

Optimization of Pitch Value for a Fixed Tilted Bifacial Grid-connected Photovoltaic System for Solar Farm in Tropical Malaysia

Nur Diyana Nadirah Fuadi^a, Hedzlin Zainuddin^{a*}, Shahril Irwan Sulaiman^b, Nor Syafiqah Syahirah Mohamed^{b,c},
 Nurmalessa Muhammad^a & Bibiyana Ishak^a

^aFaculty of Applied Science,
 Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia,

^bSchool of Electrical Engineering, College of Engineering,
 Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia

^cFaculty of Electrical Engineering Technology,
 Universiti Malaysia Perlis, 02600, Arau, Perlis, Malaysia,

*Corresponding author: hedz1506@uitm.edu.my

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ABSTRACT

The optimal pitch value for a fixed-tilted bifacial grid-connected photovoltaic system is crucial to maximize technoeconomic benefits. The insufficient studies on the optimal pitch value for bifacial photovoltaic (bPV) systems in tropical climates, with self-shading and electrical mismatch caused by design errors of tilt angle and pitch coupling, present a significant challenge for maximizing system efficiency and lead to financial losses. This study investigates the optimal pitch value for a 45 MW fixed-tilted bifacial grid-connected photovoltaic system for solar farms in Sungai Petani, Kedah via simulation using PVsyst software. The study simulated three cases which were one module in height (Case A), two modules in height (Case B), and three modules in height (Case C) without space constraints. The bifacial design key parameters of albedo, module height, pitch, and tilt angle were incorporated into the simulations. The simulations revealed that increasing the pitch enhances specific yield but reaches a saturation point. The saturation point represents the optimal pitch values, which were 4.1 m, 5.5 m, and 7.2 m, for Cases A, Case B, and Case C. Moreover, the corresponding GCRs and specific yields for Case A, Case B, and Case C were 41.4%, 62.1%, and 71.3%, and 1568 kWh/kWp/yr, 1522 kWh/kWp/yr, and 1501 kWh/kWp/yr, respectively. It is worth highlighting that this study provides insight on the relationship of optimum pitch value with energy yield for cases of one, two, and three modules in height under scenario of no space constraint for tropical regions.

Keywords: Bifacial photovoltaic system; pitch; specific yield; ground coverage ratio; tropical climate

INTRODUCTION

Malaysia's strategic location within the equatorial region and the Government of Malaysia's solar photovoltaic dynamic incentives give a significant advantage in generating electricity via capturing solar energy, making it highly capable of achieving success in this field (Zainuddin et al. 2021). The installed capacity of solar PV systems in Malaysia reached 1933 MW in 2022, and their share of installed renewable energy systems reached 21.4%,

according to the International Renewable Energy Agency (IRENA) Report 2023. The market and academic groups' interest in crystalline silicon cells has shifted from monofacial photovoltaic (mPV) technology to bifacial photovoltaic (bPV) technology. This shift is documented in the International Technology Roadmap for Photovoltaic (ITRPV) 2023, which states that the market will reach 80% in 2027 from 70% in 2023. Since it can collect irradiance from both, the front and rear sides, the bPV modules system has an advantage over the mPV modules, creating 15% to 20% more electricity (Mohamed et al. 2022).

A study conducted in Perlis, Malaysia, reported that the total energy produced by bPV systems to the grid annually is 1699.6 MWh, whereas the total energy produced by mPV systems to the grid annually is 1645.3 MWh (Kahar et al. 2023). The bPV system broke even in roughly 7 years and generated a profit of almost 357% in terms of return on investment (ROI) while an mPV system was reported to have a payback period of about 8.1 years and an ROI of 290.4% (Kahar et al. 2023). Furthermore, the specific yield of the bPV system is 10.58% greater than the predicted output of the mPV system (Sreenath et al. 2021). However, designing a bPV system is way more complicated compared to an mPV system because many key design parameters need to be considered such as tilt angle, orientation, pitch, albedo, and module height. Research on the ideal pitch is warranted for a larger range of case studies that include different site conditions of technologies since it influences the ground coverage ratio (GCR), which then affects specific yield loss (Patel et al. 2019; Rehman et al. 2020; Rodrigo et al. 2024; Tonita et al. 2023).

Decisions on array pitch and tilt coupling are crucial for life-cycle economics (Rodrigo et al. 2024). Life-cycle economics can be significantly improved even with minor changes to the array's tilt and pitch coupling. The self-shading between arrays that results in electrical mismatch can be caused by design errors, leading to significant financial losses and affecting specific yield and installation costs (Rodrigo et al. 2024; Shah et al. 2019). As the tilt angle increases, the pitch also increases, leading to a reduction in the total number of modules that can be installed in the system. This, in turn, can indirectly decrease the annual final yield (Mohamed et al. 2024). Even though the optimum tilt angle for PV arrays for tropical regions has been established, the pitch value optimization for bPV solar farm applications in tropical Malaysia has not been established. Understanding the pitch parameter is crucial for designing efficient bPV installations, as it directly influences the overall performance and effectiveness of the PV system.

An actual case study for location with latitude 21°N to 51°N conducted by (Johnson & Manikandan, 2023) reported that increasing the pitch from 0.8 m to 2.0 m significantly enhances the bifacial gain (BG), allowing more light to reflect off the ground and hit the rear of the panels. Beyond a 2.0 m pitch, further increment did not significantly affect the system performance. This result indicates an optimal pitch value of 2.0 m.

A comparative simulation analysis between mPV and bPV systems for grid-connected solar power plants in Mashhad, Iran (36.29°N) was evaluated using PVsyst software (Eidiani et al. 2022). The study used the pitch value of 6.0 m with a GCR of 50.0% for bPV and mPV systems, which generated specific yields of 1677 kWh/kWp/yr and 1492 kWh/kWp/yr, respectively.

This showed that the specific yield obtained for the bPV system is 5.84% more than the mPV system.

(Khan et al. 2017) conducted a comprehensive review of vertical bifacial solar farms globally with latitudes up to 60°N, assessing the energy gains associated with various pitch settings. The study suggested that a reasonable adjustment in the pitch to 2.0 m can result in an energy gain ranging from 10-20%.

