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ANALYSIS OF SOLAR POWER GENERATION TECHNOLOGY FOR ELECTRIC VEHICLE CHARGING

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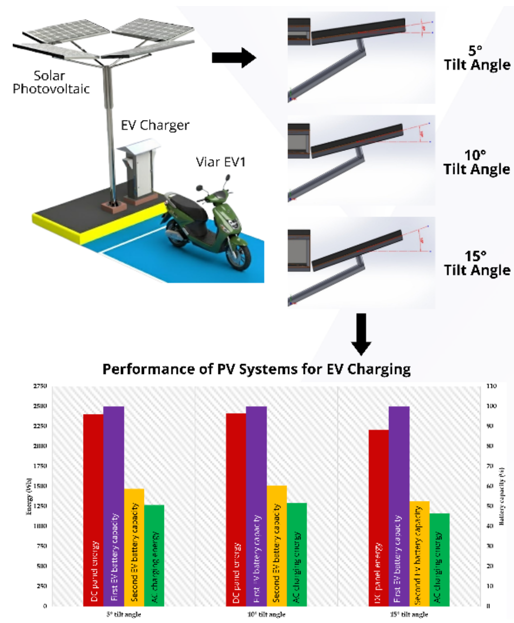

Abstract

In the era of energy transition and the rising demand for electric vehicles, ensuring the availability of efficient, sustainable, and environmentally friendly power resources has become a major challenge. This study analyzes the performance of a Solar Power Generation System as a charging solution for electric vehicles by evaluating the influence of different panel tilt angles on the energy produced. An experimental approach was implemented using three tilt-angle variations—5°, 10°, and 15°—on an off-grid solar power system without a solar tracker. The system consists of four 250 Wp monocrystalline solar panels mounted on a 3-meter pole in a solar-tree configuration. Tests were conducted at Universitas Negeri Surabaya using a lux meter, a DC digital electric meter, and a multifunction digital meter, with quantitative analysis used to determine energy output and system efficiency. The results show that a 10° tilt angle delivers the most optimal performance, achieving the highest efficiency of 6.2% and an average energy output of 40.4 Wh per hour, followed by the 5° angle at 5.44% (39.6 Wh) and the 15° angle at 5.33% (36.35 Wh). In the simulation of charging a Viar EV1 electric vehicle, the system successfully charged one unit from 40% to 100% and continued charging a second unit up to 61%, 59%, and 52% at tilt angles of 10°, 5°, and 15°, respectively. These findings demonstrate that small adjustments in panel tilt angle significantly affect the performance of static solar power systems for electric vehicle charging in tropical regions.

Keywords: solar photovoltaic; renewable energy; electric vehicle; EV charging; tilt angle optimization

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1. Introduction

As a country with a large population, Indonesia faces serious challenges related to transportation and pollution. The increasing number of motor vehicles has become a major contributor to greenhouse gas emissions due to the combustion of fossil fuels, leading to heightened health risks and environmental degradation. The transportation sector alone accounts for approximately 22.9% of total global CO_2 emissions [1], while atmospheric CO_2 concentrations have continued to rise, reaching 400.26 ppm [2]. To address these issues, the adoption of electric vehicles is considered an effective solution, as they produce significantly lower levels of pollutants compared to gasoline- and diesel-powered vehicles [3].

In Indonesia, the development of electric vehicles is being accelerated with the goal of positioning the country as a global electric car manufacturing hub by 2027–2028 [4]. The government has also issued regulations through Presidential Regulation No. 55/2019 to promote the rapid development of electric vehicle ecosystems and charging infrastructure. As of the first semester of 2024, more than 1,582 public fast-charging stations (SPKLU), 2,182 battery-swapping stations (SPBKLU), 9,956 public electric outlets (SPLU), and

14,524 home charging units have been installed [5]. However, major challenges remain, including the uneven distribution of charging stations and the dependence on fossil-based electricity sources such as coal and natural gas. Therefore, renewable energy–based charging infrastructure must be further developed.

Indonesia possesses vast renewable energy potential, particularly solar energy due to its location along the equator. In East Java, for example, the regional energy plan (RUED-P) targets a renewable energy share of 17.09% by 2025 and 19.56% by 2050 [6]. The renewable energy potential in the region is estimated at 188,410 MW, dominated by solar energy at 176,390 MW [7]. Solar energy is a promising alternative because it is abundant, environmentally friendly, and can be harnessed through Solar Power Plants [8]. However, a key limitation of this technology is its relatively low conversion efficiency, with monocrystalline panels achieving only about 20% [9]. PLTS efficiency can be improved by adjusting the tilt angle of solar panels to optimize light intensity [10].

