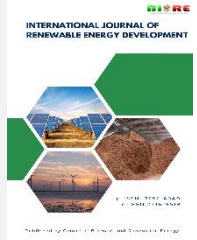




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Research Article

Effects of structure height and temperature to power generation of a 4.86 kWp solar land

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Abstract. Efficient heat transfer significantly improves both the efficacy of photovoltaic (PV) systems and the longevity of PV panels. Lower temperatures facilitate improved power generation and minimize heat-related damage. Conduction, convection, and radiation are the primary heat transfer mechanisms that are involved in this process. This study investigated the effects of PV panel structure heights—specifically 1 meter, 1.5 meters, and 2 meters—on the temperature differences between the top and bottom of the panels, as well as their corresponding power generation, while accounting for the heat transfer that occurred. The PV system comprised nine 540-watt monocrystalline PV panels arranged at these three heights in Khlong Si, Khlong Luang, and Pathum Thani. Data on temperature, power output, and other meteorological variables were collected at 5-minute intervals from 6:00 AM to 6:00 PM over a two-month period from March to April 2024. To evaluate the impact of panel height on performance, all collected data were analyzed. The actual power outputs were compared with simulations conducted using PVsyst. Additionally, the costs associated with each panel height were assessed to identify the optimal height that would achieve both high power output and low costs. The findings revealed that increasing the panel height contributed to a reduction in temperature buildup within the panels and enhanced power output, with increases of 8.87% and 9.45% observed at heights of 1.5 meters and 2 meters, respectively. However, this increase in height also resulted in cost escalations of 24.51% and 48.04%, respectively. Consequently, it was determined that the optimal height was 1.5 meters, as it provided an effective balance between maximizing power output and minimizing costs. Furthermore, the results from the PVsyst simulations indicated significant discrepancies, with measured values approximately 20% lower than expected.

Keywords: PV panel, Structure height, Power generation, 4.86 kWp solar land, Heat transfer



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1. Introduction

Over the past decade, solar photovoltaic (PV) technology has emerged as a critical solution for sustainable energy production. It offers a promising alternative to fossil fuels, which have significantly contributed to increasing carbon dioxide emissions and climate change, while also addressing the issue of depleting fossil fuel resources (Jain, 2019; Victoria *et al.*, 2021; Tamoor *et al.*, 2022; Gamonwet and Dhakal, 2023). Solar PV systems use semiconductor materials to convert sunlight into electricity and can operate in various environments, including cloudy and rainy days. These systems are extremely promising and scalable, capable of generating affordable electricity for a wide range of applications, from small residential installations to large power plants (Varma *et al.*, 2016; Ngamprasert *et al.*, 2020; Rodrigues *et al.*, 2022; Dada and Popoola, 2023). There are two types of PV systems: stand-alone (off-grid) and grid-connected. Stand-alone systems generate power independently and frequently contain battery backups for energy storage, whereas grid-connected systems augment electricity from utility companies and can export excess energy back to the grid, lowering electricity bills (Bhatia, 2024). Because PV panels are exposed to direct sunlight, various factors influence their efficiency and energy output, including construction,

installation, maintenance, and environmental conditions such as irradiance, temperature, dust accumulation, wind speed, shade, and humidity (Bilen and Erdoğan, 2023; Bošnjaković *et al.*, 2023; Shaik *et al.*, 2023).

Numerous studies have investigated how environmental conditions affect the efficiency of PV systems. Hashim and Hassan (2022) examined various environmental and operational factors that influence PV systems, including solar irradiance, temperature, dust deposition, soiling, wind speed, shade, and humidity. The review found that proper panel orientation is crucial for maximizing solar irradiance. Higher irradiance increases power generation, consistent with the findings of Basu *et al.* (2015), Khan *et al.* (2019), Dawood *et al.* (2023), and Jathar *et al.* (2023). Higher temperatures lower efficiency, as reported by Dubey *et al.* (2013), necessitating cooling techniques. Dust accumulation reduces light transmission, requiring regular cleaning. Wind can cool panels, as noted by Zhe *et al.* (2016), but also cause dust accumulation in arid areas; similarly, Amer Dahham *et al.* (2023) found that higher wind velocities created thick dust layers, lowering output power. Shading caused significant energy losses, necessitating optimal array arrangements. High humidity enhanced dust adherence and moisture-related deterioration, emphasizing the importance of thorough cleaning and encapsulation. Proper orientation,

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cooling, and cleaning improved efficiency, but advances in materials, installation, and maintenance were critical for long-term dependability (Hasan *et al.*, 2022). This review is also consistent with the reviews of Said *et al.* (2018) and Ranjan Das, (2019).

