EVOLUTION IN ELECTRICAL AND ELECTRONIC ENGINEERING
e-ISSN: 2756-8458

EEEE

Vol. 7 No. 1 (2026) 60-67
https://publisher.uthm.edu.my/periodicals/index.php/eeee

Performance Analysis of Solar PV System with Tilt Angle Optimization to Enhance Energy Efficiency

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DOI: https://doi.org/10.30880/eeee.2026.07.01.009

Article Info

Received: 15 January 2026
Accepted: 11 April 2026
Available online: 30 April 2026

Keywords

Photovoltaic System, Renewable Energy, Solar Panel Orientation, PVSyst Software, Energy Production, Cost Analysis, Return on Investment

Abstract

Solar energy is a key component of clean, green energy technology to meet the rising demand for electricity in today's world. Solar system efficiency is dependent on many factors, including installation quality, measurement instruments, and cost analysis. Solar system installation plays a vital role in energy production. Poor installation leads to lower energy output, high cost and system failure. The accuracy of measurement instrumentation helps identify key parameters such as solar irradiance, voltage, and current. The main objective of this research work is to analyse the relationship between installation quality, measuring instruments, and their cost. Simulation tools are used to model the real-world case study scenario and analyse the effect of the tilt angle on solar system performance. The findings indicate that high installation quality can enhance measurement precision, leading to more reliable performance and better financial outcomes. Accurate instrumentation lowers maintenance costs and increases operational efficiency, thereby promoting the long-term sustainability of the solar system project.

1. Introduction

Energy is one of the essential needs of daily human lives, and the demand is increasing rapidly in the commercial and domestic markets. As a result of the depletion of non-renewable energy, renewable energy resources are in high demand among consumers [1]. This created significant demand for engineers and engineering students to develop solutions that transition from non-renewable energy to renewable energy sources, which offer a reliable supply of power without the worry of depletion [2].

To generate electricity, the solar photovoltaic (PV) system is used as a power system consisting of one or more solar panels combined with an inverter and other electrical and mechanical components. This system can convert sunlight into electricity by utilising the photovoltaic effect. This is a process in which semiconducting materials generate voltage and current when exposed to light. Besides that, photovoltaics provides 100% clean and renewable energy, which allows for being less dependent on fossil fuels, reducing carbon dioxide emissions and preventing global warming [3]. Renewable energy emerged as the obvious choice to meet the growing need for energy while reducing carbon dioxide emissions, which are the main contributor to global warming [4].

In Malaysia, residential energy use accounts for more than 14,365 GWh or 19% of the total electricity consumed in Peninsular Malaysia in 2006. Hence, Malaysia promotes renewable energy, especially solar PV, through various incentives. As subsidies decline, fuel price volatility becomes critical, since electricity generation still depends heavily on coal and natural gas resources [5]. There are many organisations organising green campaigns, such as Environmental Protection Society Malaysia (EPSM), Malaysia Environment NGOs (MENGO), and Treat Every Environment Special Sdn. Bhd. (TRESS) [6]. These organisations promote the benefits of solar energy use and the environmental effects to create public awareness. Besides that, the government also introduced the Net Energy Metering 3.0 (NEM 3.0) on 29th December 2020 to provide more opportunities for electricity consumers to install solar PV systems on the roofs of their premises to save their electricity bills [7].

SEDA Malaysia has introduced two main solar PV programs for consumers. The Net Energy Metering (NEM) scheme, which is still active, allows users to offset their electricity consumption. Meanwhile, the Feed-in Tariff (FiT) programme, which was implemented from 2017 to 2020, allowed all electricity generated by a PV system to be exported directly to the utility grid. Under this scheme, utility companies pay a fixed rate to Feed-in Approval Holders (FiAH) for the electricity supplied over a period of 21 years [8]. This programme gained popularity in Malaysia due to its attractive selling rates. Through Net Energy Metering, the users can send back the excessive electricity to the energy provider grid, which significantly saves their electricity usage cost [9].

2. Methodology

This research work utilises a simulation technique to evaluate the installation quality of a solar PV system by taking into consideration a real-world case study. Numerous factors and their influence on efficiency have been evaluated, including tilt angle, solar irradiance, and wiring quality. The research commences with an extensive literature review on previous simulation studies, actual data from FKEE are obtained and compared with the simulation results. The data analysis reveals the effectiveness of tilt angle on output power and PV performance. The detailed methodological steps are provided in Fig. 1.