Several previous studies have examined the influence of solar panel tilt angles. Tamimi et al. [11] investigated tilt variations in an active solar-tracking prototype and found that certain angles produced higher power output; however, their study focused on tracking mechanisms and did not assess applications in electric vehicle charging. Another study by Setyawan and Ulinuha [12] evaluated an off-grid solar power system for charging stations. Their results indicated that battery charging required approximately 15 hours under clear weather, and the stored energy could charge an electric bicycle up to three times. However, the study did not examine the effect of tilt-angle variations nor system performance under operational conditions relevant to electric vehicle charging.

Based on these considerations, the present study focuses on two main issues: the effect of tilt-angle variations of 5°, 10°, and 15° on the electrical energy output and efficiency of a solar power system, and the performance of the system in supporting electric vehicle charging. This research is expected to contribute to the development of more efficient and sustainable renewable energy–based charging infrastructure, thereby supporting efforts to reduce greenhouse gas emissions and strengthen Indonesia's electric vehicle ecosystem.

2. Material and Method

The design of the solar power generation system was developed based on the energy requirements for electric vehicle charging. The solar panels were arranged in series and parallel configurations to produce the voltage and current levels needed for battery charging. The electrical energy generated by the panels is directed to a PWM-type solar charge controller, where it is regulated and conditioned before being stored in the battery bank. The battery bank is configured in a series–parallel arrangement, resulting in a total voltage of 24 V with a capacity of 44.6 Ah. The stored electrical energy is then supplied to a pure sine wave inverter to produce 220 V AC output, which can be utilized for electric vehicle charging through a dedicated charger.

2.1. Material

The materials and equipment used in this research consisted of primary components and measurement instruments. The primary components included solar panels with a total capacity of 1000 Wp as the main energy source, a 100 A PWM-type solar charge controller (SCC) to regulate the current and voltage from the panels to the batteries, and four VRLA batteries rated at 12 V and 22.3 Ah, arranged in a series–parallel configuration to obtain the voltage and capacity required by the system. The stored electrical energy was converted into alternating current through a 2000 Wp pure sine wave inverter, enabling its use for electric vehicle charging. Additionally, a 3-meter mounting pole, steel framing for panel support, copper cables, socket boxes, and various connecting components were employed to ensure system stability and safety.

The measurement instruments consisted of a lux meter to measure solar irradiance, a DC electric digital meter to measure the current, voltage, power, and energy output of the solar panels (DC side), and a multifunction digital meter used to measure current, voltage, power, and electrical energy on the load side (AC side) during the electric vehicle charging process. The combination of these instruments enabled comprehensive monitoring of electrical parameters, ensuring accurate data collection and providing a reliable representation of the solar power system's performance in converting solar energy into electrical energy efficiently.