On the other hand, (Xingshu Sun et al. 2017) suggested that an optimal pitch for vertical bPV systems was around 1.0 m for panels with a corresponding height of 1.0 m. A study conducted in Wuhai, China (39.65 °N) investigated optimizing a fixed-tilt bPV system (Liu et al. 2021).

Through modeling and experimental field testing, a pitch value of 8.0 m was selected for the system with three height modules to evaluate the mPV and bPV Nominal Module Operating Temperature (NMOT). According to the study conducted for El Gouna, Egypt (27.40°N) and Constance, Germany (47.67 °N), bPV system performance was found to be better with larger pitch values due to higher BG (Shoukry et al. 2016). This study investigated the influence of pitch towards BG and came out with the optimal pitch value of 2.5 m for the PV modules in a PV array with five sheds, each with eleven modules and one module in height.

The performance of bPV modules under different operating conditions in Minas Gerais, Brazil (17.93°N) was conducted by (Braga et al. 2023). This actual case study highlighted the understanding of how changes in pitch value affect the GCR and the efficiency of bPV modules. This study reported that when the pitch increases, the GCR will drop where the surface area that reflects light onto the rear side of the modules increases, increasing BG.

A comprehensive study on optimal GCR of 31 locations for fixed-tilt bPV systems at latitude 17° to 75° was conducted by (Tonita et al. 2023). The study reported that GCR between 0.14 and 0.68 resulted in 5% inter-row energy yield loss for bifacial modules. The study found that the GCR of fixed-tilt arrays in regions closer to the equator can achieve a value of 0.55 without causing shading losses above 2.5%.

A case study in the Atacama Desert, Chile (23.86 °N), was conducted to investigate the influence of the installation condition and performance of bPV modules on energy yield by simulating the bPV system using PVsyst software (Zhang et al. 2023). This study showed that when the GCR is below 50%, more beams are reflected from the ground, resulting in better system production compared to GCR above 50%.

Another study on pitch issues was conducted by (Rodrigo et al. 2024), which simulated and analyzed a comprehensive GCR analysis of large-scale fixed-tilt bPV

plants located at latitudes 0° to 60°. The findings indicated that as the latitude increased, the GCR decreased due to the higher shading effect caused by lower sun height angles, which required increased pitch.

A case study was conducted in Fiji Island (17.29°N) and Katunayaka, Sri Lanka (7.17 °N) using PVsyst software, where the pitch value was set to be 6.60 m which is the default value provided by the software (Milan & Huiqing, 2019). However, the default value provided is not an optimal pitch value. Another study of bPV system simulation was conducted in Manisa, Türkiye (38.47°N) and Kedah, Malaysia (5.67°N) using PVsyst software, where the pitch value used for the simulation was 5.0 m and 5.5 m respectively using optimization tools in PVsyst software. However, these optimization tools are not applicable to determining optimal pitch value because it will only select the maximum pitch value when the user inserts the pitch value range to be simulated.

From the reviewed case studies on the pitch value, it can be noted that pitch value significantly influences the GCR, which consequently affects the shading losses, which finally affects the energy yield. Globally, studies on fixed tilt bPV systems have shown an optimal pitch span between 1.5 m and 8.0 m, whereas vertical bPV system installations have an optimal pitch range between 1.0 m and 3.6 m. By categorizing it into one module in height, two in height, and three in height, the optimal pitch value was reported

to be in the range of 1.5 m to 6.6 m, 1.5 to 5.5 m, and 1.5 to 8.0 m, respectively.

However, the case studies on pitch value for tropical climates, particularly in tropical Malaysia latitudes ranging from 1° to 7° have not yet shown conclusive results to propose the optimal pitch value for a bPV system towards specific yield. To facilitate a clearer overview of optimal pitch value for different climates with the relevant design parameters involved in the respective case studies. Table 1 investigated 20 case studies in order to summarize and identify the research gap. This summary indicates that the design parameters used in various case studies differed significantly. Furthermore, it was observed that not only did the selection of design parameters vary, but the optimal pitch identified also did not consider scenarios involving multiple modules stacked in height, which could assist the bPV system designer.

Therefore, this study aims to investigate the optimal pitch value for a fixed tilted bifacial grid-connected photovoltaic (bGCPV) system, for three case studies of one, two, and three modules in height towards the specific yield. The simulation assumed unlimited land area, allowing for varying pitch values without space constraints/limitations. The findings will offer guidelines for system designers on selecting the optimal pitch value when designing and simulating bGCPV systems for tropical Malaysia.

TABLE 1. Summarised of 20 case studies to facilitate the overview of pitch value for different climates with relevant design parameters.

No.	Author	Site Location & Latitude	Climate	Software	Pitch value (m)	Design parameter										
						Albedo	Pitch	Tilt angle	Height	Shading	Azimuth	Irradiance	Climate	Bifaciality	Location	
1	(Wang et al. 2020)	Changzhou, China (31°48N)	Cfa	(simulate)	-	√	√			√	√	√				
2	(Khan et al. 2017)	Global (up to 60°N)	-	(simulate)	2.0 m (vertical)	√	√	√	√	√	√	√				√
3	(Mohamed et al. 2022)	Kedah, Malaysia, (5.67°N)	Af	PVsyst (simulate)	5.5 m (fixed tilt)	√	√	√	√	√		√				√
4	(Türkdoğru & Kutay, 2022)	Manisa, Türkiye (38.47°N)	Csa	PVsyst (simulate)	5.0 m (fixed tilt)	√	√	√	√	√	√	√				
5	(Rattanatham et al. 2021)	Ratchasima, Thailand (14.97 °N)	Aw	PVsyst (simulate)	3.6 m (vertical)	√	√	√	√		√					
6	(Xingshu Sun et al. 2017)	Global (up to 30°N)	-	(simulate)	1.0 m (vertical)	√	√	√	√	√	√	√				√
7	(Patel et al. 2018)	Global (up to 30°N)	-	(simulate)	-	√	√	√	√	√	√	√			√	√
8	(Eidiani et al. 2022)	Mashdad, Iran (36.29°N)	BSk	PVsyst (simulate)	6.0 m (fixed tilt)	√	√	√	√		√	√			√	√

continue ...

