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Research Original Article

Design and Analysis of a 10 MW On-Grid Solar Power Generation System in Lhokseumawe with Variation of Tilt Angle and Interrow Spacing

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Abstract
The primary focus of this study is to develop a ground-mounted solar power generation system with the optimal tilt angle and inter-row spacing to generate electricity in Indonesia, specifically in Lhokseumawe City. The research involves conducting simulation tests using Meteonorm software for solar resource assessment. Additionally, the HelioScope software is employed for modeling the ground-mounted solar power generation system, analyzing the PV system's performance in terms of annual generation, system losses, and performance ratio, as well as studying the solar panel's performance, current-voltage, and power-voltage curves for varying irradiance levels. The Single Line Diagram (SLD) reveals that 12 strings are connected to each inverter, and the output power of inverters is combined using 20.0 A circuit interconnects. The efficiency of solar power generation systems is influenced by the tilt angle and interrow spacing. Based on the simulation results for all scenarios, it is concluded that the solar power generation system installed at 0° tilt angle with a 0.9-meter interrow spacing outperforms other solar power generation systems. This is attributed to the maximum total collector irradiance of 1731.6 kWh/m2 compared to other tilt angles. At 0° tilt angle, the annual production of the solar power generation system is 14.77 GWh, with a performance ratio of 80.6%. This research aims to provide valuable insights for energy system designers, planners, and investors, guiding the development of strategies for the implementation of solar power generation energy systems not only in Indonesia but also globally.
Keywords: Renewable Energy; Solar Energy; Plant Designing; Tilt Angle; Energy Estimation

Introduction
Energy plays a crucial role in supporting sustainable economic growth and improving the quality of human life (BP, 2023), (Muneer et al., 2005). However, the sustainability of energy utilization is a significant concern, given the limitations of fossil resources and their negative impact on the environment (Prof. Brian Yuliarto, S. T. , M. Eng., 2011). Therefore, the utilization of renewable energy sources, including solar energy, has become a global focus. Renewable energy offers significant advantages, such as lower greenhouse gas emissions and the potential to meet long-term energy needs (Muneer & Asif, 2007).

In Indonesia, the potential for renewable energy is abundant (Humas EBTKE, 2021). With a vast land area of 2 million km2, Indonesia has a solar energy potential of 112,000 GWp, but its utilization is currently only around 150 MW (KESDM, 2010). To optimize the utilization of solar energy, solar power energy generation systems have become a primary focus. Solar power energy generation system technology is a crucial means of converting solar energy into clean and sustainable electricity(Hayat et al., 2019).

Solar energy exhibits considerable potential, propelled by technological advancements and its environmentally sustainable attributes (Lukman et al., 2020). Nevertheless, forthcoming challenges for solar energy encompass its intermittent availability across the calendar year, a dearth of materials essential for solar cells, and the considerable upfront capital expenditure (Hayat et al., 2019), (Kurniawan et al., 2023).

Therefore, this study aims to conduct a comprehensive analysis of the impact of the tilt angle and spacing between rows of solar panels on the efficiency of solar power generation systems in Indonesia. Considering the specific geographic and climatic conditions of the Indonesia region, this research is expected to provide optimal recommendations for designing efficient and productive solar power systems. The study will utilize simulation methods employing the HelioScope software, which has proven effective in designing solar power generation systems and predicting performance in various tilt angle and row spacing scenarios. In this simulation process, Indonesia climate and topography data will be incorporated to ensure accurate and relevant results.

To implement solar energy on a large scale, high-capacity Solar Power Plants become a smart choice. A 10 MW solar power plant in Lhokseumawe, an area rich in solar potential, not only positively impacts the provision of clean and sustainable energy but also carries significant economic implications.

This research will specifically examine the design and analysis of a 10 MW solar power plant connected to the power grid in Lhokseumawe. The primary focus of the study will be on the influence of the tilt angle and spacing between rows of solar panels on the performance of the solar power plant. Through comprehensive analysis, this research is expected to provide valuable insights into optimizing the performance of the solar power plant through precise adjustments to the solar panels. Thus, the solar power plant can make a more substantial contribution to meeting energy needs while maintaining environmental sustainability.

The outcomes of this research are anticipated to provide a deeper understanding of how the tilt angle and spacing between rows of solar panels influence the efficiency of solar power systems in Indonesia. This information is expected to serve as a valuable guide for energy system designers, planners, and investors in formulating optimal strategies for installing solar power generation systems in Indonesia.

Materials & Methods

This study encompassed a series of experiments aimed at determining the optimal tilt angle and interrow spacing for solar panels, as well as assessing the solar power generation energy potential at a designated location. The investigation involved an analysis of various tilt angles and interrow spaces to identify the configuration that would yield the maximum solar power energy generation. It is well-established that tilting solar panel arrays at the optimal angle is a crucial technique for maximizing energy output (Hailu & Fung, 2019). (Liu et al., 2021). The experiment was structured into five distinct cases.

Through systematic exploration, it was observed that an azimuth angle of 180° outperformed other azimuth values. Consequently, an azimuth angle of 180° was consistently employed in all five cases.