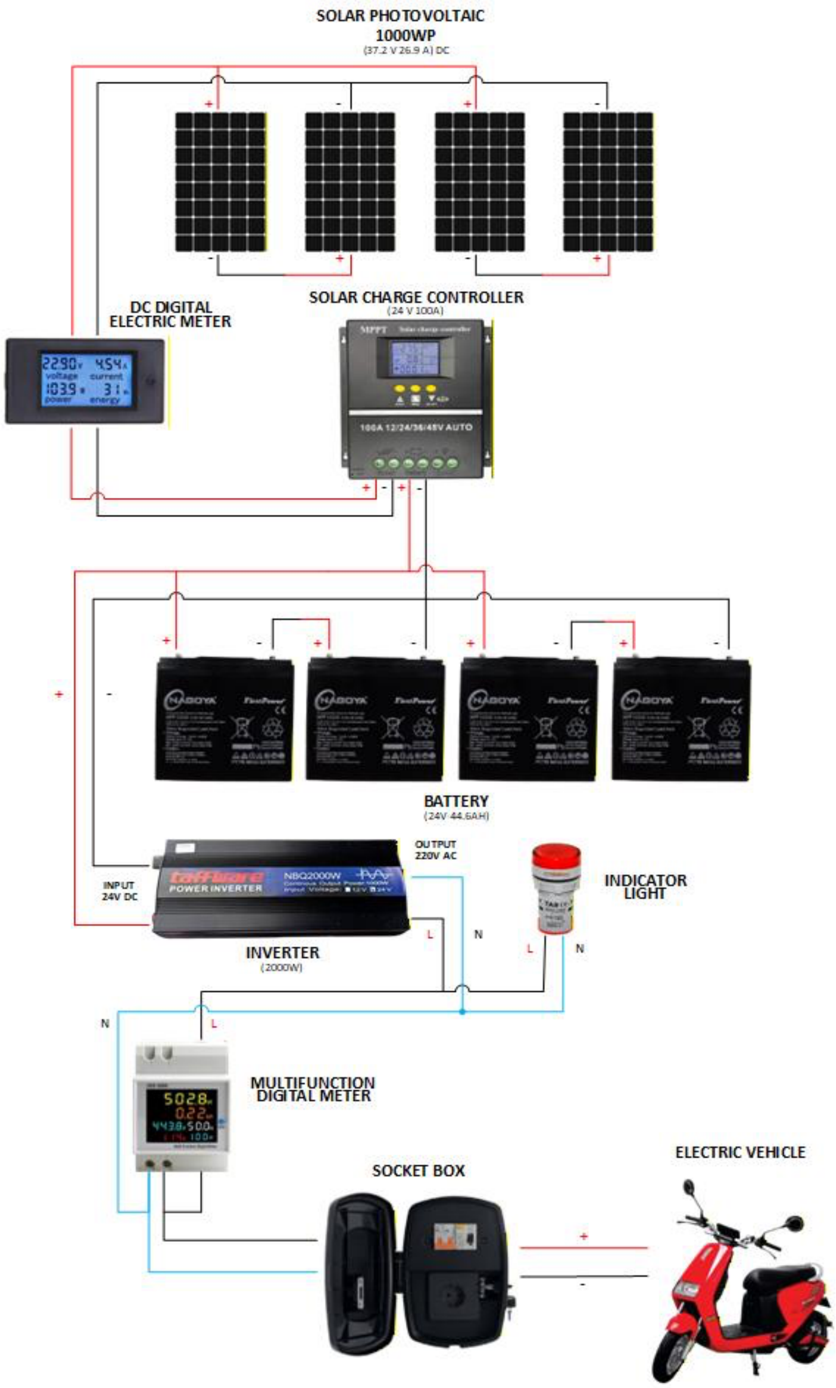

Figure 1. Solar power generation control system

2.2 Method

This study employed an experimental method aimed at evaluating the technical performance of a solar power generation system in meeting the power requirements of an electric vehicle charging station. A quantitative approach was applied, as the analysis involved numerical data to assess system efficiency and the electrical energy produced. All experimental activities were conducted using equipment arranged according to the research needs to accurately represent real operating conditions of the system.

The research titled "Analysis of Solar Power Generation Technology for Electric Vehicle Charging" began with the preparation of tools and materials at the Electric Vehicle Laboratory, Building A7, First Floor, Faculty of Engineering, Universitas Negeri Surabaya. The system testing process was carried out in July in the outdoor area beside Building A7, Faculty of Engineering, Universitas Negeri Surabaya. A research roadmap was developed to ensure that each stage proceeded in an organized and systematic manner. These stages are illustrated in the following flowchart.