... cont.

9	(Johnson & Manikandan, 2023)	Global (21°N - 51°N)	-	(actual)	2.0 m (fixed tilt)	√	√	√	√	√	√	√	√
10	(Prasad & Prasad, 2023)	Fiji Island (17.29°N)	Af	PVsyst (simulate)	6.6 m (fixed tilt)	√	√	√	√	√	√	√	√
11	(Liu et al. 2021)	Wuhai, China (39.65 °N)	BWk	PVsyst (simulate)	8.0 m (fixed tilt)	√	√	√	√	√	√	√	√
12	(Milan & Huiqing, 2019)	Katunayaka, Sri Lanka (7.17 °N)	Af	PVsyst MATLAB (simulate)	6.6 m (fixed tilt)	√	√	√	√	√	√	√	√
13	(Shoukry et al. 2016)	El Gouna, Egypt (27.40°N) Constance, Germany (47.67 °N)	BWh Cfb	(simulate)	2.5 m (fixed tilt)	√	√	√	√	√	√	√	√
14	(Lei Chen et al. 2019)	Detroit, MI (42.33°N)	Dfa	(simulate)	-	√	√	√	√	√	√	√	√
15	(Zhang et al. 2020)	Atacama Desert, Chile (23.86 °N)	BWk	PVsyst (simulate)	1.5 m (fixed tilt)	√	√	√	√	√	√	√	√
16	(Braga et al. 2023)	Minas Gerais, Brazil (17.93 °N)	Aw	(actual)	-	√	√	√	√	√	√	√	√
17	(Shah et al. 2019)	Bahawalpur, Pakistan (29.35 °N)	BSh	(actual)	Case 1: 3.0 m Case 2: 3.8 m (mPV) (fixed tilt)	√	√	√	√	√	√	√	√
18	(Tonita et al. 2023)	Global (17°N - 75°N)	-	(simulate)	-	√	√	√	√	√	√	√	√
19	(Rehman et al. 2020)	Auckland, New Zealand (36.85 °N)	Cfb	(simulate)	-	√	√	√	√	√	√	√	√
20	Rodrigo et al. 2024)	Global (up to 60°N)	-	Radiance (simulate)	4.0 m (fixed tilt)	√	√	√	√	√	√	√	√

METHODOLOGY

When simulating a bPV system, several essential design elements must be considered, including climate, geographical location, system capacity, module orientation, irradiance, albedo, tilt angle, pitch, module height, losses, and bifaciality factor.

This study utilized PVsyst software, a widely popular tool for simulating bPV systems. PVsyst is commonly used for estimating power generation and optimizing the design of solar power plants. With the release of PVsyst software version 6.6.0 in 2017, a bifacial model for a fixed tilt of ground-mounted systems with regular rows was first introduced. The bifacial evaluation of PVsyst includes direct and diffuse sky contributions on the back side and ground scattering to the front and rear of PV modules (Mohamed et al. 2022).

The pitch in photovoltaic system design refers to the horizontal distance between two consecutive rows of solar

modules as illustrated in Figure 1. Pitch is crucial in PV design as it influences shading losses, GCR, and energy yield. Smaller pitch increases GCR and land use efficiency however it may cause self and mutual shading, and reducing system performance. Larger pitch minimizes shadings and improves bifacial module rear-side irradiance by allowing more reflected light. Optimal pitch depends on factors like tilt angle, latitude, sun path, site constraints, and economic considerations, requiring a balance between energy output and land utilization.

The simulation was divided into 3 cases to investigate the optimal pitch value for Case A (one module in height), Case B (two modules in height), and Case C (three modules in height) as illustrated in Figure 2. In order to determine the optimal pitch value on energy yield for a bPV system using PVsyst software without space constraints, a design simulation has to be executed following a step-by-step approach as shown in Figure 3. The step-by-step approach consists of 3 major sections which are orientation, system design, and shading analysis. An essential step in the

simulation of a bPV system is configuring the bifacial settings in the system parameters, which requires the input

of the albedo value, and another step is the input of the pitch value in the near shading parameter.

