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OPTIMIZATION OF TILT ANGLE FOR FIXED TILT SOLAR PV SYSTEM: CASE STUDY FOR USIM, NILAI, NEGERI SEMBILAN

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Abstract— This study investigates the optimal tilt angle for fixed-tilt solar photovoltaic (PV) systems and identifies a suitable site for solar farm development at Universiti Sains Islam Malaysia (USIM) in Nilai, Negeri Sembilan, Malaysia. Experimental data were collected from Terco PST2291 solar modules positioned at various tilt angles of 5°, 10°, 20°, 30°, 40°, and 50°, and supplemented with PVsyst software simulations. The results indicate that a 5° tilt angle maximizes energy yield under local climatic conditions. A site suitability analysis was conducted to determine the best location for a solar farm within the USIM campus. Five potential sites

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were evaluated based on economic viability, energy production potential, accessibility, and land availability. Site 4 emerged as the most suitable option, with the highest energy generation of 9963 MWh/year, offering optimal conditions for solar energy harvesting and infrastructure development. Site 4's larger area and superior solar irradiance result in the highest energy generation potential. Economic analysis confirms its feasibility, with a competitive Levelized Cost of Electricity (LCOE) and strong Return on Investment (ROI), making it a financially viable choice for sustainable energy production. This article provides valuable insights into optimizing solar PV system design and deployment in Malaysia, supporting USIM's sustainability goals and serving as a reference for future solar energy projects in similar climatic regions.

I. Introduction

The growing global energy demand, alongside the significant environmental impacts of fossil fuel reliance, has accelerated the adoption of renewable energy technologies. Solar photovoltaic (PV) systems have gained prominence due to their widespread availability, decreasing costs, and low environmental impact [1-5]. The efficiency of solar PV systems is influenced by several factors, including solar irradiance, ambient temperature, and system design parameters [6, 7]. Solar irradiance, defined as the solar power received per unit area, varies significantly based on geographic location, time of day, and weather conditions.

A key design parameter is the tilt angle of PV panels, as illustrated in Figure 1, which plays a crucial role in optimizing energy yield [8]. The tilt angle, representing the inclination of the panels relative to the horizontal plane, directly affects the amount of solar radiation captured over daily and seasonal cycles [9-11]. Proper alignment of the panels with the sun's trajectory enhances the interception of solar energy, thereby maximizing the system's electrical output. However, the optimal tilt angle is location-specific and depends on the desired energy production profile.

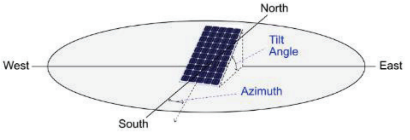


Figure 1: Representation solar PV tilt angle

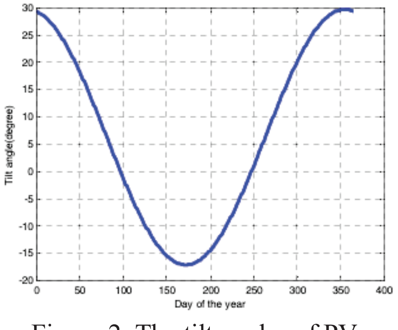


Figure 2: The tilt angles of PV modules in Perlis, Malaysia [11]

Figure 2 presents the optimal tilt angle for photovoltaic (PV) modules in Perlis, Malaysia, across the year. The tilt angle, defined as the angle between the PV module and the horizontal plane, plays a critical role in determining the solar irradiance captured and, ultimately, the energy output of the PV system.

The graph reveals a sinusoidal variation in the optimal tilt angle, reflecting the changing position of the sun relative to Perlis as the Earth orbits the sun. In fixed-tilt PV systems, the panel angle remains constant, offering a simpler and more cost-effective alternative to tracking systems, which dynamically adjust to follow the sun's path. However, the fixed nature of these systems requires careful optimization of the tilt angle to maximize annual energy yield. This underscores the importance of selecting an angle that balances seasonal variations in solar irradiance for optimal performance.

II. Methodology

This section outlines the methodology used to investigate the optimization of tilt angles for fixed-tilt solar PV systems at USIM, Nilai, Negeri Sembilan.

It details the research design, experimental setup, simulation parameters, data collection procedures, and analysis techniques employed to achieve the study's objectives.