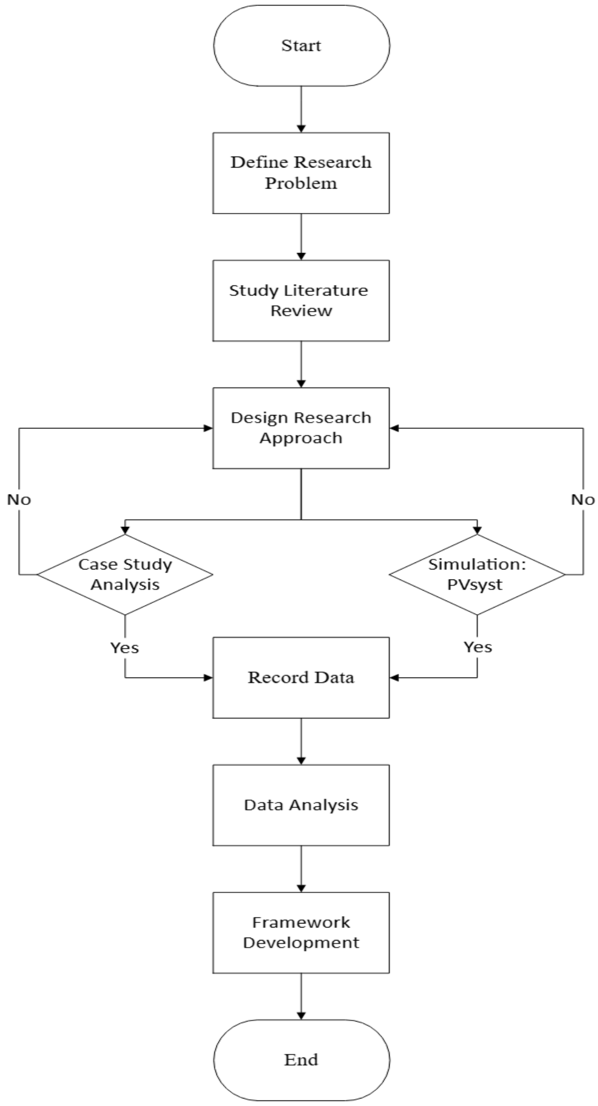


Fig. 1 *Flowchart of the project*

2.1 Case Study Analysis

In this research, data have been collected from the PV installation at the Universiti Tun Hussein Onn Malaysia (UTHM) Parit Raja campus, Batu Pahat, Johor. The installed PV system capacity is 6.9 MWp. This system supports Malaysia's net-zero emissions goal and renewable energy production. The PV panels are installed in 25 different locations, including parking lots, auditoriums, and academic blocks. The main objective of this research is to analyse the effect of tilt angle on PV system performance. The parking lot of the FKEE building has a capacity of 300.6 kW, connected to 3 grid-tied inverters, and has been in operation for more than a year, as shown in Fig. 2. Data from these inverters have been collected for comparison in the simulation studies.

(a) **(b)** **(c)**

Fig. 2 *(a) Site location (b) Existing solar structure (c) Inverter and distribution box panel arrangement*