In the context of specific challenges, Lee *et al.* (2018) examined power performance loss factors in building-integrated photovoltaic (BIPV) systems, highlighting significant losses due to module temperature (6.0%), dust and soiling, and DC-AC conversion inefficiencies. Similarly, Onaifo *et al.* (2021) analyzed the effects of temperature and humidity on PV performance, showing indirect impacts through material degradation. In hot climates, Sani and Sule (2020) demonstrated the role of water-cooling systems in mitigating temperature-related losses, achieving higher efficiency and output. Moreover, Hashim and Hassan (2022) reported compensatory seasonal effects on PV system performance in desert conditions, while Eldehn *et al.* (2016) underscored the need for optimized thermal management in irrigation applications. These studies collectively underscore the importance of addressing environmental and operational factors to enhance PV efficiency.

Attyagalle and Chandrasiri, (2017) examined how temperature affects the efficiency of electricity generation in PV systems. They measured parameters such as I_{sc} (short-circuit current), V_{oc} (open-circuit voltage), and P_{max} (maximum power). They observed that as the operating temperature of the PV modules increased, their efficiency decreased. During the same period, Adeeb, Farhan, and Al-Salaymeh (2019) studied polycrystalline, monocrystalline, and thin-film solar cell technologies in Amman, Jordan, using data from PV systems with similar design parameters. The findings revealed that temperature variations had the least effect on thin-film panels, with temperature coefficients of -0.0984%, -0.109%, and -0.124% for thin-film, monocrystalline, and polycrystalline panels, respectively. These data help determine the best solar cell technology for various areas depending on typical temperatures. Ibrahim Nur Atirah *et al.* (2022) used ClimateAP software and global climate models to evaluate the effects of extreme temperatures on solar power plants in Malaysia. The study discovered that for every 1°C increase in ambient temperature, the output power of solar photovoltaic modules decreased by around 0.3 to 0.5%. Projections indicate that all solar farm locations will see temperature rises of more than 30 °C by 2080, potentially causing damage to solar panels and lowering efficiency. These studies demonstrated that temperature negatively impacts the efficiency of PV systems' electricity generation.

Effective heat transfer is crucial for enhancing PV system efficiency and extending solar panel lifespan. Lower temperatures improve power generation and reduce heat damage. Key mechanisms include conduction, convection, and radiation. Conduction transfers heat from solar cells to adjacent materials, enhancing efficiency. Convection, either forced (using fans) or natural (due to density gradients), carries heat away with airflow. Designing panels with airflow gaps improves convection. Radiation involves heat transfer via electromagnetic waves, and optimizing panel surfaces for radiation helps lower temperatures (Forsberg, 2021a, 2021b). Several studies have focused on selecting PV materials and installing cooling systems to reduce the temperature of PV modules. Xu *et al.* (2023) investigated phase change materials (PCM) as a way to improve the cooling of solar PV panels. They found that PCM lowered surface temperatures by 33.94°C and 36.51°C within 300 minutes, which increased power output by 1.35 W and improved power generation efficiency by 1.63%. PV panels with PCM took 480 minutes to cool to room temperature, compared to 60 minutes without PCM, indicating prolonged

cooling and reduced thermal stress. Wang *et al.* (2023) demonstrated that combining PCM with fins, optimized at 6 mm fin spacing and 70 mm fin height, decreased panel temperatures by 31.9°C and improved efficiency under higher solar radiation and ambient temperature. Zhang and Xu (2020) used thermal infrared remote sensing on 23 large PV power plants, finding a significant cooling effect on surface temperatures that was more pronounced during the day. Villemin *et al.* (2022) examined the thermal and electrical behavior of a 310 W photovoltaic panel under a 6-kW halogen light in a controlled 48 m³ climatic room. Results showed that panel temperature decreased exponentially with increased airspeed. Forced convection significantly improved cooling, highlighting the importance of controlled conditions for accurate characterization and the challenges posed by variable outdoor environments. Chandra *et al.* (2018) examined two polycrystalline PV modules, one cooled by a DC fan and the other not. Results indicated that wind speed played a crucial role in cooling the modules. The adaptive cooling mechanism effectively reduced thermal losses and improved energy yield.

In addition to the above studies, several others have investigated the impact of installation height on PV performance. Smith *et al.* (2022) conducted wind tunnel experiments to investigate how increasing the height of PV panels affects their cooling efficiency. They found that elevating PV panels significantly improved heat dissipation due to enhanced airflow and increased turbulent mixing, with convection improving up to 1.88 times compared to nominal-height panels. Nnamchi *et al.* (2023) found that increasing altitude significantly boosts solar power gain, with a 2.5% gain at 1,000 meters and a 23% gain at 8,100 meters. Higher altitudes and wind speeds improve solar power output by enhancing panel cooling. The study suggests using high-altitude platforms to optimize solar power generation in regions with different elevations, consistent with the findings of Ranjan Das (2019). However, Osma *et al.* (2016) investigated the effect of installation height on the performance of PV panels integrated into a green roof. The experiment compared two installation heights, 50 cm and 75 cm, on both black and green roofs. Results showed that lower installation height (50 cm) and green roofs independently increased power output by 2.0% and 1.0%, respectively, with a combined effect of 2.8%.