To conduct a comprehensive analysis, the HelioScope software developed by Folsom Labs was utilized. This software facilitated detailed modeling, including system analysis, annual generation estimations, and assessments of system losses. The research unfolded under the following distinct cases:

Case 1: Assessment of energy production by a solar power generation system installed at 0° tilt angle;
Case 2: Assessment of energy production by a solar power generation system installed at 5° tilt angle;
Case 3: Assessment of energy production by a solar power generation system installed at 10° tilt angle;
Case 4: Assessment of energy production by a solar power generation system installed at 15° tilt angle;
Case 5: Assessment of energy production by a solar power generation system installed at 20° tilt angle;

Identification of Solar Power Plant Location

The location chosen for the solar power generation plant in this study is situated to the west of PT. Perta Arun Gas, with a latitude of 5.220979 and a longitude of 97.071584 in the city of Lhokseumawe, Aceh Province, Indonesia—as illustrated in Figure 1. The selected site encompasses a land area of approximately ± 356,493.5 square meters and is within the Arun Special Economic Zone. This location is well-connected to transportation with easy access to main highways.

Figure 1. Solar Power Generation Site Location

Selecting an appropriate location for a solar power energy generation plant involves crucial considerations such as solar irradiation, distance to the grid station, road accessibility, proximity to metropolitan areas, and land usage. These factors play a significant role in the strategic planning of optimal renewable energy management. This meticulous planning is essential to ensure the sustainable and long-term development of energy production from solar power generation systems, adhering to established criteria (Rediske et al., 2019), (Mubarak et al., 2020).

Climate conditions for modeling

In Indonesia, particularly in Lhokseumawe, there are two seasons: the dry season and the rainy season, where the maximum temperature reaches 34.2 degrees Celsius. The rainy season occurred between September and peaked in December, with the highest rainfall recorded at 455 mm. Throughout the year, the average rainfall is 123.9 mm, and the average sunshine duration is 5.96%. The average surface wind speed is 13 knots, and the average humidity is 84.6%.

Solar Resource Assessment

For the assessment of solar energy sources, various professional tools are available to acquire meteorological data from satellite imaging (Taneza et al., 2024). In this research, the Meteonorm software and database were utilized. Monthly radiation data from the predetermined location is presented in Table 1. From the table, it can be observed that during the summer season, the radiation levels are highest, particularly in March. The average annual global horizontal irradiation (GHI) is 1835 kWh/m², and horizontal diffuse irradiation is 883 kWh/m² at the proposed location. GHI represents the total solar irradiation incident on the horizontal surface.

Table 1. Monthly Radiation Data of Solar Power Generation Site from Meteonorm

	Gh (kWh/m²)	Dh (kWh/m²)	Bn (kWh/m²)	Ta (°C)	Td (°C)	FF (m/s)
January	164	65	154	26.7	23.5	2
February	161	73	125	27.1	23.4	1.9
March	175	78	135	27.6	24	1.8
April	164	81	114	27.9	24.2	1.7
May	162	82	114	28.3	24.2	1.8
Juni	157	71	124	28.4	23.8	1.7
Juli	165	73	132	28	23.6	1.7
August	163	87	106	27.8	23.6	1.7
September	142	69	102	27.4	23.6	1.6
October	126	75	75	27	23.6	1.6
November	129	64	100	26.7	23.9	1.6
Desember	126	64	98	26.5	23.6	1.9
Year	**1835**	**883**	**1380**	**27.5**	**23.7**	**1.8**

Solar Power Plant System Designing and Proposed System Components

The HelioScope simulation tool is employed to evaluate solar power generation systems in the Arun Special Economic Zone. The proposed location covers an approximate land area of ± 356,493.5 m². Various input parameters for the solar power plant system simulation are detailed in Table 2.

Table 2. Input Parameter for Solar Power Generation System Simulation

Data	Value
Azimuth angle	180°
Orientation.	Landscape (horizontal)
Frame size	4 and 1
Interrow spacing	1.2 meters
Alignment	Central
Setback from edges	1 meter
String size	3–26 Solar panels.

Solar Panels

The monocrystalline JA Solar 500Watt solar panel (JAM66S30-500/MR) is chosen. Table 3 presents the specifications of the selected solar panel.

Table 3. Solar Panel Specification

Parameter	Parameter Value
Rated Maximum Power (Pmax)	500 Wp
Cells	Mono-crystalline 132 (6×22)
Power Tolerance	0~+5 W
Maximum Power Voltage (Vmp)	38.35 V
Open Circuit Voltage (Voc)	45.59 V
Temp Coefficient of Voc (β_Voc)	-0.275%/°C
Short Circuit Current (Isc)	13.93 A
Temp Coefficient of Isc (α_Isc)	0.045%/°C
Maximum Power Current (Imp)	13.04 A
Temp Coefficient of Pmax (γ_Pmp)	0.350%/°C
Module Efficiency (η)	21.1 %
Maximum Series Rating of Fuse	25 A
Junction Box	IP68, 3 diodes
Safety Class	Class II
Fire Performance	UL Type 1
Maximum Static Load (Front)	5400 Pa (112 lb/ft²)
Maximum Static Load (Back)	2400 Pa (50 lb/ft²)

Inverter

A solar inverter, commonly referred to as a PV inverter, is an electrical converter designed to transform the variable direct current (DC) output generated by a solar panel into alternating current (AC). This converted AC can then be injected into utility grids or utilized by local power grids, including off-grid systems. The specifications for the inverter are outlined in Table 4.

Table 4. Inverter Specification

Parameter	Value
Model	SUN2000-100KTL-M1
Maximum input current per MPP tracker	26 A
Maximum short-circuit current per MPP tracker	40 A
Maximum DC voltage	1,100 V
Start Voltage	200 V
No MMPT tracker	10
No. of PV strings per MPP tracker	20
AC nominal power	100,000 W
Maximum alternating current apparent power	110,000 VA
Range of nominal AC voltage	480 V/ 400 V/ 380
Maximum output current	133.7 A, 160.4 A, 168.8 A
AC grid frequency	50 Hz / 60 Hz
AC grid connection type	3W+(N)+PE
THDi	<3%
Maximum efficiency	98.8%, 98.6%
MPPT efficiency	99.9%
AC/DC surge protection	Type II/ Type II
Operating temperature range	-25°C ~ 60°C

The design layout and single-line diagram (SLD) of the Solar power generation are depicted in Figures 8 and 9, respectively. From the SLD, it is indicated that 12 arrays are connected to the Huawei inverter (SUN2000-100KTL-M1), with each array containing 20 to 22 solar panels. This configuration is employed for 80 inverters. The cable configuration is crucial for an effective system installation, as it can reduce system losses and enhance operational safety.