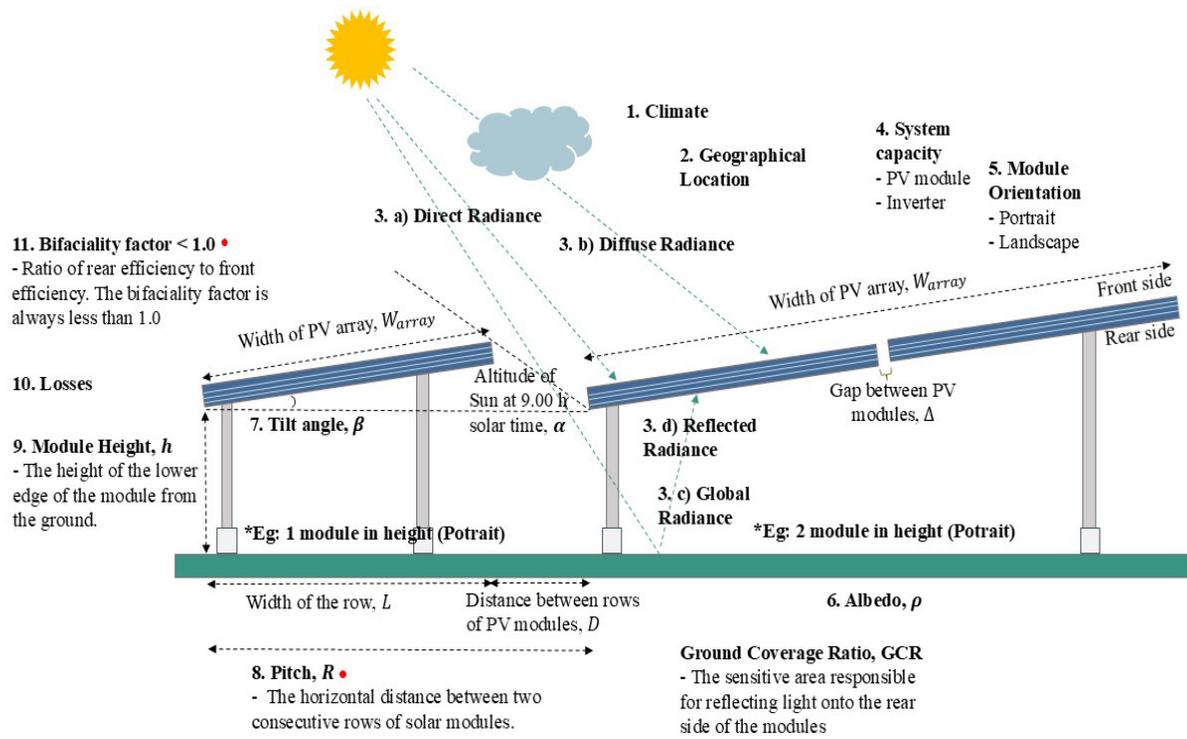


FIGURE 1. Design parameters that influence the bPV system

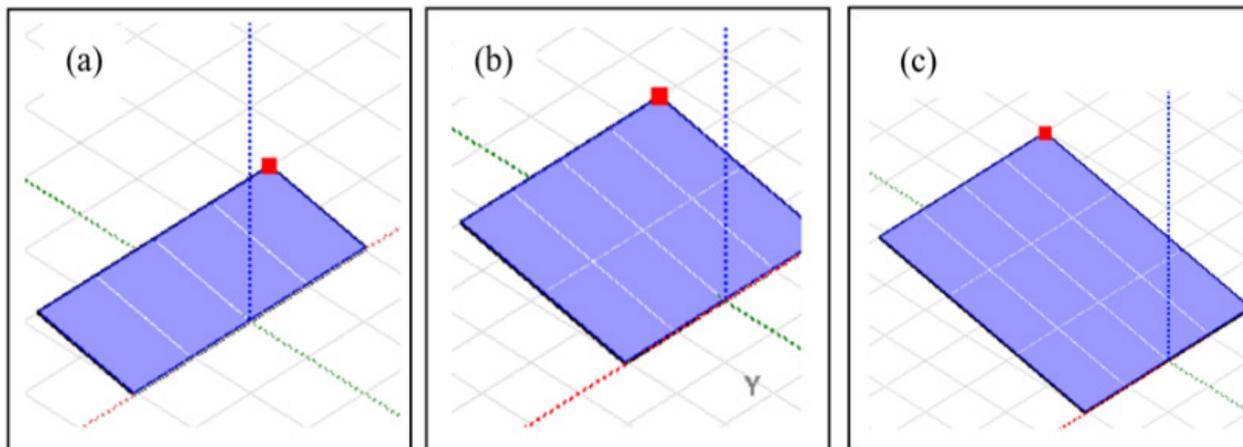


FIGURE 2. (a) Case A for one module in height, (b) Case B for two modules in height, and (c) Case C for three modules in height

