (mono-Si)
Normalized power output	°C^{-1}	0.037	0.0225	0.0263
Current coefficient	mA °C^{-1}	37	22.5	26.3
Voltage coefficient	mV °C^{-1}	-31.8	-39.4	-32.6
Power coefficient Conversion	W °C^{-1}	-0.1036	-0.2525	-0.1742
Efficiency coefficient	% °C^{-1}	-0.0214	-0.072	-0.0523

Kamkird, et al. [2] have described a methodology to find the temperature dependence coefficients of amorphous silicon (a-Si), poly crystalline (p-Si) and Heterojunction Intrinsic thin layer (HIT) photovoltaic (PV) module. There are measured under Thailand Operating Condition (north latitude 16°47’, east longitude 100 °16’). The data have been recorded since year 2008 January to 2009 December. It is analyzed by linear regression technique. Upon analysis, the study will show the Temperature coefficient of current, voltage, power and efficiency on array temperature obtained from linear regression. These findings of the field test investigation found that the temperature coefficient value of PV array different from the factory value and the results have an impact on systems design and sizing in similar climate regions of the world take due address to these results.

Table 3 Summary of field test result from Thailand climate regions [2]

Parameter	Unit	a-Si		p-Si		HIT	
		2008	2009	2008	2009	2008	2009
Current coefficient	mA/°C	71.6	49.1	23.6	12.1	35.8	11.3
	(%/°C)	0.4841	0.3320	0.1685	0.0818	0.3631	0.1146
Voltage coefficient	mV/°C	-49.5	-77.93	-117.9	-123.9	-71.6	-89.4
	(%/°C)	-0.0230	-0.0359	-0.0495	-0.0519	-0.0276	-0.0345
Power coefficient	W/°C	0.0104	0.0031	-0.0048	-0.0077	0.0046	-0.0027
	(%/°C)	0.0005	0.0002	-0.0002	-0.0004	0.0003	-0.0002
Current coefficient	mA/°C	71.6	49.1	23.6	12.1	35.8	11.3
	(%/°C)	0.4841	0.3320	0.1685	0.0818	0.3631	0.1146
Voltage coefficient	mV/°C	-49.5	-77.93	-117.9	-123.9	-71.6	-89.4
	(%/°C)	-0.0230	-0.0359	-0.0495	-0.0519	-0.0276	-0.0345
Power coefficient	W/°C	0.0104	0.0031	-0.0048	-0.0077	0.0046	-0.0027
	(%/°C)	0.0005	0.0002	-0.0002	-0.0004	0.0003	-0.0002

Mattei, et al. [3] studied and compare varies equation for the performance of a photovoltaic module versus environmental variables such as solar irradiance, ambient temperature and wind speed. The PV module temperature model and the PV module electrical efficiency model were chosen and validated utilizing experimental data from two experiments: an 850 Wp grid connected photovoltaic system and a p-Si module with eight temperature sensors integrated into the module. Both models have been coupled to determine the PV array output power versus the three meteorological parameters (solar irradiance, module temperature and wind speed). This simple model using a simple energy balance and neglecting the radiation effects is in good agreement with the experimental data. They determined the PV array output power for various ambient temperatures, solar irradiance and wind speeds. The influences of these environmental parameters have been compared with the literature and the results obtained by the model are in accordance with previous works.

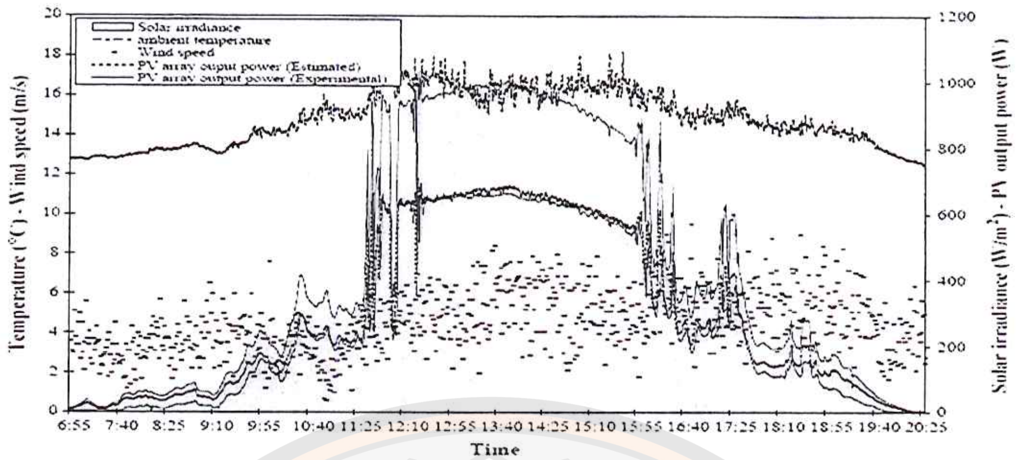

Figure 1 Verification of the PV array output power model for one particular day [3]

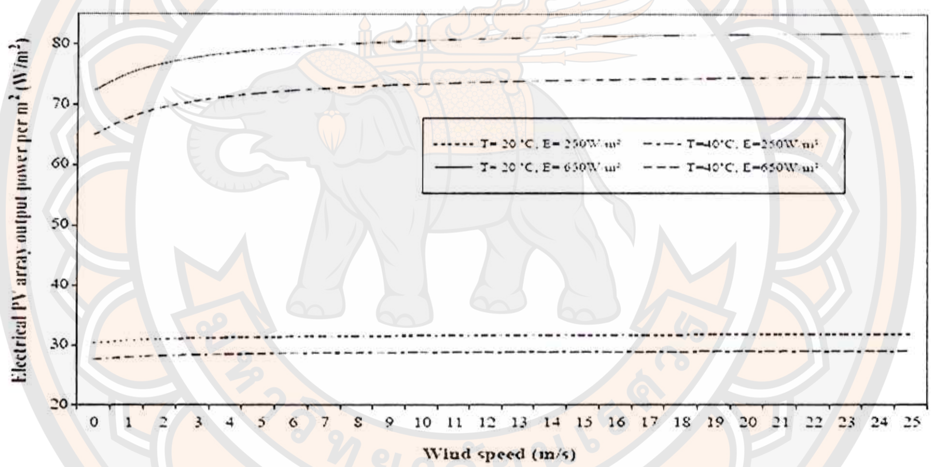

Figure 2 The influence of the wind speed on the PV module production [3]

The performances of five different types of photovoltaic modules have been measured for more than a year in the temperate climate of Perth. This data have been analyzed and compared by Carr and Pryor [4]. Western Australia. Perth averages over 5.4 peak sun hours (PSH) each day, from less than 3in the winter months to over 8 at the height of summer. The average sun-up temperatures range between 16.5 ˚C and 28 ˚C. The types of photovoltaic modules as: crystalline silicon (c-Si), laser grooved buried contact (LGBC) c-Si, polycrystalline silicon (p-Si), triple junction amorphous silicon (3j a-Si) and copper indium diselenide (CIS). The annual and monthly performance ratios (PRs) have been calculated for the different modules and a comparison is presented here. The I–V characteristics and maximum power at standard test conditions have been measured for each module prior to, and at regular intervals, during outdoor exposure. The findings, results are shown that the triple junction a-Si modules produce over 15% more energy than BP275(c-Si) does in summer, and around 8% more in winter. The CIS module consistently produces between 9% and 13% more energy than BP275.

They used these values results for compared to the manufacturers' values, and monitored over time for the modules operated in the field.

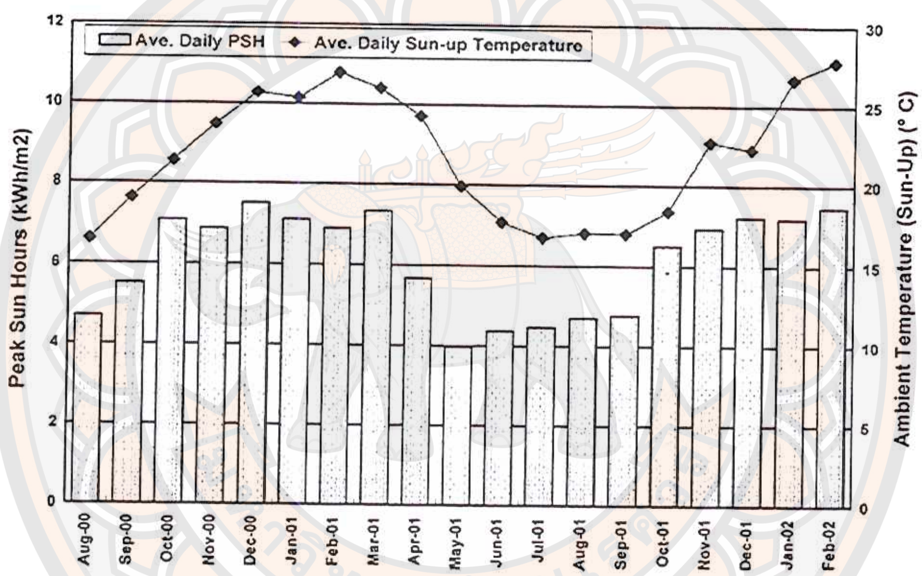

Figure 3 The average daily plan of array peak sun hours (PSH) and average daily ambient sun-up temperatures measured on the MUERI monitoring system [4]

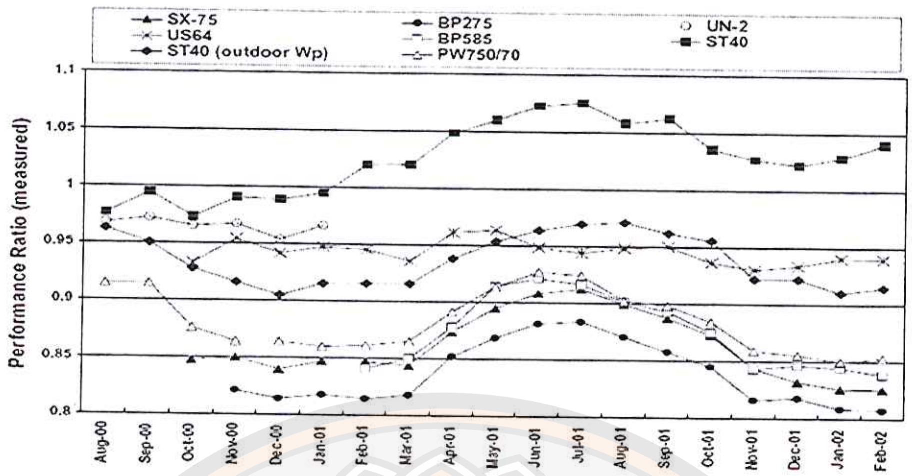

Figure 4 Monthly performance ratio, normalised to regularly measured STC peak power (Wp-measured) [4]

Cueto [5] was presented and compared the Performance data for 14 photovoltaic modules deployed at fixed latitude tilt in the field. Module performance is monitored continuously for optimum power characteristics. Flat-plate module technologies representative of crystalline, amorphous, and polycrystalline silicon, and cadmium telluride and copper indium Diselenide, are scrutinized for energy production, effective efficiency and performance ratio (PR) of effective to reference efficiency. The finding showed that the most performance ratios exhibit seasonal fluctuations largely correlated to air or module temperatures, varying between 80% and 100%.

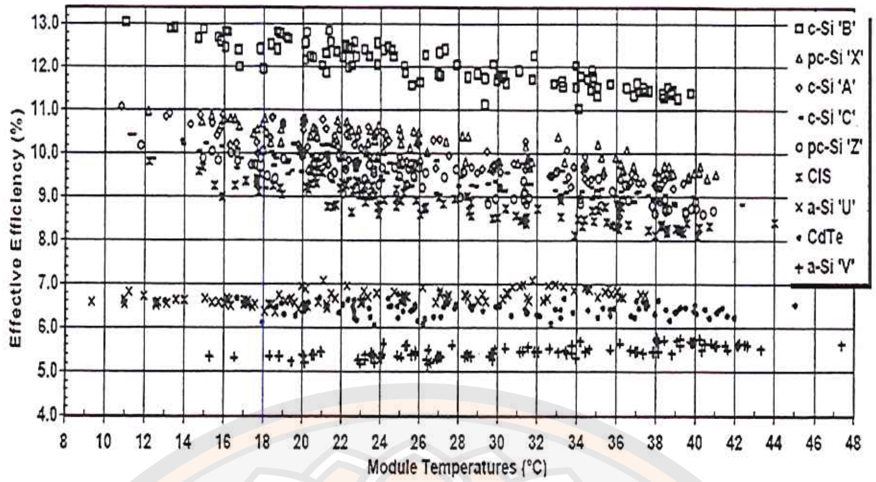

Figure 5 Effective efficiency data for all module types plotted against average daily module temperatures [5]

In his research find that The PR data of PV modules composed of c-Si and poly-c-Si types are depicted, respectively, in the upper and lower portions of Fig., plotted against time. The highest and lowest values depicted on the abscissas are 102% and 80%, respectively. These data exhibit clear seasonal variation arising largely from the temperature dependence of η_{EFF} in these materials. In c-Si modules, the PRs fluctuate from 84%-88% in summertime and up to 95%-101% in the winter, with module types A and B obtaining very similar values, and the type C exhibiting PR values about 2% lower. For poly-c-Si, the PR data range from 80%-85% in summer and up to 92%-97% in winter, with the type X modules outperforming the type Z modules by about 2%-3% at all comparable times.

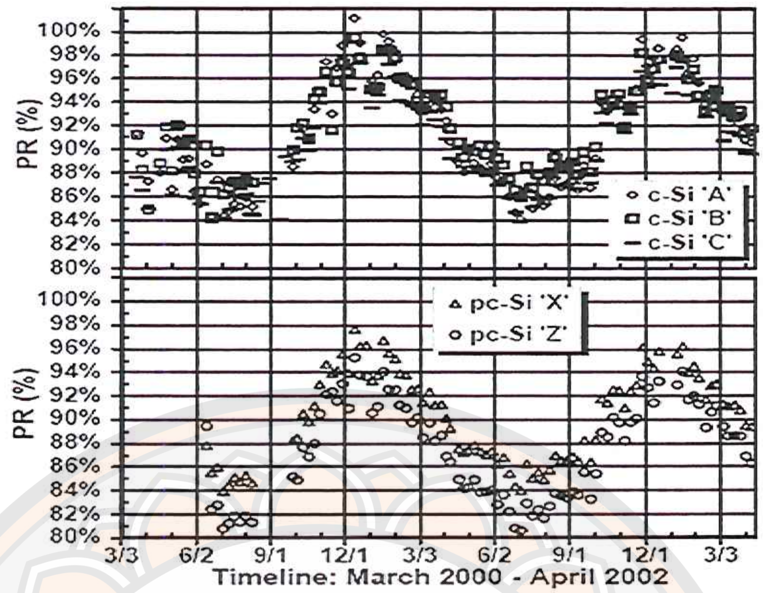

Figure 6 Performance ratio data of bulk-material PV modules [5]

These ratios tend toward larger values during winter and vise versa, except for amorphous silicon and cadmium telluride modules. In a-Si modules, the situation appears reversed: better PRs are obtained during late summer. The effective efficiency, PR and average daily and yearly energy production are analyzed and quantified.

Solar radiation and astronomy theory

Astronomy and radiation on an inclined and tracking surface

The earth revolves around the sun in an elliptical orbit with the sun as one of the foci. The plane of this orbit is called the ecliptic. The time taken for the earth to complete this orbit defines a year. The relative position of the sun and earth is conveniently represented by means of the celestial sphere around the earth. The equatorial plane intersects the celestial sphere in the celestial equator, and the polar axis in the celestial poles. The earth motion round the sun is then pictured by apparent motion of the sun in the elliptic which is tilted at 23.4° with respect to the celestial equator. The angle between the line joining the centers of the sun and the earth and its projection on the equatorial plane is called the solar declination angle (δ).

This angle is zero at the venal (20/21 March) and autumnal (22/23 September) positions.

The earth itself rotates at the rate of one revolution per day around the polar axis. The daily rotation of the earth is depicted by the rotation of the celestial sphere about the polar axis, and the instantaneous position of the sun is described by the hour angle v, the angle between the meridian passing through the sun and the meridian of the site. The hour angle is zero at solar noon and increases toward the east. For observers on the earth's surface at a location with geographical latitude φ, a convenient coordinate system is defined by a vertical line at the site which intersects the celestial sphere in two points, the zenith and the nadir, and subtends the angle φ with the polar axis (Figure 7). The great circle perpendicular to the vertical axis is the horizon [6].

The latitude (φ) of a point or location is the angle made by the radial line joining the location to the center of the earth with the projection of the line on the equatorial plane. The earth's axis of rotation intersects the earth's surface at 90° latitude (North Pole) and -90° latitude (South Pole). Any location on the surface of the earth then can be defined by the intersection of a longitude angle and a latitude angle.

The solar altitude angle (α) is defined as the vertical angle between the projection of sun's rays on the horizontal plane and direction of sun's rays passing through the point, as shown in Fig. 1. As an alternative, the sun's altitude may be described in terms of the solar zenith angle (θ_Z) which is a vertical angle between sun's rays and a line perpendicular to the horizontal plane through the point ($\theta_Z = 90 - \alpha$). Solar azimuth angle (γ_S) is the horizontal angle measured from south (in the northern hemisphere) to the horizontal projection of the sun's rays [7].

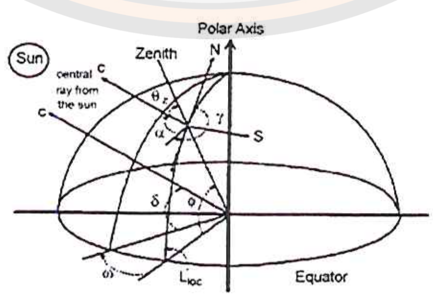

Figure 7 Schematic representation of the solar angles [6]

The solar radiation data are usually given in the form of global radiation on a horizontal surface and PV panels are usually positioned at an angle to the horizontal plane; therefore, the energy input to the PV system must be calculated accordingly. The calculation proceeds in three steps [6].

In the first step, the data for the site are used to determine the diffuse and beam components of the global irradiation on the horizontal plane. This is carried out by using the extraterrestrial daily irradiation, B_0 as a reference and calculating the ratio $K_T = G/B_0$, known as the clearness index where G is the daily global irradiation on a horizontal plane (usually the monthly mean), and K_T describes the average attenuation of solar radiation by the atmosphere at a given site during a given month.

In the second step, the diffuse irradiation is obtained using the empirical rule that the diffuse fraction D/G of the global radiation is a universal function of the clearness index K_T (D is the monthly mean daily diffuse irradiation on a horizontal plane in W/m^2). Since B = G -D, this procedure determines both the diffuse and beam irradiation on the horizontal plane (B is daily beam irradiation on a horizontal plane).

In the third step, the appropriate angular dependence of each component is used to determine the diffuse and beam irradiation on the inclined surface. With allowance for the reflectivity of the surrounding area, the albedo can also be determined. The total daily irradiation on the inclined surface is then obtained by adding the three components [6].

Sun is moving across the sky during the day. In the case of fixed solar collectors, the projection of the collector area on the plane, which is perpendicular to the radiation direction, is given by function cosine of the angle of incidence (Figure 8).

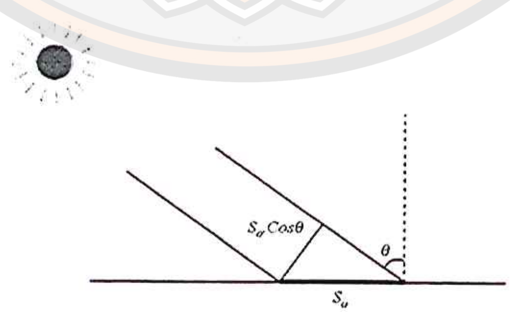

Figure 8 Angle of incidence of the solar radiation [8]

The higher the angle of incidence θ, the lower is the power. Theoretical calculation of the extracted energy in case of using tracking collectors is carried out by assuming that the maximum radiation intensity I = 1100 Wm^{-2} is falling on the area which is oriented perpendicularly to the direction of radiation. Taking the day length t =12h=43,200 s, intensity of the tracking collector which is always optimally oriented facing the sun is compared to that of a fixed collector which is oriented perpendicularly to the direction of radiation only at noon. The collector area is marked as S_0.

(a) For a fixed collector, the projection area on the area oriented perpendicularly to the radiation direction is $S = S_0 \cos\theta$, where θ is changing in the interval (-π/2, +π/2) during the day. The angular velocity of the sun moving cross the sky is ω = 2ω/T = 7.27 x10^{-5} rad/s and the differential of the falling energy is dW = IS dt. Neglecting the atmosphere influence, the energy per unit area is calculated for the whole day:

$$W = \int_{-21,600}^{+21,600} IS_0 \cos\omega t dt = IS_0\left[\frac{\sin\omega t}{\omega}\right]_{-21,600}^{+21,600} = \frac{2IS}{\omega} \quad (1)$$

$$= 3.03 \times 10^7 \text{ Ws/m}^2 \text{ day} = 8.14 \text{ kWh/m}^2 \text{ day}$$

(b) For a tracking collector, by neglecting the atmosphere influence, the energy per unit area for the whole day is

$$W = IS_0t = 4.75 \times 10^7 \text{ Ws} = 13.2 \text{ kWh/m}^2 \text{ day} \quad (2)$$

Comparing Eqs. (1) And (2), 57% more energy is calculated for the latter case. This amount of energy can be obtained, for example, on the moon's surface. The sun rays reaching the earth's surface go through the thick layer of atmosphere. As we deviate from the noon, the solar insulation on the surface is weakened.

Also, in calculations, one can consider the day length longer than 12 h. Figure 8 shows the dependence of the energy lost on the maximum tracking angle in comparison to that of an ideal tracking. It is clear that in tracking angles beyond ±60° no considerable energy gain is obtained [8].

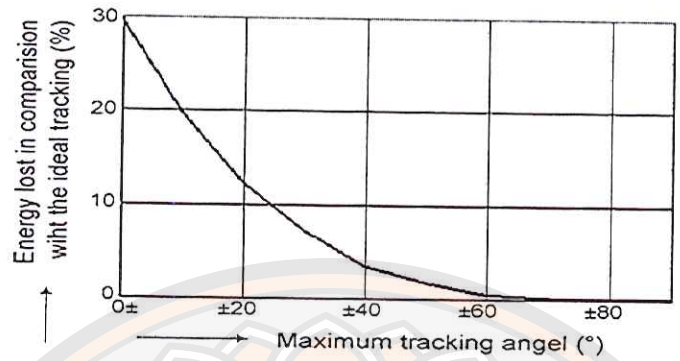

Figure 9 Energy lost in the maximum tracking angle compare with the ideal track [8]

Solar angles

The earth has two different movements; it rotates around its own axis, and it rotates around the sun. Because of these movements, solar rays from two different angles at the points where they reach the earth. These angles are named as solar azimuth angle and solar altitude angle [9].

Solar azimuth angles (a_s)

The sun makes an angle with the surface of the earth from sunrise to sunset and moves tracing this formed angle. This angle which is traced by the sun is called the surface azimuth angle. This azimuth angle (a_s) that the sun makes with the earth's surface can be mathematically calculated for each month, day and hour of the year [9, 10].

The azimuth angle is calculated as follows:

$$\cos(a_s) = \frac{[\sin(\alpha) * \sin(L) * \sin(\delta)]}{[\cos(\alpha) * \sin(L)]} \qquad (3)$$

Where L is the local latitude (°), a_s as the solar azimuth angle (°), δ the solar declination angle (°) and α the solar altitude angle (°).

Solar altitude angles (α)

The solar altitude angle (α) is defined as the angle between the horizontal plane of the area and at a point on the earth's surface a default line connecting the point on the earth and the sun. The solar altitude angle can be calculated for each day of the year at any period of time between the sunrise and the sunset (Eq. (4)). The solar altitude angle at the time of sunrise and sunset is 0°. The solar altitude angle has its maximum value at noon time in all seasons [9, 10].

The solar altitude angle is calculated as follows:

$$\alpha = \sin^{-1}\left[\left[\cos(L) * \cos(\delta) * \cos(h_s)\right] + \left[\sin(L) * \sin(\delta)\right]\right] \quad (4)$$

Where α is the solar altitude angle (°), L the local latitude (°), δ the solar declination angle (°), and h_s the hour angle (°).

Energy and radiation gain in tracking system

Solar tracking can be implemented by using one-axis, and for higher accuracy, two-axis sun-tracking systems. For a two-axis sun-tracking system, two types are known as: polar (equatorial) tracking and azimuth/elevation (altitude–azimuth) tracking.

The solar tracker, a device that keeps PV or photo-thermal panels in an optimum position perpendicular to the solar radiation during daylight hours, increases the collected energy. The first tracker introduced by Finster in 1962, was completely mechanical. One year later, Saavedra presented a mechanism with an automatic electronic control, which was used to orient an Eppley pyrheliometer [11].

Bione et al. compared the pumping systems driven by fixed, tracking and tracking with concentration PVs. The PV–V-trough system, consisted of four cavities and two PV modules to track the sun along its N–S axis, tilted at an angle of 20° towards the north. A theoretical simulation as well as experimental comparison between three cases was performed. By analyzing the daily characteristic curve for three given modes, the results (Figure 10) showed that for a given irradiance, the pumped water flow rate was significantly different from one another. They proved that the benefit ratios obtained for water volume were higher than that for collected solar energy. The fixed PV, the PV with tracker and the concentrating-tracking systems pumped 4.9, 7.4 and 12.6 m^3/day, respectively [12].