It was observed that no previous research had examined the effects of structure height and temperature on power generation in PV systems using actual power output measurements. Furthermore, previous studies did not consider PV structure heights in the 1 to 2-meter range, which is commonly used for solar rooftops and solar farms in Thailand. Examples of such installations are shown in Fig. 1, including Chokworalak Rungruangkij Rice Mill in Lopburi (1a), Rongsi Sabsirindhon in Yasothon (1b), Kaset Visai Rice Intertrade in Roi Et (1c), and Sea Sand Sun Resort and Villas in Chonburi (1d). Consequently, this study aimed to investigate the effects of structure heights at 1 meter, 1.5 meters, and 2 meters above ground level, as well as temperature differences between the top and bottom of the PV panels, on the power generation of a 4.86 kWp Solar Land system. Power output at each height was measured and compared with simulations conducted using PVsyst software to ensure accuracy and reliability. Additionally, the study assessed and compared the costs associated with each structure height against the corresponding increase in power output to determine the optimal height for maximizing both efficiency and cost-effectiveness.

The novelty of this study lies in its approach to filling a significant gap in the existing literature by directly measuring the impact of structure heights within the 1 to 2-meter range, commonly used for solar installations in Thailand. This is the



Fig. 1 Solar rooftops and solar farms in Thailand

first study to investigate how these height variations affect power generation, incorporating both actual power output measurements and simulation data. Furthermore, the study's consideration of the temperature differences between the top and bottom of the panels adds a new layer of understanding of how thermal conditions influence PV system performance in a tropical climate. The significance of this research is twofold: it provides practical insights for optimizing PV installations in similar environmental conditions and offers cost-effective solutions to maximize energy production.

2. Theory

Heat transfer in photovoltaic (PV) systems is significant, as lowering the temperature of PV panels enhances power generation efficiency and extends their lifespan. Effective heat transfer reduces the amount of heat that accumulates on the panel surface, allowing them to operate more efficiently. Moreover, it helps prevent potential damage from excessive temperatures by utilizing various mechanisms such as conduction, convection, and radiation. In this study, we partially considered heat transfer, specifically focusing on conduction and convection.

Conduction is the process of transferring heat through a material without moving it. It occurs in solids, liquids, and gases but is most effective in solids because of the tightly packed molecules. The rate of heat transfer via conduction is described by Fourier's law, as shown in Equation (1).

$$q = -kA \frac{dT}{dx} \quad (1)$$

where: q is the heat transfer rate (W), k is the thermal conductivity of the material ($W/m \cdot K$), A is the cross-sectional area perpendicular to the heat flow (m^2), and $\frac{dT}{dx}$ is the temperature gradient in the direction of heat flow (K/m).

Convection is the transfer of heat between a surface and a moving fluid (either liquid or gas), involving both conduction (heat transfer to the fluid) and advection (the transport of heat by fluid motion). There are two types of convection: natural convection, which is driven by buoyancy forces resulting from density differences caused by temperature variations within the fluid, and forced convection, which is induced by external means such as fans or blowers. Newton's Law of Cooling for convection is presented in Equation (2).

$$q = hA(T_s - T_\infty) \quad (2)$$

where: q is the heat transfer rate (W), h is the convective heat transfer coefficient ($W/m^2 \cdot K$), A is the surface area in contact with the fluid (m^2), T_s is the surface temperature (K), and T_∞ is the fluid temperature away from the surface (K) (Forsberg, 2021a).

In photovoltaic systems, efficiency indicates how well a solar panel converts solar energy into electricity. Influenced by factors like irradiance, temperature, and module properties, evaluating actual efficiency under real-world conditions highlights performance beyond standard test conditions (STC). The actual efficiency of the PV modules is given by Equation (3).

$$\eta = \frac{P_{dc}}{G \cdot A} \quad (3)$$

where η is the efficiency of the PV module (%), P_{dc} is the measured DC power output (W), G is the solar irradiance on the module surface (W/m^2), and A is the total area of the PV module (m^2) (Messenger and Abtahi, 2017).

The performance ratio (PR) is an important metric for assessing the efficiency of a photovoltaic system. It indicates how well the system is performing compared to its theoretical maximum output under ideal conditions (STC). The Performance Ratio can be calculated using Equation (4)-(6).

$$Y_F = \frac{E_{Grid}}{P_{STC}} \quad (4)$$

$$Y_R = \frac{H}{G} \quad (5)$$

$$PR = \frac{Y_F}{Y_R} \quad (6)$$

Where Y_F is the final yield, E_{Grid} is the net energy output, P_{STC} is the measured power under STC conditions, Y_R is the reference yield, H is the global horizontal irradiation, and G is the solar irradiance under STC conditions, which equals $1,000 W/m^2$ (Phowan *et al.*, 2011; Ogliari *et al.*, 2023).