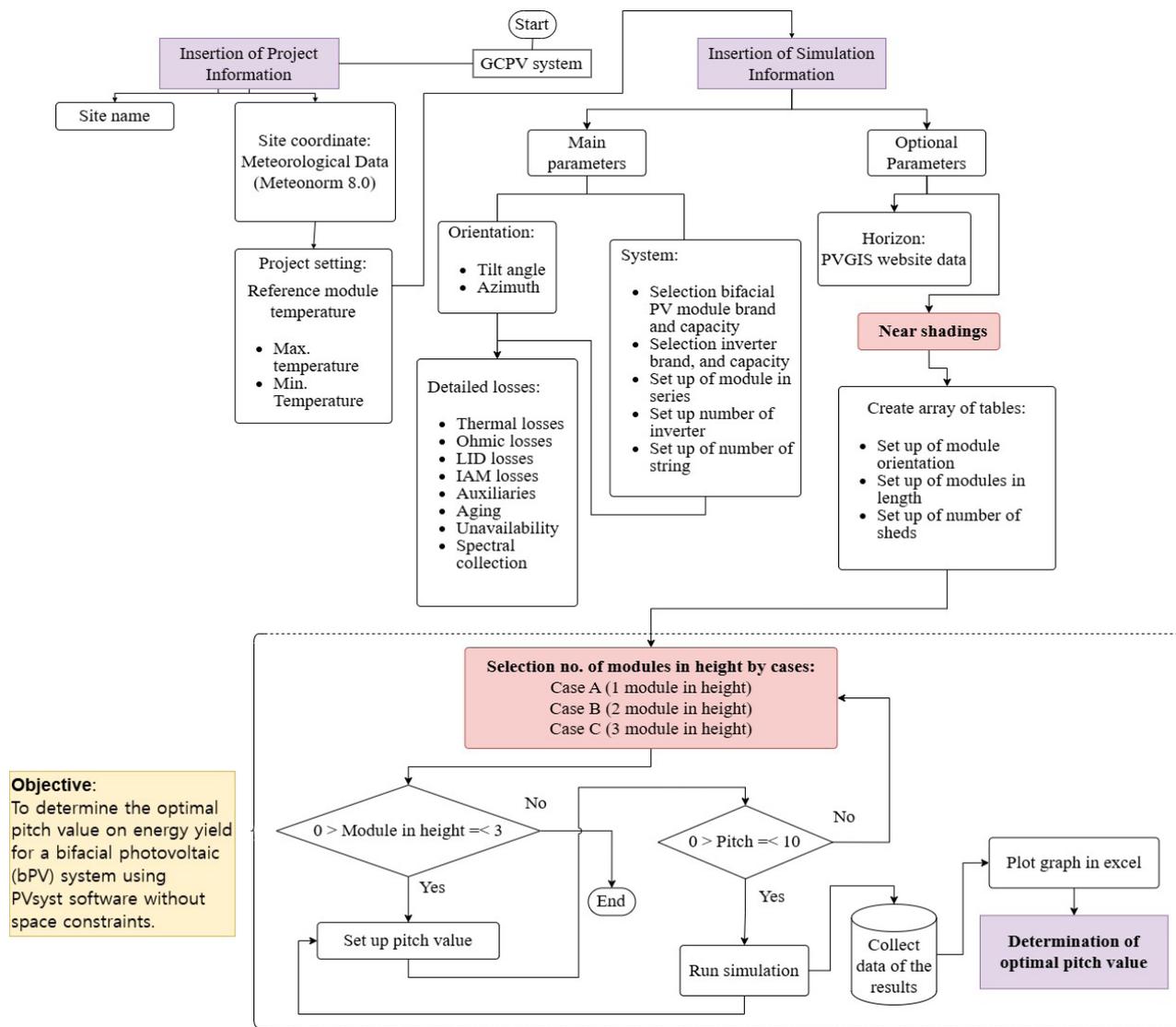


FIGURE 3. Flowchart of the design simulation using PVsyst software for optimal pitch

SITE DETAILS

A 45 MW bPV system was proposed in Sungai Petani, Kedah, with a latitude of 5.67°N, longitude of 100.62°E, and altitude of 42.9 m which is one of the most suitable states to develop solar projects since it receives high annual solar irradiance energy.

METEOROLOGICAL DATA

The meteorological data used for this study was Meteonorm 8.1 which is the available default database in PVsyst

software. The monthly irradiation, temperature, wind velocity, and humidity data are shown in Figure 4. The minimum average for global horizontal radiation at the proposed site was recorded in November with a value of 134.0 kWh/m², and the highest value recorded was in March with a value of 174.9 kWh/m². For average horizontal diffuse irradiation, the minimum value recorded was 64.0 kWh/m² in January, while the highest value was 84.0 kWh/m² in May. The highest monthly average ambient temperature was in March, while the lowest was in November with values of 28.4°C and 26.9°C, respectively.

	Global horizontal irradiation kWh/m ² /mth	Horizontal diffuse irradiation kWh/m ² /mth	Temperature °C	Wind Velocity m/s	Linke turbidity [-]	Relative humidity %
January	163.4	64.0	27.6	1.39	3.471	75.0
February	159.1	69.0	28.2	1.30	3.806	73.8
March	174.9	82.9	28.4	0.99	3.925	77.8
April	163.6	83.1	28.1	0.91	4.054	82.6
May	156.3	84.0	28.6	0.70	3.885	81.1
June	143.5	80.6	28.0	0.78	4.180	82.3
July	150.3	80.3	28.1	0.90	4.146	80.7
August	146.1	83.9	27.9	0.80	4.195	81.1
September	141.4	81.5	27.2	0.69	4.084	83.9
October	137.2	78.7	27.2	0.69	4.052	83.6
November	134.0	77.9	26.9	0.79	3.612	85.1
December	139.8	71.5	27.4	1.30	3.409	78.8
Year	1809.6	937.4	27.8	0.9	3.902	80.5

Global horizontal irradiation year-to-year variability 4.5%

FIGURE 4. Average monthly data used in evaluating the performance of the bPV system

ORIENTATION

The orientation parameter refers to the direction the PV modules face relative to true geographic directions (North, South, East, West). It is essential because the orientation affects the amount of solar radiation the modules receive, thereby impacting energy production. The PV module orientation for this bPV system was specified as a fixed tilt plane, where the plane was tilted at 10° from the horizontal with an azimuth angle of 0°. The tilt angle was chosen since it is the recommended tilt angle to allow rain to naturally wash the dirt accumulated on the PV arrays for tropical Malaysia (Mark et al, 2018).

SYSTEM DESIGN

The modules chosen were bPV modules to utilize the reflected light from the ground. Most companies offer 5-10 years more warranties for bPV due to its lower failure and have lasted longer compared to mPV. The specifications of the bPV modules and inverter utilized in this study are detailed in Table 2.

The system's specifications were selected to align closely with a case study in Sg. Petani as reported by Mohamed et al, which will later serve as a benchmark for validation and comparison. However, the tilt angle was

adjusted to 10 degrees, as this configuration is assumed to be more practical for tropical climates like Malaysia, where frequent rainfall facilitates the natural cleaning of the PV array. This modification included in the simulation was deemed essential to reflect real-world conditions and optimize system performance for the study location. While this introduces a slight variation, it does not compromise the validity of the comparative analysis, as the adjustment is based on well-established best practices for maintaining efficiency in similar environments.

In the system parameter, the bPV system setting was set up where albedo and module height were inserted. Albedo is the sensitive area for reflected irradiance to reach the rear side of the module. The albedo of a black surface is zero, indicating that it absorbs all incident light rays. A perfect reflector, characterized by a white surface, has an albedo value of 1.

The typical ground surface for solar farms is grass or sand with values of 0.25 and 0.40, respectively. In this study, the chosen albedo was 0.25. This value is consistent with similar studies conducted in tropical regions and was chosen to accurately reflect local conditions, ensuring the relevance of the simulation results. Another design parameter that influences the reflection of sunlight is module height. The height of 1.5 m was selected based on average installation standards for tropical regions (Mohamed et al. 2022; Prasad & Prasad, 2023; Johnson & Manikandan, 2023).

TABLE 2. Specifications of PV module and inverter

System parameters	
Nominal PV Power	45MWp
Module Model	JKM325M-60H-BDVP-Bifacial
Nominal power at STC (W)	325Wp
Maximum voltage (V_{mpp})	33.9V
Maximum Current (I_{mpp})	9.59A
Open Circuit Voltage (V_{oc})	40.7V
Short Circuit Current (I_{sc})	10.08A
No of modules in series	34
No of string	4072
No of modules	138448
Total module area	235555 m ²
Nominal AC Power	41MWac
Inverter Model	Sunny Central 2930 UP
No of inverter	14
Pnom ratio	1.10

DETAILED LOSSES

In PV systems, losses represent factors that reduce energy output from the system's maximum potential, impacting accurate performance assessment and optimization. Thermal losses occur due to module heating, which decreases efficiency, while ohmic losses arise from electrical resistance within the system. Module-specific losses, such as light-induced degradation (LID) and

mismatch, reflect performance variability, and soiling losses result from dirt accumulation, which reduces sunlight absorption. Incidence Angle Modifier (IAM) losses are caused by sunlight striking the modules at suboptimal angles. As the system is newly installed, this study excluded aging, auxiliary consumption, unavailability, and spectral correction. Table 3 summarizes the 9 detailed losses considered and assumed in the simulation. Defining these losses specifically leads to more accurate performance analysis.