The solar panels are connected in series with DC Copper 6 mm^2 cables. The output power from all inverters is combined using 15 interconnection circuits (each interconnection circuit rated at 20.0 A). Two types of disconnect switches are utilized in this system; AC disconnects are installed between the utility grid and the inverters, and DC disconnects are installed between the solar panels and the inverters.

After the interconnection circuits, a service panel is installed. The connection between the AC cables from the national utility grid and the Solar power generation is made through the electrical service panel. The bidirectional meter consists of current and voltage measurement circuits, measuring instantaneous current and voltage, respectively. The processing unit is an Arduino Uno, and the net energy is displayed on an LCD screen at regular intervals. The bidirectional meter can detect the direction of current flow and record information in separate registers.

During the daytime, when the load is at its minimum, surplus energy generated by the solar power generation system is sent back to the utility grid (Export). At this time, the direction of the current flow is reversed, and the bidirectional meter records information in the export register. At night, when there is no solar power energy generation, electricity is imported from the utility grid to operate the load. Now, the direction of the current flow is forward, and the bidirectional meter records information in the import register.

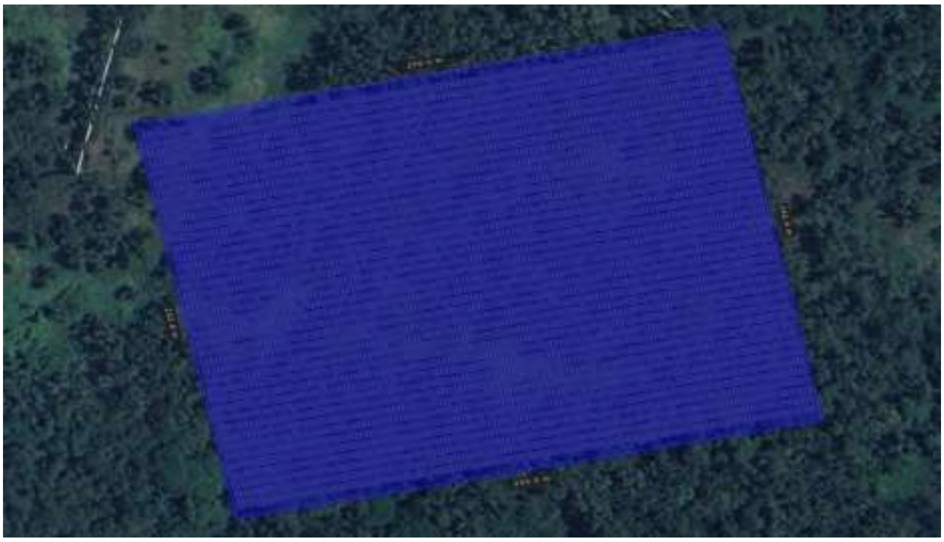

Figure 2. Layout Design for Solar Power Generation System

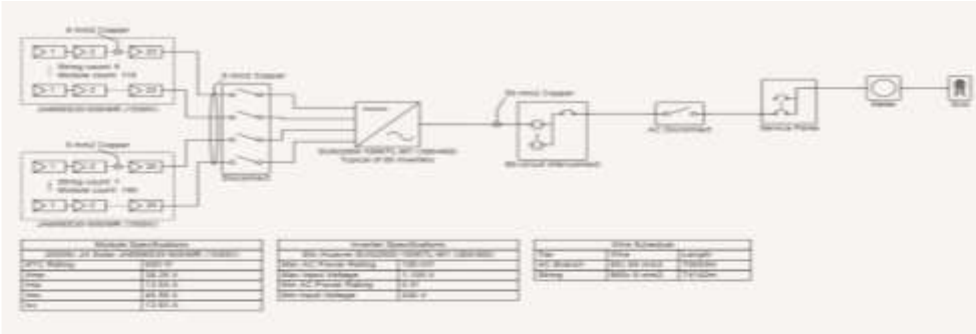

Figure 3. Single-line diagram of Solar Power Generation System

Results

Case 1: Energy Production at 0° Tilt Angle

In Case 1 (as mentioned earlier), a tilt angle of 0° has been selected. In the designated area, a simulation study is first conducted to compare the output of the Solar power generation and find the most suitable row spacing for a 0° tilt angle. Table 5 presents the total installed capacity, annual production, performance ratio, and load ratio with various row spacings.

Table 5. Performance Comparison of Solar Power Generation System at 0° Tilt Angle with Different Interrow Spacing

Line Spacing	Installed Capacity	Annual Production	Performance Ratio	Load Ratio
0.3 meter	10 MW	14.72 GWh	80.3%	1.25
0.6 meter	10 MW	14.72 GWh	80.3%	1.25
0.9 meter	10 MW	14.77 GWh	80.6%	1.25
1.2 meter	10 MW	14.69 GWh	80.2%	1.25

The solar power generation system with row spacings of 0.3 and 0.6 meters exhibits low-performance ratios due to a reduction in system efficiency caused by the AC system. In the solar power generation system with a row spacing of 1.2 meters, the overall installed capacity of the solar power energy generation system decreases. The performance of solar panel generation systems is influenced by row spacing. By increasing the row spacing between solar panels, AC system losses increase, along with an increase in land and electrical cable costs.