3. Experiments and Simulations

3.1 PV Experiments

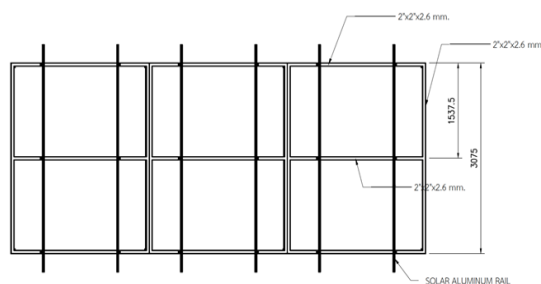
The experiments were conducted in Khlong Si, Khlong Luang, Pathum Thani, at a geographic location of $14.05^\circ N$ latitude and $100.69^\circ E$ longitude. The PV module used in the study had a total area of 23.2 square meters and a cell area of 21.4 square meters. The panels were installed at a tilt angle of 15° with an azimuth angle of 0° . The PV system had a capacity of 4.86 kWp and was configured with one string of nine series-connected modules.

The setup consisted of nine 540-watt monocrystalline PV panels arranged at three different heights: 1 meter, 1.5 meters, and 2 meters. Each height level included three panels, allowing for a comparative analysis of panel performance at varying structure heights. As illustrated in Fig. 2, the panels were installed at these three distinct heights in a side-by-side configuration.

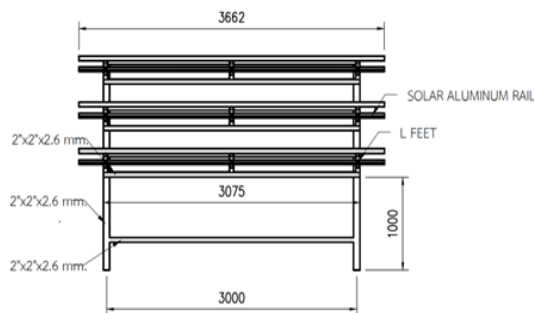
The detailed structural dimensions of the PV panel mounting system are shown in Fig. 3. The system was constructed with solar aluminium rails and designed to support



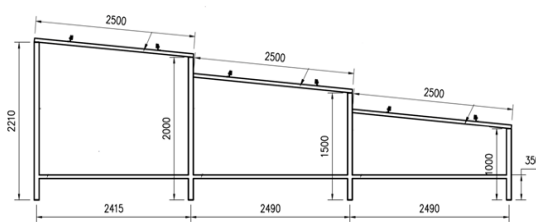
Fig. 2 The PV panels installed at 1 meter, 1.5 meters, and 2 meters



6a) Top view



6b) Front view



6c) Side view

Fig. 3 Structural design and dimensions of the PV panel mounting system

the panels at their respective heights while maintaining a tilt angle of 15°. The framework also ensures adequate stability and spacing to facilitate airflow around the panels, contributing to thermal management.

The PV system was supported by a 6-kW single-phase inverter and a battery, both provided by Growatt. Detailed specifications of the monocrystalline PV panels are presented in Table 1. Tables 2 and 3 provide data on the inverter's input (PV or DC) and output (AC), respectively. Power output was measured by recording both direct current (DC) and alternating current (AC) using two digital power meters (WT310E model), supplied by Yokogawa. For accurate tracking of temperature

Table 1

The monocrystalline PV panel specifications

Specification	Capacity
1. Maximum power (Pmax)	540Wp
2. Maximum power voltage (Vmp)	40.70V
3. Maximum power current (Imp)	13.27A
4. Open-circuit voltage (Voc)	49.42V
5. Short-circuit current (Isc)	13.85A
6. Module efficiency STC (%)	20.94%
7. Maximum system voltage	1,000/1,500VDC (IEC)
8. Temperature coefficients of Pmax	-0.35%/°C
9. Temperature coefficients of Voc	-0.28%/°C
10. Temperature coefficients of Isc	0.048%/°C

Table 2

Input data (PV or DC) of inverter specifications

Specification	Capacity
1. Max. recommended PV power (for module STC)	10,600W
2. Max. DC voltage (Vmp)	550V
3. Start voltage	120V
4. MPP voltage range/ nominal voltage	120V
5. Short-circuit current (Isc)	13.85 A ± 4%
6. No. of MPP trackers	2
7. No. of PV string per MPP tracker	1
8. Max. input current per MPP tracker	13.500A
9. Max. short-circuit current per MPP tracker	16.90A

differences, six surface temperature sensors (DLE124 model from LSI LASTEM) were placed on the top and bottom of each level of PV panels to measure temperature. Additional meteorological instruments, including a wind speed and direction meter (model DNA827), a temperature and humidity meter (model DMA875), and a solar radiation meter (model DPA855), all from LSI LASTEM, were also installed. The collected data were managed and recorded using a Yokogawa GP10 data recorder, which facilitated precise measurement and analysis of the PV system's performance under various conditions.