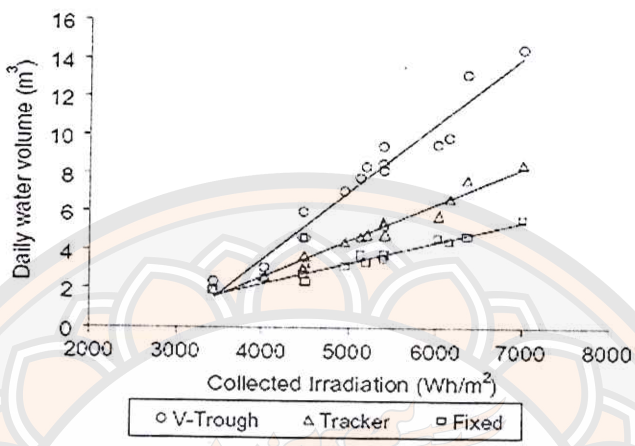

Figure 10 Water volume pumped by the three systems against irradiation [12]

Ai, et al. proposed and compared the azimuth and hour angle three-step trackers. The day length on the south facing slope was divided into three equal parts in order to adjust the tilt angle. The sum of the direct radiation received in each time interval and the sky diffusion and ground reflection radiation during a day were considered to derive the mathematical formula for the three-step tracking system to estimate the daily radiation on planes. They concluded that for the whole year, the radiation on the slope with optimized tilt angle was 30.2% and that for the two-axis azimuth three-step tracking was 72% higher than that on the horizontal surface. No significant difference was found between one-axis azimuth three-step tracking and hour angle three-step tracking power [13].

Sangani, et al. fabricated and tested a V-trough (2-sun) concentrator using different sun trackers to reduce generated electric cost with PV. Their tracking modes were seasonal tracking (A), one-axis N–S tracking (B) and diurnal tracking (C). Experimental results for I–V characteristic curves and output power from the PV module at an insolation level of 900 W/m^2 assembled at different tracking modes are shown in Figure 11 [14].

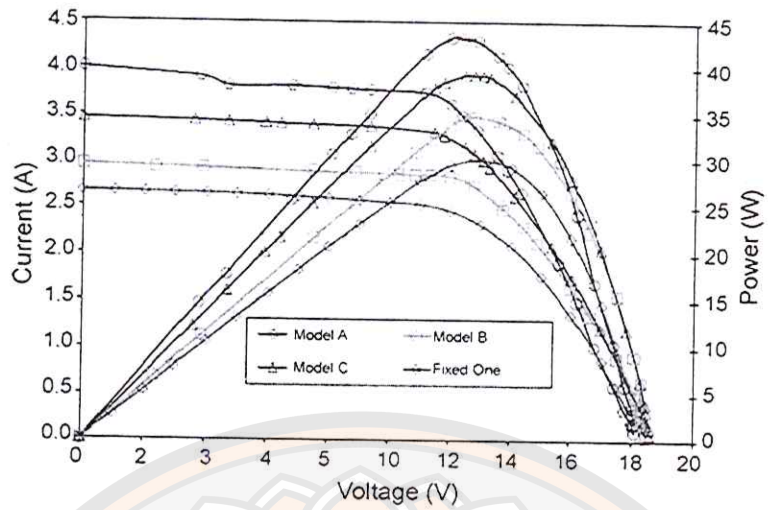

Figure 11 I–V curves and power output for different V-troughs concentrator PV systems assembled according to model-A, model-B and model-C [14]

Ibrahim constructed an electronically one-axis concentrating collector with an electric motor for forced circulation. The collector was hinged at two points for its tilt adjustment with a tightening screw to continuously track the sun from east to west through a range of 1808. The collector efficiency was measured for different values of mass flow rates. It was concluded that the collector efficiency increases (reaching the maximum value of 62% as the mass flow rate increases [15].

Baltas, et al. evaluated the power output for fixed, step tracking and continuous tracking systems in several locations. They used direct radiation, total radiation on horizontal surface and dry bulb temperature data for computer simulation. They stated that Freon-driven trackers are good for a flat plate array unlike for concentrating PV systems, due to their independence of good tracking accuracy. By comparing the energy output from various tracking systems for a typical year, they concluded that the two step tracking arrays (E–W) direction varying twice per day, south facing tilt varying monthly) provides about 95% of the energy obtained from continuous tracking arrays. Also, the continuous tracking mode provided 33, 25.5 and 22.5% more energy in different locations over fixed arrays, respectively. Continuous tracking increased the energy production 29.2 and 33% over south facing fixed arrays, respectively, for reflection non-accounting and refection accounting systems [16].

Nann evaluated the potentials for tracking systems relative to the cost and irradiance received from a fixed (40°) system. It was mentioned although the fraction of direct normal irradiance on a surface normal to the sun was 54% greater than that of the fixed one, the surplus of irradiance received by one-axis tracking and two-axis tracking systems were 34 and 38%, respectively and at today's module costs, tracking the sun can improve the cost effectiveness of the PV plant by up to 20%. The comparison between three stationary, one-axis and two-axis tracking systems showed that irradiation received by one-axis tracker is nearly as the same as the two axis trackers; however its tracker cost is approximately half of that of the two-axis one [17].

Braun, et al. calculated the optimum geometry for fixed and tracking surfaces. They evaluated theoretically the zenith, sun azimuth, surface azimuth and slope angles for one-axis and two-axis sun trackers and concluded that for a two-axis tracking surfaces, radiation beam is maximized when surface azimuth is equal to sun azimuth and surface slope is equal to zenith [18].

Abdallah, et al. [19]. designed and constructed a two-axes, open loop, PLC controlled sun-tracking system. Their work principle is based on mathematical definition of surface position that is defined by two angles: the slope of the surface, and azimuth angle. The slope was considered to be equal as zenith angle of the sun. Two tracking motors, one for the joint rotating about the horizontal N–S axis and the other for the joint rotating about the vertical axis were used. The daylight divided into four intervals and during each of them the solar and motors speed were defined and programmed into PLC. They predicted that the power consumption to drive motors and control systems hardly exceeds 3% of power saved by the tracking system. Figure 12 shows energy comparison between the tracker and the fixed surface inclined at 32.8°. They concluded that the use of two-axes tracking surfaces results in an increase in total daily collection of about 41.34% as compared to that of a fixed one [19, 20].

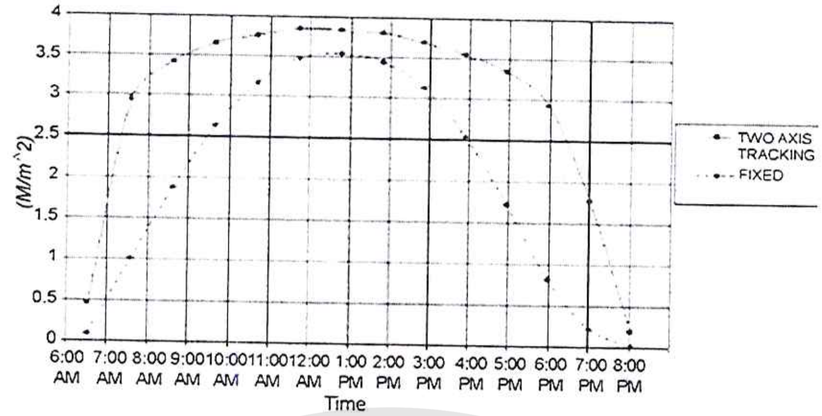

Figure 12 Energy comparison between tracking and fixed solar system [19]

Al-Mohamad [21]. Designed a single-axis sun-tracking system based on a programmable logic controlling (PLC) unit to investigate the improvement in the daily output power of a photo-voltaic module. Two photo-resistive sensors were separated by a barrier to provide shadow for one of them. As solar radiation intensity increases the resistivity of the sensor decreases. Two output signals of the unit are connected directly to the analog inputs of the PLC and compared in order to produce a proper output signal to activate an electromechanical sun-tracking system. The tracker scans through an angle of about 120° E–W. For PLC, a proper program to control, monitor and to collect data was developed using special software. A special computer program for automatic detection and PC communication with RS232 was developed using Visual Basic 5. The performance of the sun-tracker was evaluated and monitored. The output power showed a considerable increase during the early and late hours of the day. In fact, the overall improvement, in the tracking mode, exceeded 40% for the period from 6:00 to 10:00 a.m. and for the period from 15:00 to 17:00 p.m. However, the improvement was about 2–4% during mid-day. The average overall improvement during the whole day was better than 20% in comparison with that of a fixed module.

Abdallah, et al. designed and constructed four electromechanical open loop solar tracking systems: a two-axis, one-axis vertical, one-axis E–W and one-axis N–S tracker, in order to estimate the current-voltage characteristics and compare to that of a fixed one with 32.8 inclination to the south. The required position was calculated in advance and was programmed into PLC. The PLC controls the actuator to adjust the panel to maintain position perpendicular to the sun. They claimed that consumed power by the control system was less than 2% of the collected energy by the tracking system. After drawing several voltage–current and power generation characteristic curves for different sun trackers, they concluded that there were increases up to 43.87, 37.53, 34.43 and 15.69% of electrical power gain, respectively for the two-axis, E–W, vertical and N–S tracking, as compared to that of the fixed one. His experiment can show in Table 4 [22].

Table 4 The measured maximum power at the output of FPPV on May 29, 2002 [22]

Time	P_{out} (W)				
	2-axes	N-S	Vertical	E-W	Fixed
7:30 am	29.6	10.4	20.7	26.6	6.7
8:30 am	30.6	17.7	27.9	29.2	11.5
9:30 am	30.3	24.6	29.6	28.9	19.6
10:30 am	31.0	29.6	29.6	28.9	25.3
11:30 am	30.6	28.9	28.9	28.9	27.6
12:30 pm	30.6	29.6	29.9	29.2	26.2
1:30 pm	31.0	30.3	31.3	30.0	27.2
2:30 pm	29.2	27.9	28.2	28.6	25.9
3:30 pm	29.6	25.9	28.2	29.2	21.3
4:30 pm	29.2	17.7	27.6	28.9	18.4
Average (W)	30.17	24.26	28.19	28.84	20.97
Power gain (%)	43.8722	15.2891	34.4301	37.5298	-

Rubio, et al. [23] discussed the design and implementation of a two-axis PV sun-tracker using a combination of an open loop tracking strategy with microprocessor in which the controller is based on a solar movement model, and a closed loop strategy which corresponds to the electro-optical controller. The instantaneous power generated by the arrays is measured by a sensor that emits a signal proportional to this power. Finally, they implemented a proportional and integral (PI) control strategy for each coordinate, independently. Their tracking strategy produced a close approximation of the evolution of the sun's elevation and azimuth even if the solar equations yield quite large errors.

As can be seen in Figure 13, the positioning system supports flat plate PV arrays instead of concentrating PV system. Figure 13 show the experimental power attained using the open loop tracking strategy. They concluded that the electric power generated using the hybrid strategy is, in mean values, 55% higher than that of the open loop one.

Figure 13 Mechanical structure of the solar tracker [22]

Mousazadeh, et al. [24] His report had consideration all reviewed articles. Sun trackers are categorized solely in one-axis or two-axis devices. However, the tracking surfaces including passive or active trackers may also be classified as in Figure 14.

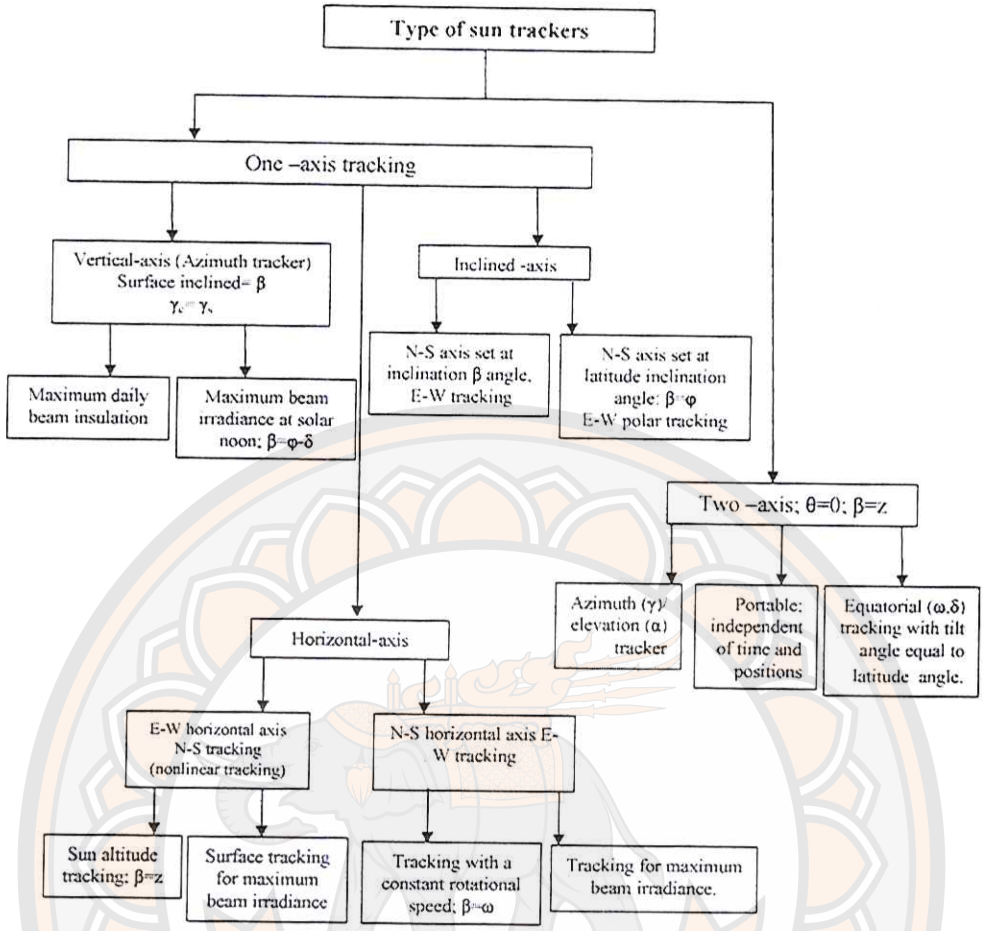

Figure 14 Types of sun trackers [24]

In conclusion, the most research interest about Power prediction for tracking system almost high latitude area and the effect of module temperature on fixed installation system. There research article hardly mentioned about the Mathematical model to prediction power output for tracking system on high latitude area. But this thesis is aim to find the relationship between module temperature and power output on photovoltaic systems as; fixed, 1-axis, 2-axis and developing the Mathematical model for predicting performance and economic installation of fixed system and tacking system in low latitude area.

CHAPTER III

RESEARCH METHODOLOGY

This chapter presents the methodology of this research including materials, apparatus and methods. The detail of each topic is described below.

Methodology

This research will evaluate the relation of solar irradiation, temperature and power output of photovoltaic module on Photovoltaic tracking system in an Energy park area in the School of Renewable Energy Technology (SERT), Naresuan University and develop software for evaluation power output of PV tracking system. There are 5 main steps of the dissertation methodology (Figure 15) as following;

1. Review of the literatures
2. Design of experimental procedure and data measurement
3. Analyzes collected data
4. Develop mathematical model
5. Design simulation program

Section 1 step 1-3 to study the effect of Temperature on power output of photovoltaic module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate conditions as following;

Step 1 and 2 Review of the literatures and Data collecting in this research module temperature ambient temperature and all power production parameters in DC part were collected by data recorder and PV analyzer every 10 minute from January – December in 2010, start at 08.00 AM to 16.00 PM (8 hr)

Step 3 The data from step 2 was evaluated in term of power production, then the effect of Temperature on power output and performance of photovoltaic module in tracking and fixing system are found in this step.

Section 2 step 4 Develop the mathematical model for the effect of temperature on power output of photovoltaic module in tracking system.

Section 3 step 5 Develop the software for evaluation power output of PV tracking System.

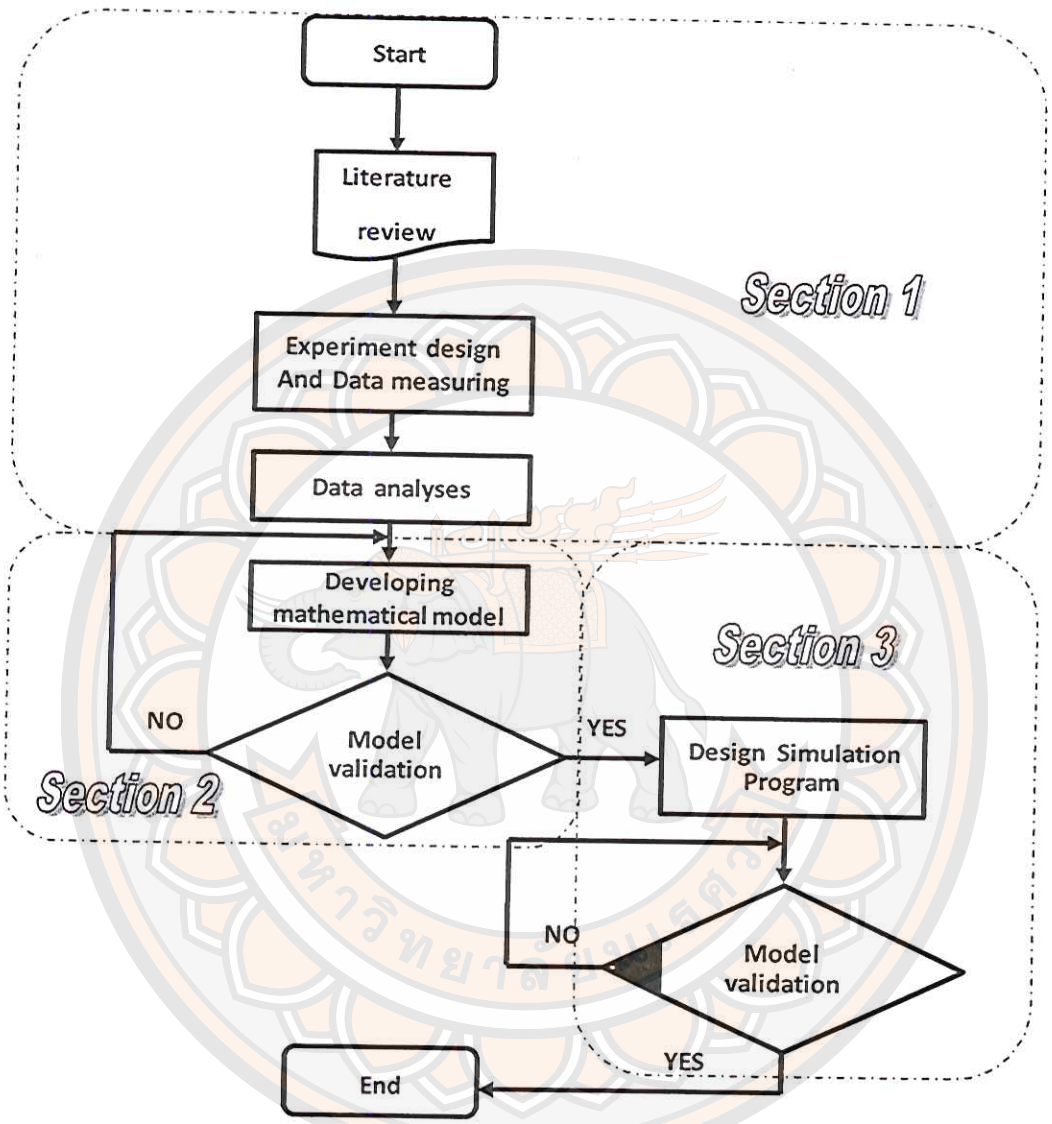

Figure 15 Flowchart of dissertation methodology

The experiment design

As follows the objective of this dissertation; to find a relationship equation of of solar irradiation, module temperature and power output of photovoltaic module on PV tracking system under Thailand hot climate conditions. The solar irradiation, module temperature and power output of photovoltaic module on tracking system would be measured and evaluated.

List of equipment

The equipment for this experiment consists of Tracking systems, PV array, pyranometer, spectro-radiometer, PV analyzer, and thermocouple.

1. **Solar tracker**

1-axis tracker

The solar tracker system is installed at Energy Park, School of Renewable Energy Technology, Naresuan University (north latitude 16°47', east longitude 100° 16'). The solar single axis trackers have one degree of freedom that acts as an axis of rotation. (Figure 16) is used for track following the sun (Azimuth). It is composed with control box and rotor unit. It connects with pyranometer and thermocouple for measuring solar irradiation, module temperature and ambient temperature. The specifications of Solar Tracker are shown in Table 5.

Figure 16 The 1-axis solar tracker

Table 5 The specifications track and rotor of single axis

Slewing Drive Performance Data	
Gear	73:1
Rate Output Torque	766 N.m
Output Torque (Max.)	1050 N.m
Output Speed	0.1 rpm
Tilting Moment Torque (Max.)	13.5k.m
Axial Load (Max.)	136 kN
Weight	23 kg
24 VDC Planetary Reducer Moter Performance Data	
Rate Output Torque	35 N.m
Intermitlent Output Torque	48 N.m
Rated Output Speed	7.7 rpm
Rated Voltage	24 VDC
Rated Current	< 2.8 A
Intermitlent Current	< 3.5 A
Noises	< 60 dB
IP Class	IP55
Temperature	-40-80 C

2-axis tracker

The solar tracker system is installed at Energy Park, School of Renewable Energy Technology, Naresuan University (north latitude 16°47', east longitude 100 °16'). The solar tracker II of EGIS (Figure 17) is used for track following the sun. It is composed with control unit and rotor unit. It connects with pyranometer and thermocouple for measuring solar irradiation, module temperature and ambient temperature. The specifications of Solar Tracker are shown in Table 6-7.

Figure 17 The 2-axis solar tracker II of EGIS

Table 6 The specifications of control computer: EPS-103 mod

lin voltage		220/110 V AC (12 V/24 VDC versions available also
power consumption		Approx.. 180 VA
data indication		LCD diplay
programmable memory		Up to 400 satelite orbit positions and names
motor power supphy		24 V DC, for azimuth and elevation motor
internal resolution:	azimuth	0,00100° / pulse*
	elevation	0,0025° / pulse*
pulse reading frequency		Max. 500 Hz *
analog sampling rate		approx. 250 Hz
dimensions: (W x D x H)		300 x 80 x 200 mm
weight		4 kg
shipping carton (W x H x D)		39 x 29 x 15 cm
temperature limits:	operational	- 5 °C to +40 °C
	survive & storage	- 15 °C to +60 °C

Table 7 The specifications of rotor unit: EPS-203 mod

features		2 separate motors for azimuth and elevation
motor operating voltage		24 V DC
motor power consumption		max. 20 W
pulse transmitting rate		max. 400 Hz
control device to rotor' cable		10 x 0.6 mm^2 schilded (telephone cable can be used)
		4 x 1.0 mm^2 (for motor power supply) – over 50 m wire 1.5 mm^2
control mechanism		pinion and gear transmission
max. azimuth tracking range		360° *
max. elevation range		90° *
reproduction accuracy		0,2° (40° EL version) 0,5° (90° EL version) **
tracking speed:	azimuth	approx. 4°/sec
	elevation	at 40° - stroke = 1°/sec. or 4°/sec. *
		at 90° - stroke = 2°/sec. or 16°/sec. *
usable carrying capacity		approx. 85kg approx. 60kg using the 90° head extension EL90
cabinet		aluminum die - cast, weather resistant
dimensions:		approx. 318 mm & approx. 625 mm
weight		27 kg
shipping carton (W x D x H)		75 x 34 x 41 cm
dimension of mechanical connections:	antenna	-
	Mast mounting	approx. 240 mm Ø- 4 threaded (bolts are supplied)
max. permis sible antenna		for 40 ° or 50 ° EL version up to 2.5 m (8 feet) *
diameter		for 90 ° EL version up to 1.8 m (6 feet) *
wind speed		62,5 km/h (41 MPH) during operation, 129 -160 km/h
		depending on antenna diameter in quiescent state
temperature limits:	operational	- 20 °C to +65 °C
	survive & storage	- 30 °C to +65 °C

2. Photovoltaic array

The photovoltaic tracking systems are installed at Energy Park, School of Renewable Energy Technology, Naresuan University (north latitude 16°47', east longitude 100 °16'). It will be evaluated in this dissertation, consists of technologies of PV as follows amorphous silicon (a-Si), mono crystalline silicon (m-Si) and poly crystalline silicon (p-Si).

(a) (b) (c)

Figure 18 PV module technologies (a) Amorphous Silicon (b) Mono crystalline silicon (c) Poly crystalline silicon

Table 8 The average electrical specifications of photovoltaic modules

Parameters	**Photovoltaic Module Technology**		
	a-Si	**mono-Si**	**poly-Si**
Maximum power (*W*)	40 W	75 W	120 W
Open circuit voltage (V_{oc})	62.2 V	21.4 V	22.1 V
Short circuit current (I_{sc})	1.14 A	4.75 A	4.80 A
Maximum power voltage (V_{pm})	44.8 V	17.0 V	17.6 V
Maximum power current (I_{pm})	0.93 A	4.45 A	4.55 A
Dimensions (*mm*)	1245x635x7	1578x826x46	1209x537x50

Note: At Standard Test Conditions: Air mass 1.5, Irradiance 1000 W/m^2, Temperature 25 °C.