In comparison, we analyzed that a Solar Power Generation System installed at tilt angle of 0° with a row spacing of 0.9 meter is more efficient. For this case, simulation results indicate that the annual production of Solar power generation is 14.77 GWh, the energy generated (kWh/kWp) is 1,477.2, and the performance ratio (PR) of the solar power energy generation system is 80.6%.

Figure 4 illustrates various losses in the solar power generation system at tilt angle of 0° for a row spacing of 0.9 meter. In this figure, losses such as AC system losses, shading, reflection, pollution, irradiance, temperature, mismatch, cable losses, trimming losses, and inverter losses are highlighted. These losses are directly related to the output of the solar power generation system. For Case 1, AC system losses are 2.2%, shading losses are 0%, reflection losses are 3.6%, pollution losses are 2.0%, irradiance losses are 0.5%, temperature losses are 7.6%, mismatch losses are 3.5%, cable losses are 0.6%, trimming losses are 0.1%, and inverter losses are 1.4%.

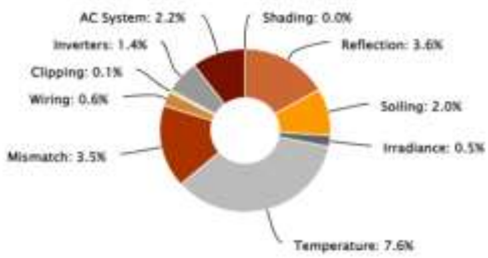

Figure 4. Solar Power Generation System Losses at 0° Tilt Angle.

The standard solar panel working temperature is 25 °C. Temperature is the most important factor that affects the working performance of solar panels. However, the proposed PV site is located in a tropical climate area in Lhokseumawe, Indonesia, so the ambient temperature (Ta) of solar panels can increase. It can be calculated as (Kim et al., 2021):

$$T_m = E\left(e^{a+b(Ws)}\right) + T_a \tag{1}$$

Where:

- Tm: solar panels temperature (°C);
- Ta: ambient temperature (°C);
- Ws: wind speed;
- E: solar radiation on the solar panel (W/m^2);
- a: coefficient for the solar panel's upper-temperature limit;
- b: coefficient that determines how much the temperature of the solar panel reduces when the wind speed increases.

By using Equation (1) for solar panels' temperature, a 7.6% loss is calculated, and it is found that solar panels' efficiency is reduced when solar panels' temperature is increased. When the operating temperature of the Solar power generation is increased, the performance of the system decreases. This problem is reduced by using a passive cooling method. This method used a combination of PCM and aluminum metal foam to regulate the temperature of the solar power generation system (Sharaf et al., 2022). The solar irradiance reflected from the surface of the solar panels is another reason for the loss of PV energy generation. These losses are calculated as (Umer et al., 2019).

$$IRC = \alpha \left(\frac{1-\cos\sum C}{2}\right) + IGH \tag{2}$$

Where:

- IRC: solar irradiance reflected from the surface of the solar panels (W/m2);
- α: Albedo coefficient;
- IGH: measured global irritation (W/m^2);
- ∑ C: collector tilt.

By using Equation (2) for solar irradiance reflected from the surface of the solar panels, a 3.6% loss area was calculated.

From the simulation results of Case 1, we found that the total collector irradiance is 1,731.6 kWh/m^2. The total energy delivered to the utility grid is 14,771,507.0 kWh. The average operational ambient temperature is 28.8 °C, while the average operational cell temperature is 39.0 °C, as shown in Table 6.

Table 6. Solar Power Generation System Annual Production Results at 0° Tilt Angle

	Description	Output	Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	1,832.4	
	POA Irradiance	1,832.5	0.0%
	Shaded Irradiance	1,832.5	0.0%
	Irradiance after Reflection	1,766.9	-3.6%
	Irradiance after Soiling	1,731.6	-2.0%
	Total Collector Irradiance	**1,731.6**	**0.0%**
Energy (kWh)	Nameplate	17,318,694.8	
	Output at Irradiance Levels	17,235,196.2	-0.5%
	Output at Cell Temperature Derate	15,925,844.8	-7.6%
	Output after Mismatch	15,366,389.2	-3.5%
	Optimal DC Output	15,359,484.9	0.0%
	Constrained DC Output	15,334,884.7	-0.2%
	Inverter Output	15,119,853.0	-1.4%
	Energy to Grid	**14,771,507.0**	**-2.3%**
Temperature Metrics	Avg. Operating Ambient Temp	28.8 °C	
	Avg. Operating Cell Temp	39.0 °C	

Case 2: Energy Production at 5° Tilt Angle

In Case 2, we have selected a 5° tilt angle. In the available space in the Arun Special Economic Zone, a simulation study was first conducted to compare the output of the Solar power generation and find the most suitable row spacing for a 5° tilt angle. Table 7 shows the total installed capacity, annual production, performance ratio, and load ratio with different row spacings.