The PV system's operating principle, as shown in Fig. 4, was that the PV panels converted solar energy into direct current (DC) electricity, which was recorded at each height level. This DC electricity was subsequently converted into alternating current (AC) using an inverter. Another set of digital energy meters measured the resulting AC output. The generated AC electricity was either stored in batteries or directed to a load for immediate use. To monitor temperature differences, surface temperature sensors were installed on the top and bottom of the PV panels at each height level. The meteorological instruments for measuring wind speed and direction, relative humidity, ambient temperature, and solar irradiance were also integrated into the system. All these instruments' data was transmitted to a data recorder for further analysis. The experiments were conducted under the following assumptions: 1) uniform sunlight was received in the area; 2) airflow around all panels was consistent; and 3) humidity levels were the same for each panel. All data, including surface temperatures at the top and bottom of the panels, power output, solar irradiance, wind direction and speed, and humidity, were recorded every 5 minutes from 6:00 AM to 6:00 PM over a two-month period from March 2024 to April 2024.

The experiments were conducted to investigate the effects of structure heights of 1 meter, 1.5 meters, and 2 meters above ground level, temperature differences between the top and bottom of the PV panels, and power generation. Actual power generation measurements were compared with predictions

Table 3
Output data (AC) of inverter specifications

Specification	Capacity
1. AC nominal power	6,000W
2. Rate AC apparent power	6,000VA
3. Nominal AC voltage (range)	230V/(180Vac-260Vac)
4. AC grid frequency (range)	50Hz/60Hz
5. Rate output current	27A
6. Adjustable power factor	0.8leading-0.8lagging
7. THDi	<3%
8. AC grid connection type	Single phase

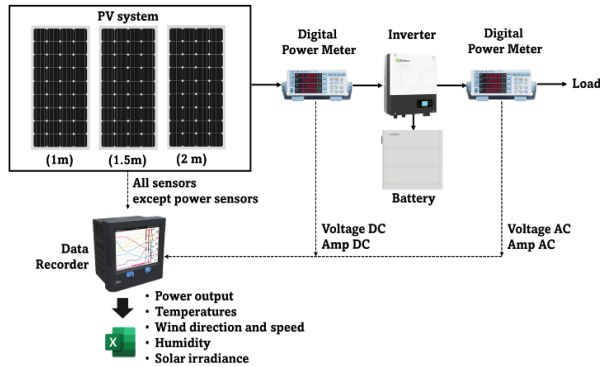


Fig. 4 The operating principle of the PV system

from PVsyst software, with all conditions relating to location, installation, equipment specifications, and timing held constant. Additionally, environmental factors were documented to ensure a thorough analysis.

3.2 PVsyst Simulations

To simulate the power output of the PV system, PVsyst version 7.4 software was used. This software allowed for comprehensive modeling by incorporating various parameters, such as the system's location, specifications of the PV modules and inverters, and the tilt and azimuth angles of the panels.

The specific PV system was located in Khlong Si, Khlong Luang, Pathum Thani, at a latitude of 14.05°N and a longitude of 100.69°E. Solar irradiance data was sourced from Solargis, a reputable solar radiation information provider. Wind velocity and ambient temperature were also factored into the simulation, as these environmental conditions significantly affect the electrical energy generated by PV panels.

In the simulation, the PV panels were set with a tilt angle of 15° and an azimuth angle of 0°. The specifications for both the PV modules and the inverters, as detailed in Tables 1 to 3, were input into the software to ensure accurate results. The simulation results were compared with actual measurements from the PV system to confirm the simulation's accuracy. This comparison was essential for confirming that the modeled performance closely matched real-world data, thereby ensuring the reliability and credibility of the simulation results, (Grover *et al.*, 2020; Kadir *et al.*, 2023; Wang *et al.*, 2024).

3.3 Cost Evaluation of PV Panel Structures

The costs associated with constructing PV panel structures at heights of 1 meter, 1.5 meters, and 2 meters were thoroughly evaluated to compare the power output generated at each height and determine the optimal structure height that offers high power output while minimizing costs. The items that were

used to estimate the construction costs for the PV panel structure were as follows:

- The steel square pipe had dimensions of 2 inches x 2 inches x 2.6 mm. This served as the main material for a structure that required strength and durability, effectively capable of supporting weight.
- Mounting equipment: rails and L-Feet. These were used to install PV panels on the structure.
- Consumables: grinding discs, cutting discs, and welding wire. These were used for cutting and connecting structural components.
- Painting work. This was done to prevent rust and extend the structure's lifespan.
- Assembly work. This involved the assembly of all components into a strong and complete structure.