2.2 PVSyst Simulation Software

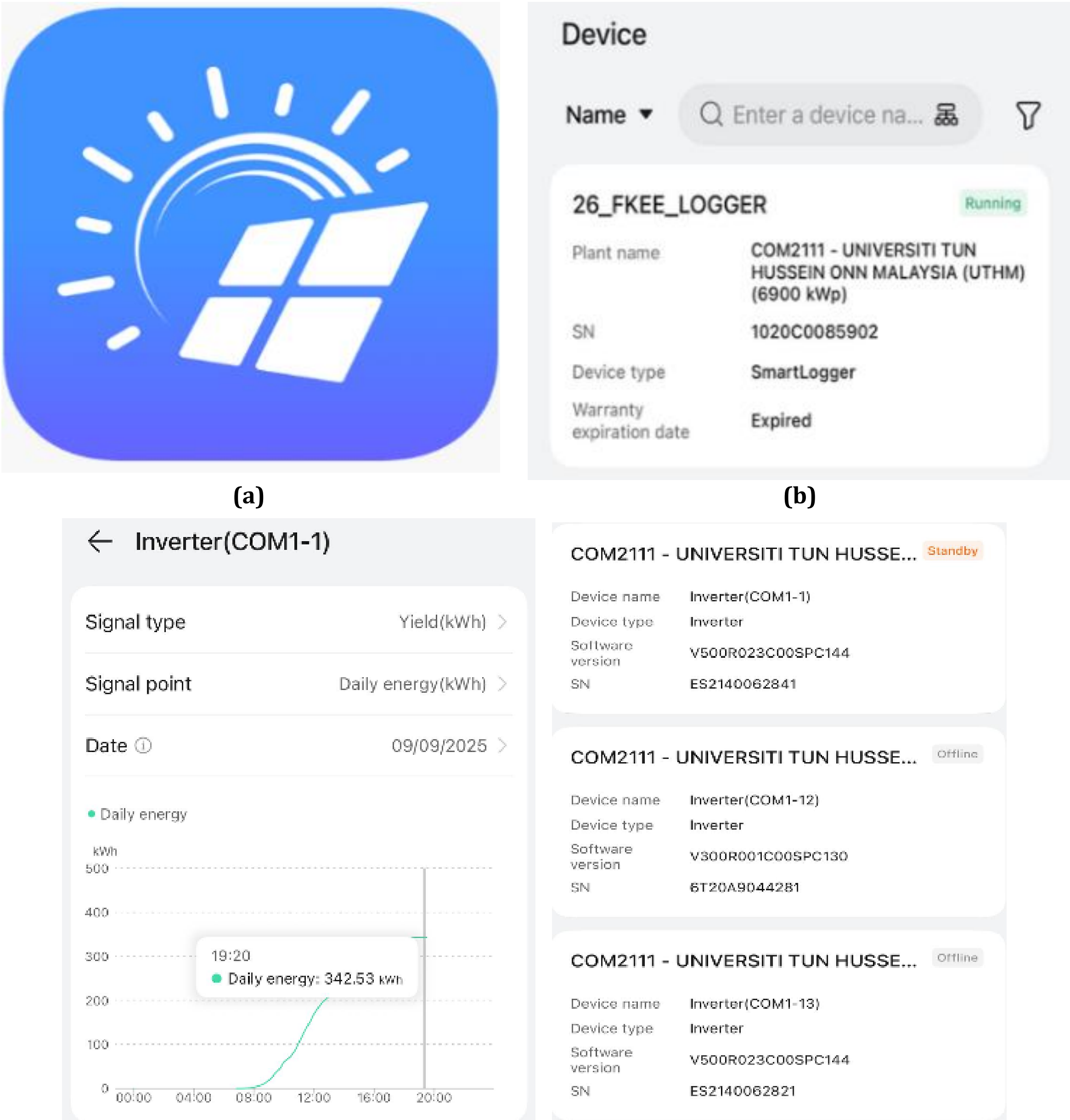
In this research work, the PVSyst software tool was utilised to analyse the influence of installation quality on PV system performance. This simulation package is commonly used for analysing, planning and modelling PV systems. Numerous parameters can be considered in this tool, such as tilt angle, orientation, radiation levels and shading. The software can predict the energy production on the basis of historical weather data, along with evaluating economic aspects of installation as well. The tools use comprehensive mathematical models considering site layout, weather and components to provide better insights into the PV system. Hence, the software can effectively design a PV system that is technically sound and cost-effective.

The software is fed with actual data from the facility, including location, weather, module type, inverter specification and panel orientation. These input parameters help the software predict accurate incident radiation and PV performance with different tilt angles. Hence, calculate the expected energy production by considering practical system losses such as temperature effects, wiring losses, inverter efficiency, and mismatch conditions. The simulation results were then compared with measured energy data from the operating PV system. This approach allows reliable performance comparison between different installation configurations under consistent conditions.

3. Result and Discussion

3.1 Actual Solar PV Data

The actual operational data of the solar photovoltaic (PV) system installed at the parking lots FKEE, collected through the FusionSolar monitoring application connected to the data logger FKEE. The data represent a three-month monitoring period with 30 days of recorded power generation per month from three grid-connected inverters. The daily energy output from each inverter is to be used to calculate the monthly and total energy production of the PV system. Data from multiple inverters is to be used to provide more accurate data on system performance. The example is shown in Fig. 3.