Table 7. Performance Comparison of Solar Power Generation System at 5° Tilt Angle with Different Interrow Spacing

Line Spacing	Installed Capacity	Annual Production	Performance Ratio	Load Ratio
0.3 meter	10 MW	14.71 GWh	79.9%	1.25
0.6 meter	10 MW	14.73 GWh	80.0%	1.25
0.9 meter	10 MW	14.75 GWh	80.1%	1.25
1.2 meter	10 MW	14.74 GWh	80.1%	1.25

The solar power generation system with row spacings of 0.3 and 0.6 meters has a low-performance ratio due to reduced system efficiency caused by shading effects on the solar panels. In the solar power generation system with a row spacing of 1.2 meters, the overall installed capacity of the solar power energy generation system is reduced. The performance of solar power generation systems is influenced by row spacing. By increasing the row spacing of solar panels, the shading effects on the solar panels decrease, but this also increases land and electrical cable costs. In comparison, we analyzed that a solar power generation system installed at 5° tilt angle with a row spacing of 0.9 meter is more efficient. For this case, simulation results show that the annual production of the Solar power generation is 14.75 GWh, the energy generated (kWh/kWp) is 1,474.9, and the performance ratio (PR) of the solar power energy generation system decreases to 80.1%.

Figure 5 illustrates various losses in Solar power generation at 5° tilt angle with a row spacing of 0.9 meter. For Case 2, the AC system loss is 2.3%, the shading loss is 0.4%, the reflection loss is 3.4%, the pollution loss is 2.0%, the irradiance loss is 0.5%, the temperature loss is 7.6%, the mismatch loss is 3.5%, cable loss is 0.5%, pruning loss is 0.2%, and inverter loss is 1.4%.

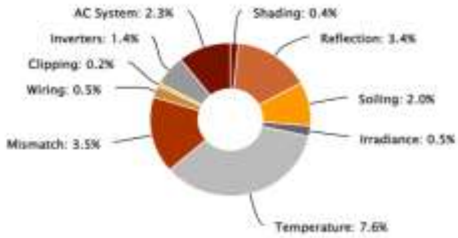

Figure 5. Solar Power Generation System Losses at 5° Tilt Angle

From the simulation results of Case 2, we found that the total irradiance from the collector is 1,737.8 kWh/m2. The total energy (kWh) that can be delivered to the utility grid is 14,749,475.0 kWh. The average operational ambient temperature is 28.8 °C, while the average operational cell temperature is 39.0 °C, as shown in Table 8.

Table 8. Solar Power Generation System Annual Production Results at 5° Tilt Angle

	Description	Output	Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	1,832.4	
	POA Irradiance	1,841.5	0.5%
	Shaded Irradiance	1,835.0	-0.4%
	Irradiance after Reflection	1,773.2	-3.4%
	Irradiance after Soiling	1,737.8	-2.0%
	Total Collector Irradiance	**1,737.8**	**0.0%**
Energy (kWh)	Nameplate	17,380,474.1	
	Output at Irradiance Levels	17,297,068.7	-0.5%
	Output at Cell Temperature Derate	15,978,282.0	-7.6%
	Output After Mismatch	15,417,491.1	-3.5%
	Optimal DC Output	15,336,480.3	-0.5%
	Constrained DC Output	15,311,789.0	-0.2%
	Inverter Output	15,097,079.0	-1.4%
	Energy to Grid	**14,749,475.0**	**-2.3%**
Temperature Metrics	Avg. Operating Ambient Temp	28.8 °C	
	Avg. Operating Cell Temp	39.0 °C	

Case 3: Energy Production at 10° Tilt Angle

In Case 3, we selected a tilt angle of 10°. In the available space in the Arun Special Economic Zone area, we first conducted a simulation study and compared the output of the Solar power generation to find the most suitable inter-row spacing for a 10° tilt angle. Table 9 shows the total installed capacity, annual production, performance ratio, and load ratio with different inter-row spacings.

Table 9. Performance Comparison of Solar Power Generation System at 10° Tilt Angle with Different Interrow Spacing

Line Spacing	Installed Capacity	Annual Production	Performance Ratio	Load Ratio
0.3 meter	10 MW	14.31 GWh	77.8%	1.25
0.6 meter	10 MW	14.52 GWh	78.9%	1.25
0.9 meter	10 MW	14.58 GWh	79.2%	1.25
1.2 meter	10 MW	14.61 GWh	79.4%	1.25

Solar power generations with inter-row spacings of 0.3, 0.6, and 0.6 meters exhibit low-performance ratios due to reduced system efficiency caused by shading effects on the solar panels. In comparison, we analyzed that a solar power generation system installed at 10° tilt angle with an inter-row spacing of 1.2 meters is more efficient. For this case, simulation results indicate that the annual production of the Solar power generation is 14.61 GWh, the energy generated (kWh/kWp) is 1,461.5, and the performance ratio (PR) of the solar power generation system decreases to 79.4%.

Figure 6 illustrates various losses in Solar power generation at 10° tilt angle with an inter-row spacing of 1.2 meters. For Case 3, the AC system loss is 2.3%, the shading loss is 1.3%, the reflection loss is 3.2%, the pollution loss is 2.0%, the irradiance loss is 0.5%, the temperature loss is 7.6%, the mismatch loss is 3.5%, cable loss is 0.5%, trimming loss is 0.2%, and inverter loss is 1.4%.

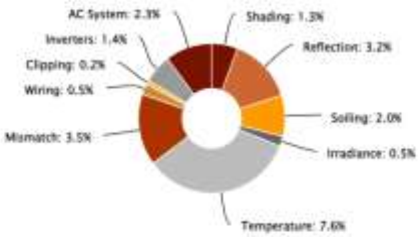

Figure 6. Solar Power Generation System Losses at 10° Tilt Angle

From the simulation results of Case 3, it is found that the total irradiance from the collector is 1,722.5 kWh/m2. The total energy (kWh) that can be delivered to the utility grid is 14,614,506.0 kWh. The average operational ambient temperature is 28.8 °C, while the average operational cell temperature is 38.9 °C, as seen in Table 10.