3. PV analyzer

PV analyzer of Kernel (Figure 19) is used for measuring the characteristic curve of the PV array. It connects with pyranometer and thermocouple for measuring solar irradiation, module temperature and ambient temperature. The specifications of PV analyzer are shown in Table 9

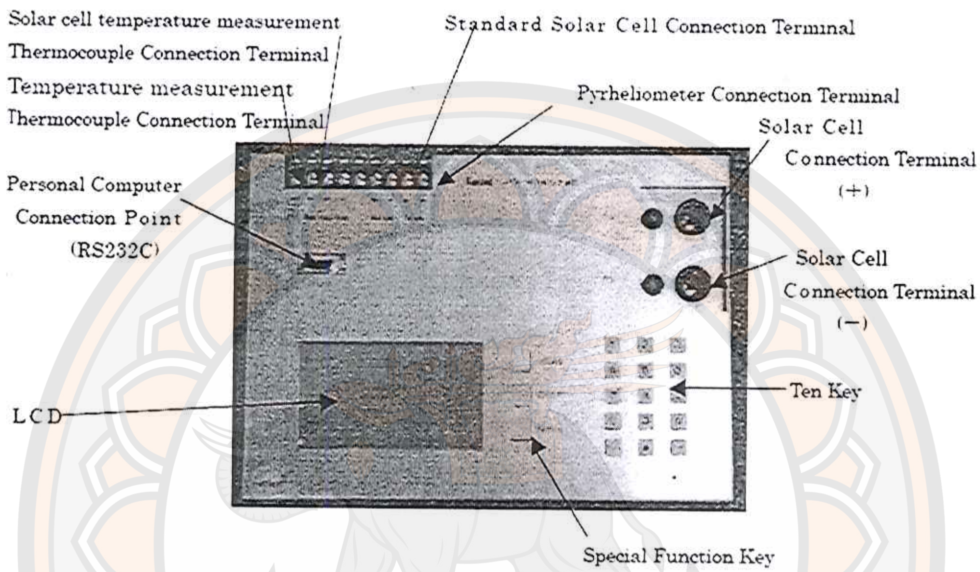

Figure 19 PV analyzer and connection port

Table 9 The specifications of PV analyzer

Model	PVA01982
Measurement range	
Power (kW)	2– 10
Voltage (V)	10 – 400
Current (A)	0.5 - 30

Table 9 (cont.)

Model	PVA01982
Measuring time	
V_{oc}/I_{sc} under 170 V	200 ms
V_{oc}/I_{sc} 170 - 300 V	300 ms
V_{oc}/I_{sc} over 300 V	700 ms
Operating temperature (°C)	0 to 50
Dimension (W x D x H) in mm	300 x 205 x 700

4. Data logger

Yokogawa DX 220 data logger. A data logger (also data logger or data recorder) is an electronic device that records information over a period of time for later reference. It connects with pyranometer and thermocouple for measuring solar irradiation, module temperature and ambient temperature by using connection port. In this type can connect maximum 20 ports.

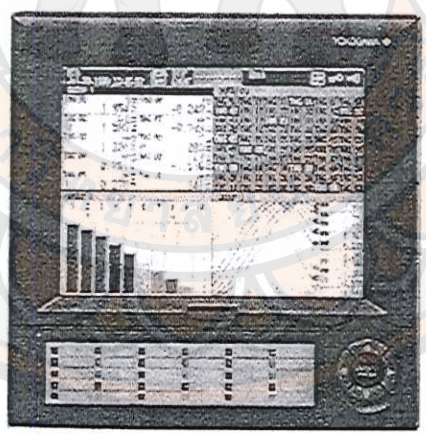

Figure 20 DX220 data logger of YOKOGAWA Company

5. Pyranometer

Pyranometer of EKO model MS-601 is used for measuring the global solar irradiance on an inclined surface (G_T). It will be connected to PV analyzer and the measured values are displayed in the data recorder in terms of mV. It installed at the same geometry with the PV module shows in Figure 21. Table 10 shows the specifications of pyranometer. The reading can be converted to W/m^2 by the following expression:

$$Value \quad in \quad W / m^2 = \frac{Value \quad in \quad mV \quad x \quad 1000}{Sensitivity \quad Factor}$$

Table 10 The specifications of pyranometer

Model	MS-601
ISO 9060 classification	Second Class
Response time 95%	17
Spectral selectivity (0.35 – 1.5 μm)	-1.1 %
Sensitivity (mV/kW/m^{-2})	7.02
Operating temperature (°C)	- 20 to 60
Wavelength (more than 50 % of transmittance)	305– 2800 nm

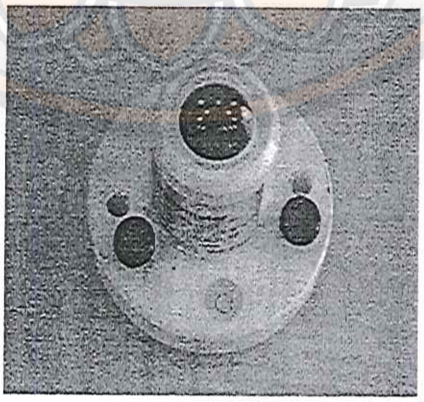

Figure 21 Pyranometer

6. **RTD PT100**

The RTD PT100 is used for measuring module temperature and ambient temperature. The specifications of thermocouple are shown in Table 11.

Table 11 The specifications of thermocouple

Type	RTD PT100
Temperature range (°C)	-40 – 80 °C
Accuracy (°C)	+ / - 0.5 °C

Method data measuring

The measured output power and other parameter are tabulated as three systems, each systems have three types of photovoltaic technology. The experiment and a flow chart of data measuring have been shown in Figure 22 and 23, respectively. The methodology is as follows:

1. The date of the module temperature, solar incident irradiance, output power of the module which has nominal output power of 1 kW, and the wind speed we can measured by an anemometer.

2. The following steps are repeated for the data measured every 10 minutes from 8:00 – 16:00, the data with irradiance higher than 0.15 kW/m^2 were used in this dissertation because from literature review [36] found that there is typically less than a 5% change in the voltage coefficients over a tenfold change in irradiance 150 W/m2 to 1000 W/m^2 which the voltage values are assumed to be independent of the solar irradiance level and air mass and effect to the power output from PV module.

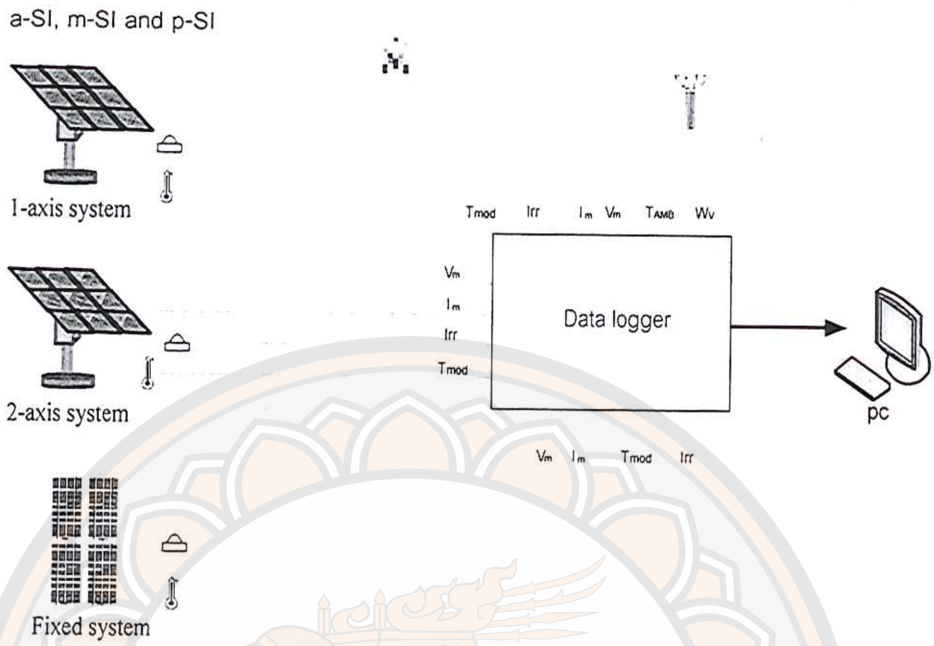

Figure 22 The measuring point of an experiment

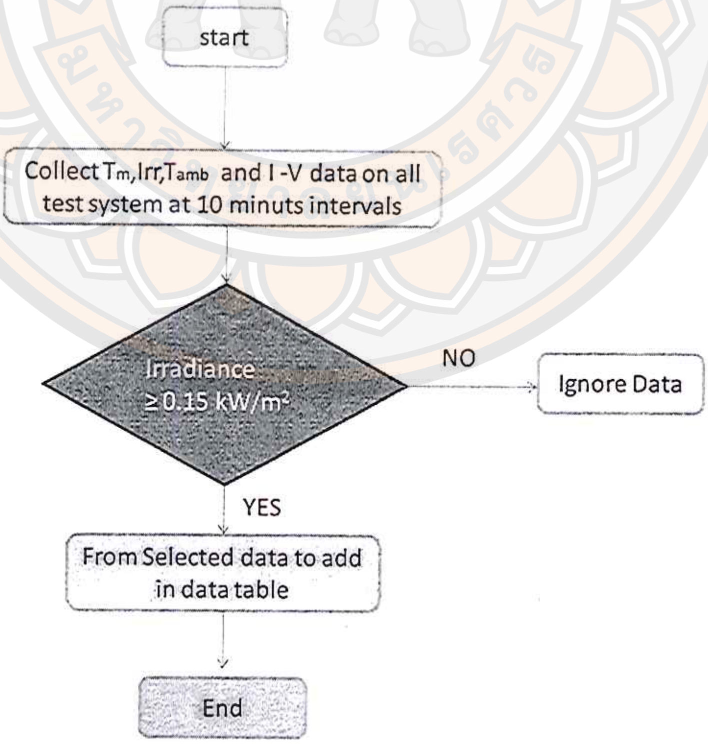

Figure 23 The flow chart of data measuring

Data analysis

In this section, the technical performance of PV will be evaluated such as Energy produced by PV and Module temperature

1. Energy produced by the PV array (E_A)

Energy produced by PV array is the energy that produced by photovoltaic array can be calculated by the equation

$$E_A = I_{PV} V_{PV} \qquad \text{(kWh)} \tag{5}$$

2. Temperature of the solar cell

The parameters that effect to power output are solar radiation, ambient temperature, wind velocity and module temperature.

So that The power of the photovoltaic system is a function of solar radiation, ambient temperature, wind velocity and module temperature.

$$f(P_{pv}) \propto f(G_t, T_a, V_w, T_m) \tag{6}$$

In module temperature case. The parameters that effect to module temperature are solar radiation, ambient temperature and wind velocity. Which different in a type of module technology.

So that the module temperature is a function of solar radiation, ambient temperature, wind velocity.

$$f(T_m) \propto f(G_t, T_a, V_w) \tag{7}$$

The working temperature of the solar cell (T_m) depends exclusively on the irradiance, (G) wind speed (V_W) and on the ambient temperature (T_a) according to the linear relation [25].

$$T_m = T_a + \frac{G_{a,0}}{a + b.V_W} \tag{8}$$

Where

a, b are module dependent parameters in investigation field.

$G_{a,0}$ = Solar irradiation. (W/m^2)

V_W = Wind speed. (m/s)

3. Module temperature and modeling techniques

The published module temperature models in the past were based on linear and nonlinear models. In this study, Simple linear regression and multiple linear regressions became the tool to develop the simple linear and multiple linear models respectively. Thus, this section will try to highlight the strength, weakness and significance of applying the modeling techniques in terms of model input, model simplicity and prediction accuracy.

3.1 Simple Linear Regression

Simple Linear Regression is the simplest computation and basic regression technique to rerate only one independent variable with dependent variable. Simple Linear Regression technique can be excited using commonly used software such as Microsoft office excels software. Simple Linear Regression has been applied in energy and environment works [26]. The approach of developing a Simple Linear Regression module temperature model demonstrated in this thesis serves as a fundamental approach in developing any Simple Linear module temperature model from PV system that has been installed.

3.2 Multiple Linear Regressions

Multiple Linear Regressions are statistical techniques that capable of analyzing the relationship between a criterion variable and a set of predictor' variable. Multiple Linear Regressions have the advantage of simple computation and easy implement [26]. Multiple Linear Regressions are frequently used as a tool to fulfill three objectives [27, 28].

3.2.1 Finding the best prediction equation for a set of variable; i.e., given X and Y (the predictors), what is Z (the criterion variable)?

3.2.2 Controlling the confounding factors to evaluate the contribution of a specific variable or set of variable; i.e., identifying independent relationships.

3.2.3 Finding the structural relationships and provide explanations for seemingly complex multivariate relationships.

In this thesis, Multiple Linear Regressions are used to develop module temperature model with the set of standard variable as; ambient temperature, solar irradiance and develop power output models with the set of standard variable as; module temperature, solar irradiance.

Mathematical model for the power output evaluation of PV tracking system

There are 2 main mathematical models which will develop in this part as following:

1. P_{array} is a function of solar radiation and module temperature.

From the basic equation of multi regression analysis "$Y = a_{00}+a_1X_1+a_2X_2$". After the data were evaluated, the mathematical model of PV arrays can be developed. In additional, mathematical model of PV arrays of this study can be written in form of "$P_{Array} = a_0 + a_1 IRR + a_2 T_m$". From the matrix method, the a0, a1, a2, was found by using linear regression from curve fitting tool of the MATLAB program License from Naresuan University (License Number: 660086).

2. T_{module} is a function of solar radiation and ambient temperature.

From the basic equation of multi regression analysis "$Y = a_{00}+a_1X_1+a_2X_2$". After the data were evaluated, the mathematical model of PV arrays can be developed. In additional, mathematical model of PV arrays of this study can be written in form of "$P_{Array} = a_0 + a_1 IRR + a_2 T_a$". From the matrix method, the a0, a1, a2, was found by using linear regression from curve fitting tool of MATLAB program.

Software developing for the power output evaluation of PV tracking system simulation program

As I mention before in the objective to develop the program to accurately estimate the power output of photovoltaic module on tracking system power plant in large scale and investment cost optimization. This Simulation program is used software such as Microsoft Office Excels2007 License from Nakhon Sawan Rajabhut University (Agreement ID : V1025911) by using the mathematical model of power output, module temperature form the second part and the economical formula will be helpful for interested users to evaluate the performance and economics of PV tracking system power plant for any location of Thailand.

This thesis will develop the program by using the mathematical model from later mythology to develop the program to estimate both of technical performance in power production and module temperature.

Performance ⟶ Energy Production

In economical part this program will estimate in the unit cost per unit (COE), The annuity corresponds to the average annual cash flow and The net present value of the investment equals its value at the time of investment in solar tracking power plant system in the large scale for Helps in the decision of the investor.

Economic ⟶ IRR, COE, Payback period
Net Present Value, NPV

The internal rate of return

The internal rate of return is a rate of return used in capital budgeting to measure and compare the profitability of investments. It is also called the discounted cash flow rate of return.

$$\text{The internal rate of return} = r_a + \frac{NPV_a}{NPV_a - NPV_b}(r_b - r_a) \quad (9)$$

Where:

r_a, r_b = lower and higher discount rate

t = the time of cash flow

n = the planning horizon, year

The cost per unit, COE

The cost per unit (COE: Baht/kWh) driven by the PV system according to the following parameters:

$$COE = \frac{A_{total}}{E_{Load}} \tag{10}$$

Where:

A_{total} = the total annuity, Baht/year

Q_a = the energy consumption, kWh/year

The Payback period

The payback period is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. The Payback period can define by the following equation:

$$\text{Payback period} = \frac{\text{Initial Investment}}{\text{Cash Inflow per Period}} \tag{11}$$

Net Present Value, NPV

The net present value of the investment equals its value at the time of investment, because the investment takes place at the beginning of the planning horizon (t =0).

$$NPV = \sum_{n=0}^{n} NCF_t (1+i)^{-t} \tag{12}$$

Where:

NCF_t = the net cash flow at a time

t = the time of cash flow

n = the planning horizon, year

CHAPTER IV

RESULTS AND DISCUSSION

In this chapter, experimental results will be mentioned in three main sections. Firstly, the effect of Temperature on power output of photovoltaic module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate conditions were evaluated. Secondly, the mathematical models for evaluating the effect of temperature on power output of photovoltaic module in tracking system were developed. Finally, the program to accurately estimate the power output of photovoltaic module on tracking system power plant in large scale and investment cost optimization were developed.

Sections 1 The effect of temperature on power output of photovoltaic module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate condition

This topic presents the result of relationships between the operation parameters to the performance of PV. Figure 24–47 shows the relationships between Solar irradiance, power output, module temperature and operate time in tracking and fixing system on three different technologies of PV.

From Figure 24-27, the graphical relationship between the solar irradiance of amorphous PV on each system and power output at an operating time in three seasons shown that the high Power output of amorphous technologies is summer, winter and rainy season respectively this trend is similar by the three seasonal. On fixed system the rise of power output is deepened by the solar irradiance increasing. In summer season, the percent of power on operate time in summer and winter season rise than rainy season are 22.26%, 9% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 29.90%, 13.36% respectively. On 1-axis system the rise of power output is deepened by the solar irradiance increasing in summer season. The percent of power on operate time in summer and winter season rise than rainy season are 20%, 4.37% respectively.

The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 26.70%, 7.71% respectively. On 2-axis system the rise of power output is deepened by the solar irradiance increasing in summer season. The percent of power on operate time in summer and winter season rise than rainy season are 22.26%, 12.20% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 28.71%, 17.00% respectively.

From Figure 27, the graphical shown that the first high power output of amorphous technologies is 2-axis system. The second is 1-axis system and the last are fixed the system. The average percent of power rise than the fixed system of all seasons are 21.72%, 7.87% and the average percent of the solar irradiance on operate time of all seasons are 26.56%, 9.30% respectively.

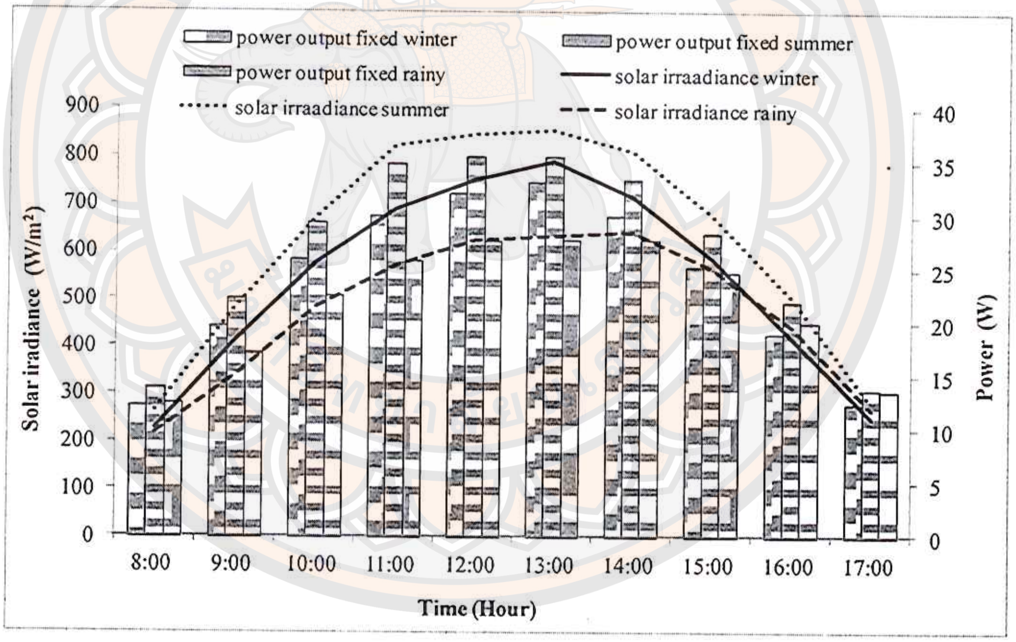

Figure 24 The power output and irradiation of amorphous PV on fixing in three seasons

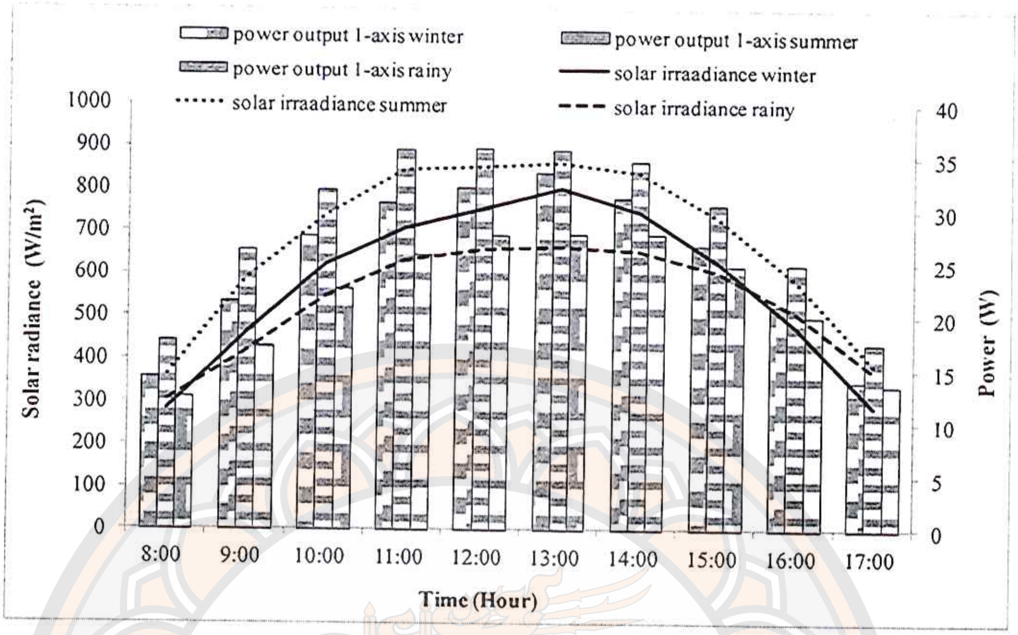

Figure 25 The power output and irradiation of amorphous PV on 1-axis in three seasons

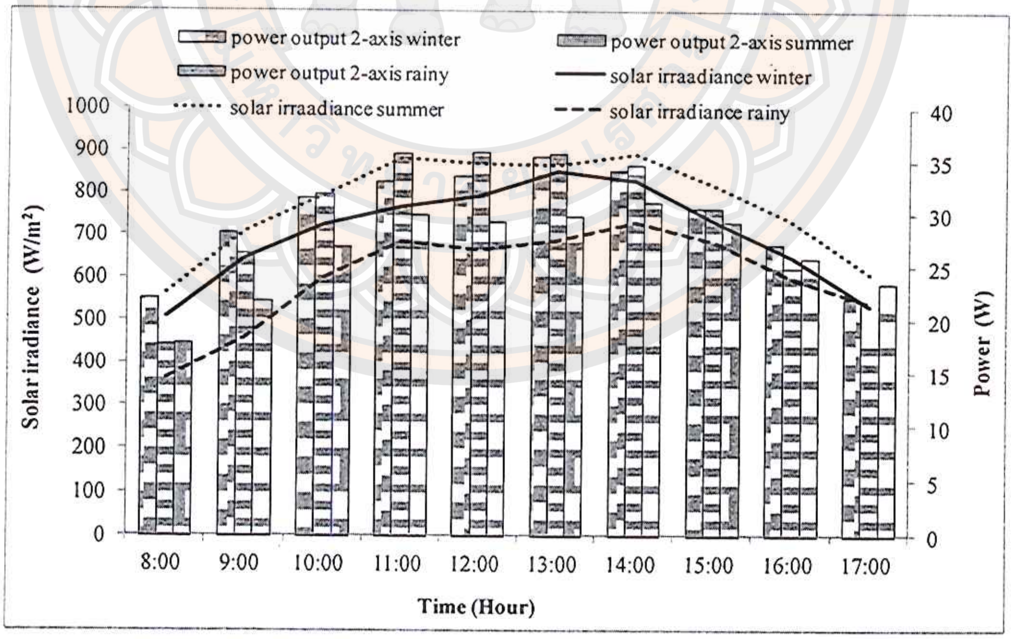

Figure 26 The power output and irradiation of amorphous PV on 2-axis in three seasons

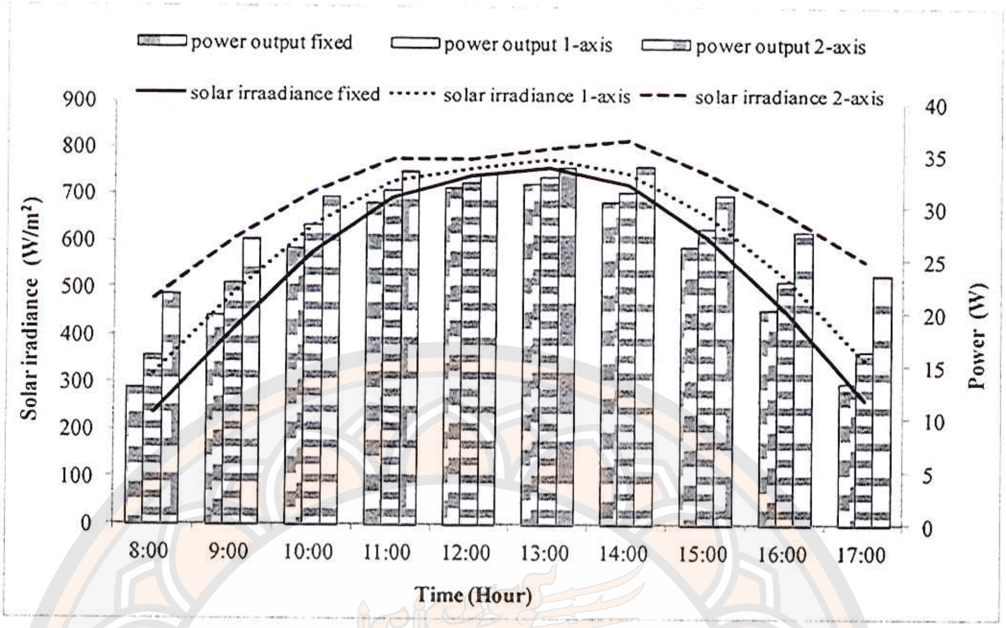

Figure 27 The power output and irradiation of amorphous PV in three systems

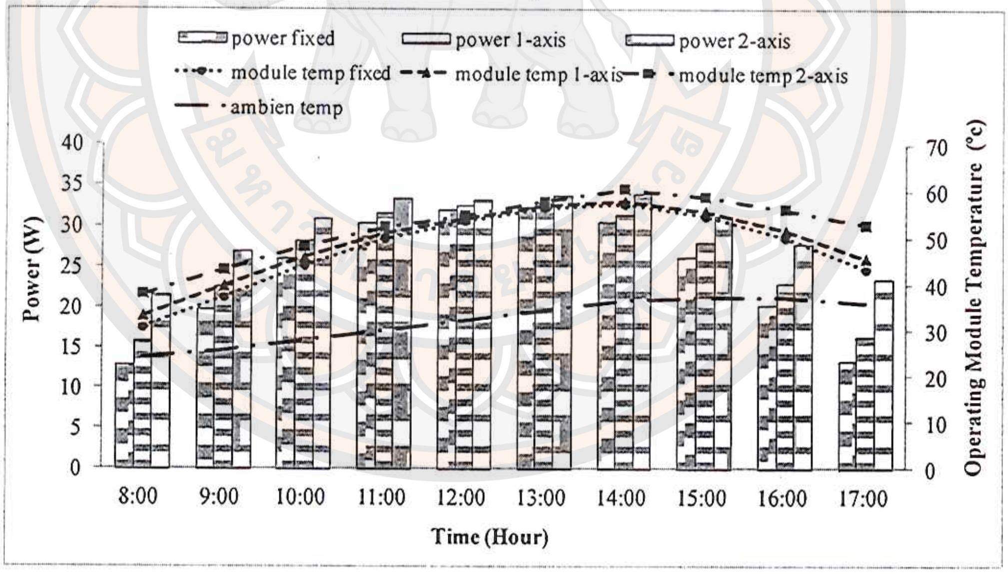

Figure 28 The comparison of the power output and module temperature on amorphous PV in three seasons

Figure 28 shows the comparison of module temperature, ambient temperature and power output on each system with amorphous silicon PV. The result from graphical shown that the difference module temperature rise in operate time the first high is 2-axis system. The second is 1-axis system and the last is fixed system. The percent of module temperature on operate time of 2-axis and 1-axis are rise than a fixed system approximate 9.38%, 2.98% respectively.