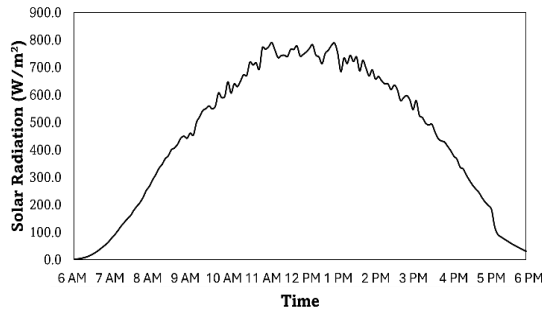
4. Result and Discussion

4.1 PV Experimental results

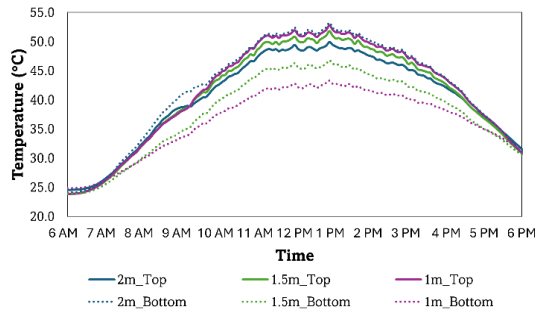
This study investigated the effects of structure heights of 1 meter, 1.5 meters, and 2 meters above ground level, as well as the temperature differences between the top and bottom of the PV panels and the power generation of a 4.86 kWp Solar Land system. Experimental data, including surface temperatures at the top and bottom of the PV panels, power output, wind speed and direction, relative humidity, ambient temperature, and solar irradiance, were recorded every 5 minutes from 6:00 AM to 6:00 PM over a two-month period, from March 2024 to April 2024. The average meteorological data for March and April demonstrated stable and consistent atmospheric conditions. Wind speed remained constant at 0.03 m/s, indicating negligible fluctuations in air movement during the period. The average wind direction of 216.00 degrees reflected a relatively uniform prevailing wind pattern. Relative humidity averaged 64.22%, signifying moderate atmospheric moisture levels. The ambient temperature, with an average of 54.73°C, highlighted a notably high-temperature environment across both months. Solar radiation increased gradually from 6 AM, peaked around midday, and then decreased steadily until 6 PM, as shown in Fig. 5a. The average solar radiation of 453.88 W/m² indicated substantial solar energy availability, creating highly favorable conditions for photovoltaic applications. These findings underscore the suitability of the climatic conditions for solar energy studies during the observed timeframe. The average temperatures on both the top and bottom surfaces of the PV panels, recorded alongside the other meteorological data, are shown in Fig. 5b. The temperature profiles showed similar trends at all three heights. Temperatures on both surfaces of the PV panels began to rise shortly after sunrise at 6:00 AM, corresponding to the gradual increase in solar radiation. The temperatures rose steadily until peaking at 12:55 PM, matching the period of maximum solar radiation, as noted in a related study by Kumpanalaisatit *et al.* (2019). Following this peak, temperatures on both surfaces gradually decreased as solar radiation intensity diminished, as supported by a related study by Irwan *et al.* (2016), eventually reaching their lowest levels by sunset at 6:00 PM.

Increasing the height of the PV panels reduced the top surface temperature, as shown by the solid line in Fig. 5b. This reduction was attributed to improved convective heat transfer. The larger gap beneath the panels allowed for enhanced airflow, which increased the convective heat transfer coefficient and facilitated more effective heat dissipation from the top surface, as described by the convection equation in Equation (2).

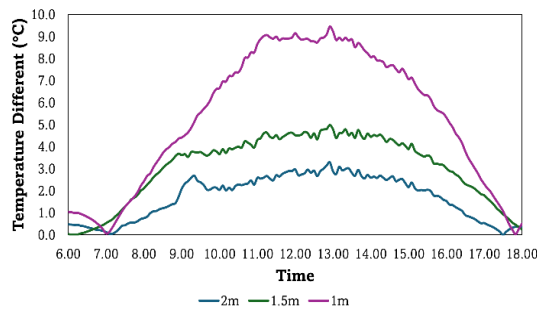
Conversely, the bottom surface temperature increased with panel height, as indicated by the dashed line in Fig. 5b. This



5a) The average solar radiation



5b) The average temperature at both the top and bottom of the PV panels.



5c) The average temperature difference of the PV panels

Fig. 5 Overview of solar radiation and temperature measurements for PV panels over a two-month period from March 2024 to April 2024, recorded from 6:00 AM to 6:00 PM

increase was due to a combination of conductive and radiative heat transfer mechanisms. Despite the improved airflow, the bottom surface absorbed additional radiative heat from the ground and the supporting structure. Furthermore, conductive heat transfer from the supporting structure to the bottom surface contributed to the temperature rise, as described by the conduction equation in Equation (1).

However, an analysis of the temperature differences between the top and bottom surfaces of the panels at each height level, as shown in Fig. 5c, revealed that the temperature difference was smallest at a height of 2 meters, followed by 1.5 meters and 1 meter. This finding suggested that, as the height of the structure increased, the panels experienced less internal heat accumulation. This reduction in temperature difference was likely attributed to enhanced airflow and improved heat dissipation at greater heights, which allowed heat to escape more efficiently.