Table 10. Solar Power Generation System Annual Production Results at 10° Tilt Angle

	Description	Output	Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	1,832.4	
	POA Irradiance	1,840.1	0.4%
	Shaded Irradiance	1,816.2	-1.3%
	Irradiance after Reflection	1,757.7	-3.2%
	Irradiance after Soiling	1,722.6	-2.0%
	Total Collector Irradiance	**1,722.5**	**0.0%**
Energy (kWh)	Nameplate	17,228,156.8	
	Output at Irradiance Levels	17,143,054.2	-0.5%
	Output at Cell Temperature Derate	15,840,332.6	-7.6%
	Output After Mismatch	15,285,392.0	-3.5%
	Optimal DC Output	15,206,173.1	-0.5%
	Constrained DC Output	15,175,039.4	-0.2%
	Inverter Output	14,962,153.0	-1.4%
	Energy to Grid	**14,614,506.0**	**-2.3%**
Temperature Metrics	Avg. Operating Ambient Temp	28.8 °C	
	Avg. Operating Cell Temp	38.9 °C	

Case 4: Energy Production at 15° Tilt Angle

In Case 4, we selected a tilt angle of 15°. In the available space in front of the Department of Electrical Engineering, we first conducted a simulation study and compared the output of the Solar power generation to find the most suitable interrow spacing for a 15° tilt angle. Table 11 shows the total installed capacity, annual production, performance ratio, and load ratio for different interrow spacings.

Table 11. Performance Comparison of Solar Power Generation System at 15° Tilt Angle with Different Interrow Spacing

Line Spacing	Installed Capacity	Annual Production	Performance Ratio	Load Ratio
0.3 meter	10 MW	13.79 GWh	75.5%	1.25
0.6 meter	10 MW	14.07 GWh	77.0%	1.25
0.9 meter	10 MW	14.25 GWh	78.0%	1.25
1.2 meter	10 MW	14.35 GWh	78.5%	1.25

Solar power generation with interrow spacings of 0.3, 0.6, and 0.9 meters exhibits low-performance ratios due to reduced system efficiency caused by shading effects on the solar panels. In comparison, we found that Solar power generation installed at 15° tilt angle with an interrow spacing of 1.2 meters is more efficient. For this case, simulation results indicate that the annual production of the Solar power generation is 14.35 GWh, the energy generated (kWh/kWp) is 1,379.4, and the performance ratio (PR) of the solar power generation system decreases to 78.5%.

Figure 7 illustrates various losses in Solar power generation at 15° tilt angle with an interrow spacing of 1.2 meters.

For Case 4, the losses in the AC system are 2.3%, shading losses are 2.5%, reflection losses are 3.2%, contamination losses are 2.0%, irradiation losses are 0.5%, temperature losses are 7.5%, mismatch losses are 3.5%, cable losses are 0.5%, trimming losses are 0.2%, and inverter losses are 1.4%.

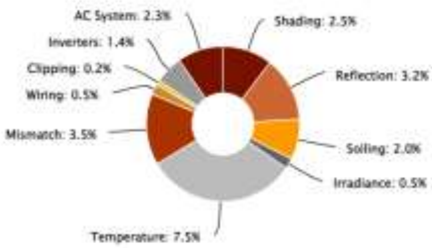

Figure 7. Solar Power Generation System Losses at 15° Tilt Angle

From the simulation results of Case 4, we found that the total irradiance from the collector is 1,690.8 kWh/m2. The total energy (kWh) that can be delivered to the utility grid is 14,350,271.0 kWh. The average operational ambient temperature is 28.8 °C, while the average operational cell temperature is 38.7 °C, as shown in Table 12.

Table 12. Solar Power Generation System Annual Production Results at 15° Tilt Angle

	Description	Output	Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	1,832.4	
	POA Irradiance	1,828.2	-0.2%
	Shaded Irradiance	1,782.7	-2.5%
	Irradiance after Reflection	1,725.4	-3.2%
	Irradiance after Soiling	1,690.9	-2.0%
	Total Collector Irradiance	**1,690.8**	**0.0%**
Energy (kWh)	Nameplate	16,911,088.9	
	Output at Irradiance Levels	16,822,923.7	-0.5%
	Output at Cell Temperature Derate	15,555,358.5	-7.5%
	Output After Mismatch	15,007,286.1	-3.5%
	Optimal DC Output	14,930,281.5	-0.5%
	Constrained DC Output	14,895,034.8	-0.2%
	Inverter Output	14,686,011.0	-1.4%
	Energy to Grid	**14,350,271.0**	**-2.3%**
Temperature Metrics	Avg. Operating Ambient Temp	28.8 °C	
	Avg. Operating Cell Temp	38.7 °C	

Case 5: Energy Production at 20° Tilt Angle

In Case 5, we opted for a 20° tilt angle. In the available space within the Arun Special Economic Zone, we initially conducted a simulation study and compared the output of the solar power generation system to find the most suitable inter-row spacing for a 20° tilt angle. Table 13 presents the total installed capacity, annual production, performance ratio, and load ratio for various inter-row spacings.

Table 13. Performance Comparison of Solar Power Generation System at 20° Tilt Angle with Different Interrow Spacing

Line Spacing	Installed Capacity	Annual Production	Performance Ratio	Load Ratio
0.3 meter	10 MW	13.15 GWh	72.8%	1.25
0.6 meter	10 MW	10.78 GWh	58.9%	1.25
0.9 meter	10 MW	11.04 GWh	60.4%	1.25
1.2 meter	10 MW	11.12 GWh	60.8%	1.25

The solar power generation system with inter-row spacings of 0.6, 0.9, and 1.2 meters exhibits low-performance ratios due to reduced system efficiency caused by shading effects on solar panels. In contrast, our analysis indicates that the solar power generation system installed at 20° tilt angle with a 0.3-meter inter-row spacing is more efficient. For this case, simulation results reveal that the annual production of the Solar power generation is 13.15 GWh, the generated energy (kWh/kWp) is 1,314.8, and the performance ratio (PR) of the solar power generation system is reduced to 72.8%.