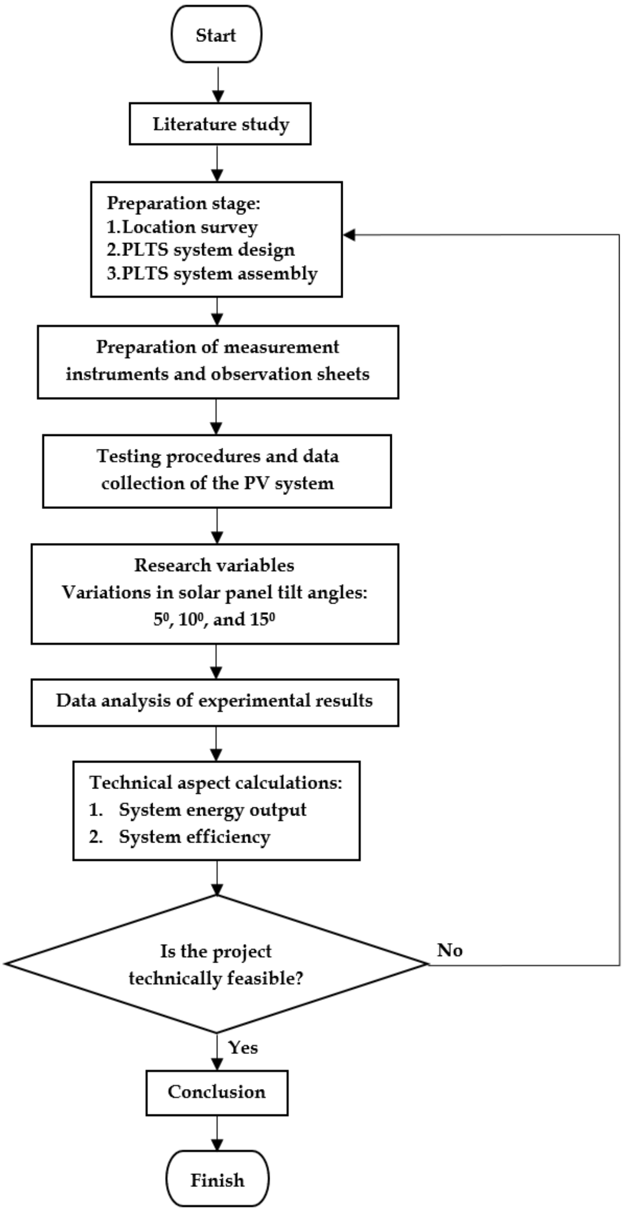

Figure 2. Research road map

The research variables consisted of independent and dependent variables. The independent variable was the solar panel tilt angle, which was varied at 5°, 10°, and 15°, while the dependent variables were the system's electrical energy output (Wh) and system efficiency (%). The tilt-angle variations were selected to determine the optimal panel position for maximizing energy production, whereas the output parameters were used to evaluate the overall performance of the system.

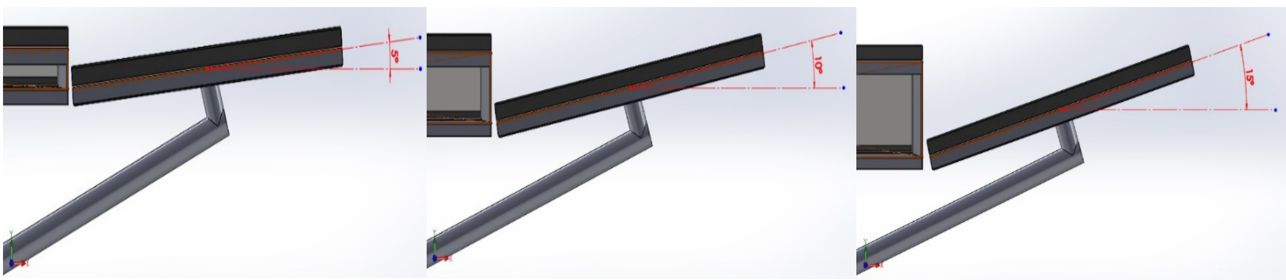

Figure 3. Variation of solar panel tilt angles

The research procedure was carried out in two stages: the preparation stage and the implementation stage. The preparation stage included site surveying, system design, component assembly, and initial system configuration to ensure operational readiness. The implementation stage was conducted by operating the system from 08:00 to 16:00 Western Indonesian Time (WIB). Data collection was performed periodically at 15-minute intervals, including measurements of solar irradiance, current, voltage, power, and the electrical energy produced. The collected data were systematically recorded for further analysis.

The performance analysis of the solar power generation system was conducted using a mathematical approach to assess the capability of the solar panels in converting solar radiation into usable electrical energy. The calculations included the estimation of input energy, output energy, and the efficiency of the solar power generation system for electric vehicle charging.

The input energy (P_{in}) represents the solar radiation energy received by the surface of the solar panels during the testing process[13]. Solar irradiance measurements were taken using a lux meter placed on a plane parallel to the solar panel surface to ensure that the measured illumination accurately reflected the actual conditions on the module. Since energy calculations require irradiance values in watts per square meter (W/m²), the measured lux data were converted using a standard conversion factor based on the spectral characteristics of sunlight [14], expressed as.

$$1\ lux = 0{,}0079\ W/m^2 \tag{1}$$

The panel surface area (A) was calculated based on the physical dimensions of the 250 Wp monocrystalline module, where each panel is rectangular with a length of 1.53 m and a width of 0.76 m [15]. Thus, the panel area is determined as:

$$A = p\ x\ l \tag{2}$$

After obtaining the irradiance (G) in W/m² through the conversion process, the input energy at each measurement interval was calculated by multiplying the irradiance by the panel area and the duration of the time interval (t) [16], as shown in Equation (3):

$$P_{in} = \mathrm{G\ x\ A\ x\ t} \tag{3}$$

The output energy (P_{out}) represents the electrical energy generated by the solar power system during the testing period. The value of P_out was obtained from the readings of the Multifunction Digital Meter installed in the system, expressed in watt-hours (Wh). This data represents the total energy successfully converted from solar radiation into electrical energy under actual operating conditions.