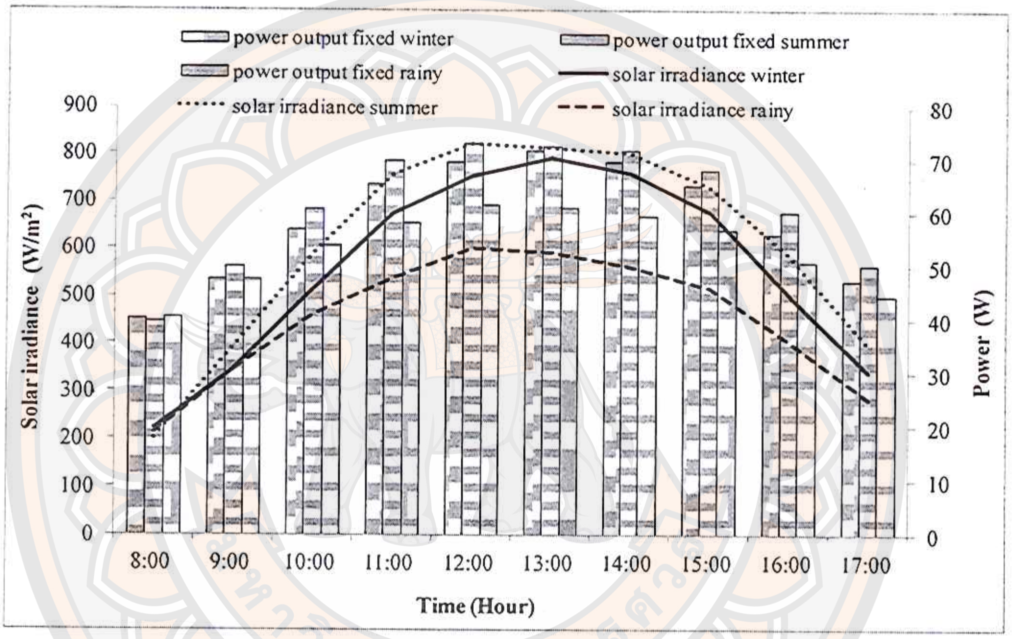

Figure 29 The power output and irradiation of mono crystalline silicon PV on fixed in three seasons

From Figure 29-31, the graphical relationship between the solar irradiance of mono crystalline silicon PV on each system and power output at an operating time in three seasons shown that the high power output of mono crystalline silicon technologies are summer, winter and rainy season respectively this trend is similar by the three seasonal. On fixed system the rise of power output is deepened by the solar irradiance increasing. In summer season, the percent of power on operate time in summer and winter season rise than rainy season are 15.48%, 10.37% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 34.72%, 23.45% respectively. On 1-axis system the rise of power output is depened by the solar irradiance increasing in summer season. The percent of power on operate time in summer and winter season rise than rainy season are 14.86%, 12.06% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 30.89%, 24.96% respectively. On 2-axis system the rise of power output is deepened by the solar irradiance increasing in summer season. The percent of power on operate time in summer and winter season rise than rainy season are 15.10%, 14.50% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 30.51%, 28.92% respectively.

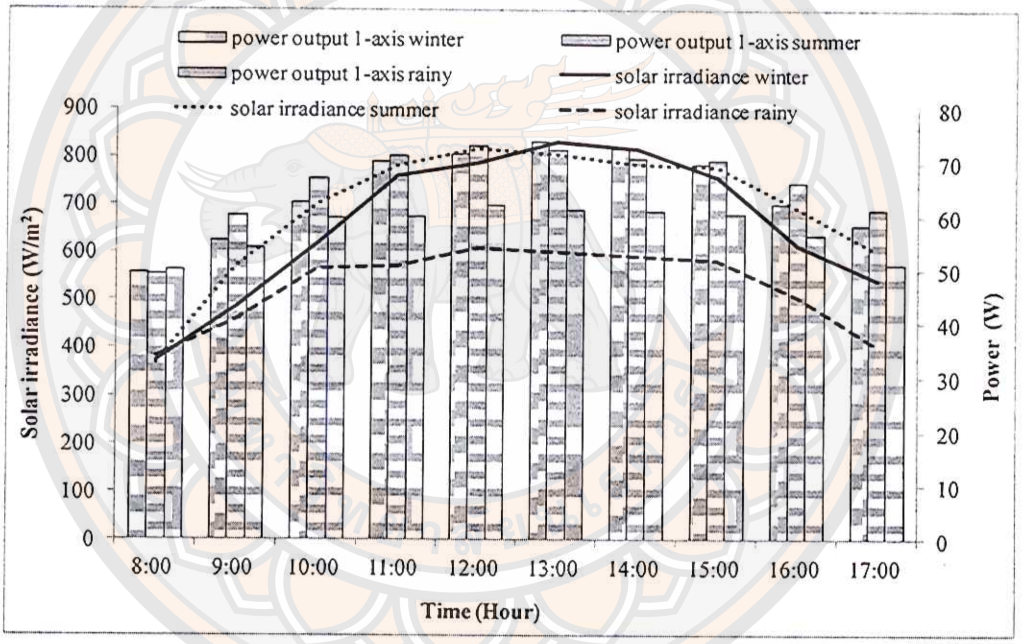

Figure 30 The power output and irradiation of mono crystalline silicon PV on 1-axis in three seasons

From Figure 32, the graphical shown that the first high power output of mono crystalline silicon technologies is 2-axis system. The second is 1-axis system and the last are fixed the system. The average percent of power rise than the fixed system of all seasons are 12.00%, 8.30% and the average percent of the solar irradiance on operate time of all seasons are 23.40%, 15.18% respectively.

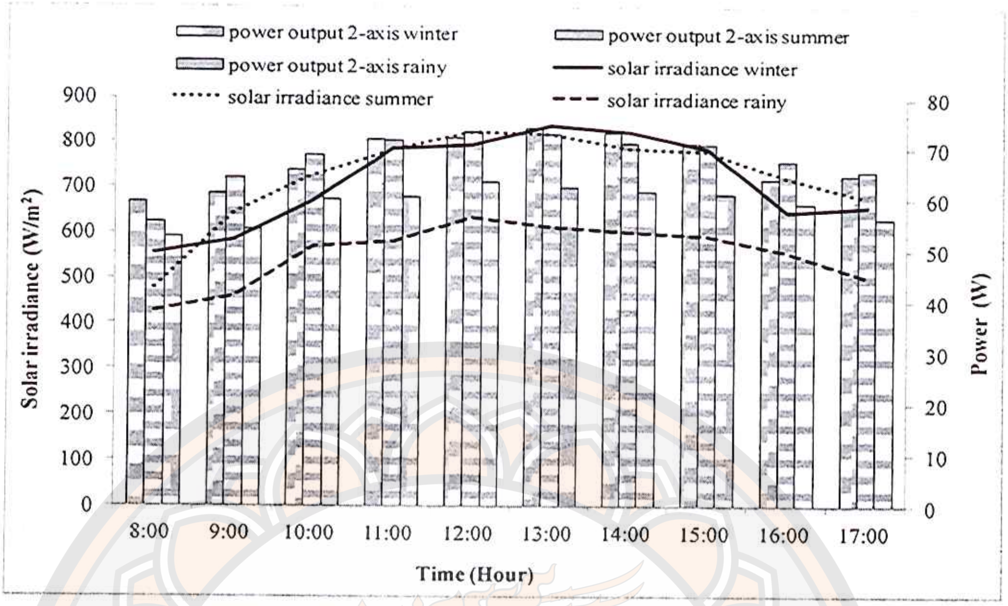

Figure 31 The power output and irradiation of mono crystalline silicon PV on 2-axis in three seasons

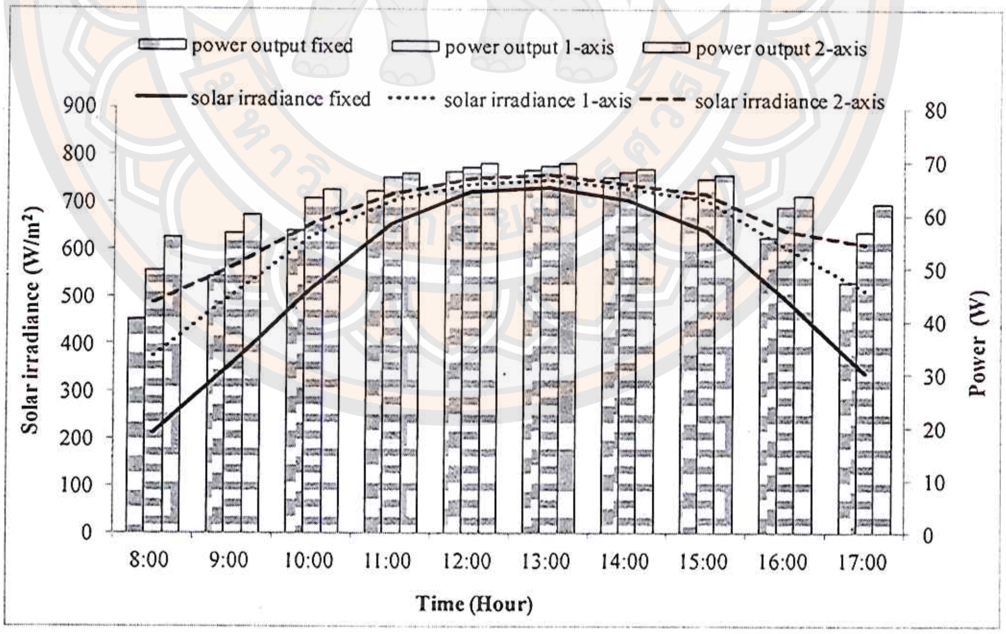

Figure 32 The power output and irradiation of mono crystalline silicon PV in three systems

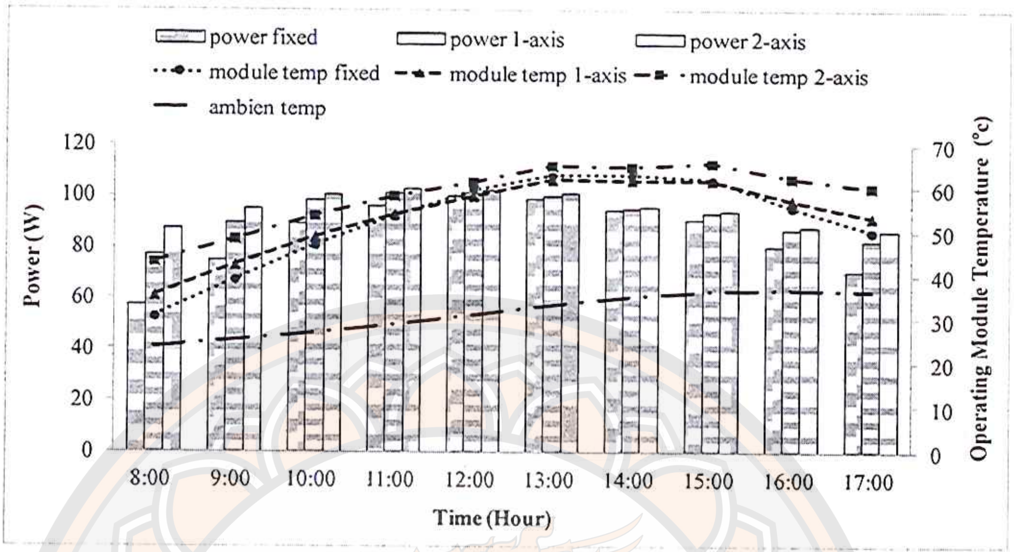

Figure 33 The comparison of the power output and module temperature on mono crystalline silicon PV in three systems

Figure 33 shows the comparison of module temperature, ambient temperature and power output on each system with mono crystalline silicon PV. The result from graphical shown that the difference module temperature rise in operate time the first high is 2-axis system. The second is 1-axis system and the last is fixed system. The percent of module temperature on operate time of 2-axis and 1-axis are rise than a fixed system approximate 9.71%, 6.54% respectively.

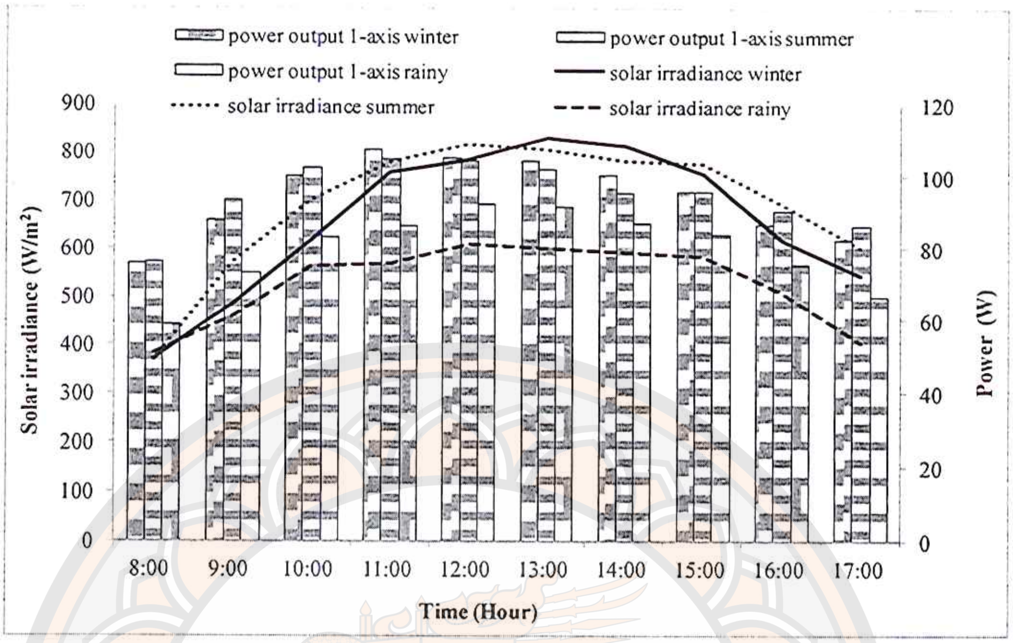

Figure 34 The power output and irradiation of poly crystalline silicon PV on fixing in three seasons

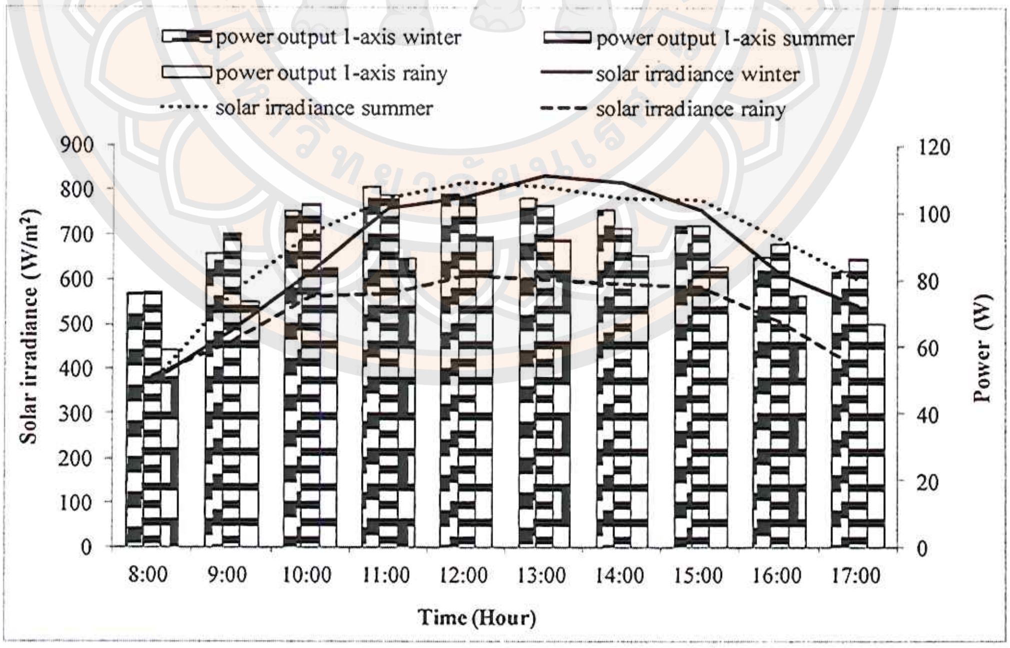

Figure 35 The power output and irradiation of poly crystalline silicon PV on 1-axis in three seasons

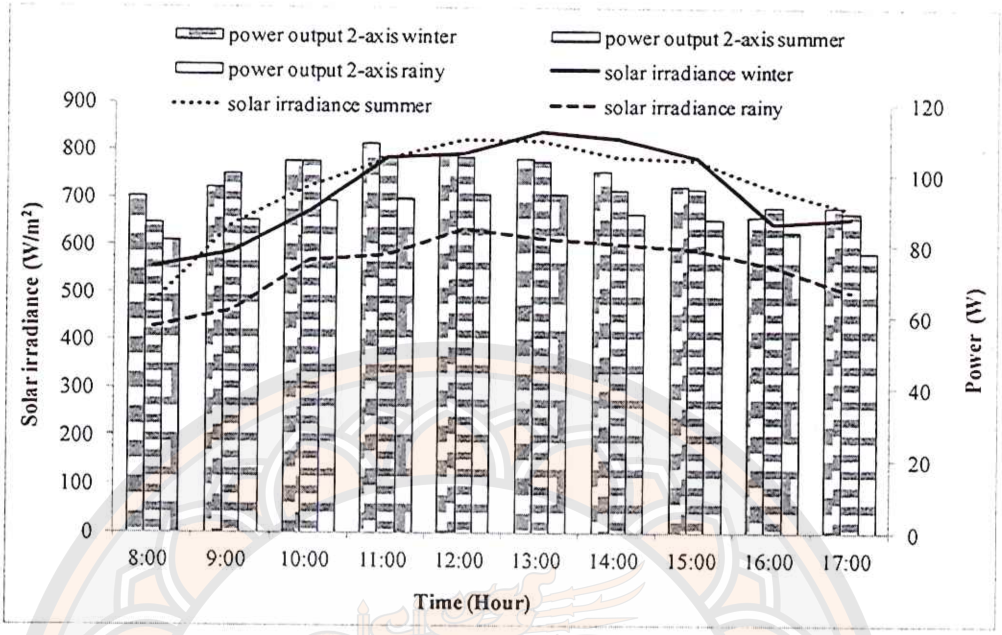

Figure 36 The power output and irradiation of poly crystalline silicon PV on 2-axis in three seasons

From Figure 34-36, the graphical relationship between the solar irradiance of poly crystalline silicon PV on each system and power output at an operating time in three seasons shown that the high power output of poly crystalline silicon technologies is nearly between summer and winter. The worst is rainy season. This trend is similar by the three seasonal. On fixed system the rise of power output is not only deepened by the solar irradiance increasing. In summer season, the percent of power on operate time in summer and winter season rise than rainy season are 10.28%, 8.34% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 30.42%, 1.03% respectively. On 1-axis system the rise of power output is the same trend with the fixed system. The percent of power on operate time in summer and winter season rise than rainy season are 10.19%, 9.60% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 29.36%, 22.07% respectively. On 2-axis system the rise of power output is the same trend with the fixed system. The percent of power on operate time in summer and winter season rise than rainy season are 10.60%, 12.18% respectively. The percent of the solar irradiance on operate time in summer and winter season rise than rainy season are 30.63%, 27.97% respectively.

From Figure 37, the graphical shown that the first high power output of poly crystalline silicon technologies is 2-axis system. The second is 1-axis system and the last are fixed the system. The average percent of power rise than the fixed system of all seasons are 11.76%, 8.51% and the average percent of the solar irradiance on operate time of all seasons are 33.89%, 25.61% respectively.

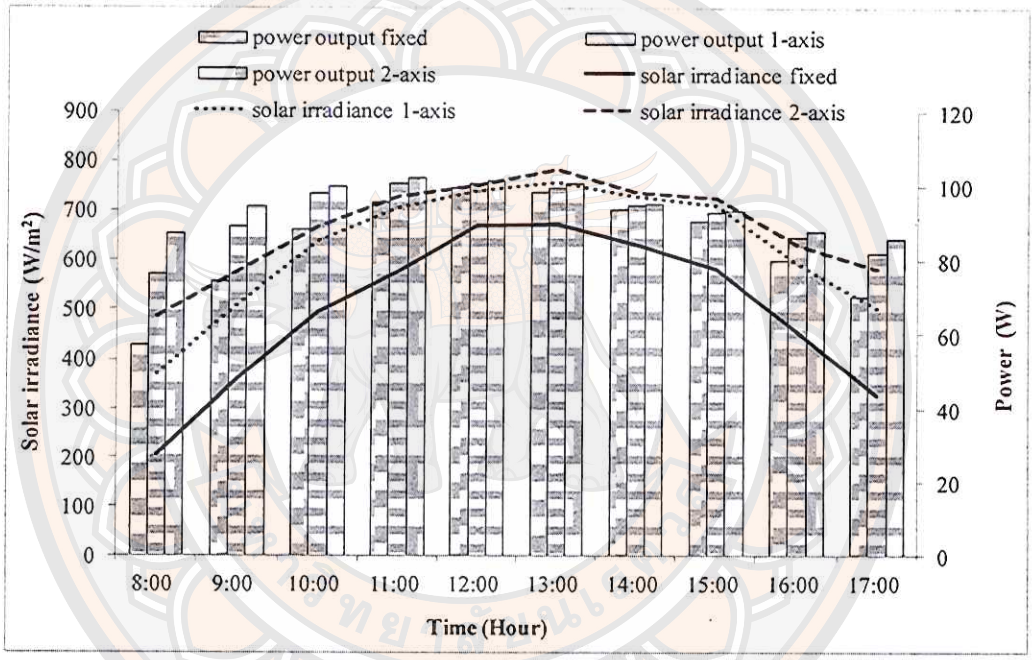

Figure 37 The power output and irradiation of poly crystalline silicon PV three systems

Figure 38 shows the comparison of module temperature, ambient temperature and power output on each system with poly crystalline silicon PV. The result from graphical shown that the difference module temperature rise in operate time the first high is 2-axis system. The second is 1-axis system and the last is fixed system. The percent of module temperature on operate time of 2-axis and 1-axis are rising than a fixed system approximate 11.25%, 2.17% respectively. The result shows that the module temperature of poly crystalline silicon PV have effect to the power output more than the amorphous and mono crystalline silicon technology because the increase solar irradiance can not convert to all of electricity but it convert to the heat of module temperature too and it have effect to electricity decreasing.