Figure 8 illustrates various losses in the solar power generation system at 20° tilt angle for a 0.3-meter inter-row spacing. For Case 5, AC losses are 2.0%, shading losses are 9.5%, reflection losses are 3.2%, pollution losses are 2.0%, irradiance losses are 0.7%, temperature losses are 7.2%, mismatch losses are 4.3%, cable losses are 0.5%, trimming losses are 0.0%, and inverter losses are 1.4%.

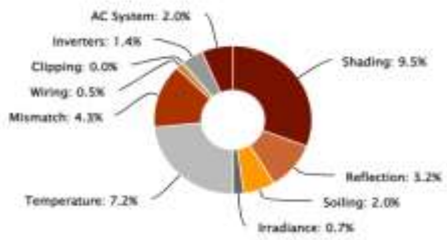

Figure 8. Solar Power Generation System Losses at 20° Tilt Angle

From the simulation results of Case 5, we found that the total irradiance from the collector is 1,549.8 kWh/m2. The total energy amount (kWh) that can be fed into the utility grid is 13,147,523.0 kWh. The average operational ambient temperature is 28.8 °C, while the average operational cell temperature is 37.9 °C, as shown in Table 14.

Table 14. Solar Power Generation System Annual Production Result at 20° Tilt Angle

	Description	Output	Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	1,832.4	
	POA Irradiance	1,805.9	-1.4%
	Shaded Irradiance	1,634.7	-9.5%
	Irradiance after Reflection	1,581.8	-3.2%
	Irradiance after Soiling	1,550.1	-2.0%
	Total Collector Irradiance	**1,549.8**	**0.0%**
Energy (kWh)	Nameplate	15,500,717.9	
	Output at Irradiance Levels	15,398,611.4	-0.7%
	Output at Cell Temperature Derate	14,285,556.0	-7.2%
	Output After Mismatch	13,673,513.0	-4.3%
	Optimal DC Output	13,607,073.6	-0.5%
	Constrained DC Output	13,603,094.8	0.0%
	Inverter Output	13,412,597.0	-1.4%
	Energy to Grid	**13,147,523.0**	**-2.0%**
Temperature Metrics	Avg. Operating Ambient Temp	28.8 °C	
	Avg. Operating Cell Temp	37.9 °C	

The comparison of monthly energy production of PV (kWh) installed at different tilt angles (0° to 20°) is illustrated in Figure 9. The Monthly Energy Production Comparison of solar power generation systems at different tilt angles provides an overview of how monthly energy production varies with different tilt angles for the solar power generation system.

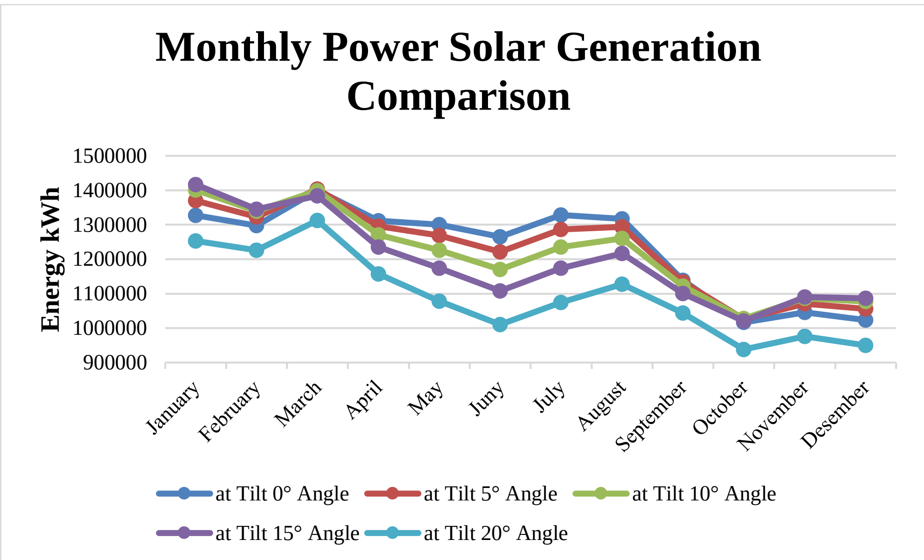

Figure 9. Monthly Solar Power Energy (kWh) Generation Comparison at Different Tilt Angles