A. Simulation Setup

To accurately replicate the experimental setup at Makmal Kejuruteraan (MKJ) USIM within PVsyst software, a detailed simulation framework was developed to determine the optimal tilt angle for maximizing energy yield from a solar panel installation. The process began by defining the project's geographical location, as illustrated in Figure 3, and integrating site-specific meteorological data, including solar irradiance, ambient temperature, and wind speed, as shown in Figure 4. These factors are critical in influencing the performance of the solar panels and were carefully incorporated into the simulation to ensure accuracy.

The single line diagram illustrates in Figure 5 shows a grid-tied solar power system. The system consists of three strings of solar panels which each connected to a dedicated 1kVA microinverter. A string monitoring device, labelled as FU325M NEXT, oversees the performance of the entire array. The microinverters convert the direct current (DC) power generated by the solar panels into alternating current (AC) power.

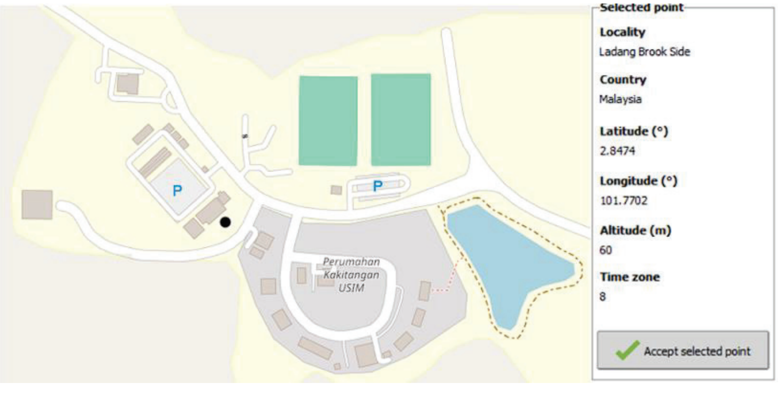
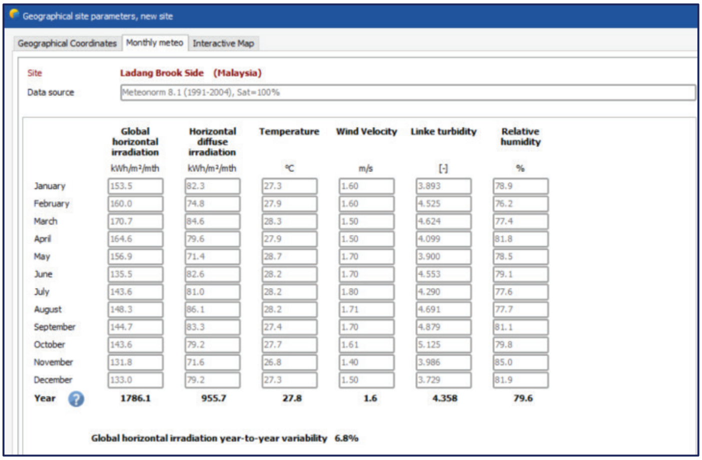


Figure 3: Project's geographical location



	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	kWh/m²/mth	kWh/m²/mth	°C	m/s	[-]	%
January	153.5	82.3	27.3	1.60	3.893	78.9
February	160.0	74.8	27.9	1.60	4.525	76.2
March	170.7	84.6	28.3	1.50	4.624	77.4
April	164.6	79.6	27.9	1.50	4.099	81.8
May	156.9	71.4	28.7	1.70	3.900	78.5
June	135.5	82.6	28.2	1.70	4.553	79.1
July	143.6	81.0	28.2	1.80	4.290	77.6
August	148.3	86.1	28.2	1.71	4.691	77.7
September	144.7	83.3	27.4	1.70	4.879	81.1
October	143.6	79.2	27.7	1.61	5.125	79.8
November	131.8	71.6	26.8	1.40	3.986	85.0
December	133.0	79.2	27.3	1.50	3.729	81.9
Year	**1786.1**	**955.7**	**27.8**	**1.6**	**4.358**	**79.6**

Figure 4: Meteorological data from Meteonorm 8.1

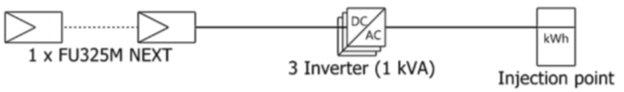


Figure 5: Single line diagram

B. Hardware Setup

The PST2291 is a solar power generation module comprising three photovoltaic (PV) panels equipped with on-grid micro-inverters, a junction box, a fuse box, a microinverter assembly, and a main control module located in the power laboratory as illustrated in Figure 6. It is integrated with other modules in the Terco Power Systems and Transmission simulator.