TABLE 3. Detailed Losses for the simulation

No	Losses	Value	Description	
1	Thermal parameter	Constant loss factor	29.0 W/m ² K	Free standing installation
2	Ohmic Losses	Loss fraction at STC	1.50 %	Default
		Voltage Drop	0.7 V	Default
3	Module quality – LID – Mismatch	Module quality	-0.8%	Default
		Module mismatch losses	2.0%	Default
		LID loss factor	2.5%	Refer as per PV module datasheet
		String voltage mismatch	0.15%	Default
4	Soiling Loss	Yearly soiling loss factor	3.0%	Default
5	IAM Losses			Uses definition of the PV module
6	Auxiliaries		Not included	
7	Aging		Not included	Newly installed
8	Unavailability (System downtime)		Not included	Newly installed
9	Spectral correction		Not included	Used crystalline broad spectrum with minimal spectral defect

SHADING ANALYSIS

The horizon represents the obstruction of the skyline by nearby objects like buildings, trees, or terrain features. Including horizon information in simulations can provide more accurate predictions by accounting for shading effects caused by these obstructions. The far shading data were imported from the PVGIS website. Near shading allows users to specify shading effects caused by nearby objects directly affecting individual PV modules. It can significantly impact the performance of a PV system, especially in urban environments where buildings and other structures may cast shadows on the modules at different times of the day.

Design parameters, including pitch, no. of sheds, no. of the module in height, no of the module in length, and module spacing, were set up in this section. These shading parameters in Table 4 were identical for all cases. The width of the PV array, W_{array} for Case A, Case B, and Case C were calculated using equation below:

$$W_{array} = N_{mod,height}(L_{mod,portrait}) + N_{gap}(\Delta) \quad (1)$$

The $N_{mod,height}$ is number of modules in height, $L_{mod,portrait}$ is length of the module in portrait, N_{gap} is number of gaps between modules, and Δ is length of the gap between the module.

The pitch values ranging from 1.0 m to 10.0 m were used in this simulation. This pitch value range is deduced based on the case studies as tabulated in Table 1 for 1 module in height, 2 modules in height, and 3 modules in height.

TABLE 4. Specifications of near shading parameter

Shading parameters	
Number of modules in length	1018
Module spacing, Δ	0.02 m
Module length, L_m	1698 mm
Module width, W_m	1002 mm
Orientation	portrait
No of sheds	68
W_{array} for Case A	1698 mm
W_{array} for Case B	3416 mm
W_{array} for Case C	5134 mm

RESULT AND DISCUSSION

This section will be categorized into two sections, the relation between specific yield and pitch and the relation between GCR and pitch.

RELATIONSHIP BETWEEN SPECIFIC YIELD AND PITCH

Figure 6 presents the relationship between specific yield and pitch for Case A, Case B, and Case C, showing a similar trend that specific yield increases nonlinearly as pitch increases. These relationships follow the polynomial trend as listed below:

$$A: y = 0.0041x^3 - 0.6904x^2 + 35.380x + 1045.7 \quad (2)$$

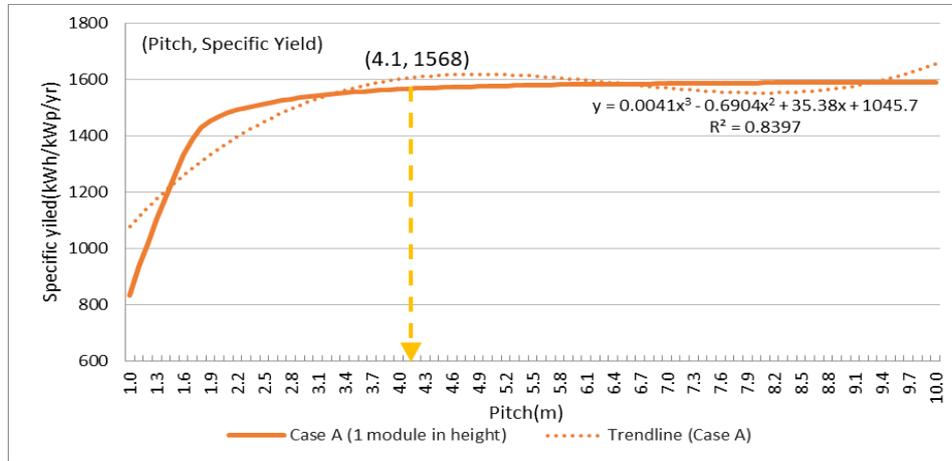
$$B: y = 0.0056x^3 - 1.0517x^2 + 63.387x + 319.69 \quad (3)$$