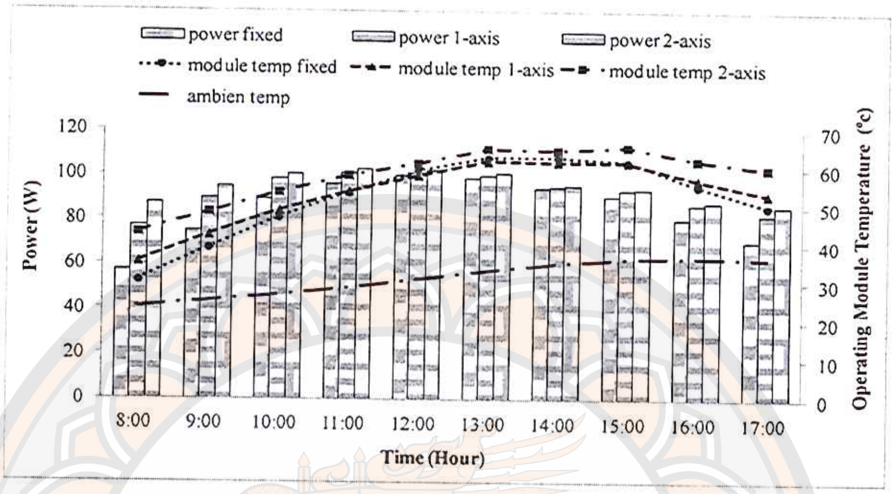

Figure 38 The comparison of the power output and module temperature on poly crystalline silicon PV in three systems

The comparison data of power output in a field test result from Thailand climate regions were shown on Table 12 from the table show that the power output of the 1-axis is higher than the fixed average 8% and the 2-axis is higher than the fixed average 12-22% because the 2-axis was track to the sun all time.

Table 12 The comparison data of power output in field test result from Thailand climate regions

Condition	a-Si		m-Si		p-Si	
	1-axis rise than fixing (%)	2-axis rise than fixing (%)	1-axis rise than fixing (%)	2-axis rise than fixing (%)	1-axis rise than fixing (%)	2-axis rise than fixing (%)
Power output (Winter)	5.43	24.08	9.6	14.88	9.38	14.26
Power output (Summer)	8.08	20.55	7.36	10.38	8.03	10.67
Power output (Rainy)	10.11	20.54	7.95	10.74	8.12	10.35
Power output Average	7.87	21.72	8.30	12.00	8.51	11.76

The values from table 13 shown that The amorphous silicon on 1-axis and 2-axis have percent difference between winter, summer, rainy seasons and the fixed system are 2.47%, 3.31%, 3.12% and 10.67%, 9.07%, 8.40% respectively. The mono crystalline silicon on 1-axis and 2-axis have percent difference between winter, summer, rainy seasons and the fixed system are 7.96%, 5.41%, 6.25% and 12.44%, 7.96%, 8.71% respectively. The poly crystalline silicon on 1-axis and 2-axis have percent difference between winter, summer, rainy seasons and the fixed system are 2.80%, 4.71%, 1.60% and 13.57%, 10.91%, 9.28% respectively in field test result from Thailand climate regions.

Table 13 The comparison data of the module temperature in field test result from Thailand climate regions

Condition	a-Si		m-Si		p-Si	
	1-axis rise than fixing (%)	2-axis rise than fixing (%)	1-axis rise than fixing (%)	2-axis rise than fixing (%)	1-axis rise than fixing (%)	2-axis rise than fixing (%)
Module Temperature (Winter)	2.47	10.67	7.96	12.44	2.8	13.57
Module Temperature (Summer)	3.31	9.07	5.41	7.96	4.71	10.91
Module Temperature (Rainy)	3.12	8.4	6.25	8.71	1.6	9.28
Module Temperature Average	2.98	9.38	6.54	9.71	2.17	11.25

On the other hand this research, analyzing how both module temperature and solar irradiation is a paramount importance for further understanding the effect of module temperature for power production of PV module. Figure 39–47 illustrate the variation of power with both solar irradiation and module temperature of a-Si, m-Si and p-Si on fixed, 1-axis and 2-axis respectively.

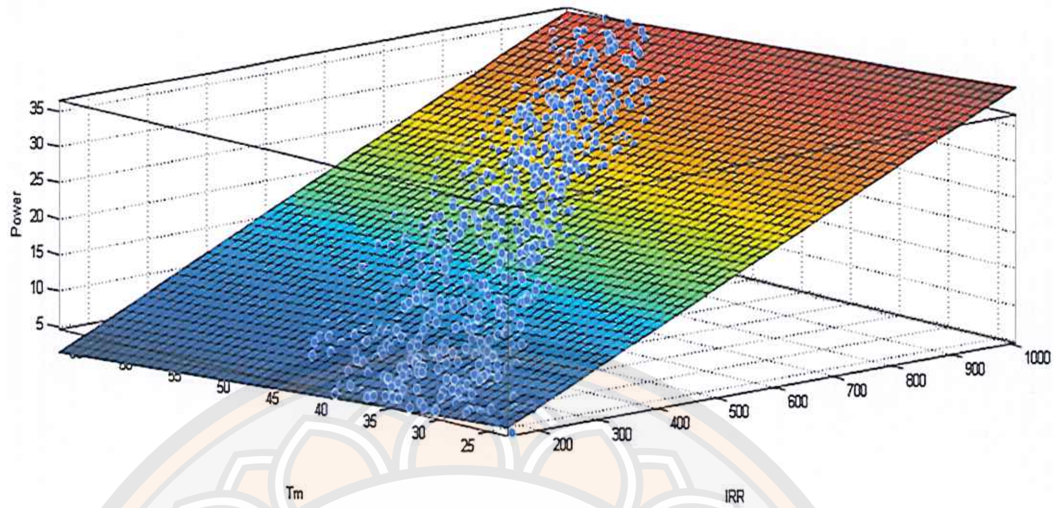

Figure 39 Effect of solar irradiance and module temperature on power productions of fixed a-Si PV module

Notably from Figure 39 is shown that the power production of a fixed PV module has direct effects to solar irradiance. But the temperature was less effects to power production of a-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

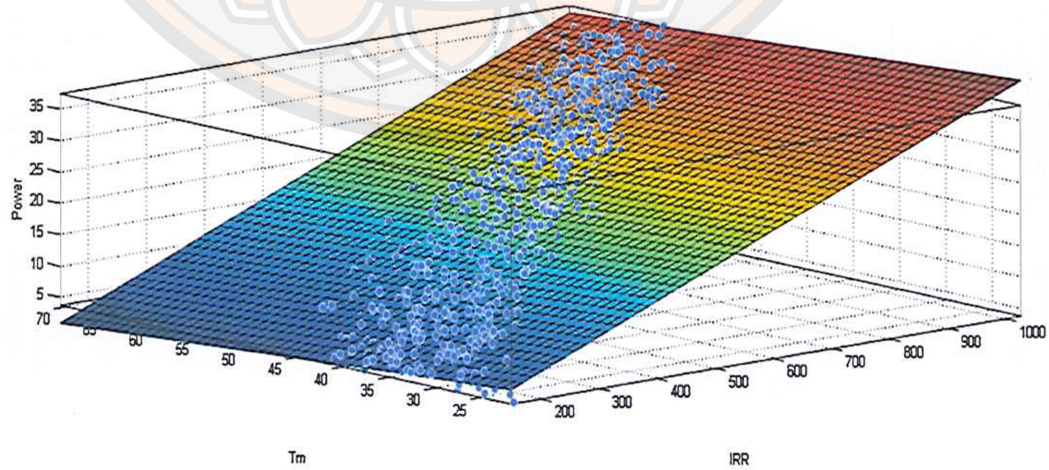

Figure 40 Effect of solar irradiance and module temperature on power productions of 1-axis a-Si PV module

Notably from Figure 40 is shown that the power production of 1-axis PV module has direct effects to solar irradiance. But the temperature was less effects to power production of a-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

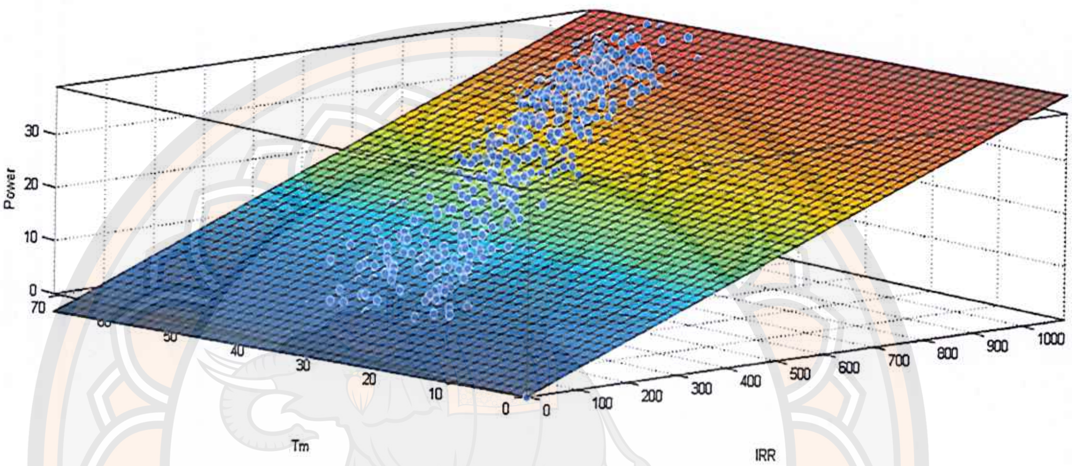

Figure 41 Effect of solar irradiance and module temperature on power productions of 2-axis a-Si PV module

Notably from Figure 41 is shown that the power production of 2-axis PV module has direct effects to solar irradiance. But the temperature was less effects to power production of a-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

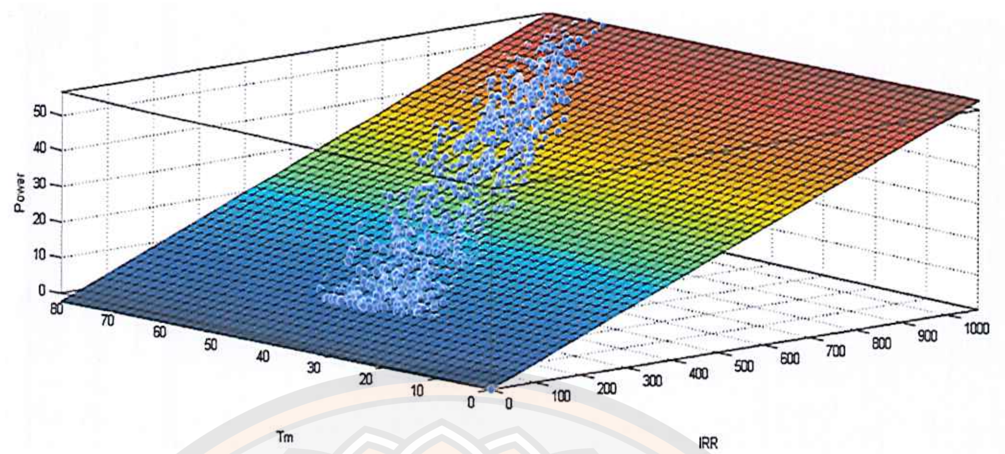

Figure 42 Effect of solar irradiance and module temperature on power production of fixed m-Si PV module

Notably from Figure 42 is shown that the power production of a fixed PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of m-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

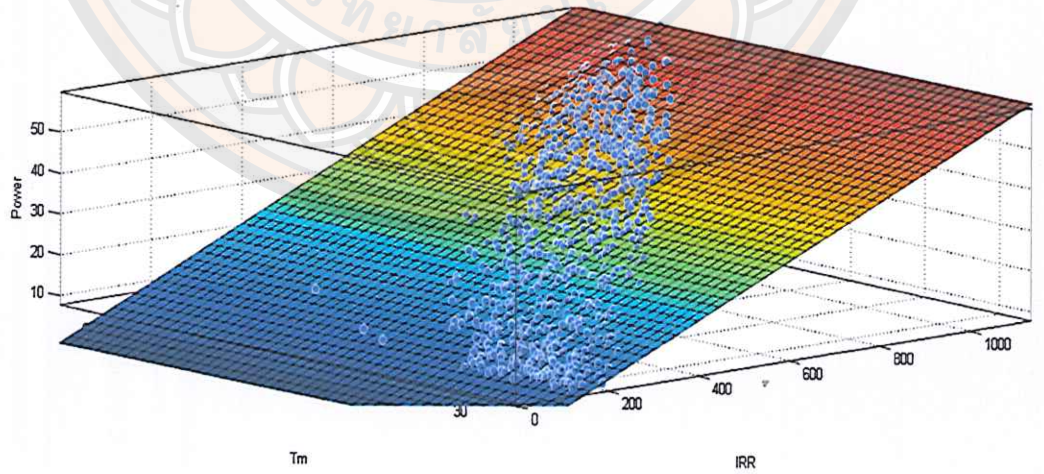

Figure 43 Effect of solar irradiance and module temperature on power productions of 1-axis m-Si PV module

Notably from Figure 43 is shown that the power production of 1-axis PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of m-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

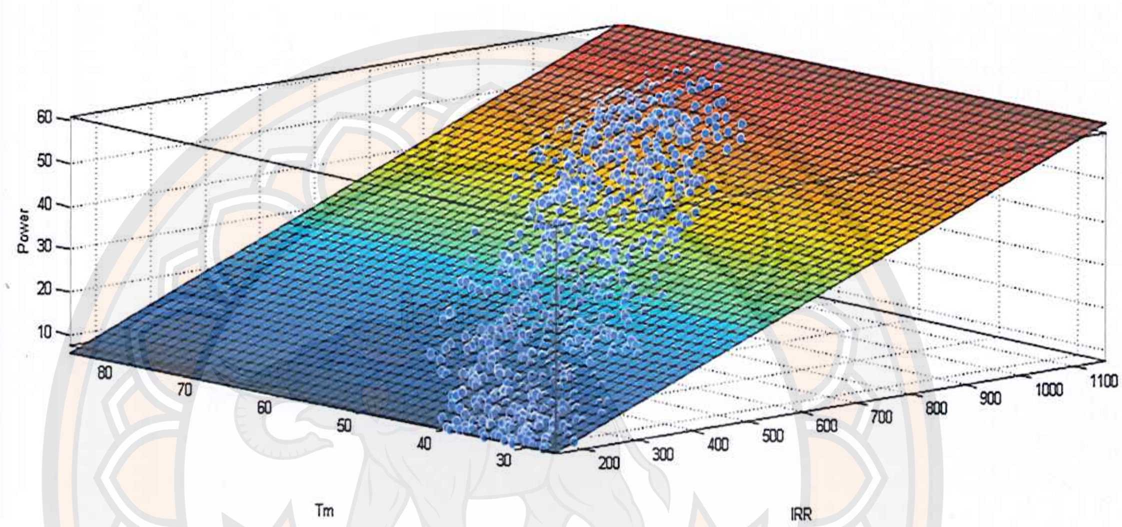

Figure 44 Effect of solar irradiance and module temperature on power production of 2-axis m-Si PV module

Notably from Figure 44 is shown that the power production of 2-axis PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of m-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

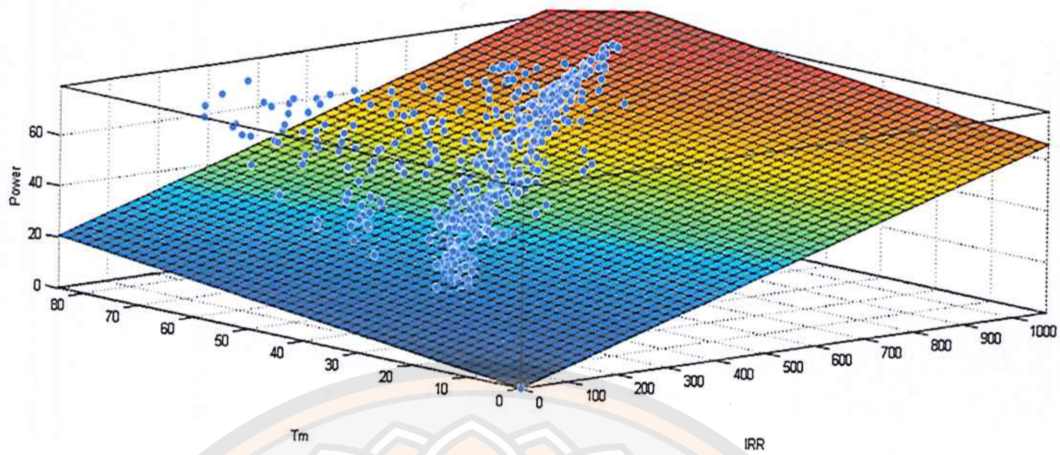

Figure 45 Effect of solar irradiance and module temperature on power productions of fixed p-Si PV module

Notably from Figure 45 is shown that the power production of a fixed PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of the p-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

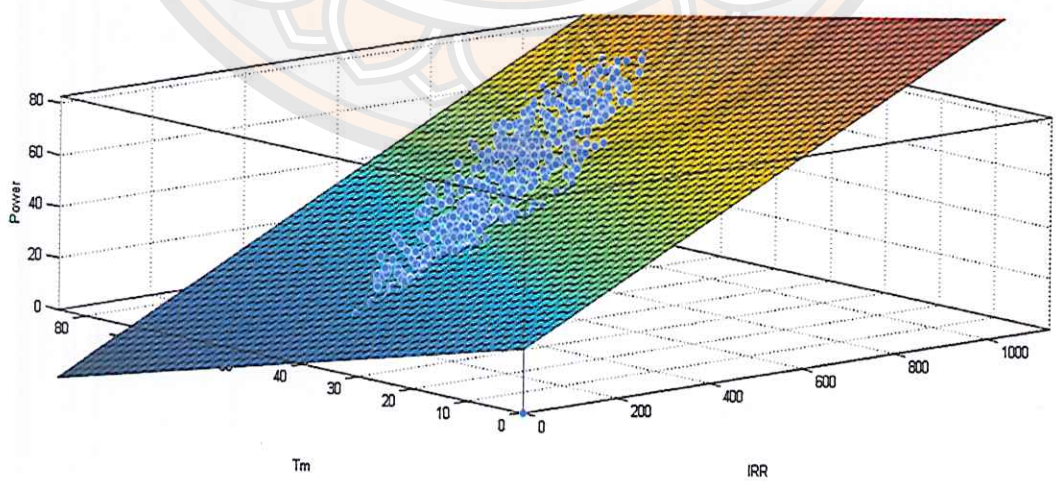

Figure 46 Effect of solar irradiance and module temperature on power production of 1-axis p-Si PV module

Notably from Figure 46 is shown that the power production of 1-axis PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of the p-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

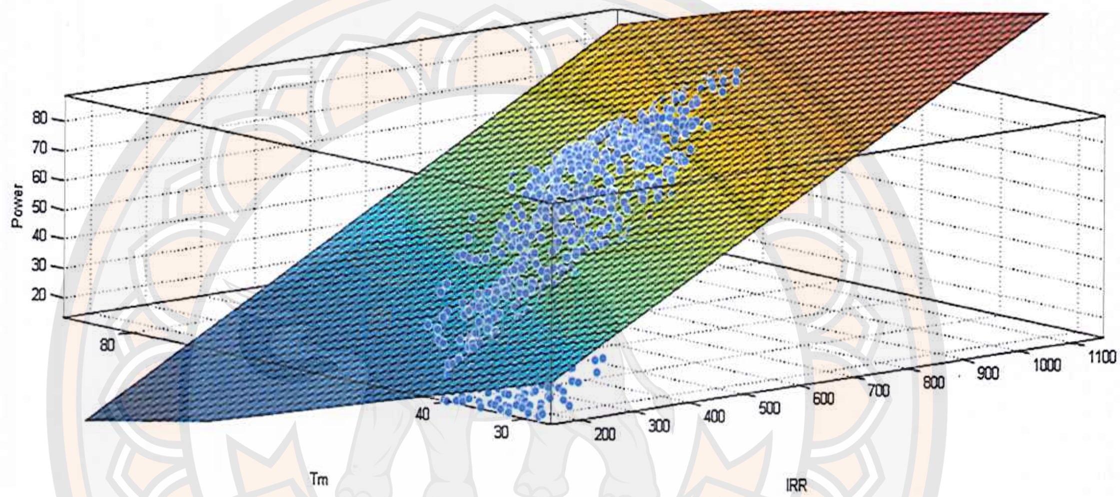

Figure 47 Effect of solar irradiance and module temperature on power production of 2-axis P-Si PV module

Notably from Figure 47 is shown that the power production of 2-axis PV module has direct effects to solar irradiance. But the temperature was more effects to power the production of the p-Si PV module. The maximum power production occurs at high solar irradiance and low module temperature as shows in the dark red color. And the dark blue color shows the minimum value of the power production of PV module.

In conclusion, it was found that the power of the p-Si and m-Si modules depended almost only on a module temperature, while that of the a-Si was little effect of module temperature. The behaviors were reasonable considering from the operating mechanisms of PV modules. These results demonstrate that solar irradiance is a reasonable and useful index to describe the module temperature for evaluating the power production and the performance of PV modules each PV technology.

Sections 2 The mathematical models for evaluating the effect of temperature on power output of photovoltaic module in tracking system

From the results of the first part, parameters, which have affected to the PV array power output, were solar irradiance and module temperature. Therefore, bringing together all parameters that affected to the PV array power output to develop the mathematic model as showed in this section. After the data were evaluated, the mathematical model of PV arrays can be developed. From the multiple linear regression models with k predictor variables, it is shown in Equation 4.1

$$y = a_0 + a_1x_1 + a_2x_2 + ... + a_kx_k \tag{4.1}$$

Let each of the k predictor variables, $x_1, x_2, ..., x_k$, have n levels. For example $y_1, y_2 ... y_n$ recorded for each of these n levels can be expressed in the following

$$y_1 = a_0 + a_1x_{11} + a_2x_{21} + ... + a_kx_{1k} \tag{4.2}$$

$$y_2 = a_0 + a_1x_{21} + a_2x_{22} + ... + a_kx_{2k} \tag{4.3}$$

$$y_n = a_0 + a_1x_{n1} + a_2x_{n2} + ... + a_kx_{nk} \tag{4.4}$$

The system of n equations shown previously can be represented in matrix notation as follows:

$$y = xa \tag{4.5}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} \qquad x = \begin{bmatrix} 1 & x_{11} & x_{12} & . & . & . & x_{1k} \\ 1 & x_{21} & x_{22} & . & . & . & x_{2k} \\ . & & & & & & \\ . & & & & & & \\ . & & & & & & \\ 1 & x_{n1} & x_{n2} & . & . & . & x_{nk} \end{bmatrix}$$

Where:

$$a = \begin{bmatrix} a_1 \\ a_2 \\ . \\ . \\ . \\ a_n \end{bmatrix}$$

The matrix in Equation 4.8 is referred to as the design matrix. It contains information about the levels of the predictor variables at which the observations are obtained. The vector "a" contains all the regression coefficients. To obtain the regression model, "a" should be known. "a" is estimated using least square estimates. The following equation is used:

$$\hat{a} = (x'x)^{-1}x'y \tag{4.6}$$

Where $'$ represents the transpose of the matrix while $^{-1}$ represents the matrix inverse. Knowing the estimates, $\hat{a}$, the multiple linear regression model can now be estimated as:

$$\hat{y} = x\hat{a} \tag{4.7}$$

The estimated regression model is also referred to as the fitted model. The observations, y_i, may be different from the fitted values $\hat{y}_i$ obtained from this model. The difference between these two values is the residual, e_i. The vector of residuals, e, is obtained as

$$e = y - \hat{y} \tag{4.8}$$

In additional, mathematical model of PV arrays of this study can be written in form of "Power = a_0+ $a_1 \times$IRR + $a_2 \times T_m$". From the matrix method, the a_0, a_1, a_2, was found by using linear regression from equation 4.6 or curve fitting tool of MATLAB program. Thus the mathematical model of PV arrays with respect to solar irradiance and module temperature to predicting the power output of a-Si PV array, m-Si PV array and p-Si PV array on three systems as shown in equation 4.9-4.17 respectively.

$$P_{a\text{-}Si,\ Fixed} = 2.161 + (0.0399 \times IRR) + (-0.09667 \times T_m) \tag{4.9}$$

$$P_{a\text{-}Si,\ 1\text{-}axis} = 2.256 + (0.04029 \times IRR) + (-0.1043 \times T_m) \tag{4.10}$$

$$P_{a\text{-}Si,\ 2\text{-}axis} = 9.341e\text{-}017 + (0.03902 \times IRR) + (-0.04773 \times T_m) \tag{4.11}$$

$$P_{m\text{-}Si,\ Fixed} = -0.0002007 + (0.05483 \times IRR) + (-0.02951 \times T_m) \tag{4.12}$$

$$P_{m\text{-}Si,\ 1\text{-}axis} = -0.06943 + (0.05396 \times IRR) + (-0.0159 \times T_m) \tag{4.13}$$

$$P_{m\text{-}Si,\ 2\text{-}axis} = 0.4412 + (0.05478 \times IRR) + (-0.0328 \times T_m) \tag{4.14}$$

$$P_{p\text{-}Si,\ Fixed} = -4.708e\text{-}013 + (0.06162 \times IRR) + (0.2397 \times T_m) \tag{4.15}$$

$$P_{p\text{-}Si,\ 1\text{-}axis} = 24.76 + (0.09653 \times IRR) + (-0.5987 \times T_m) \tag{4.16}$$

$$P_{p\text{-}Si,\,2\text{-}axis} = 35.42 + (0.1104 \times IRR) + (-0.9015 \times T_m) \quad (4.17)$$

Therefore, mathematical models were used to calculate power output of three different types of PV technology and their accuracy also need to be validated. A previous topic of this study was used to validate these mathematical models. The results of output power are shown in Figure 48-56 respectively.