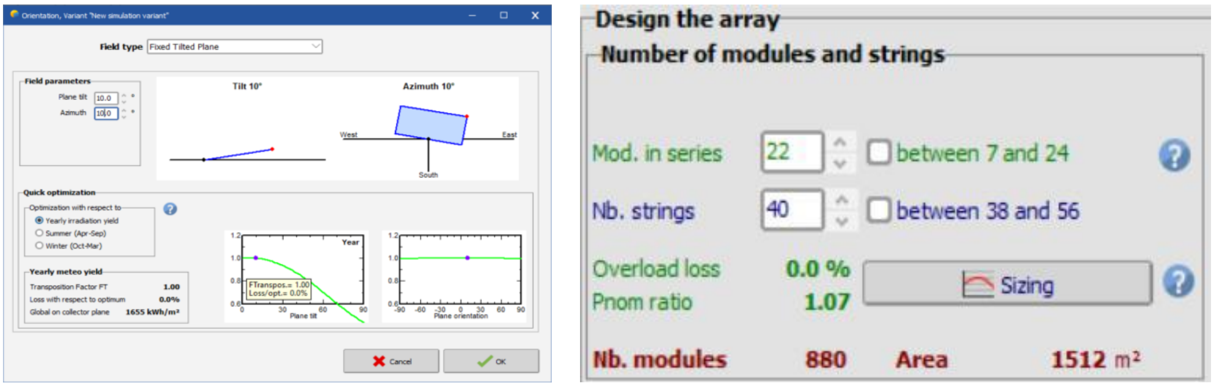


(c) (d)

Fig. 3 *(a) FusionSolar apps (b) FKEE logger (c) Inverter COM (d) Daily energy production*

3.2 Input Parameters PVSyst Simulation

The PV system configuration is an important input for the PVsyst simulation, especially the panel orientation and tilt. In this study, the tilt angle and azimuth were set to 10° according to the actual installation conditions. As the system is using a fixed mount without tracking, a “Fixed Tilted Plane” was selected. The configuration also includes the total number of PV modules, connected in series and parallel strings, and the total number of strings, so that the simulation is very similar to the layout of the real system. The parameter settings in the PVSyst software are shown in Fig. 4.



(a) **(b)**

Fig. 4 *Panel orientation setup (a) PV array design (b) Inverter & PV modules settings (C)*

3.3 Panel Tilt Angle Adjustment

Table 1 presents the total electrical energy produced by the solar PV array in a year for different tilt angles. From the table, it can be seen that 10° and 20° tilts provide more energy yearly than the 30°. The power output at all tilt angles is higher in the first three months of the year, and it decreases in May and July due to lower radiation and rainfall. The 20° tilt angle in January, March, October, November, and December gives optimal performance. On the other hand, 30° tilt generated the least energy in all months, concluding that the large tilt angle is not satisfactory in our case study.

It is observed that the highest annual energy yield is obtained from a 10° tilt angle; however, a 20° tilt provides a better solution for everyday operation. It reduces the maintenance cost as with a steeper angle, the accumulated dust is easily washed out by rain. Dust accumulation over time condenses to solid residue, which also affects the PV panels' efficiency. Hence, due to these advantages, it is concluded that a 20° tilt is most suitable for PV panels. Considering both energy yield and operational sustainability, the 20° tilt provides a balanced solution between performance efficiency and maintenance.

Table 1 *Simulated energy production within a year*

Month	Array Energy Output (kWh)		
	Tilt (10°)	**Tilt (20°)**	**Tilt (30°)**
Jan	32731	34566	31561
Feb	32757	33836	30235
Mar	34076	34160	29598
Apr	30700	29910	25062
May	28344	26644	21408
June	25579	23784	18890
July	28601	26844	21574
Aug	29366	28236	23337
Sep	29438	29228	25058
Oct	29687	30215	26623
Nov	26659	27789	25070
Dec	26718	28069	25554

The annual energy production is shown in Fig. 5. It can be seen that, however, 20° in some months exceeds the electricity generation, but due to the practical and easy maintenance along with better energy output, 20° is considered more appealing. On the other hand, a 30° tilt presents lower energy output and hence lower overall performance.