Functioning as a generator station, the PST2291 delivers three-phase solar-generated power to a power network, simulating a solar farm. It includes all essential equipment for switching, protection, and voltage transformation before connecting to the grid.

The tilt angle of the solar panels can be adjusted to one of six specified angles: 5°, 10°, 20°, 30°, 40°, or 50° as shown in Figure 7. This adjustment is critical, as the panel's angle relative to the sun significantly influences the amount of solar energy captured and, consequently, the system's overall energy output. Data is captured between 9 AM to 3 PM daily. Only one tilt angle is tested per day, using three solar panels to gather comprehensive data for that specific angle.

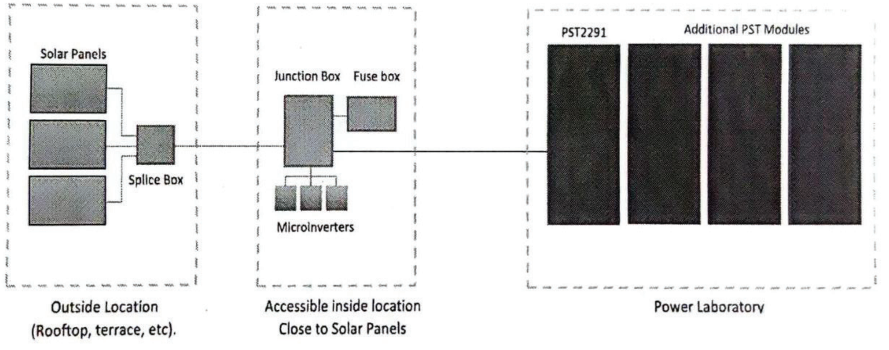


Figure 6: Illustrates setup of PST2291

Figure 7: Adjusting part of solar panel

III. Results and Discussion

This section provides a detailed analysis of the output power generated by a fixed-tilt solar photovoltaic (PV) system installed at USIM, Nilai, Negeri Sembilan. The performance of the system is evaluated across multiple tilt angles using experimental data obtained from the Terco PST2291 Solar Power Module and simulation results generated via PVsyst software using the same power module. The findings offer insights into the impact of tilt angles on energy yield, enabling optimization of the system's design and operation.

A. Simulation Result

In this section, detailed analysis of the simulation data obtained from PVsyst software is provided. The focus is on the total energy produced and the energy produced per hour at various tilt angles of 50°, 40°, 30°, 20°, 10°, and 5°. Table 1 and Figure 8 summarize and illustrate these findings.

The results reveal a clear trend: reducing the tilt angle leads to an increase in both total energy production and average hourly energy output. This aligns with the expectation that tilt angles closer to Nilai's latitude (2.8° N) capture more direct solar irradiance over the year, enhancing energy yields. Specifically, the 5° tilt angle achieved the highest total energy production of 3636Wh, marking a 119% increase compared to the 50° tilt angle. This underscores the importance of optimizing tilt angles to maximize energy generation in fixed-tilt PV systems.

Table 1: Total energy produces from simulation setup

Tilt Angle (°)	Total Energy Produces (Wh)	Energy Produced Per Hours (W)
50°	1658	138.16
40°	2174	181.17
30°	2672	222.67
20°	3113	259.42
10°	3482	290.17
5°	3636	303.00

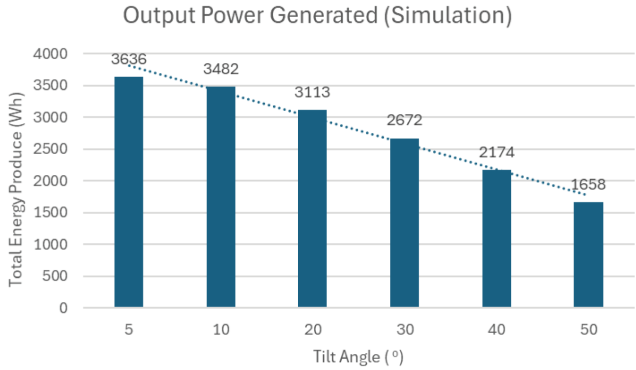


Figure 8: Graft output generated for simulation setup

B. Experimental Result

The experimental setup consisted of a Terco PST2291 Solar Power Module configured at various tilt angles to measure the output power. Table 2 presents the total energy produced and the average energy produced per hour for each tilt angle over the experimental period.