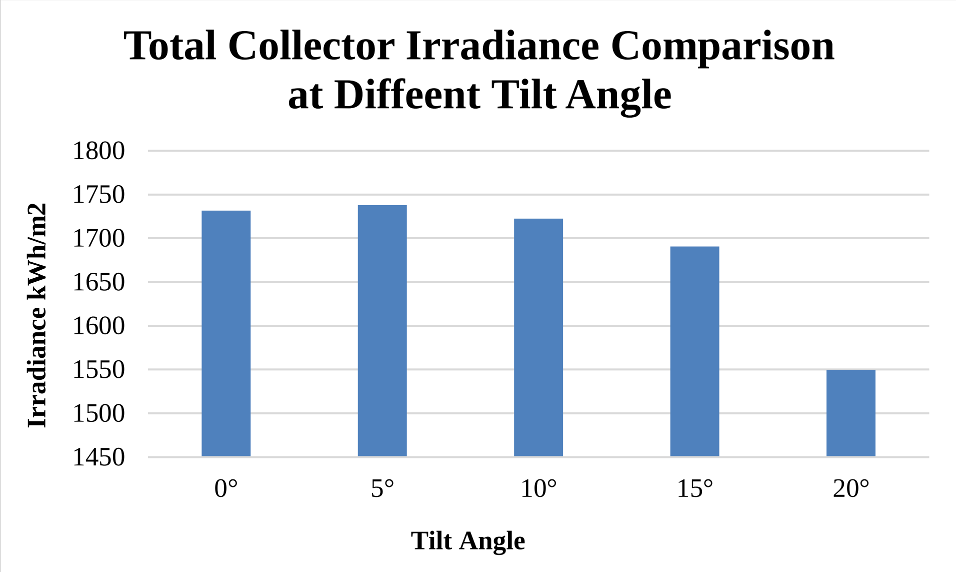

Figure 10. Comparison of Total Collector Irradiance.

Discussions

The performance of solar power generation systems is influenced by the tilt angle and row spacing. By increasing the spacing between solar panels, the shading effect on solar panels is reduced, but it also increases land and electrical installation costs. In conclusion, when analyzing the experimental results, For Case 1, at tilt angle of 0°, the annual production of the solar power generation system is 14.77 GWh, and the system performance ratio (PR) is 80.6% with a row spacing of 0.9 meters. For Case 2, using a tilt angle of 5°, the annual production of the solar power system is 14.75 GWh, and the performance ratio (PR) of the solar power energy generation system is 80.1% with a row spacing of 0.9 meters. For Case 3, with a tilt angle of 10°, the annual production of the solar power system is 14.61 GWh, and the performance ratio of the solar power generation system is 79.4% with a row spacing of 1.2 meters. For Case 4, at tilt angle of 15°, the annual production of the solar power system is 14.35 GWh, and the performance ratio (PR) of the solar power energy generation system is 78.5% with a row spacing of 1.2 meters. For Case 5, with a tilt angle of 20°, the annual production of the solar power generation system is 13.15 GWh, and the performance ratio (PR) of the solar power energy generation system is 72.8% with a row spacing of 0.3 meters. In all five cases, it is observed that the tilt angle and row spacing impact the energy generation output of the solar power system. When looking at the plane of array radiation (POA) for each case, it is evident that the plane of array losses increases with the increasing tilt angle of the Solar power generation. The PV energy production is influenced by the plane of array radiation (POA).

From the simulation results of all cases, it is concluded that the Solar power generation installed at tilt angle of 0° is more efficient than the solar power generation system installed at other angles, as it achieves the maximum collector plane radiation (1,731.6 kWh/m2) at tilt angle of 0°, as shown in Figure 9 and also has a higher performance ratio. Additionally, at this angle, the solar power generation system produces the maximum annual output energy (14,771,507.0 kWh).

The main objective of this study is to create a valid model that will assist energy system designers, planners, and investors, especially in developing countries like Indonesia, where the issue of optimal area/location for installation is crucial. Therefore, the optimal number of solar panels, their orientation, and row spacing have become crucial factors considered in designing large-scale Solar power generations. While it may not be possible to create a model with universal validity, this research explores technical approaches, methodologies, and software solutions that can provide technical assistance to developing countries in formulating appropriate strategies for the design and installation of solar power plants.

Conclusions

HelioScope software is used to design ground-mounted solar panel generation systems and predict the plant performance at different tilt angles and interrow spacing to select the optimal angle and row space to meet the demand for electrical energy in Indonesia. Lhokseumawe City, Aceh, was selected as the research location. According to a climatic and geographical study, Indonesia especially in Aceh has a huge solar energy potential, with an average value of 900 to 1400 .0 kWh/m2 per year or 2.4 to 3.8 kWh/m2 per day. Overall, the system has shown potential and proved its feasibility to meet the energy demands of Indonesia.

By analyzing the results of the experiments, we concluded that the Solar power generation installed at 0° angle with 0.9-meter interrow spacing is more efficient than the Solar power generation installed at another tilt angle with different interrow space because total collector irradiance is maximum (1731.6 kWh/m2) at 0° tilt angle and performance ratio of solar power generation system is also higher. In addition, at this tilt angle, Solar power generation produces maximum annual output energy (14,771,507.0 kWh). System losses such as AC system, shading, reflection, soiling, irradiance, temperature, mismatch, wiring, clipping, and inverters are highlighted during simulation results. For Solar power generation installed at 0° tilt angle with 0.9-meter interrow spacing, the AC system losses are 2.2%, shading losses are

0.0%, reflection losses are 3.6%, soiling losses are 2.0%, irradiance losses are 0.5%, temperature losses are 7.6%, mismatch losses are 3.5%, wiring losses are 0.6%, clipping losses are 0.1% and inverters losses are 1.4%.

For Indonesia, this study discusses the designing and energy estimation of solar power energy generation systems installed at optimal tilt angles and interrow spacing. This study evaluates the performance of solar power generation systems as well as helps to find the maximum usage of available space that is important for solar power plant investments. Currently, there is no research study available in Indonesia that is related to the methodologies and findings presented in this study. Some international researchers have touched on this research area in certain aspects such as (Babatunde et al., 2018). (Hartner et al., 2015). (Yunus Khan et al., 2020). (Kim et al., 2021). In addition, the findings of this research can help energy system designers, planners, and investors formulate strategies for solar power energy generation system installation in Indonesia and all around the world.

The most important global validity of this research is to design the ground-mounted solar power generation systems and predict the plant performance at different tilt angles and interrow spacing. This is to select the optimal angle and row space to avoid the unnecessary costs of oversized systems and to utilize the available space optimally.

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