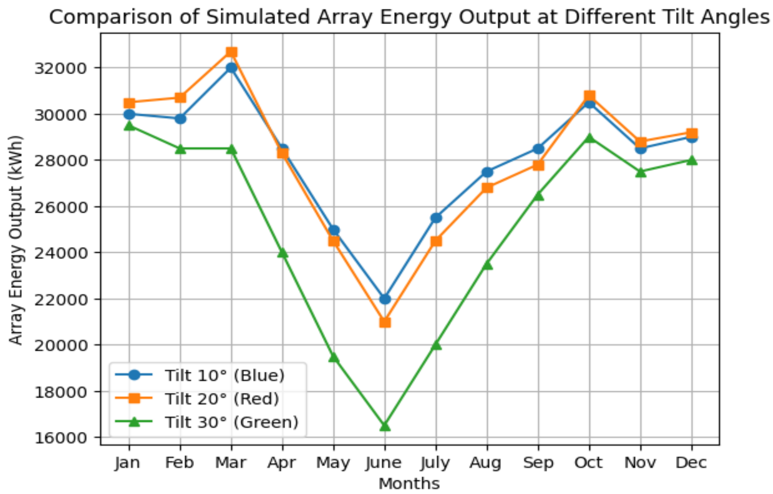


Fig. 5 *Graph of annual array energy production*

3.4 Actual Data Acquisition and Simulation Data

The average daily solar irradiance and three months of data from 1st September to 31st November, 2025, are used for this research work. The comparison of actual energy produced and simulation results is shown in Table 2. The simulation data is based on tilt angle and solar irradiance measured at the parking area of FKEE. The simulation results reveal comparative results to actual data and prove its worth in tilt angle optimisation in real-world scenarios. The little difference is due to weather, system losses and other site-specific factors.

Table 2 *Energy production data and daily average irradiance*

Month	Solar Irradiance (kWh/m^2)		Energy Production (kWh)			
			Tilt 10°		Tilt 20°	Tilt 30°
	Actual	Simulation	Actual	Simulation	Simulation	Simulation
Sep	148.96	137.7	18740	27267	29228	25058
Oct	146.02	135.6	26643	27498	30215	26623
Nov	122.50	118.6	21197	24693	27789	25070
Total	417.48	391.9	66580	79458	87232	76751

The strong relationship between irradiance and energy output is seen in September and October, with an average of around 147 kWh/m^2, as can be seen in Fig. 6. October records the highest output of 26,643 kWh at a 10° tilt. The overall energy production dropped in November for all tilt angles to about 122.5 kWh/m^2 (actual) and 118.6 kWh/m^2 (simulated). The system performance is greatly affected by panel tilt and operating. It is observed that simulation results at 20° tilt show better efficiency during this period, reaching up to 30,215 kWh. On the other hand, actual power output at 10 ° tilt in September is considerably lower than the simulated result. Hence, it is concluded that weather conditions, shading, and maintenance can reduce PV panels' performance.