The experimental results align closely with the simulation findings, showing that reducing the tilt angle leads to higher total energy production and greater average hourly energy output. This trend supports the theoretical principle that tilt angles closer to Nilai's latitude (2.8° N) optimize the capture of direct solar irradiance over the year. Notably, the 5° tilt angle achieved the highest total energy production of 2909.1Wh, representing a significant 163.5% increase compared to the 50° tilt angle. These results highlight the critical role of tilt angle optimization in maximizing the performance of fixed-tilt solar PV systems.

Table 2: Total energy produces from experimental setup

Tilt Angle (°)	Total Energy Produces (Wh)	Energy Produced Per Hours (W)
50°	1103.8	183.97
40°	1593.3	265.55
30°	1759.1	293.18
20°	2007.0	334.50
10°	2720.6	453.43
5°	2909.1	466.67

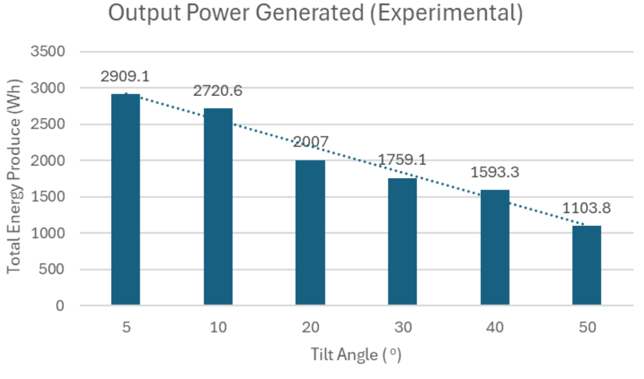


Figure 9: Graft output generated for experimental setup

C. Identify the optimum site area for solar farm in USIM

A thorough evaluation was conducted to determine the optimal site for a solar PV system installation within USIM. Five potential sites were assessed, with a primary focus on the available area, a critical factor influencing energy generation potential. This analysis aimed to identify the site best suited for maximizing solar energy output while considering practical constraints.

Table 3 offers a comprehensive overview of the proposed solar PV system configurations for each potential site at USIM. It details the number of PV modules, inverters, nominal PV power (kWp), and estimated annual energy production (MWh/year) for every site, providing a clear comparison of their energy generation potential and system requirements. This data serves as a critical foundation for selecting the most viable site for solar PV deployment. Note that this is based purely on calculation for simulation purposes.

Table 4 provides an economic analysis of the potential solar PV installation sites at USIM, evaluating key financial metrics such as installation costs, total yearly costs, levelized cost of electricity (LCOE), payback period, and return on investment (ROI). This analysis offers a comparative assessment of the economic viability of each site, aiding in the selection of the most financially sustainable option for solar PV deployment.

Table 3: Estimated annual energy production for proposed solar PV system at various sites within USIM

Site	No. PV Modul	No. Inverter	Nominal PV Power (kWp)	System Production (MWh/year)
1	16360	2	5235.2	7155
2	4900	1	1568.0	2183
3	13620	2	4358.4	6063
4	22700	3	7264.0	9963
5	6920	1	2214.4	3049

Table 4: Economic analysis each site

Site	Installation Cost (MYR/m^3)	Total Yearly Cost (MYR/m^3/year)	LCOE (MYR/kWh)	Payback Period (Year)	Return on Investment (ROI)
1	643.00	18.43	0.1929	9.2	111.9%
2	823.38	44.47	0.3207	Unprofitable	-59.8%
3	664.57	21.91	0.2088	10.6	88.8%
4	629.81	16.97	0.1842	7.9	154.0%
5	737.41	31.49	0.2589	Unprofitable	-9.6%

The mathematical formula for this economic analysis is beyond the scope of this article, since the values are given and simulated through the PVsyst software. Site 1 and Site 4 are the two sites with the lowest installation cost because of the smaller size area. The snapshot of the parameters used are shown in Figure 10.