The parameters that have affected to the module temperature of PV arrays were solar spectrum irradiation, ambient temperature, humidity and wind speed. However, solar irradiation and module temperature have higher affected on the module temperature of PV arrays than wind speed and humidity. Therefore, bringing together all parameters that affected to the PV arrays performance to develop the mathematical model as shown in following section.

From the basic equation of multi regression analysis "$Y = a_0+a_1X_1+a_2X_2$". After the data were evaluated, the mathematical model of PV arrays can be developed. In additional, mathematical model of PV arrays of this study can be written in form of "$T_{My} = a_0+ a_1 \times Ta + a_2 \times IRR$. From the matrix method, the a_0, a_1, a_2, can be calculated by using excel program. Thus the mathematical model of PV arrays with respect to solar irradiation and ambient temperature for predicting module temperature of a-Si PV array, m-Si PV array and p-Si PV array as shown in equation 4.18-4.26 respectively.

$$T_{m,a\text{-}Si,\,Fixed} = -\,0.3162 + (0.02896 \times IRR) + (1.001 \times T_a) \quad (4.18)$$

$$T_{m,a\text{-}Si,\,1\text{-}axis} = -\,0.3376 + (0.02893 \times IRR) + (1.004 \times T_a) \quad (4.19)$$

$$T_{m,a\text{-}Si,\,2\text{-}axis} = -\,0.2080 + (0.02898 \times IRR) + (1.002 \times T_a) \quad (4.20)$$

$$T_{m,m\text{-}Si,\,Fixed} = -\,0.7229 + (0.03958 \times IRR) + (1.007 \times T_a) \quad (4.21)$$

$$T_{m,m\text{-}Si,\,1\text{-}axis} = -\,0.7778 + (0.03959 \times IRR) + (1.014 \times T_a) \quad (4.22)$$

$$T_{m,m\text{-}Si,\,2\text{-}axis} = -\,0.7178 + (0.03963 \times IRR) + (1.013 \times T_a) \quad (4.23)$$

$$T_{m,p\text{-}Si,Fixed} = -\,4.7500 + (0.03334 \times IRR) + (1.275 \times T_a) \quad (4.24)$$

$$T_{m,a\text{-}Si,\,1\text{-}axis} = -\,1.6140 + (0.03654 \times IRR) + (1.029 \times T_a) \quad (4.25)$$

$$T_{m,a\text{-}Si,\,2\text{-}axis} = -\,0.6277 + (0.04061 \times IRR) + (1.010 \times T_a) \quad (4.26)$$

Therefore, mathematical models were used to calculate power output of three different types of PV technology and their accuracy also need to be validated.

For accuracy the mathematical models also need to be validated. The first models was used to validate with the specific experiment was carried out in January, March and November 2010, the results of a-Si, m-Si and poly-Si power output on three systems are shown in Figure 48 - 56 respectively.

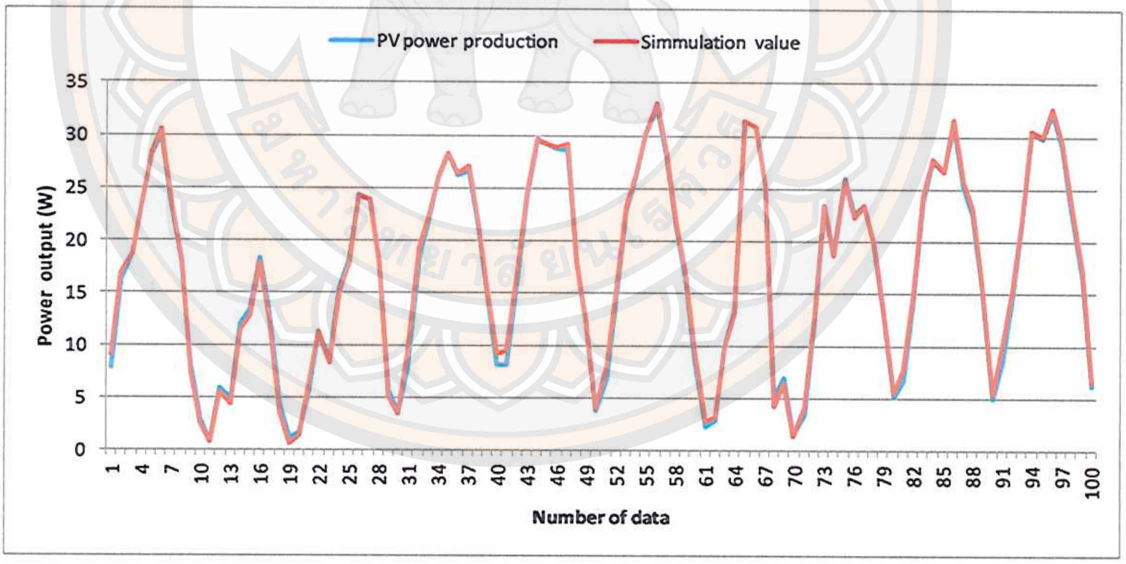

Figure 48 Comparison of simulated and experimental results of fixed a-Si PV power output

From Figure 48, the comparison of simulated and experimental results of a-Si PV technology on fixed system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±0.17%, this difference is based on the experimental results.

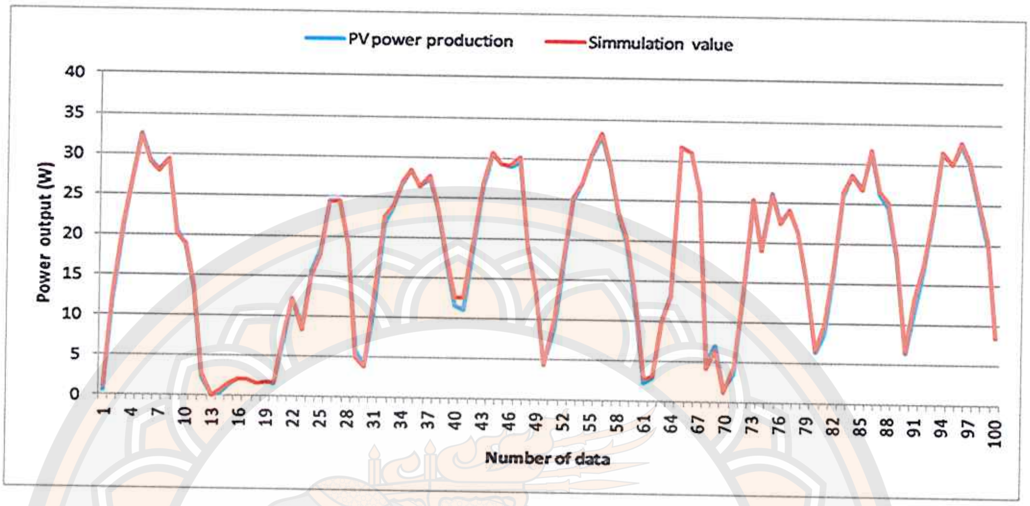

Figure 49 Comparison of simulated and experimental results of 1-axis a-Si PV power output

From Figure 49, the comparison of simulated and experimental results of a-Si PV technology on a 1-axis system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±5.06%, this difference is based on the experimental results.

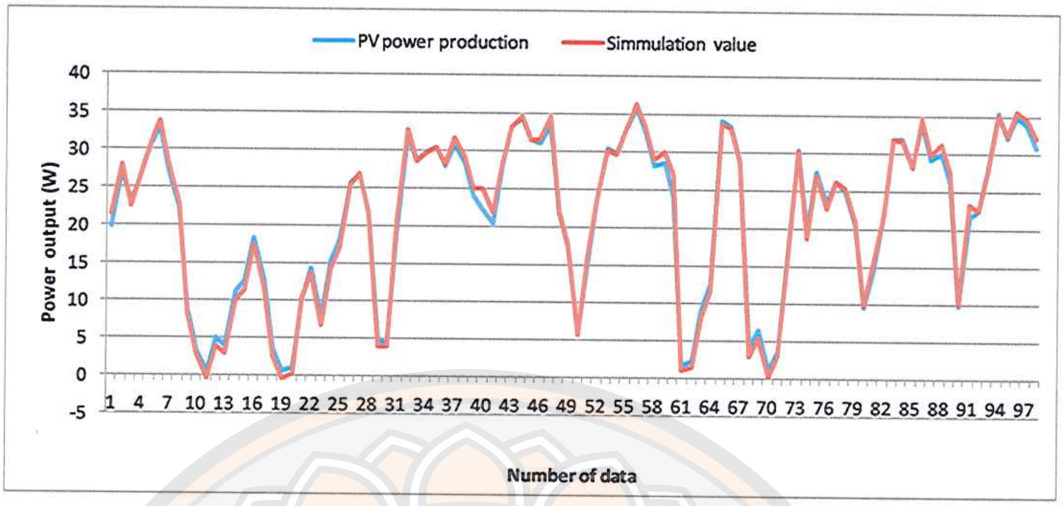

Figure 50 Comparison of simulated and experimental results of 2-axis a-Si PV power output

From Figure 50, the comparison of simulated and experimental results of a-Si PV technology on a 2-axis system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±2.52%, this difference is based on the experimental results.

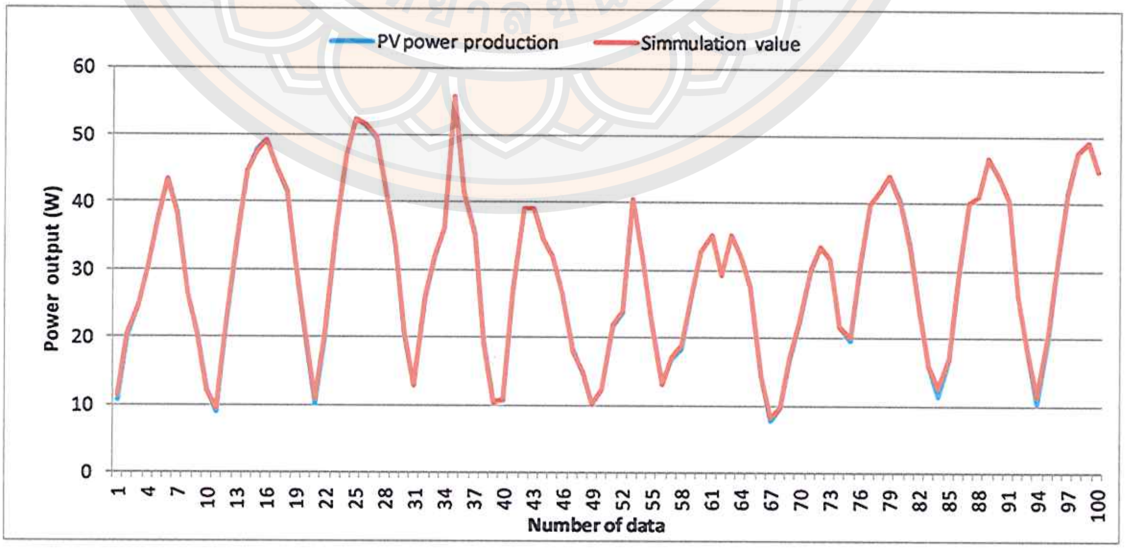

Figure 51 Comparison of simulated and experimental results of fixed m-Si PV power output

From Figure 51, the comparison of simulated and experimental results of m-Si PV technology on fixed system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±0.71%, this difference is based on the experimental results.

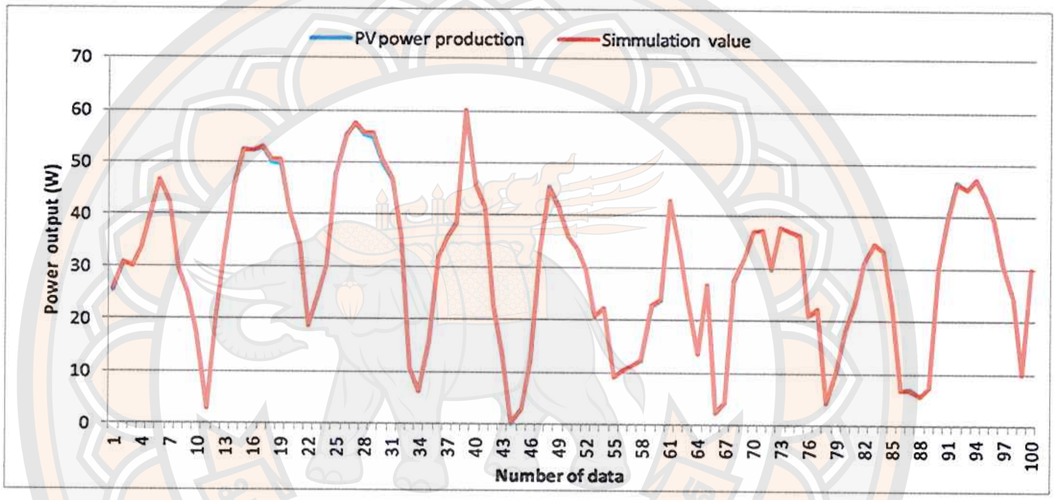

Figure 52 Comparison of simulated and experimental results of 1-axis m-Si PV power output

From Figure 52, the comparison of simulated and experimental results of m-Si PV technology on a 1-axis system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±0.69%, this difference is based on the experimental results.

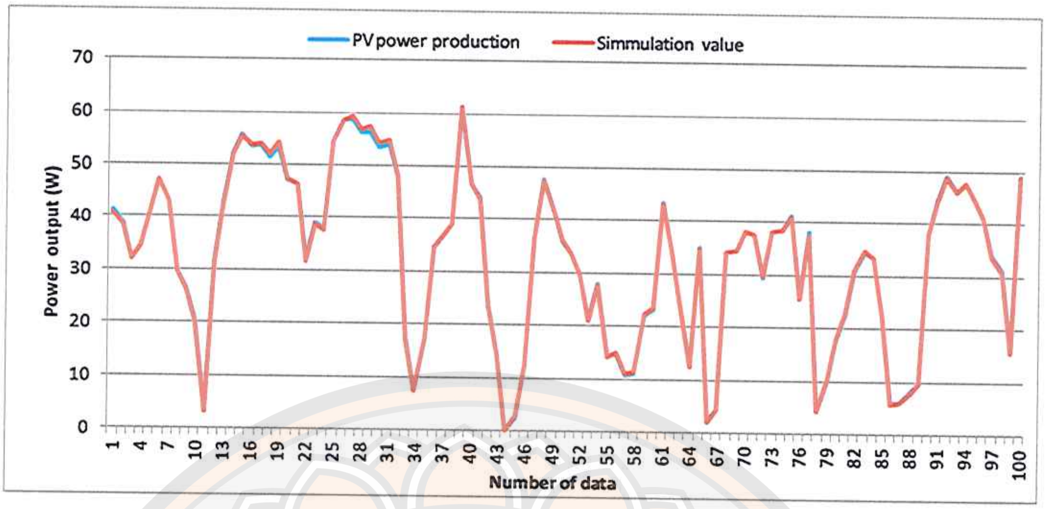

Figure 53 Comparison of simulated and experimental results of 2-axis m-Si PV power output

From Figure 53, the comparison of simulated and experiment results of m-Si PV technology on 2-axis system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±0.74%, this difference is based on the experimental results.

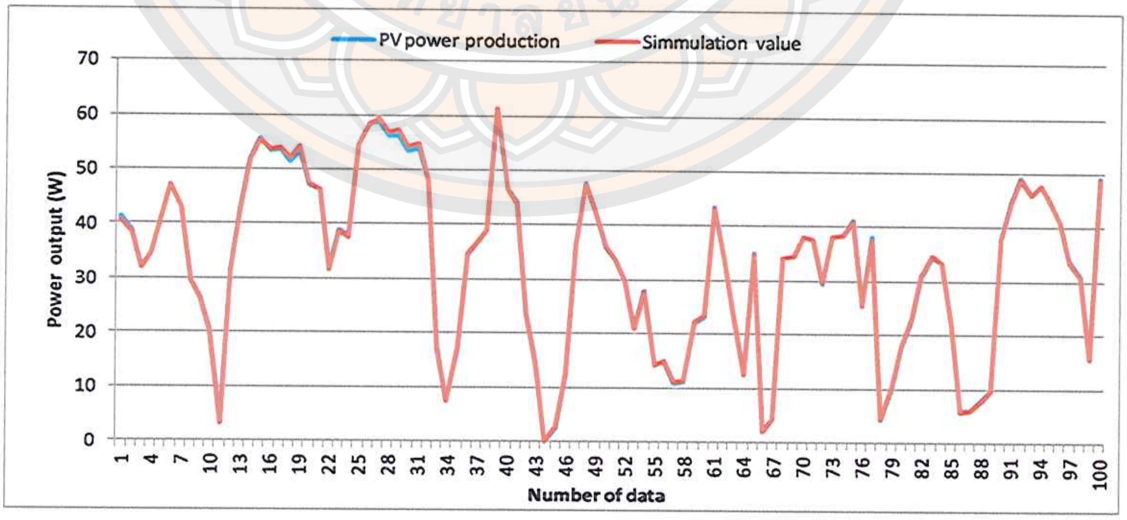

Figure 54 Comparison of simulated and experimental results of fixed p-Si PV power output

From Figure 54, the comparison of simulated and experimental results of p-Si PV technology on fixed system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±0.72%, this difference is based on the experimental results.

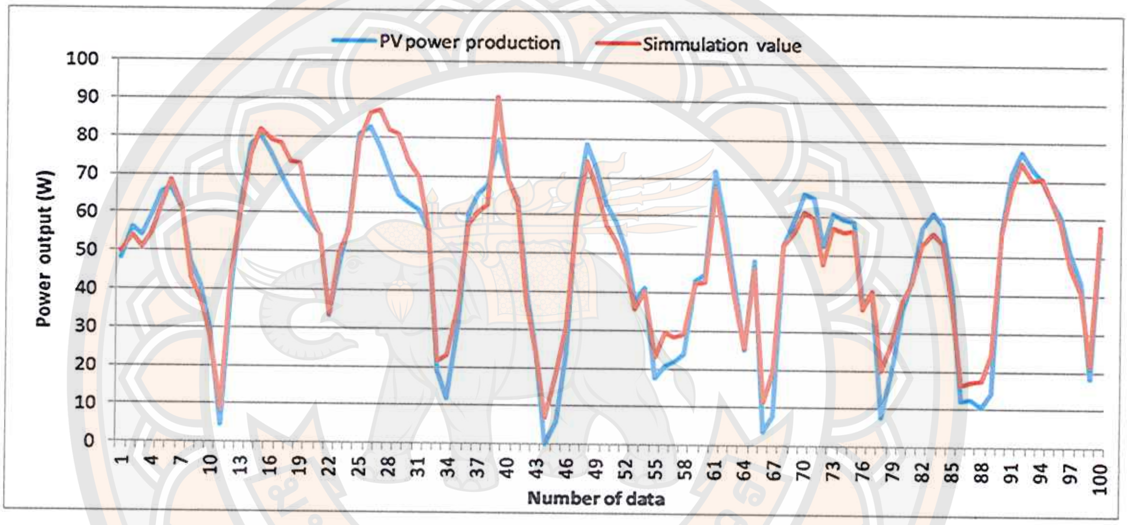

Figure 55 Comparison of simulated and experimental results of 1-axis p-Si PV power output

From Figure 55, the comparison of simulated and experimental results of p-Si PV technology on a 1-axis system showed that the PV power production at any time is nearly similar by analyzing the data; it was found that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±6.42%. The miss match percents have more than the other type has cause by the other parameter such as wind speed and humidity. This difference is based on the experimental results.

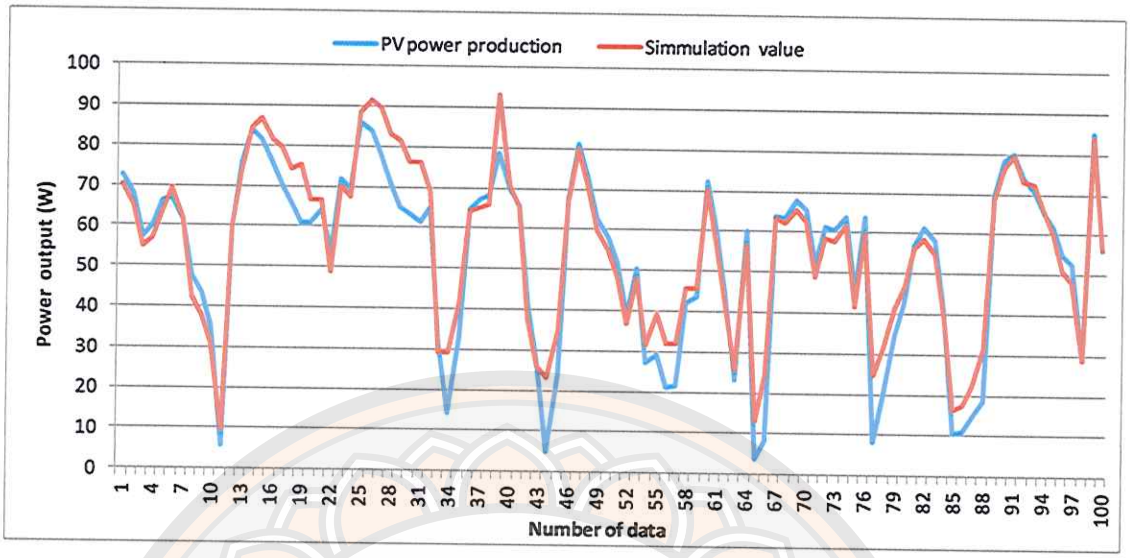

Figure 56 Comparison of simulated and experimental results of 2-axis p-Si PV power output

From Figure 56, the comparison of simulated and experimental results of psi PV technology on a 2-axis system showed that the PV power production at any time is nearly similar by analyzing the data. From Table 14, the results show that the majority of the simulation results by mathematical model are a bit greater than the experiment results. The maximum difference between experimental and simulation results approximately ±7.09%. The miss match percents have more than the other type has cause by the other parameter such as wind speed and humidity. This difference is based on the experimental results.

Table 14 The power output comparison between mathematical model and field test data

Condition	a-Si			m-Si			p-Si		
	fixed (%)	1-axis (%)	2-axis (%)	fixed (%)	1-axis (%)	2-axis (%)	fixed (%)	1-axis (%)	2-axis (%)
Error form Measuring (%)	±0.17	±5.06	±2.52	±0.71	±0.69	±0.74	±0.72	±6.42	±7.09

Sections 3 The program for accurate estimation of the photovoltaic module power output of tracking system power plant in large scale and investment cost optimization

The mathematical models in the developing were used to calculate the module temperature, power output of three difference types of PV technology and three systems as; Fixed, 1-axis and 2-axis tracking for use in the simulation program with Microsoft Office Excels 2007 in this section and compare with the commercial program.

Performance Analysis

The result of the Development PV program in energy production term when compare with the PVsyst V5.41 Program license from the School of Renewable Energy Technology (Customer ID: 30051902). The module temperature was calculated from 4.18–4.26 equation and the energy production was calculated from 4.9–4.17 equation and convert to the 1 MW when the other loss in a system such as; the mismatch, soiling loss and DC loss were calculated by each system. This comparison was used the solar irradiance and the ambient temperature in Phitsanulok province, Thailand. Figure 57 shows the solar irradiance are 1,756 kWh/m^2•year.