The average DC power outputs and average current recorded throughout March and April were used as representative data to compare power generation performance at heights of 1 meter, 1.5 meters, and 2 meters. The relationship

Table 4

The average actual module efficiency over a two-month period from March 2024 to April 2024, recorded from 6:00 AM to 6:00 PM

Parameters	Heights (m)		
	1	1.5	2
Average DC power output (W)	437.31	475.95	478.53
Total area of the PV module (m ²)	7.13	7.13	7.13
Average solar irradiance (W/m ²)	453.88	453.88	453.88
Average actual module efficiency (%)	13.51	14.70	14.78

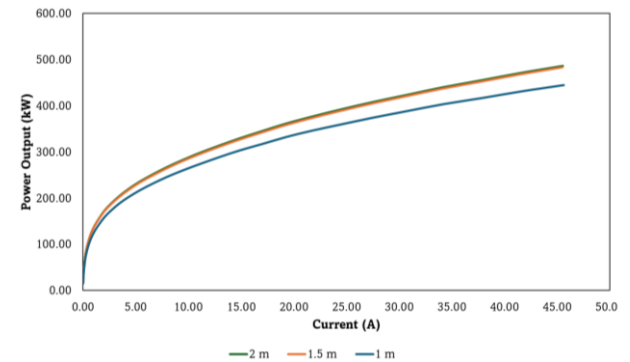


Fig. 6 The Power-Current (P-I) curve

between current and power output of solar panels (Power-Current (P-I) curve) installed at different heights (1 meter, 1.5 meters, and 2 meters) is shown in Fig. 6. It demonstrated that as the current increased, the power output also increased. The panel installed at 2 meters (green solid line) produced the most power due to better heat dissipation from being mounted higher, allowing the panel to operate most efficiently. In contrast, the panel installed at 1 meter (blue solid line) generated the least power due to higher heat buildup from being closer to the ground. Therefore, installing solar panels at higher elevations helped reduce heat accumulation and significantly improved power generation efficiency.

When evaluating the efficiency of solar panels using Equation (3), the average actual module efficiencies at heights of 1 meter, 1.5 meters, and 2 meters were calculated to be 13.51%, 14.70%, and 14.78%, respectively, as shown in Table 4. These values were lower than the module efficiency of 20.94% specified under Standard Test Conditions (STC). This discrepancy can be attributed to real-world factors, including heat buildup, dust and dirt on the panel surface, suboptimal tilt angles, and system losses in wiring and inverters. While increased height improved airflow and reduced heat accumulation, these environmental and operational factors collectively limited efficiency compared to ideal laboratory conditions. These findings underscore the importance of optimizing system design and addressing environmental influences to enhance the real-world performance of PV systems.

4.2 PVsyst Simulation Results

Power generation calculated using PVsyst software, as illustrated in Fig. 7, provided detailed insights into the PV system's performance. The results showed normalized energy production per installed kilowatt-peak (kWp) and performance ratio. The analysis identified two main types of losses. Collection loss, amounting to 0.75 kWh/kWp/day, resulted from several factors, including shading, which blocked sunlight

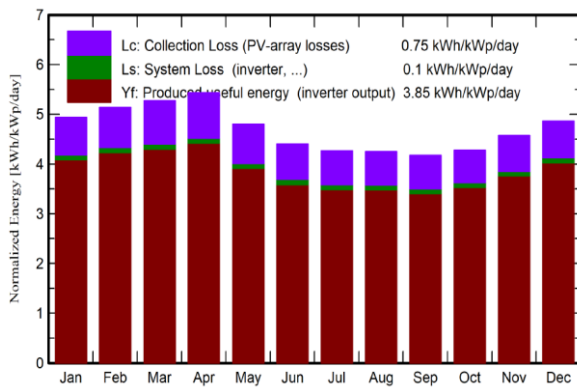


Fig. 7 Power generation calculated using PVsyst software

Table 5
PVsyst simulation result

	E_{Array} (kWh)	E_{Grid} (kWh)	PR (Ratio)
January	630.80	616.0	0.828
February	589.70	576.30	0.823
March	663.80	648.60	0.817
April	660.10	644.70	0.814
May	605.40	589.70	0.815
June	538.80	523.50	0.815
July	541.00	525.40	0.818
August	539.60	524.50	0.819
September	511.30	496.70	0.816
October	546.30	531.70	0.825
November	562.70	548.50	0.822
December	621.60	607.20	0.828
Year	7,011.00	6,832.80	0.820

from reaching the panels; soiling, which referred to the accumulation of dirt and debris on the panels; and temperature fluctuations, which affected the efficiency of the panels.