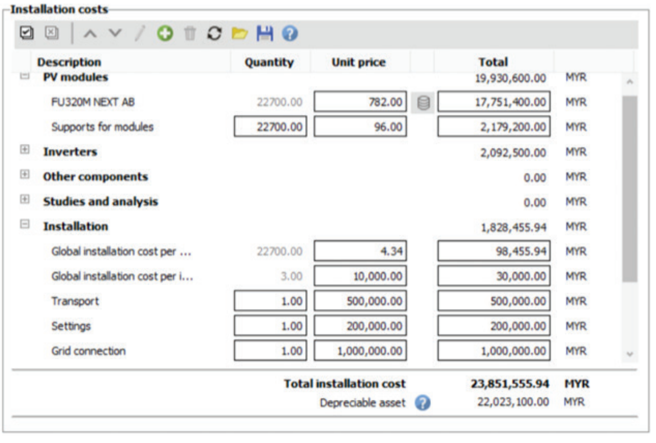


Figure 10: The parameters used to calculate the installation cost and other economic analysis

Figure 11 highlights the inverse relationship between total yearly cost and payback period for potential solar PV installation sites at USIM. Sites 2 and 5, despite having the highest total yearly costs, show no payback within the considered timeframe, making them financially unfeasible. In contrast, Site 1 has the lowest total yearly cost, resulting in the shortest payback period of 9.2 years. Site 4, with a moderately higher total yearly cost, achieves a shorter payback period of 7.6 years, underscoring its financial viability and attractiveness for solar PV deployment.

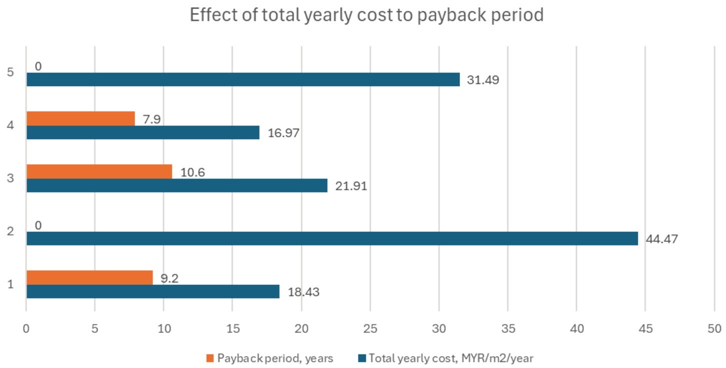


Figure 11: Effect of total yearly cost to payback period

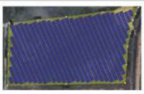
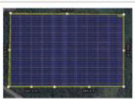
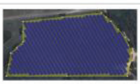
Site	Site	Area
1		517,763.3ft^2
2		187,422.7ft^2
3		407,899.2 ft^2
4		707,436.1 ft^2
5		229,050.9 ft^2

Figure 12: Area of five areas in USIM

Figure 12 shows the area of the five areas. The size of the available area directly correlates with the number of solar panels that can be installed, thereby influencing the system's overall energy output. A meticulous evaluation of each site's dimensions revealed Site 4 as the most spacious, boasting an expansive area of 707,436.1 ft². These sites, with their generous proportions, present a promising opportunity to accommodate a large-scale solar PV system capable of generating considerable energy. While the sheer size of an area is a crucial factor, it is essential to acknowledge that other considerations, such as the terrain, topography, and existing infrastructure, may influence the effective usable area for solar panel installation. These factors would need to be thoroughly evaluated during the detailed design phase of the project in the future.

This study demonstrates that optimizing the tilt angle of solar photovoltaic (PV) systems at USIM, Nilai, to 5° significantly boosts energy production by maximizing solar radiation capture. Furthermore, Site 4 was identified as the most suitable location for a solar farm on campus. Its larger available area and favorable solar irradiance conditions enable the highest energy generation potential. Economic analysis confirms its viability, with a competitive Levelized Cost of Electricity (LCOE) and strong Return on Investment (ROI), making it a financially attractive choice for sustainable energy production. These findings provide valuable insights for optimizing solar PV systems and supporting USIM's renewable energy goals.

IV. Conclusion

This study successfully identified the optimal tilt angle and location for maximizing solar energy capture and system efficiency at the proposed solar farm site in USIM, Nilai. Through detailed PVsyst simulations and experimental validation using a Terco PST2291 Solar Power Module, the optimal tilt angle was determined to be 5°. This angle maximizes energy yield by aligning the solar panels with the region's solar irradiance patterns and climatic conditions.

Additionally, a comprehensive site evaluation identified Site 4 as the most suitable location for the solar farm within the USIM campus. This decision was based on a multi-criteria analysis, including site size, solar irradiance levels, accessibility, and compatibility with existing infrastructure. These findings provide a robust foundation for the development of an efficient and sustainable solar energy system at USIM.

V. Acknowledgement

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