The system efficiency (η) was calculated by comparing the output energy (P_{out}) with the input energy (P_{in}), then multiplying by 100% to obtain the value in percentage form (%) [17], as shown in Equation (4):

$$\eta = \frac{Pout}{Pin}\ x\ 100\% \tag{4}$$

Data analysis was conducted using a descriptive quantitative approach aimed at illustrating the characteristics of the data and the relationships between the research variables. The collected data were tabulated and presented in graphical form, then described using clear and concise statements to facilitate interpretation and address the research objectives. The analyzed parameters included the system's output energy (Wh) and overall efficiency (%). Output energy was calculated based on the total electrical energy generated by the solar panels during the testing period, while system efficiency was determined by comparing the electrical energy produced with the total solar radiation energy received by the panels. This analysis was employed to assess the extent to which variations in panel tilt angle influence the performance of the solar power system in supporting electric vehicle charging.

3. Result and Discussion

The performance evaluation of the Solar Photovoltaic Power System (PLTS), consisting of four monocrystalline solar panels each rated at 250 Wp, was conducted under a series–parallel configuration mounted on a 3-meter pole in a solar-tree arrangement. Each tilt-angle variation was tested three times to ensure data consistency and experimental reliability. During the testing period, the weather conditions varied but remained generally clear, allowing the incident solar radiation to be considered sufficiently representative for system performance assessment. Based on these experimental procedures, the following results were obtained.

- Comparison of tilt angle factors on the electrical energy produced by the solar panels

Table 1. Average energy generated every 15 minutes for each variation over a 3-day period

No	Time	Variation of Solar Panel Tilt Angles					
		5° Tilt angle		10° Tilt angle		15° Tilt angle	
		Pin (Wh)	Pout (Wh)	Pin (Wh)	Pout (Wh)	Pin (Wh)	Pout (Wh)
1	08.00	317,59	0,00	509,96	0,00	530,18	0,00
2	08.15	385,85	45,36	589,65	37,29	621,56	37,62
3	08.30	367,24	46,23	677,55	41,48	551,29	38,52
4	08.45	518,62	48,74	723,77	44,83	748,07	39,06
5	09.00	569,23	42,17	779,79	44,41	890,45	40,86
6	09.15	749,30	41,64	897,75	47,55	616,82	41,76
7	09.30	801,69	33,46	993,40	45,46	899,26	38,70
8	09.45	907,85	37,09	703,91	33,73	932,16	34,56
9	10.00	949,95	37,47	675,50	30,79	783,95	30,24
10	10.15	962,55	32,92	706,37	38,54	724,72	27,54
11	10.30	1.017,39	36,49	674,83	41,06	631,86	41,94
12	10.45	1.033,41	29,65	535,00	43,57	932,87	35,46
13	11.00	1.015,42	28,94	787,67	47,76	733,51	37,80
14	11.15	1.040,73	28,17	330,76	36,24	1.078,55	40,86
15	11.30	982,01	41,55	713,99	38,96	1.079,20	37,62
16	11.45	1.043,30	42,74	831,39	34,14	1.054,70	33,30
17	12.00	1.045,76	45,20	1.081,35	36,66	1.020,16	30,42
18	12.15	1.026,43	43,54	1.074,65	35,82	999,87	37,44
19	12.30	987,61	42,36	724,06	34,98	880,77	37,08
20	12.45	951,62	43,52	1.004,11	36,66	921,83	37,26
21	13.00	936,96	42,04	715,05	38,54	667,97	43,02
22	13.15	877,46	42,89	923,80	51,53	818,18	42,12
23	13.30	810,06	41,44	562,08	43,78	565,41	41,58
24	13.45	760,53	36,73	325,14	44,83	513,22	43,38
25	14.00	627,07	50,44	482,92	51,74	322,77	41,58
26	14.15	511,79	43,75	519,51	49,23	435,53	41,40
27	14.30	438,99	41,40	602,48	52,16	373,51	36,54
28	14.45	392,60	44,45	506,85	43,99	440,52	39,42
29	15.00	329,51	49,86	296,35	33,34	181,98	17,21
30	15.15	271,12	35,68	360,24	38,89	192,90	27,93
31	15.30	251,32	34,79	278,03	28,73	306,62	38,79
32	15.45	226,94	33,49	223,68	34,79	204,00	28,73
33	16.00	169,25	22,92	284,57	31,46	160,20	23,40