Table 6
Cost evaluation of PV panel structures

Description	Qty.	Unit	Cost (Baht)		Total Cost (Baht)
			Per Unit	Total	
PV Panel Structures at 1 meter					
1. Steel Square Pipe (2"x2"x2.6 mm.)	5	Pcs.	700.00	3,500.00	3,500.00
2. Consumables	1	Lot.	2,000.00	2,000.00	2,000.00
3. Mounting equipment (rails and L-Feet)	1	Lot.	1,200.00	1,200.00	1,200.00
4. Painting work	1	Lot.	1,500.00	1,500.00	1,500.00
5. Assembly work	1	Lot.	2,000.00	2,000.00	2,000.00
10,200.00					
PV Panel Structures at 1.5 meters					
1. Steel Square Pipe (2"x2"x2.6 mm.)	6	Pcs.	700.00	4,200.00	4,200.00
2. Consumables	1	Lot.	2,500.00	2,500.00	2,500.00
3. Mounting equipment (rails and L-Feet)	1	Lot.	1,200.00	1,200.00	1,200.00
4. Painting work	1	Lot.	1,800.00	1,800.00	1,800.00
5. Assembly work	1	Lot.	3,000.00	3,000.00	3,000.00
12,700.00					
PV Panel Structures at 2 meters					
1. Steel Square Pipe (2"x2"x2.6 mm.)	7	Pcs.	700.00	4,900.00	4,900.00
2. Consumables	1	Lot.	3,000.00	3,000.00	3,000.00
3. Mounting equipment (rails and L-Feet)	1	Lot.	1,200.00	1,200.00	1,200.00
4. Painting work	1	Lot.	2,000.00	2,000.00	2,000.00
5. Assembly work	1	Lot.	4,000.00	4,000.00	4,000.00
15,100.00					

System loss, quantified at 0.10 kWh/kWp/day, arose from inefficiencies in various system components. This included the inverters, which convert DC to AC electricity but are not perfectly efficient, and the wiring, which incurred resistance losses that reduced overall efficiency. Despite these losses, the system achieved a usable energy output of 3.85 kWh/kWp/day and had a performance ratio of 82.00%. This performance ratio indicates that the system performed effectively relative to ideal conditions. The performance ratio can be calculated using Equations (4) - (6).

The total energy produced by the system was 6,832.80 kWh (as shown in Table 5). In comparison, the total array nominal energy at STC efficiency, before accounting for losses, was 8,138.00 kWh, and the total array virtual energy, before accounting for inverter losses, was 7,011.00 kWh.

The AC power output was used for comparison with the power output calculated by the PVsyst software because AC power represented the final output after accounting for system losses, providing a more accurate basis for evaluating the system's real-world performance. When the measured AC power output for March and April—520.55 kWh and 501.72 kWh, respectively—was compared to the calculated power output by PVsyst—648.60 kWh and 644.70 kWh for the same months—the measured values were much lower, with a difference of about 20% on average. This difference was likely caused by factors such as system losses, measurement errors, or limitations within the PVsyst calculation model. Analyzing these results provided insight into the accuracy of the calculations and highlighted the need for improvements to enhance precision in future assessments.

4.3 Cost Evaluation Result of PV Panel Structures

The cost evaluation of PV panel structures was presented in Table 6. The costs for constructing PV panel structures at heights of 1 meter, 1.5 meters, and 2 meters were 10,200, 12,700, and 15,100 baht, respectively. It was evident that raising the height from 1 meter to 1.5 meters resulted in a cost increase of 24.51%. Meanwhile, raising the height from 1 meter to 2 meters led to a substantial cost increase of 48.04%, nearly

doubling the expense. In contrast, the increase in power output was only 0.58%. Therefore, it could be concluded that constructing PV panel structures at a height of 1.5 meters was the most suitable option, as it balanced high power output while minimizing costs.

5. Conclusion

This study investigated the effects of PV panel structure heights—1 meter, 1.5 meters, and 2 meters above ground level—along with temperature differences between the top and bottom of the PV panels on the power generation of a 4.86 kWp Solar Land system. The results indicated that increasing the panel height, particularly to 2 meters, helped reduce temperature buildup within the PV panels and increased power output. Specifically, raising the PV panel structure heights from 1 meter to 1.5 meters and 2 meters resulted in power output increases of 8.87% and 9.45%, respectively.

However, this increase in height also raised the PV panel structure costs by 24.51% and 48.04%, respectively. Based on these findings, the optimal height was determined to be 1.5 meters, as it provided a balance between maximizing power output and minimizing costs. The PVsyst simulation results showed that the measured values were approximately 20% lower than expected, on average. When evaluating the efficiency of solar panels, the average actual module efficiency at heights of 1 meter, 1.5 meters, and 2 meters was calculated to be 13.51%, 14.70%, and 14.78%, respectively. The actual module efficiencies were slightly lower than the STC-rated 20.94%, influenced by factors such as heat buildup, dust, suboptimal tilt angles, and system losses. While increased height helped improve airflow and reduce heat, these factors still affected overall performance. This highlights the importance of refining system design and addressing environmental conditions to enhance PV system efficiency.

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