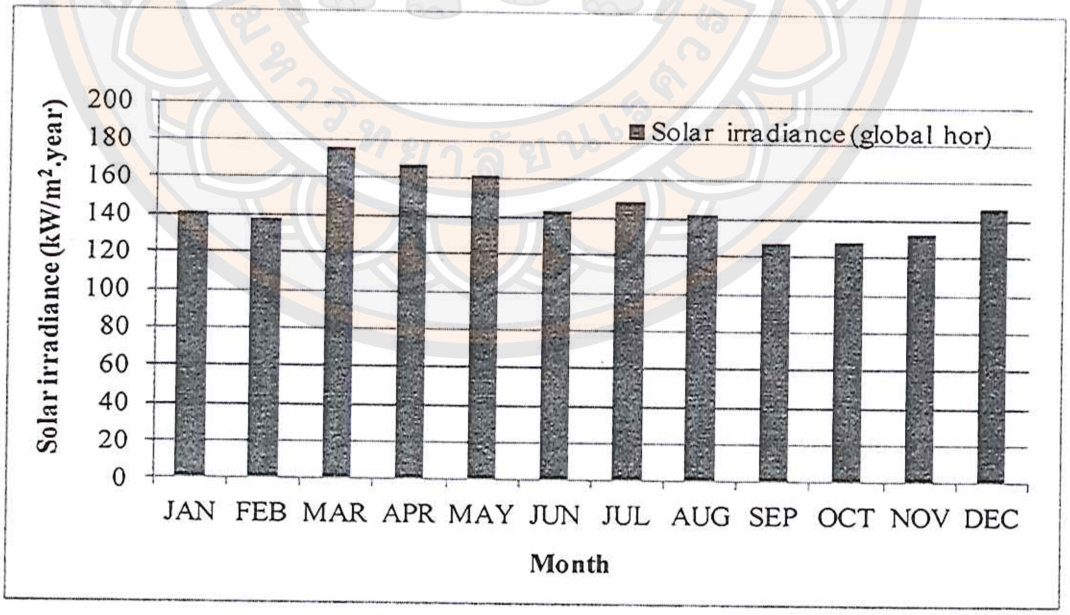

Figure 57 The solar irradiance at Phitsanulok province, Thailand

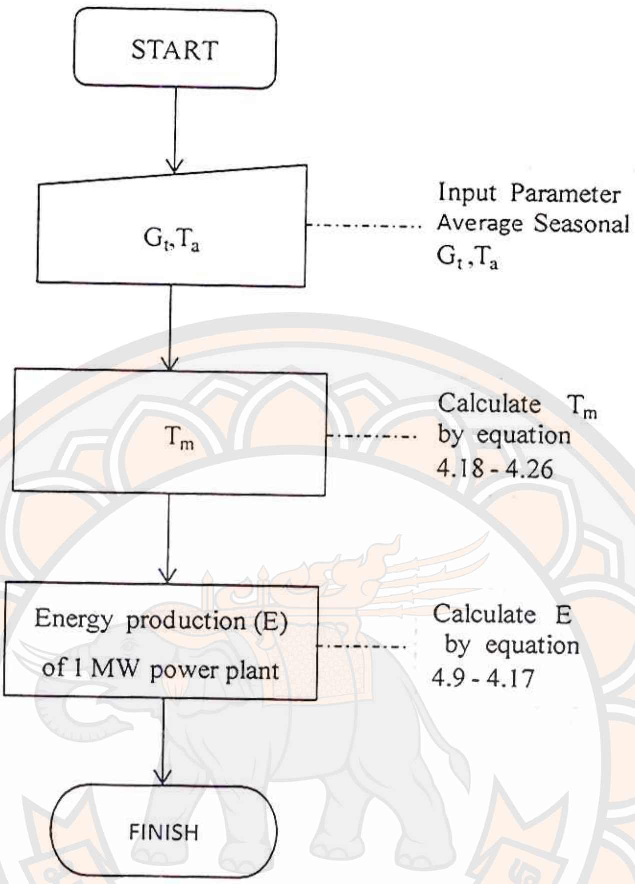

Figure 58 The simulation block diagram with input and output parameter

When calculate the energy production the loss in a system of 1 MW power plant is used data depend the PVsyst 5.21 Program. In amorphous silicon the mismatch, soiling loss and DC loss are 1.5%, 2.5% and 1.5% respectively. The mono crystalline silicon are 1.5%, 5% and 1.5% respectively. The poly crystalline silicon are 1.5%, 5% and 1.5% respectively. Figure 58-60 the graphical show the amorphous silicon PV on fixed system Electrical Energy Production (kWh/year) of the development program is 1397.20 kWh/year and the PVsyst 5.21 Program is 1429.06 kWh/year. The percent difference between the development program and the commercial program is 2.80%. The amorphous silicon PV Electrical Energy Production on 1-axis system of the development program is 1590.71 kWh/year and the PVsist 5.21 Program is 1652.09

kWh/year. The percent difference between the development program and the commercial program is 4.22%. The amorphous silicon PV Electrical Energy Production on 2-axis system of the development program is 1718.45 kWh/year and the PVsist 5.21 Program is 1846.07 kWh/year. The percent difference between the development program and the commercial program is 7.78%. The electrical energy production of the development program is decrease than the commercial program. It's cause of the module temperature and the other environmental parameter has an effect to the electrical energy production this result is based on Thailand climate regions.

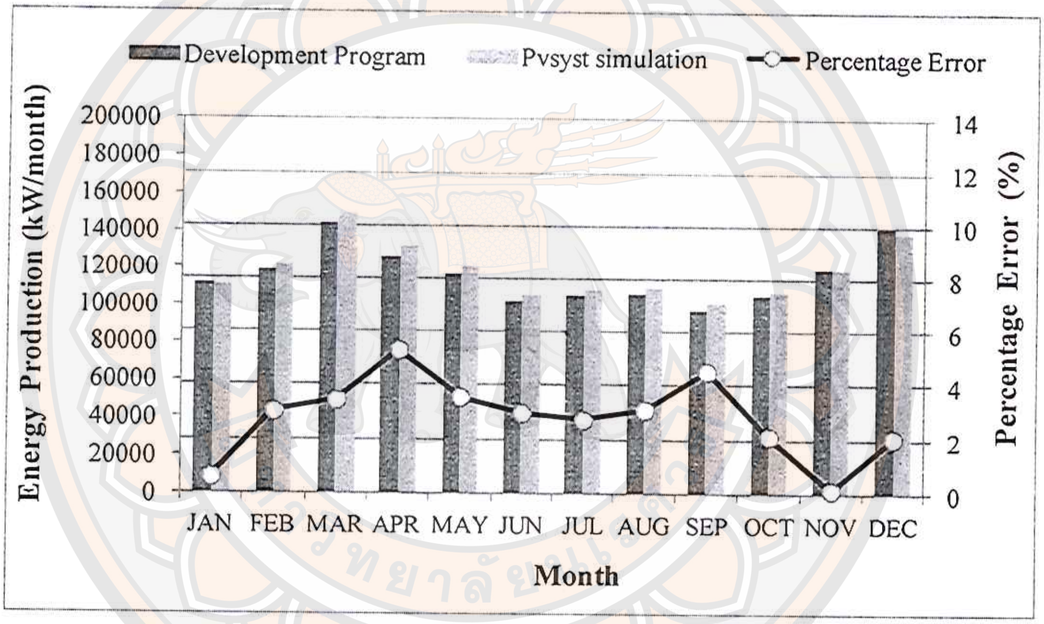

Figure 59 Comparison in energy production between development program and PVsyst program on 1 MW a-Si fixed PV system

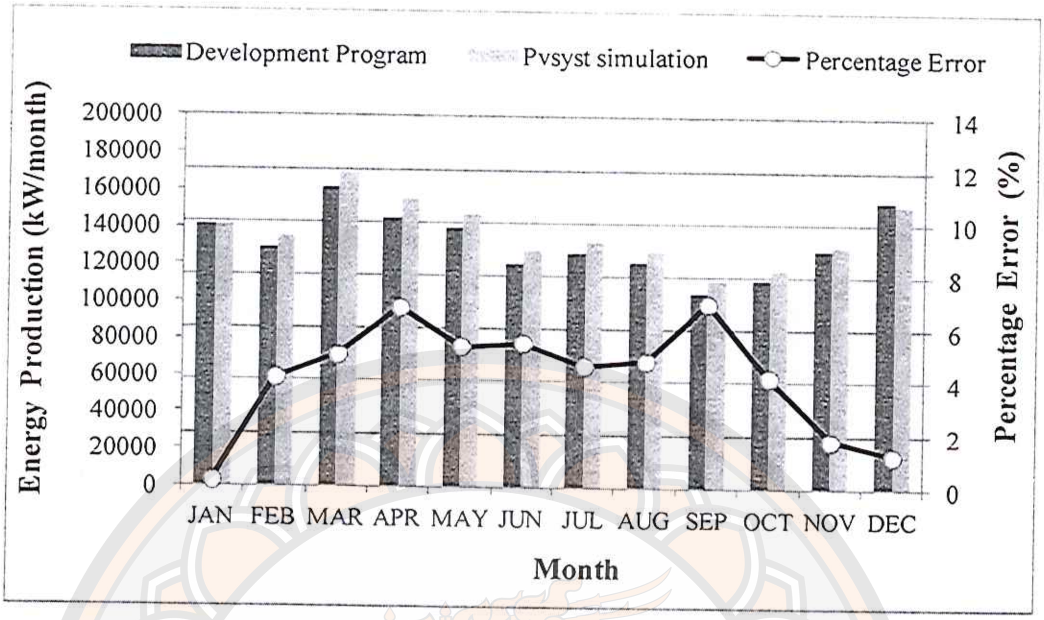

Figure 60 Comparison in energy production between development program and PVsyst program on 1 MW a-Si 1-axis PV system

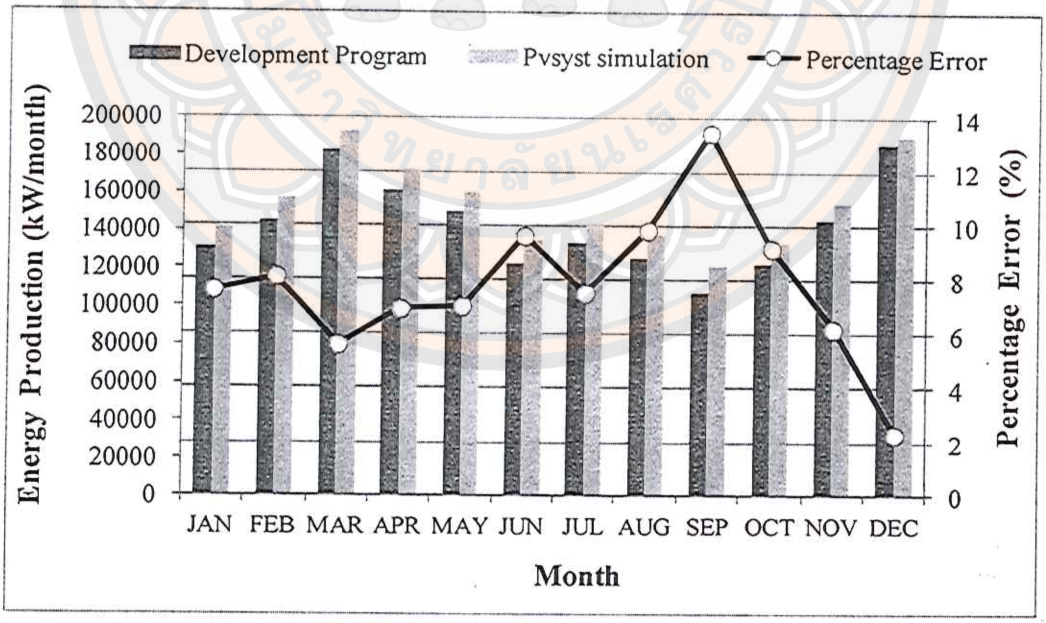

Figure 61 Comparison in energy production between development program and PVsyst program on 1 MW a-Si 2-axis PV system

From Table 15, the finding has shown that the environment parameter has an effect to the power output of the power plant in Thailand hot climate. The energy production of a-Si PV 1 MW on fixed, 1-axis and 2-axis system less than the commercial program which is approximately 2.80%, 4.22% and 7.78% respectively. The energy production of m-Si PV 1 MW on fixed, 1-axis and 2-axis system less than the commercial program are approximately 8.83%, 9.91% and 11.09 % respectively. The energy production of p-Si PV module on fixed, 1 axis and 2 axis system less than the commercial program are approximately 7.05%, 12.15% and 13.49% respectively. This difference is based on the experimental results.

Table 15 The comparison between the development program and the commercial program in 1 MW power plant

Condition	a-Si			m-Si			p-Si		
	fixed	1-axis	2-axis	fixed	1-axis	2-axis	fixed	1-axis	2-axis
Development Program (kWh/year)	1397.2	1590.71	1718.81	1271.62	1410.2	1582.95	1269.57	1345.2	1523.49
Pvsyst Program (kWh/year)	1429.06	1652.09	1846.07	1392.84	1564.15	1778.15	1361.24	1538.2	1733.68
Difference percent from the commercial program (%)	2.8	4.22	7.78	8.83	9.91	11.09	7.05	12.15	13.49

Economic Analysis

In this section, the objective is to calculate and evaluate the economics of three PV systems as fixed, 1-axis and 2-axis of a grid connected PV system by using equation 9 - 12 from chapter III. The evaluation uses the data of Performance analysis in the electrical energy production and calculate depend the condition as;

1. Calculate and evaluate the electricity power plant 1 MW

2. Calculate and evaluate in three PV module technology as; 40Wp amorphous silicon (a-Si), 75Wp mono crystalline silicon (m-Si) and 120Wp poly crystalline silicon (p-Si).

3. 7.35% Discount Rate by not consider the effect of the Inflation Rate. [30]

4. 14 years working life of grid connected inverter

5. - 0.5% per year for rate of PV module efficiency

6. 1.3%, 1.94% and 2.36% for O&M on fixed, 1-axis and 2-axis respectively [31-33]

7. Price of PV module as 30, 41 and 42 Baht/watt in a-Si, m-Si and p-Si respectively [33-34]

8. Price of inverter is 10 Bath/watt

9. 25 years working life of the system

10. 6.16 Bath Feed-in Tariff for 25 years [35]

Table 16 The economic results of grid connected a-Si PV system between the data from Development program and the Commercial program [31,32]

No.	Lists	PV system cost 1 MW					
		Cost (Development Program)			Cost (Commercial Program)		
		Fixing	1-axis	2-axis	Fixing	1-axis	2-axis
1	PV amorphous silicon	30,000,000	30,000,000	30,000,000	30,000,000	30,000,000	30,000,000
2	Cost of PV structure*	10,119,400	19,000,000	19,000,000	10,119,400	19,000,000	19,000,000
3	Foundation*	809,552	2,000,000	2,000,000	809,552	2,000,000	2,000,000
4	Azimuth tracking system*	-	5,000,000	5,000,000	-	5,000,000	5,000,000
5	Altitude tracking system*	-	-	2,000,000	-	-	2,000,000
6	Inverter	10,000,000	10,000,000	10,000,000	10,000,000	10,000,000	10,000,000
7	Others*	1,950,000	3,900,000	3,900,000	1,950,000	3,900,000	3,900,000
Investment Cost		52,878,952	69,900,000	71,900,000	52,878,952	69,900,000	71,900,000
Electrical Energy Production (kWh/year)		1,397,203	1,590,711	1,718,807	1,429,057	1,652,098	1,846,068
Net Present Value (NPV:THB)		28,867,348	17,204,030	19,900,877	29,797,924	21,299,528	28,391,188
Cost per Unit (THB/kWh)		4.25	5.16	5.09	4.23	4.97	4.74
Pay Back Period (year)		9.87	12.33	12.46	9.97	11.87	11.60
Internal rate of return (%)		13.42	10.17	10.51	13.60	10.82	11.79

Note: The marker data (*) base on the literature review in Thailand

From Table 16 shows the evaluation of 1 MW power plant when compare between the data of development program and the commercial program. The result shows that the benefit per cost ratio of development program is the same trend with the commercial program result of the fixed system has more interest in the benefit per cost ratio and found that the COE of the development program are higher cost than the commercial program of fixed, 1-axis and 2-axis as; 0.42%, 3.86% and 7.40% respectively. The Internal rate of return in the development program differs than the commercial program on fixed, 1-axis and 2-axis are approximate -1.37%, -5.94% and -10.87% respectively and the payback period in the development program differs than the commercial program on fixed, 1-axis and 2-axis are approximate -0.99%, 3.86% and 7.40% respectively. Which results present that the real PV installation on fixed, 1-axis and 2-axis have more payback period than the program simulation. In the mono crystalline silicon and poly crystalline silicon are the same trends with the amorphous silicon. Thus the project evaluation should give the weight of the environmental parameter such as the ambient temperature and module temperature because the rise of module temperature has effect to decrease the energy production.

CHAPTER V

CONCLUSION AND RECOMMENDATION

Conclusions

This thesis was separated into three sections. The first section is the effect of Temperature on power output of photovoltaic module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate conditions were evaluated. The second section is to develop the mathematical models for evaluation the effect of temperature on power output of photovoltaic module in tracking system. And the third section is to develop the program to accurately estimate the power output of photovoltaic module on tracking system power plant in large scale and investment cost optimization.

Sections 1 The effect of Temperature on power output of photovoltaic module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate condition.

This topic presents the result of relationships between the environmental parameters to the performance of PV described as following;

The relationship between PV power production and three difference types of PV technology and three systems as; Fixed, 1-axis and 2-axis tracking each seasonal of the year, which it was found that in Thailand condition when we compare the power output from each system tracking and fixed on varied technology in amorphous silicon has signal of most power raising between 2-axis tracking on winter season but 1-axis tracking most power raising on rainy season. In mono crystalline silicon was the most power raising both 1-axis and 2-axis tracking when compare with fixing system on winter season. In poly crystalline was same trend with mono crystalline silicon module technology. When comparing in term of module temperature. The result shown that on summer season was highest module temperature for all technologies. From these results can confirm that the efficiency of PV array is not only depending on solar irradiance but also depending on the module.

In conclusion, it was found that the power of the poly-Si modules depended almost only on a module temperature, while that of the a-Si and m-Si was little effect from module temperature. The behaviors were reasonable considering from the operating mechanisms of PV modules. These results demonstrate that solar irradiance is a reasonable and useful index to describe the module temperature for evaluating the power production and the performance of PV modules each PV technology.

Sections 2 The mathematical models for evaluating the effect of temperature on power output of photovoltaic module in tracking system.

In the part of the parameters that affected to the PV arrays power output was solar irradiation and module temperature, which that affected to the PV arrays power output to develop the mathematic model is described as follow:

The mathematical model of PV arrays with respect to solar irradiation and module temperature for predicting the power output of a-Si PV array, m-Si PV array and p-Si PV array on three systems as shown in equation:

$$P_{a\text{-}Si,Fixed} = 2.161 + (0.0399 \times IRR) + (-0.09667 \times T_m)$$

$$P_{a\text{-}Si,1\text{-}axis} = 2.256 + (0.04029 \times IRR) + (-0.1043 \times T_m)$$

$$P_{a\text{-}Si,2\text{-}axis} = 9.341e\text{-}017 + (0.03902 \times IRR) + (-0.04773 \times T_m)$$

$$P_{m\text{-}Si,Fixed} = -0.0002007 + (0.05483 \times IRR) + (-0.02951 \times T_m)$$

$$P_{m\text{-}Si,1\text{-}axis} = -0.06943 + (0.05396 \times IRR) + (-0.0159 \times T_m)$$

$$P_{m\text{-}Si,2\text{-}axis} = 0.4412 + (0.05478 \times IRR) + (-0.0328 \times T_m)$$

$$P_{p\text{-}Si,Fixed} = -4.708e\text{-}013 + (0.06162 \times IRR) + (0.2397 \times T_m)$$

$$P_{p\text{-}Si,1\text{-}axis} = 24.76 + (0.09653 \times IRR) + (-0.5987 \times T_m)$$

$$P_{p\text{-}Si,2\text{-}axis} = 35.42 + (0.1104 \times IRR) + (-0.9015 \times T_m)$$

The mathematical model of three PV technologies and three system Tracking with respect to solar irradiance and module temperature for predicting the power output of the maximum difference between experimental approximately ±7% from field test data.

The mathematical model of PV arrays with respect to solar irradiation and ambient temperature for predicting module temperature of a-Si PV array, m-Si PV array and p-Si array on three systems as shown in equation:

$$Tm_{,a\text{-}Si,Fixed} = -0.3162 + (0.02896 \times IRR) + (1.001 \times T_a)$$

$$Tm_{,a\text{-}Si,\,1\text{-}axis} = -0.3376 + (0.02893 \times IRR) + (1.004 \times T_a)$$

$$Tm_{,a\text{-}Si,\,2\text{-}axis} = -0.2080 + (0.02898 \times IRR) + (1.002 \times T_a)$$

$$Tm_{,m\text{-}Si,Fixed} = -0.7229 + (0.03958 \times IRR) + (1.007 \times T_a)$$

$$Tm_{,m\text{-}Si,\,1\text{-}axis} = -0.7778 + (0.03959 \times IRR) + (1.014 \times T_a)$$

$$Tm_{,m\text{-}Si,\,2\text{-}axis} = -0.7178 + (0.03963 \times IRR) + (1.013 \times T_a)$$

$$Tm_{,p\text{-}Si,Fixed} = -4.7500 + (0.03334 \times IRR) + (1.275 \times T_a)$$

$$Tm_{,a\text{-}Si,\,1\text{-}axis} = -1.6140 + (0.03654 \times IRR) + (1.029 \times T_a)$$

$$Tm_{,a\text{-}Si,\,2\text{-}axis} = -0.6277 + (0.04061 \times IRR) + (1.010 \times T_a)$$

Through, the maximum difference between experimental and simulation results are ± 2.22 °C or approximately ± 5% from the average module temperature, this difference is based on the experimental results.

In conclusion, the mathematical models that have been developed, it can use for predicting the module temperature and output power of 3 different PV technologies on the tracking system under Thailand climatic conditions. These mathematical models consist of parameters as following; solar irradiance, module temperature and ambient temperature. In our study found that the solar irradiance and module temperature was the most important factors that influence the power output of three different PV technologies on the tracking system.

Sections 3 The program for accurately estimate the power output of photovoltaic module on tracking system power plant in large scale and investment cost optimization.

The program simulation from mathematical model of three PV technologies and three systems Tracking with respect to solar irradiance and module temperature for predicting the power output on 1 MW scale. The difference between the development program and the commercial program are approximately 3-13% of the development program have less than the commercial program. In the poly crystalline technology and poly crystalline technology has more difference than the amorphous silicon This results show that the environment parameters like a temperature has an effect to the energy output of the power plant in Thailand hot climate. On the economic evaluation find that the development program has a more COE than evaluation of the commercial program and the payback period is used more time than the commercial program. Both of the program present in the same trend that the fixed system are more interesting than the tracking system because the high system cost of tracking as; installation structure and O&M is so expensive than the fixed system. The program simulation to predicting for performance and economic results for PV system to choosing and deciding that proper in technology in the future PV system installation in Thailand was developed.

Recommendation

The recommendations for The effect of Temperature on power output of PV module and performance of photovoltaic module in tracking and fixing system under Thailand hot climate conditions are listed as follows;

1. For accurate data to predict the power production should have more data record for long term.

2. The various economic scenarios are determined, as many parameters such as investment cost, O&M and discount factor, etc., the cause of the optimal result.

REFERENCES

REFERENCES

[1] Shaari, S., Sopian, K., Amin, N. and Kassim, M.N. (2009). The emperature dependence coefficients of amorphous silicon and crystalline photovoltaic modules using Malaysian field test investigation. **American Journal of Applied Sciences**, 6(4), 586-593.

[2] Kamkird, P., Ketjoy, N., Rakwichian, W. and Sukchai, S. (2012). Investigation on temperature coefficients of three types photovoltaic module technologies under Thailand operating condition. **Procedia Engineering,** 32, 376–383.

[3] Mattei, M., Notton, G., Cristofari, C., Muselli, M. and Poggi, P. (2006). Calculation of the polycrystalline PV module temperature using a simple method of energy balance. **Renewable Energy,** 31, 553–567.

[4] Carr and, A.J. and Pryor, T.L. (2004). A comparison of the performance of different PV module types in temperate climates. **Solar Energy,** 76, 285–294.

[5] Cueto, J.A. (2002). Comparison of energy production and performance from Flat-Plate Photovoltaic module technologies deployed at Fixed tilt. In **Proceeding of 29th IEEE PV Specialists conference** (pp.1523-1526). New Orleans: Louisiana.

[6] Markvart, T. (1996). **Solar electricity** (2nd ed.). New York: John Wiley and Sons.

[7] Khlaichom, P. and Sonthipermpoon, K. (2006). **Optimization of solar tracking system based on genetic algorithm.** Retrieved December 10, 2013, from http://www.thaiscience.info/

[8] Poulek, V. and Libra, M. (2007). **New bifacial solar trackers and tracking concentrators.** Retrieved December 10, 2013, from http://www. solar-trackers.com.

[9] Jhonn, A.D and Beckman, A.W. (1991). **Solar engineering of thermal processes.** New York: Wiley-Interscience Publication.

[10] Uyarel, A.Y. and Oz, E.S. (1987). **Solar energy and applications**. Ankara: Emel Publishers.

[11] Roth, P., Georgiev, A. and Boudinov, H. (2005). Cheap two-axis sun following device. **Energy Conversion and Management**, 46(7-8),1179–1192.

[12] Bione, J., Vilela, O.C. and Fraidenraich, N. (2004). Comparison of the performance of PV water pumping systems driven by fixed, tracking and V-trough generators. **Solar Energy,** 76(1), 703–711.

[13] Ai, B., Shen, H., Ban, Q., Ji, B. and Liao, X. (2003). Calculation of the hourly and daily radiation incident on three step tracking planes. **Energy Conversion and Management**, 44, 1999–2011.

[14] Sangani, C.S. and Solanki, C.S. (2007). Experimental evaluation of V-trough (2 suns) PV concentrator system using commercial PV modules. **Solar Energy Materials and Solar Cells**, 91, 453–459.

[15] Ibrahim, S.M.A. (1996). **The forced circulation performance of a sun tracking parabolic concentrator collector**. Retrieved December 10, 2013, from http://cat.inist.fr/.

[16] Baltas, P., Tortoreli, M. and Russell, P.E. (1986). Evaluation of power output for fixed and step tracking PV arrays. **Solar Energy**, 37(20), 147–63.

[17] Nann, S. (1990). Potential for tracking PV systems and V-troughs in moderate climates. **Solar Energy,** 45(6), 385–93.

[18] Braun, J.E. and Mitchell, J.C. (1983). Solar geometry for fixed and tracking surfaces. **Solar Energy**, 31(5), 439–44.

[19] Abdallah, S. and Nijmeh, S. (2004). Two axes sun tracking system with PLC control. **Energy Conversion and Management**, 45(11-12), 1931–1939.

[20] Mamlook, R., Nijmeh, S. and Abdallah, S.M. (2006). A programmable logic controller to control two axis sun tracking system. **Information Technology Journal**, 5(6), 1083–1087.

[21] Al-Mohamad, A. (2004). Efficiency improvements of photo-voltaic panels using a sun-tracking system. **Applied Energy,** 79(3), 345–354.

[22] Abdallah, S. (2004). The effect of using sun tracking systems on the voltage–current characteristics and power generation of flat plate PV. **Energy Conversion and Management**, 45, 1671–1679.