Solar panel tilt angle	5°	10°	15°
Total input power (Wh)	23.277,15	21.096,15	21.814,58
Total output power (Wh)	1.267,15	1.292,93	1.163,13
Overall PLTS Efficiency (%)	5,44	6,20	5,33

Based on the data presented in Table 1 above, when illustrated in graphical form, it appears as follows:

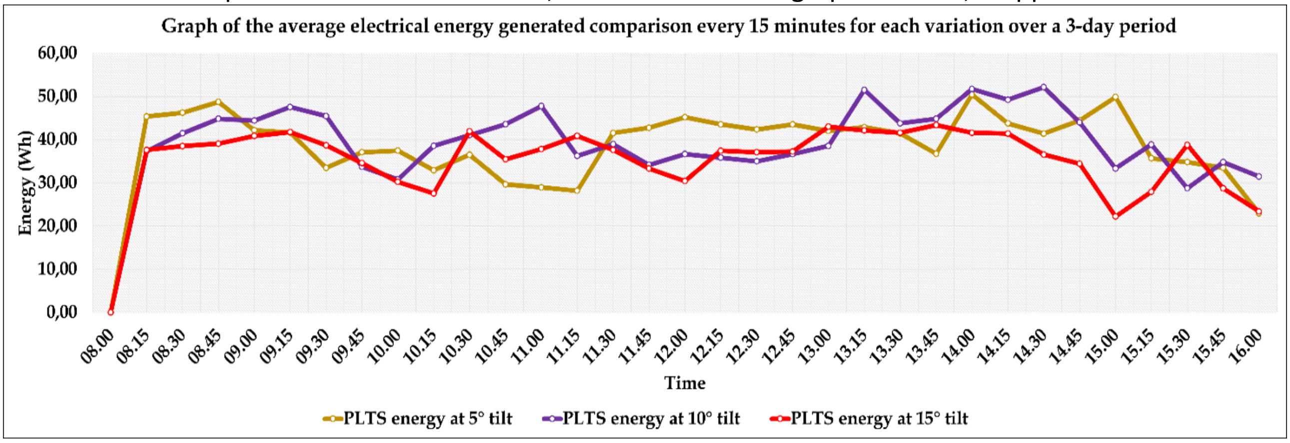

Figure 4. Graph of the average electrical energy generated comparison every 15 minutes for each variation over a 3-day period

Based on the test results and the comparative analysis of electrical energy produced by the PV system at tilt angles of 5°, 10°, and 15°, all three angles exhibited fluctuating energy patterns throughout the day. These fluctuations were influenced by variations in solar radiation intensity, atmospheric conditions, and the sun's movement from east to west. Overall, the 10° tilt angle produced the highest total daily energy output, reaching 1292.93 Wh, followed by the 5° tilt angle at 1267.15 Wh, and the 15° tilt angle at 1163.13 Wh. These differences indicate that a 10° inclination aligns more effectively with the solar elevation profile in tropical regions such as Surabaya.

The average energy per 15-minute interval also showed a similar trend. The 10° tilt angle generated an average of 40.4 Wh, higher than the 5° tilt angle (39.6 Wh), while the 15° tilt angle produced only 36.35 Wh. The lower performance at 15° resulted from the greater deviation of the solar incidence angle relative to the panel surface, which reduced the amount of effective solar radiation absorbed. During midday, the 10° panel sustained higher energy production for a longer period, reaching a peak value of 51.74 Wh at 14:00. The 5° panel reached a comparable peak of 50.44 Wh at nearly the same time. Meanwhile, the 15° panel reached its peak earlier, at 13:45, with a value of 43.38 Wh, indicating that this configuration is less capable of accommodating the dynamic movement of the sun throughout the day.