$$C: y = 0.0009x^3 - 0.3891x^2 + 42.345x + 180.16 \quad (4)$$

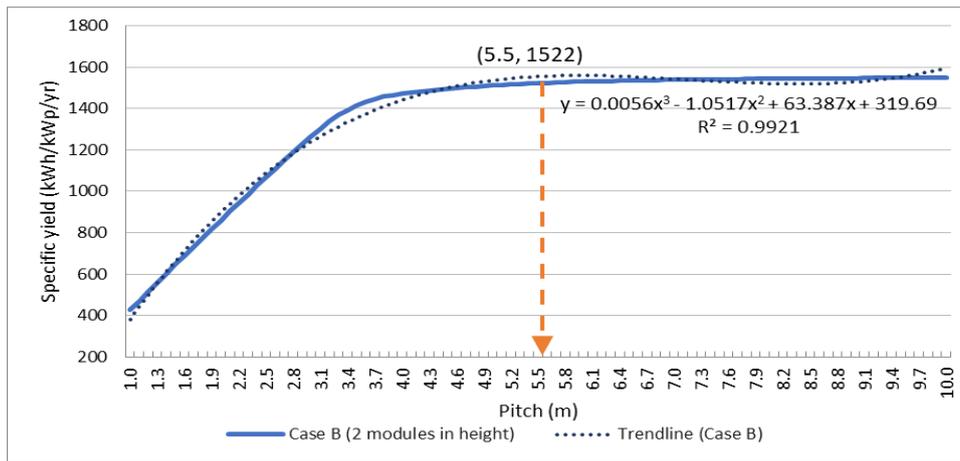
The correlation coefficients (R^2) for Case A, Case B, and Case C were 0.8397, 0.9921, and 0.9935, respectively, which indicates a strong fit for describing how specific yield changes with pitch. By increasing the pitch value for Case A, Case B, and Case C, specific yield increased but flattened at threshold pitch values of 4.1 m, 5.5 m, and 7.2 m, respectively. The threshold pitch values were identified by determining the point at which the difference between sequential specific yields approaches zero as indicated in Figure 5 (a) (b) (c). This saturated point is an optimal pitch value where the sunlight reflected to the rear side of the module has reached the maximum level. This indicates that increasing the pitch beyond this point results in negligible gains in specific yield or minimal improvements in specific yield. In other words, greater spacing between rows increases the amount of reflective irradiance to reach the rear side of the PV module, and reduces the shading effect, thus enhancing energy production however up to a certain pitch threshold value. This phenomenon is likely due to the maximum ground reflection already being achieved, which reduces the benefits of increasing the pitch further. As an element of validation, the results were compared with the benchmark case study as mentioned in methodology section. The scope of comparison was for the arrangement of two PV modules in height in terms of optimal pitch and specific yield. The benchmark case study utilized a pitch value of 5.5 m that achieved a specific yield of 1515 kWh/kWp/year. On the other hand, this study has also obtained the optimal pitch value of 5.5 m. However, the specific yield was found to be 1522 kWh/kWp/year, that was slightly higher than the benchmark case study. Despite the slight difference in specific yield, this finding is in close agreement with the benchmark case study, with a difference of only 0.46 %. The observed variation may be attributed to differing loss assumptions.

A study of the actual bPV system for latitude from 21°N to 51°N for one module in height has obtained similar results where increasing the pitch significantly enhances

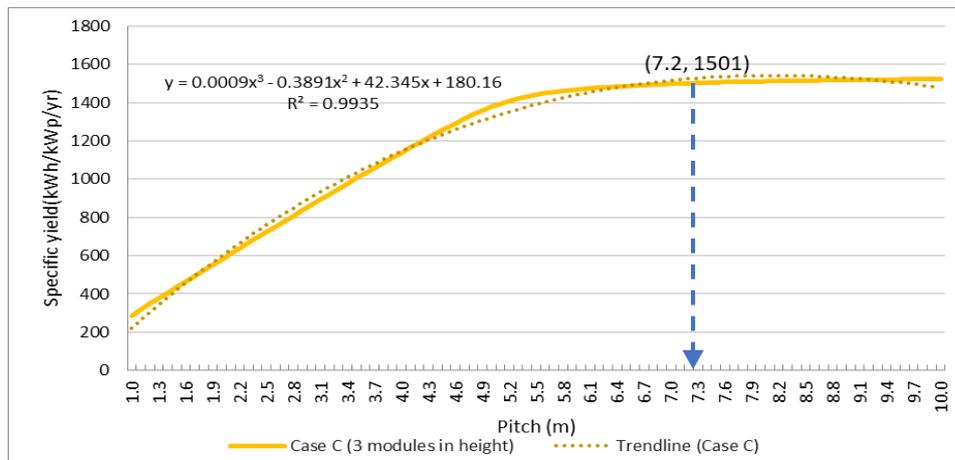
the specific yield. The study also emphasized that further increment of pitch at a certain point did not significantly affect the specific yield (Johnson & Manikandan, 2023).



(a)



(b)



(c)

FIGURE 5. Effect of pitch towards specific yield for (a) Case A, (b) Case B, and (c) Case C

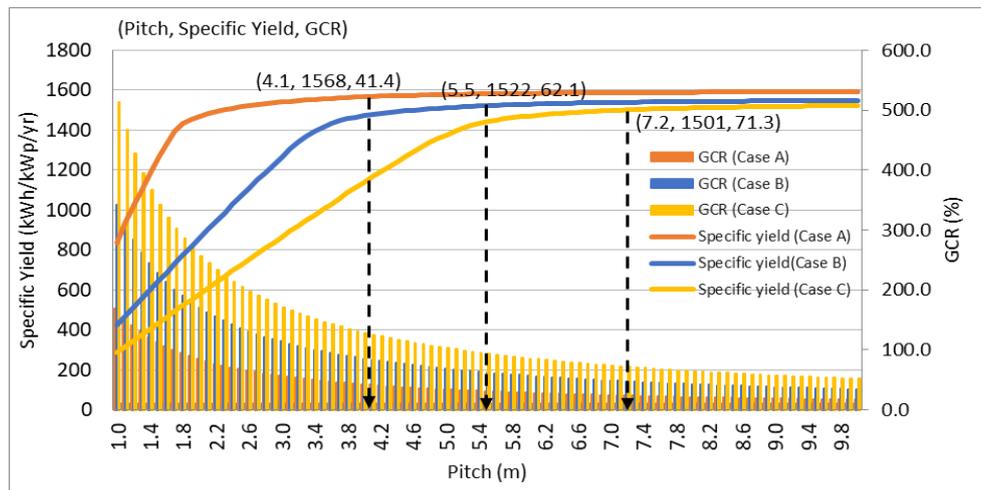


FIGURE 6. Effect of pitch on GCR and the specific yield of bPV system

Based on the results, the optimal pitch for Case A, Case B, and Case C has been determined and tabulated in Table 5. Specific yield can also be related to GCR as shown in Figure 6. In this study, we analyzed based on two ranges of GCR which were 0% to 50%, and 50% to 100%. For Case A, the GCR of 0 to 0.5 results in the specific yield dropped by 2.35%, while the GCR of 0.5 to 1.0, the specific yield dropped by 8.17%. For Case B, the GCR of 0 to 0.5 results in the specific yield dropped by 0.58%, while the GCR of 0.5 to 1.0, the specific yield dropped by 8.33%. For Case