[23] Rubio, F.R., Ortega, M.G., Gordillo. F. and Lopez-Martınez, M. (2007). Application of new control strategy for sun tracking. **Energy Conversion and Management**, 48, 2174–2184.

[24] Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K. and Sharifi, A. (2009). A review of principle and sun-tracking methods for maximizing solar systems output. **Renewable and Sustainable Energy Reviews,** 13(2009), 1800–1818.

[25] Kohl, M. (2010). **Module reliability and failure analysis**. Freibur: Fraunhofer Institute Fur Solar Energies system.

[26] Zainuddin, H. (2013). **Assessment and empirical modeling of operating PV module temperature in Malaysian climate.** Doctoral Dissertation Ph.D., University technology Mara, Mara.

[27] U1-Saufie, A. Z., Yahya, A.S. and Ramli, N.A. (2011). Improving multiple linear regression model using principal component analysis for predicting PM10 concentration in Seberang Prai, Pulau Pinang. **Internation Journal of Enviromental Sciences**, 2(2), 403-410.

[28] Ho, R. (2006). **Handbook of univariate and multivariate data analysis and interpretation with SPSS.** Boca Raton, FL: Chapman & Hall/CRC Taylor & Francis Group.

[29] Hanisen, A. D., Sorensen, P., Hansen, L.H. and Bindner, H. (2000). **Models for a stand- alone PV system.** Roskilde Riso: National Laboratory.

[30] Bank of Thailand. (2014). **Daily Interest Rates of Commercial Banks**. Retrieved May 10, 2014, from http://www.bot.or.th/english/statistics/financialmarkets/interestrate/_layouts/application/interest_rate/IN_Rate.aspx

[31] Ketjoy, N., Mansiri, K., Ngernmeesri, R., Khaosaad, N. and Sirisamphanwong, C. (2013). Techno-economic evaluation of fixing and tracking PV power plant in Thailand. **Journal MSU**, 32(5), 5-7.

[32] National renewable energy laboratory. (2010). PV O&M best practices. In **Proceedings of the 4th International conference on integration of renewable and distributed energy resources**. New Mexico: Hyatt Regency Albuquerque.

[33] Feldman, D., Barbose, G., Margolis, R., Wiser, R., Darghouth, N.and Goodrich, A. (2012). **Photovoltaic (PV) pricing trends: historical, recent, and near-term projections**. Retrieved December 10, 2013, from http://www.osti.gov/bridge

[34] PVXchange. (2014). **Price index.** Retrieved January 15, 2014, from http://www.pvxchange.com/priceindex/Default.aspx?template_id=1&langTag=en-GB

[35] Electricity Generating Authority of Thailand. (2012). **Adder for VSPP.** Retrieved December 10, 2013, from http://www3.egat.co.th/ft/CEF_Adder/VSPP%20Adder_NEPC.htm

[35] The Energy Regulatory Commission. (2014). **Rate for energy producer.** Retrieved January 30, 2014, from http://www.erc.or.th/ ERCWeb2/Front/StaticPage/StaticPage.aspx?p=200&

[36] King, D. L., Kratochvil, J. A. and Boyson, W. E. (1997). Temperature coefficients for PV modules and arrays: measurement methods, difficulties, and results. In **Proceeding of the 26th IEEE photovoltaic specialists conference** (pp. 1183–1186). Anaheim: n.p.

APPENDIXE

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Investigation on Temperature Coefficients of Three Types Photovoltaic Module Technologies under Thailand Operating Condition

P. Kamkird, N. Ketjoy*, W. Rakwichian, S. Sukchai

School of Renewable Energy Technology, Naresuan University, Muang, Phitsanulok, 65000 Thailand

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Abstract

This article describes a methodology to find the temperature dependence coefficients of amorphous silicon, poly crystalline and Heterojunction Intrinsic thin layer photovoltaic (PV) module. There are measured under Thailand Operating Condition. This study present three technologies of photovoltaic modules using 3.67 kWp (68 modules) of Amorphous Silicon Solar Cell (a-Si) ,3.60 kWp (45 modules) of Poly Crystalline Silicon Solar Cell (p-Si) and 2.88 kWp (16 modules) of Heterojunction Intrinsic Thin Layer (HIT). There were installed at Energy Park, School of Renewable Energy Technology, Naresuan University (north latitude 16°47', east longitude 100°16'). The 10 kW PV power station data have been recorded since year 2008 January to 2009 December. It is analyzed by linear regression technique. In addition, an average solar irradiance value in 2008 was 660 W/m^2 and 640 W/m^2 in the year 2009. Upon analysis, the study will show the Temperature coefficient of current, voltage, power and efficiency on array temperature obtained from liner regression. These findings of field test investigation found that the temperature coefficient value of PV array different from the factory value and the temperature coefficients in the year 2009 is higher than the year 2008. These results have an impact on systems design and sizing in similar climate regions. Thus, recommended that design and sizing of PV system in Tropical climate regions of the world take due address to these results.

Keywords: Temperature coefficients of Solar cell; PV system

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1.Introduction

In the present day, the global markets of photovoltaic cell system (PV) and production technology have amorphous thin film module (a-Si) and crystalline silicon module are mainly world market share. In hot weather, amorphous thin film is more popular than another type of PV module. Moreover, several researches studies apply PV for use. In several parts about efficiency of photovoltaic cell and behaviour of photovoltaic cell are different in type of photovoltaic module, which a-Si and crystalline module have been found in several paper [1-3]. Installation PV has temperature coefficient to be an important parameter for determine and evaluate appropriateness of use for each climate. The weather of installation site has different value each PV module types. Temperature coefficient values in field test have different with measured at standard test condition (STC: irradiation 1000 W/m, Air mass 1.5 and a module temperature of 25°C), which can found in several research and various of weather in the world [4-8,15] but in hot humid weather that similarly Thailand is very hard to be found. This study is one of work that studied specific issues with temperature coefficients of PV module system in hot humid weather. The result of this found has been useful to determine about deployment of solar cells technology , design, sizing and investment in PV power system in hot humid climate similarly Thailand regions. This paper presents method and summary of result about temperature coefficient of photovoltaic cell type a-Si, p-Si and HIT PV module in filed test on 10kW solar power system under condition of hot and humid weather in Thailand.

2. Materials and Methods

2.1. Materials and Systems installation

In this field test, three different types of stand-alone photovoltaic power systems were installed using the: amorphous thin film (a-Si) 3672W of 54W_p 68 modules are connected into 17 strings, 4 modules each. Second, polycrystalline (p-Si) 3600W of 80 W_p 45 modules are connected into 3 strings, 15 modules each and the last is Heterojunction Intrinsic thin layer (HIT) 2880W of 180 W_p 16 modules connected into 2 strings, 8 modules each .the modules facing due South and tilted at 16° from the horizontal. There modules were installed in 10Kw power station system on the Energy Park at the School of Renewable Energy Technology (SERT) in Naresuan University, Phitsanulok Province. The power conditioning system is composed of three grid-connected inverter (GI) 3.5 kW each, and three bi-directional inverter (BI) 3.5 kW. The energy storage system is 100 kWh batteries, 2V2000Ah 24 cells [9]. The schematic block circuit diagram of the 10 kWp stand-alone PV power system is shown in Fig. 1 .This system has been installed and operated since June 2005. The sizing parameters and temperature coefficient is shown in Table 1.

Table 1. Summary of the sizing parameter of field test PV from the manufacturer' specifications

Parameters	Unit	Photovoltaic Module Technology		
		a-Si	p-Si	HIT
Maximum power (W)	W_p	54	80	180
Open circuit voltage (Voc)	V	62.2	44.9	45.5
Short circuit current (Isc)	A	1.14	5.75	5.49
Maximum power voltage (Vpm)	V	44.8	36.2	36.5
Maximum power current (Ipm)	A	0.93	5.11	4.93

2.2. Monitoring Systems

The 10Kw monitoring system is fully assessed the potential of PV technology and performance of the system. The monitoring system was designed depend on IEC 61724 standard [10] and the International Energy Agency Photovoltaic Power System (IEA PVPS) Program task 2 [11-13]. For the general data recorder, a multi-function measuring device measures the parameters.

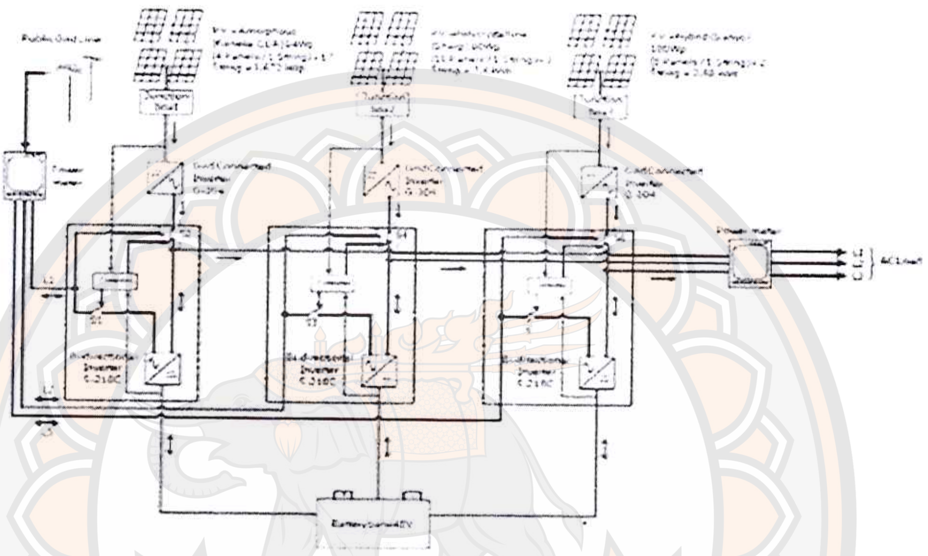

Fig. 1 Schematic block circuit diagram of the PV system

2.3. Experimental Techniques

The values of parameters that effect to module temperature are solar radiation and ambient temperature, which is different each type of solar panel.

So, module temperature is a function of solar radiation and ambient temperature.

$$f(T_m) \alpha f(G_t, T_a) \quad (1)$$

For this study, we used the relationship between module temperatures differential and solar irradiance to find the temperature dependence models is given as: [14]

$$T_m = T_a + k G_t \quad (2)$$

Where:

T_m = Module Temperature (°C)
T_a = Temperature surrounding (°C)
G_t = Solar irradiance (kWm^{-2})
k = Relationship Coefficient ($°Cm^2/W$)

In addition of the current, voltage and power dependences on temperature are often presented as [15]:

$$\Delta I/\Delta T = +\alpha mA/°C \quad (3)$$

$$\Delta V/\Delta T = -\beta mV/°C \quad (4)$$

$$\Delta P/\Delta T = -\gamma W/°C \quad (5)$$

Where:

ΔI, ΔV, ΔP and ΔT are the augmentation in current (mA), voltage (mV), power (W) and temperature under module (°C) respectively . α , β and γ are coefficients value that depend on module temperature.

From equation 3-5 was presented electric current, voltage and power that varies depends on module temperature of solar panel. Only electric current has a positive temperature coefficient but voltage and power have negative coefficients [15].

In this field test study, these data are studied and analyzed to obtain information with useful to performances based on temperature impact using specific hot and humid as Thailand field data.

3. Results and Discussion

The 10 kW PV power station data have been recorded since January 2008 to December 2009. The data of electric current, voltage and power were used to analyze in this study. In addition, an average solar irradiance value in 2008 and 2009 were 660 W/m^2 and 640 W/m^2 respectively, which this solar irradiance value is the average in 2008 and 2009 at 8.00-16.00 pm.

From this data, we can plots graphical data of Thailand field test of solar irradiance , operating temperature and surrounding temperature of PV systems in this field test are shown in Fig. 2.

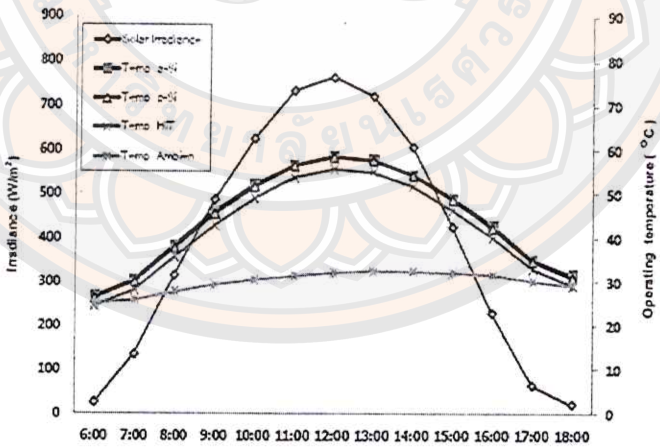

Fig. 2. The Averaged of solar irradiance, module temperatures and surrounding temperature for 10kw PV system from January 2008 to December 2009

As shown in Fig. 2. the solar irradiance had maximum value at 11.00-13.00. This trend has related to module temperature three types of PV cell and ambient temperature. which effect to power outputs are very close. From consideration. the power outputs doesn't resemble with ambient temperature trend. which reached peak values at 13.00-16.00 pm. The maximum average of solar irradiance was 764 W/m^2. The maximum average module temperature of a-Si . p-Si . HIT and ambient temperature were 58.6°C. 58.3°C. 55.7°C and 32.5°C respectively.

3.1. Relationship between current and operating temperature

In this part. graphical relationship between arrays current and operating temperature was analyzed by regressions technique. This plot shown in Fig. 3. which shown scatter plots average of array current about a-Si. p-Si and HIT and operating temperature by using data range of solar irradiance 660 W/m^2±3% and 640 W/m^2 ±3% (The Expected accuracy for daily sums of CM11 pyrometer is ±3%) in 2008 and 2009 respectively.

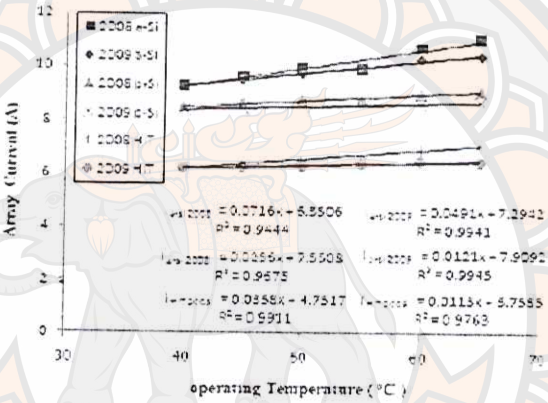

Fig. 3. Graphical plot between array current and operating temperature for three type PV system from Jan2008-Dec2009

From the relationships of Fig. 3 was shown in Table 2. These values in 2008 presented that the generated array current per degree increase in operating temperature of array. The first high rise value is a-Si array. The second is HIT array and last is p-Si as 71.6 mA/°C. 23.6 mA/°C and 35.8 mA/°C respectively.

In 2009. trend has similar result in 2008 but increasing of current per degrees is reducing than 2008 for all three types of systems.

Table 2. Summary of linear models for array current and operating array temperature.

Photovoltaic system	Linear model 2008	Linear model 2009	(mA/°C) 2008	(mA/°C) 2009
a-Si	$I_{a\text{-}Si} = 0.0716x + 6.3506$ $R^2 = 0.9444$	$I_{a\text{-}Si} = 0.0419x + 7.2942$ $R^2 = 0.9941$	71.6	49.1
p-Si	$I_{p\text{-}Si} = 0.0236x + 7.5508$ $R^2 = 0.9675$	$I_{p\text{-}Si} = 0.0121x + 7.9092$ $R^2 = 0.9945$	23.6	12.1
HIT	$I_{HIT} = 0.0358x + 4.7517$ $R^2 = 0.9911$	$I_{HIT} = 0.0113x + 5.7585$ $R^2 = 0.9763$	35.8	11.3

3.2. Relationship between voltage and operating temperature

In this part, graphical relationship between arrays voltage and operating temperature was analyzed by regressions technique. This plot shown in Fig. 4. which shown scatter plots average of array voltage about a-Si, p-Si and HIT and operating temperature by using data range of solar irradiance 660 W/m^2±3% and 640 W/m^2 ±3% in 2008 and 2009 respectively.

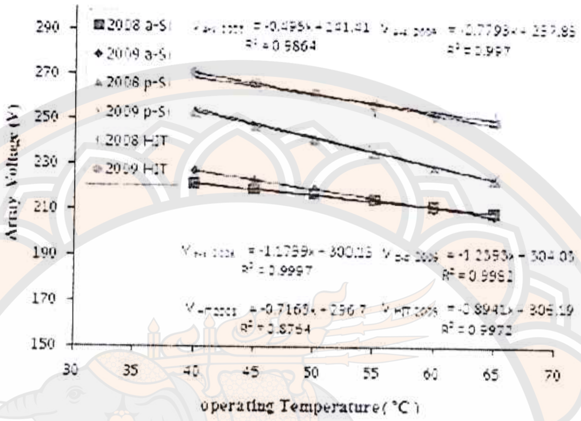

Fig.4. Graphical plot between array voltage and operating temperature for three type PV system from Jan2008-Dec2009

From the relationships of Fig. 4 was shown in Table 3. These values in 2008 presented that the generated array voltage per degree decrease in operating temperature of array. The first high reduce value is p-Si array. The second is HIT array and last is a-Si as -49.5 mV/°C, -117.9 mV/°C and -71.6 mV/°C respectively.

In 2009, trend has similar result in 2008 but decreasing of voltage per degrees is rise than 2008 for all three types of systems.

Table 3. Summary of linear models for array voltage and operating array temperature.

Photovoltaic system	Linear model		(mV/°C)	
	2008	2009	2008	2009
a-Si	$V_{a\text{-}Si} = -0.495x + 241.41$ $R^2 = 0.9864$	$V_{a\text{-}Si} = -0.7793x + 257.85$ $R^2 = 0.9970$	-49.5	-77.93
p-Si	$V_{p\text{-}Si} = -1.1799x + 300.15$ $R^2 = 0.9997$	$V_{p\text{-}Si} = -1.2393x + 304.03$ $R^2 = 0.9982$	-117.9	-123.9
HIT	$V_{HIT} = -0.7163x + 296.7$ $R^2 = 0.8764$	$V_{HIT} = -0.8941x + 306.19$ $R^2 = 0.9972$	-71.6	-89.4

3.3. Relationship between power output and operating temperature

In this part, graphical relationship between arrays power and operating temperature was analyzed by regressions technique. This plot shown in Fig.5, which shown scatter plots average of array voltage about a-Si, p-Si and HIT and operating temperature by using data range of solar irradiance 660 $W/m^2 \pm 3\%$ and 640 $W/m^2 \pm 3\%$ in 2008 and 2009 respectively.

From the relationships of Fig. 5 was shown in Table 4. These values in 2008 presented that the generated array voltage per degree rise in operating temperature of array in a-Si and HIT but reduce in p-Si. The first high reduce value is p-Si array. The increasing value of a-Si array and HIT array are 0.0076 W/°C and 0.0040 W/°C respectively and the decreasing value of p-Si array is -0.0054 W/°C.

In 2009, trend has similar result in 2008 in a-Si and p-Si array but the value per degree has difference trend in HIT array as reducing in year 2009.

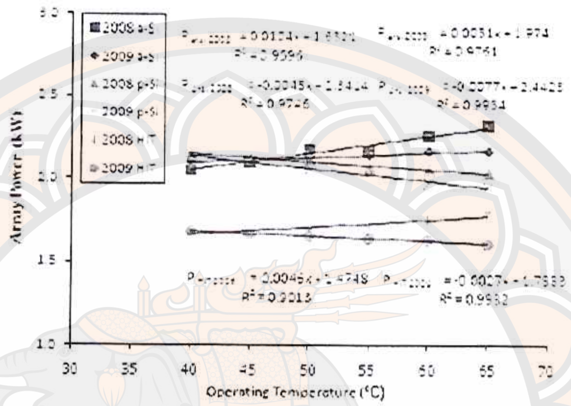

Fig. 5. Graphical plot between array power and operating temperature for three type PV system from Jan2008-Dec2009

Table 4. Summary of linear models for array voltage and operating array temperature.

Photovoltaic system	Linear model		(W/°C)	
	2008	2009	2008	2009
a-Si	$P_{a-Si} = 0.0104x + 1.6321$ $R^2 = 0.9596$	$P_{a-Si} = 0.0031x + 1.974$ $R^2 = 0.9761$	0.0104	0.0031
p-Si	$P_{p-Si} = -0.0048x + 2.3414$ $R^2 = 0.9746$	$P_{p-Si} = -0.0077x + 2.4423$ $R^2 = 0.9934$	-0.0048	-0.0077
HIT	$P_{HIT} = 0.0046x + 1.4748$ $R^2 = 0.9013$	$P_{HIT} = -0.0027x + 1.7883$ $R^2 = 0.9932$	0.0046	-0.0027

4. Conclusion

From this study found that the coefficients depend on module temperature parameter of a-Si, p-Si and HIT in field test have difference from standard test (STC: irradiation 1000 W/m, Air mass 1.5 and a module temperature of 25°C), which specified in PV module from production company. The evaluation from standard test was used three stand-alone 10Kw photovoltaic power systems and recorded values in Thailand`s hot and humid weather condition. Using linear regression technique to analyze the relationship between array current, voltages, power and operating temperature and determine temperature coefficient. The summary of study is shown in Table 5.

The values from Table 5 shown that a-Si module has been received effect from rising of module temperature in negative part less than HIT module and p-Si module respectively. So that a-Si module has been best signal significantly in term of current generated ,voltage , power outputs and lowest negative coefficients for long term installation in Thailand's hot and humid climate. This result has been beneficial for determine to design, sizing and investment in PV power system in hot and humid climate like Thailand in another part of the world.

Table 5. Summary of field test result from Thailand climate regions

Parameter	Unit	a-Si		p-Si		HIT	
		2008	2009	2008	2009	2008	2009
Current coefficient	mA/°C	71.6	49.1	23.6	12.1	35.8	11.3
	(%/°C)	0.48411	0.33198	0.16845	0.08181	0.36308	0.11460
Voltage coefficient	mV/°C	-49.5	-77.93	-117.9	-123.9	-71.6	-89.4
	(%/°C)	-0.02298	-0.03592	-0.04949	-0.05185	-0.02763	-0.03448
Power coefficient	W/°C	0.0104	0.0031	-0.0048	-0.0077	0.0046	-0.0027
	(%/°C)	0.00048	0.00015	-0.00023	-0.00038	0.00027	-0.00016

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References

[1] Zilles, R., E. Lorenzo, et al. From candles to PV electricity: a four-year experience at Iguape–Cananéia, Brazil. Progress in Photovoltaics: *Research and Applications* 2000; 8: 421-434.

[2] Singh, O. P., S. K. Singh, et al. Performance of amorphous silicon solar cell module and solar lantern. *Renewable Energy* 1997; 11(4): 421-426.

[3] Costa, H. S., P. Ragot, et al. Evaluation of amorphous silicon module outdoor performances. *Solar Energy Materials and Solar Cells* 1992; 27(1): 59-68.

[4] H. Hamadeh. Temperature dependence of pin solar cell parameters with intrinsic layers made of pm-Si:H and low crystalline volume fraction mc-Si:H. *Renewable Energy*, 2010; 35(7): 1419-1423.

[5] Katz, E. Temperature dependence for the photovoltaic device parameters of polymer-fullerene solar cells under operating conditions. *J. Appl. Phys* 2001; 90(10): 5343

[6] King, D. L., J. A. Kratochvil, et al. *Temperature coefficients for PV modules and arrays: measurement methods, difficulties, and results*. Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE.

[7] Smith, Z. E., S. Wagner, et al. Carrier lifetime model for the optical degradation of amorphous silicon solar cells. *Applied Physics Letters* 1985; 46(11): 1078-1080.

[8] Kassim M.N. and S. Shaari. An Analysis of the Technical Performances of Three Sets of Stand-Alone a-Si Based Solar Photovoltaic Systems. In: P. of Advances in Malaysian Energy , Malaysian Institute of Energy, Bangi, 2003, p. 253-262. ISBN: 983-40024-4-0.

[9] Sasitharanuwat, A., W. Rakwichian, et al. Performance evaluation of a 10 kWp PV power system prototype for isolated building in Thailand. *Renewable Energy* 2007; 32(8): 1288-1300.

[10] International Standard IEC 61724. Photovoltaic system performance monitoring–guidelines for measurement. Data exchange and analysis , London :*BSI*;1998.

[11] Jahn U, et al. International Energy Agency PVPS TASK2: analysis of the operational performance of the IEA database PV systems. In: 16th European Photovoltaic Solar Energy Conference and Exhibition ,Glasgow, UK, May 2000.

[12] Jahn U, Grimmig B, Nasse W. Task2 operational performance of PV systems and subsystems. *IEA-PVPS* ,Report IEA-PVPS T2-01, 2000.

[13] Chokmaviroj S, et al. Performance of a 500 kWp grid connected photovoltaic system at Mae Hong Son Province, Thailand: *Renew Energy* 2006; 31:19–28.

[14] Duffie, J.A. and W.A. Beckman. Design of photovoltaic systems. Chapter in Solar Engineering of Thermal Processes, 3rd., *John Wiley and Sons Inc* ,Hoboken, New Jersey; 2006.

[15] Shaari, S., K. Sopian, N. Amin and M.N. Kassim. The Temperature Dependence Coefficients of Amorphous Silicon and Crystalline Photovoltaic Modules Using Malaysian Field Test Investigation. *Am. J. Applied Sci* 2009; 6: 586-593.