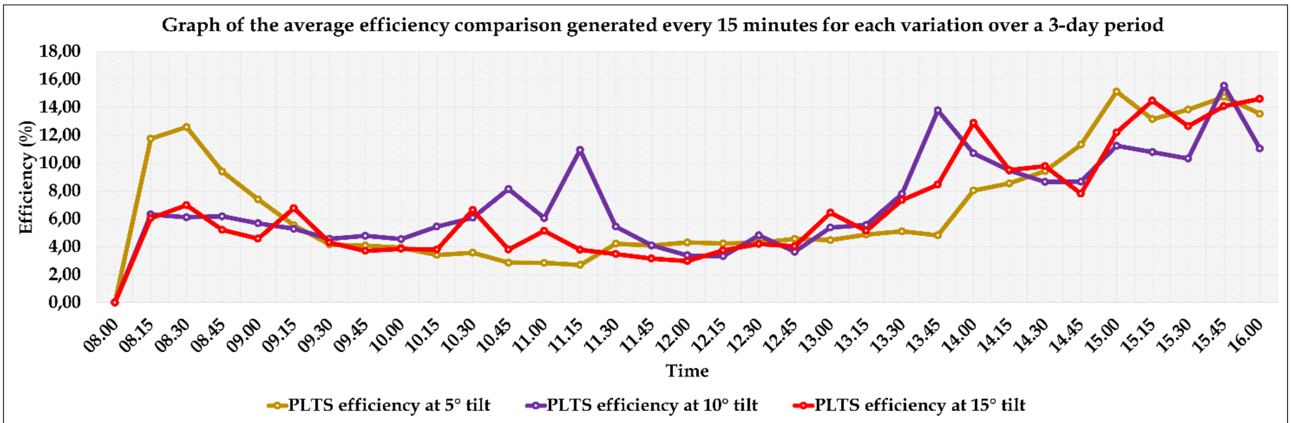

Figure 5. Graph of the average efficiency comparison generated every 15 minutes for each variation over a 3-day period

The analysis of the PV system efficiency demonstrated consistent results. The highest daily efficiency was obtained at a tilt angle of 10°, reaching 6.13%, followed by 5° at 5.44% and 15° at 5.33%. These values indicate that a smaller tilt angle allows a greater proportion of incident solar radiation to be converted into electrical energy. The highest peak efficiency was recorded at 15:45 for the 10° panel, with a value of 15.55%. This phenomenon occurs because the decrease in solar intensity during the late afternoon is accompanied by a reduction in panel temperature, thereby lowering thermal losses and increasing conversion efficiency. A similar pattern was also observed for the 5° and 15° panels, both of which exhibited an efficiency rise during the afternoon period with a comparable trend. Therefore, the 10° tilt angle provides the optimal balance between radiation absorption capability and stability in the energy conversion process.

- Charging performance of the PLTS system for electric vehicles

The electrical energy generated by the Solar Power Plant (PLTS) system cannot be used directly to charge electric vehicle batteries; instead, it must undergo a series of conversion and storage processes. The energy produced by the solar panels is first directed to a 100A PWM-type Solar Charge Controller (SCC), which regulates the voltage and current before the energy is stored in four VRLA batteries, each with a capacity of 12 V and 22.3 Ah arranged in a series–parallel configuration, resulting in a total storage capacity of 24 V and 44.6 Ah, or approximately 1,070.4 Wh. The stored energy is then converted by a 24 V 2000 W Pure Sine Wave (PSW) inverter so that it can be utilized for charging electric vehicles.

Each conversion stage has its own efficiency level, with the PWM SCC operating at approximately 70–80% [18], the VRLA batteries at 75–85% [19], and the PSW inverter at 90–95% [20]. A charging simulation was conducted to evaluate the ability of the PLTS system to recharge two Viar EV1 electric vehicles, each equipped with a 72 V 22.3 Ah battery (1,606 Wh). The charging process was performed sequentially, starting with the first vehicle until its battery was fully charged, followed by the second vehicle using the remaining available energy.

Table 3. Comparison of charging performance of the solar power generation system (PLTS) for each tilt angle variation

No	Panel tilt angles (°)	DC panel energy (Wh)	AC charging energy (Wh)	First EV battery capacity (%)	Second EV battery capacity (%)
1	5°	2396	1267	100	59
2	10°	2410	1293	100	61
3	15°	2206	1163	100	52

Based on the data presented in Table 3 above, when illustrated in graphical form, the results appear as follows:

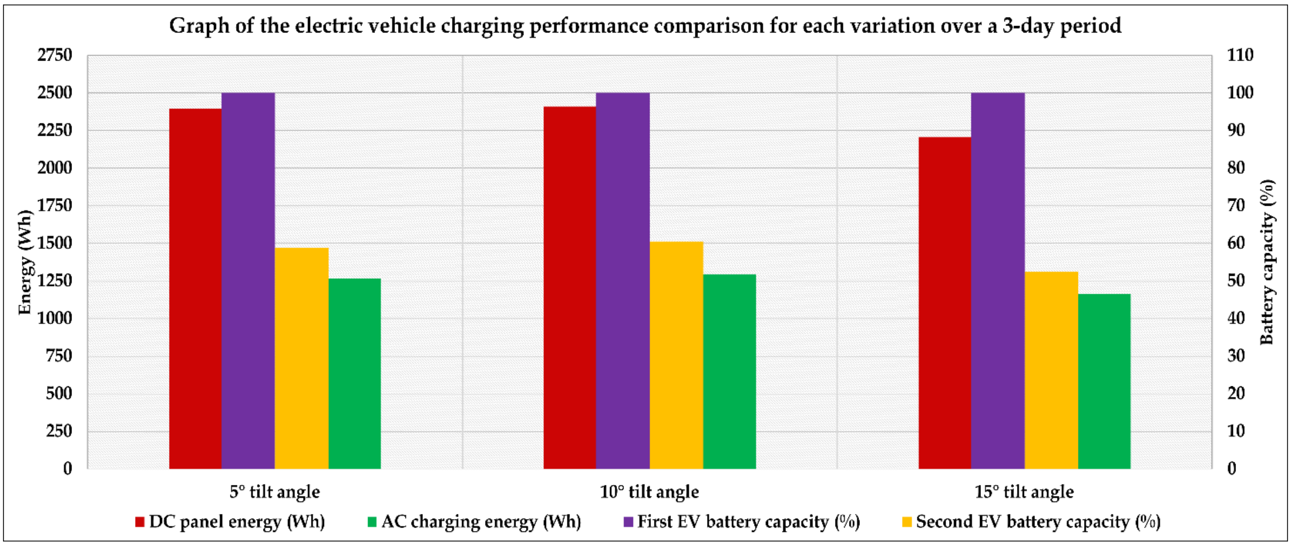

Figure 6. Graph of the electric vehicle charging performance comparison for each variation over a 3-day period

Based on the simulation results, the PLTS system was able to fully charge one electric motorcycle from an initial battery level of 40% to 100%, while the remaining energy was used to charge the second motorcycle with a charging level ranging from 52% to 61%, depending on the panel tilt angle. At a 5° tilt, the available AC energy of 1267 Wh increased the second battery's capacity to 59%, whereas at 10°, with 1293 Wh of usable energy, the capacity increased to 61%. In contrast, at 15°, the system produced only 1163 Wh, resulting in a charging level of 52%. The comparison graph indicates that the DC energy generated by the solar panels does not directly correspond to the AC energy available after passing through the SCC, battery bank, and inverter. Although the 10° tilt angle produced the highest DC energy of 2410 Wh, the remaining AC energy was only about 1293 Wh. A similar pattern occurred at 5° and 15°, where the initially comparable DC outputs experienced significant reductions due to cumulative conversion losses at each stage.

The impact of AC energy variation is clearly reflected in the system's capability to charge the electric vehicle batteries. Across all tilt variations, the first motorcycle could be charged from 40% to 100%, yet the charging capacity of the second motorcycle differed considerably. The 10° tilt provided the highest additional charging capacity at 61%, slightly higher than the 59% achieved at 5°, while the 15° tilt reached only 52%. These differences indicate that the 10° angle not only generated higher energy but also delivered a more stable power profile during critical charging periods, allowing stored energy to be utilized more effectively. Therefore, the 10° tilt angle serves as the most optimal configuration for static PLTS applications in electric vehicle charging stations within tropical regions.

4. Conclusion

The PLTS system testing was conducted in July 2025 in Surabaya (7.25° S; 112.75° E) under clear weather conditions during the dry season. The system employed a solar tree model consisting of four panels oriented toward the north, east, south, and west, with tilt angles varied at 5°, 10°, and 15°. The results showed that a 10° tilt angle produced the most optimal performance, generating a total daily energy output of 1,292.93 Wh with an average efficiency of 6.13%. Meanwhile, the 5° and 15° tilt angles produced 1,267.15 Wh and 1,163.13 Wh with efficiencies of 5.44% and 5.33%, respectively. In the charging simulation of two Viar EV1 electric motorcycles (72 V, 22.3 Ah), the system successfully charged the first unit from 40% to full capacity and continued charging the second unit with the highest achievement at 10° (61%), followed by 5° (59%) and 15° (52%). These outcomes indicate that the 10° tilt configuration is the most effective in improving energy conversion efficiency and charging capability for electric vehicles in the Surabaya region.

This study still has several limitations, particularly because data collection depended heavily on fluctuating natural weather conditions and did not include direct measurement of solar irradiance incidence angles using instruments such as a pyranometer. As a result, the determination of the optimal tilt angle was based solely on energy output. The panel orientation was also not re-verified during testing, allowing the possibility of minor deviations in alignment. For future research, it is recommended to conduct testing during different seasons, employ automatic monitoring systems such as data loggers to obtain more precise measurements, and perform comparative analyses using different types of solar panels to develop a more comprehensive understanding of PLTS performance.

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