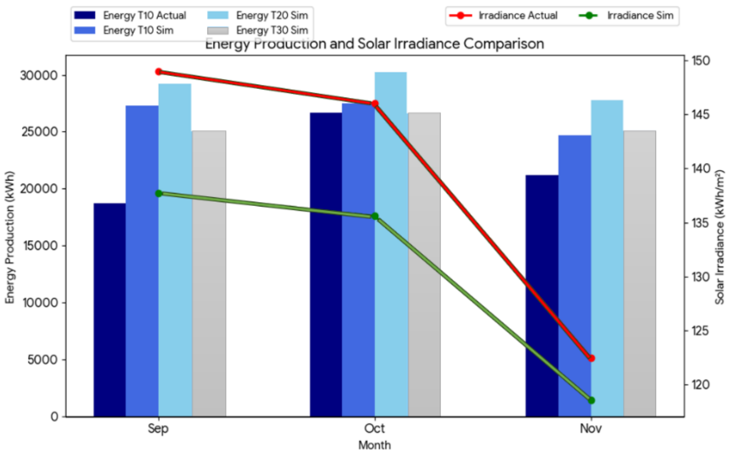


Fig. 6 *Graph comparison of energy production by solar irradiance*

3.5 Cost Analysis and Return on Investment

The total energy generated multiplied by the local electricity tariff sums up to the total revenue of PV system. When the system is capable of generating more electricity by optimising the tilt angle, it helps in reducing reliance on grid energy and hence minimises the electricity cost. It is concluded from the simulation results that the proposed system achieves higher financial returns than the existing system. The actual measured data over a three-month period (September to November), the existing PV system with a 10° tilt angle generated a total of 66,580 kWh. While the proposed system, through PVsyst simulation, with a 20° tilt angle, is estimated to produce 79,458 kWh. The proposed system can significantly increase energy production by up to 12,878 kWh. In price, the existing system generates approximately RM29,561.52, while the proposed system is expected to generate RM35,272.75 over the same period. Hence, it is estimated that the proposed system shows higher efficiency and return on investment by generating an additional revenue of RM5,711.23 within three months, as shown in Table 3.

Table 3 *Three-month energy production and revenue*

Parameter	Tilt 10° (Actual)	Tilt 20° (Simulation)
Energy Production (kWh)	66,580	79,458
Electricity Tariff (RM/kWh)	0.444	0.444
Total Revenue (RM)	29,561.52	35,272.75
Additional Energy (kWh)	–	12,878
Additional Revenue (RM)	–	5,711.23

A thorough assessment was performed to evaluate the Return on Investment (ROI) for the modified structure. The total cost of the modification was estimated at RM 92,400, including metal racking, labour, transport and an additional 10% contingency. The annual energy gain was projected to be around 22,844.92 kWh over the full year. The ROI is measured as the annual energy gain divided by the cost as a percentage. The result reveals an ROI of 24.7%, resulting in a quarter of its cost returning in a year. This highlights the financial benefit of implementing the structural modification.

The proposed system shows that it can generate more power worth RM 22,844.92 annually. This can significantly help in financial savings and minimise the cost of electricity.

3.6 Framework Development

The PV panel tilt optimisation framework is a systematic approach designed to maximise energy production and improve the financial performance. The framework consists of five main stages. First is simulation analysis, preceded by actual data collection, the gap analysis, modification to the existing system and the overall financial validation of the proposed system. The steps of the framework are shown in Fig. 7.

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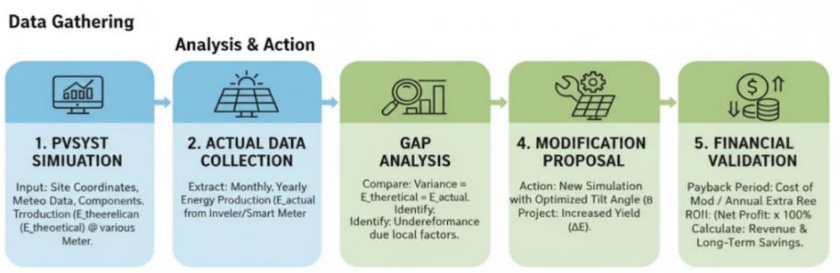

Fig. 7 *Framework development step*

4. Conclusion

This project developed a systematic approach to identify the optimal tilt angle for a PV system to improve both energy production and financial performance. The simulation software PVsyst was utilised to evaluate the total energy production by varying the tilt angles, weather conditions and system design. The simulation study helps in providing a baseline for the improved performance of the PV system. The real data for the case study was obtained from the facility inverter and smart meter to be utilised in the simulation system and comparative analysis. A thorough gap analysis was conducted by comparing the simulated and real data. It is observed that a 20-degree tilt angle provides better efficiency in energy output and more practical usage of the PV system. The results from this research work revealed that, by optimising tilt angle and considering different environmental effects, the overall energy output of the PV panel can be significantly improved.

Acknowledgement

The authors would like to thank the Faculty of Electrical Engineering, Universiti Tun Hussein Onn Malaysia, for all the resources provided.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Alif Aiman Bin Khairuddin, Rahisham Bin Abd Rahman, Rizwan Ahmed;* ***data collection:*** *Muhammad Alif Aiman Bin Khairuddin, Bala Murugan Krishnan;* ***analysis and interpretation of results:*** *Muhammad Alif Aiman Bin Khairuddin, Rahisham Bin Abd Rahman, Totok Dewantoro;* ***draft manuscript preparation:*** *Muhammad Alif Aiman Bin Khairuddin, Rahisham Bin Abd Rahman, Gezaq Abror. All authors reviewed the results and approved the final version of the manuscript.*

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