C, the GCR of 0.5 to 1.0 results in the specific yield dropped by 7.78%. The specific yield is affected by GCR values which are stated in a case study where GCR from 0 to 0.5, energy yield dropped by 9%, and while GCR from 0.5 to 1.0, specific yield dropped by 50% (Tonita et al. 2023). In summary, as GCR decreases, the energy yield will increase. This is because when the GCR is below 50%, more beams are reflected from the ground, resulting in better system production compared to GCR above 50% (Zhang et al. 2023).

TABLE 5. Result of optimal pitch value, GCR, and specific yield for Case A, Case B, and Case C

Case	Module in height	Optimal Pitch value (m)	GCR (%)	Specific yield (kWh/kWp/yr)
A	1	4.1	41.4	1568
B	2	5.5	62.1	1522
C	3	7.2	71.3	1501

RELATIONSHIP BETWEEN GCR AND PITCH

Figure 7 shows the relation between GCR and pitch for Case A, Case B, and Case C. The relationship between GCR and pitch value is nonlinear, following a polynomial of degree 3, which is a cubic trend. This means that as the pitch value changes, the GCR does not change at a constant rate. Instead, the rate of change varies, and this variation can be described by a quadratic equation for Case A, Case B, and Case C as listed below:

$$A: y = -0.0006x^3 + 0.104x^2 - 6.2471x + 150.37 \quad (5)$$

$$B: y = -0.0012x^3 + 0.2092x^2 - 12.568x + 302.51 \quad (6)$$

$$C: y = -0.0017x^3 + 0.3144x^2 - 18.889x + 454.66 \quad (7)$$

The trend of the data fits a quadratic curve very closely, with a correlation coefficient (R^2) of 0.9753 for all cases. This high R-value indicates a strong correlation, meaning the polynomial equation is a good fit for describing how GCR changes with pitch. However, the simulation result shows that when the pitch is at the minimum acceptable value for Case A, Case B, and Case C which is 1.7 m, 3.4 m, and 5.1 m, respectively, it results in a GCR larger than or equal to 100%. A GCR of 100% implies no gaps between the rows, resulting in full utilization of the ground surface for PV module placement. Therefore, the GCR value exceeding 100% was generally impractical due to no spacing between the modules or overlaps with each other which causes significant shading and impacts system

performance. The formula listed below was used in this study to calculate the minimum acceptable value of a pitch for Case A, Case B, and Case C (SEDA Malaysia, 2022; Tonita et al, 2023):

$$GCR = \frac{W_{array}}{R} \tag{8}$$

GCR is Ground Coverage Ratio, W_{array} is width of the the PV array, and R , R is Pitch.

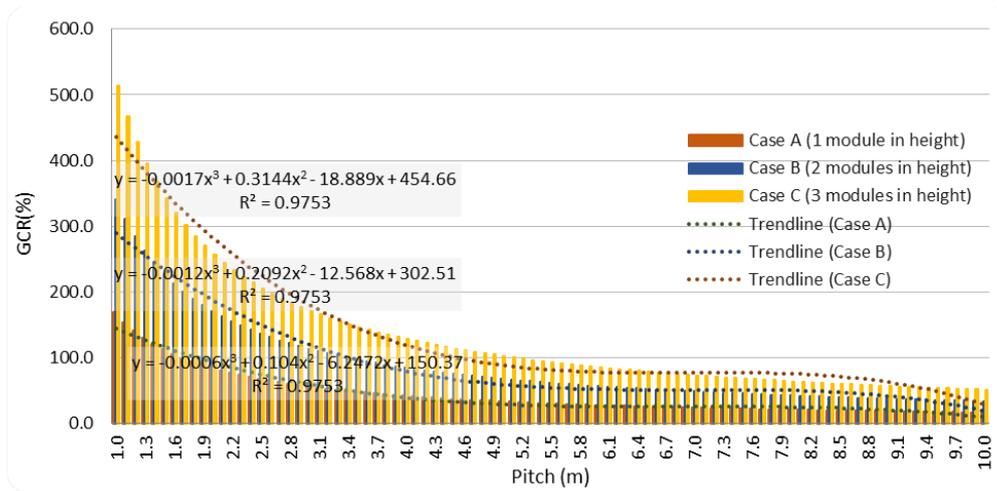


FIGURE 7. Effect of pitch towards GCR for Case A, Case B, and Case C

CONCLUSION

This study has succeeded in investigating the pitch value of a 45 MW bPV system located in Kedah, Malaysia, for three cases which were Case A (1 module in height), Case B (2 modules in height), and Case C (3 modules in height). The design and sizing simulation using PVsyst software aims to maximize specific yield for solar farms under the scenario of without space constraints. The findings revealed that increasing the pitch value increases the specific yield up to a certain threshold. Beyond this optimal point, the specific yield plateaus and is recognized as the optimal pitch value. Optimal pitch values of 4.1 m, 5.5 m, and 7.2 m were identified for cases A, B, and C, respectively, at a fixed height of 1.5 m. This optimal value serves as a crucial guideline, offering valuable insight for designers to determine the pitch that maximizes energy production. While it provides a strong reference point, it's important to note that the exact value may vary slightly depending on the dimensions of the PV modules. While this value provides valuable insights for fixed tilted GCPV systems in tropical climates for solar farms, fixed albedo & height without space constraints, further research is necessary to determine the optimal pitch for bPV systems operating within limited land area and varying consideration on design parameters.

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DECLARATION OF COMPETING INTEREST

None.

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