Optimizing tilt angle of the roof for the best performance ratio of rooftop photovoltaic

Nurhalim Dani Ali[1,2], Syaiful Bahri[1], Yusni Ikhwan Siregar[1], Suwondo[1], Anhar[2], Noveri Lysbetti Marpaung[2], Juandi Muhammad[1], Iswadi Hasyim Rosma[2]
[1]Doctor of Environmental Science, Postgraduate Program, University of Riau, Pekanbaru, Indonesia
[2]Basic Electricity Laboratory, Department of Electrical Engineering, Faculty of Engineering, University of Riau, Pekanbaru, Indonesia

Article Info

Article history:

Received Jul 29, 2025
Revised Oct 2, 2025
Accepted Oct 14, 2025

Keywords:

Performance ratio
Photovoltaic
Rooftop
Tilt angle
Topology

ABSTRACT

Rooftop photovoltaic (RPV) systems are becoming increasingly popular as a source of renewable energy. One key factor that significantly affects the performance of RPV systems is the tilt angle of the solar panels. This study aims to determine the optimal tilt angle to maximize electricity production for the RPV system installed on academic building, Department of Electrical Engineering, Faculty of Engineering, University of Riau. The research method used is the PVSyst simulation. The simulation data input was used as daily weather for one year. In this study, variations in roof tilt angles of 5°, 10°, 15°, 20°, and 25° were examined. The results show that the optimal tilt angles for this location are 5° and 10°. At a 5° tilt angle, the RPV can generate 247,128 kWh per year with a performance ratio (PR) of 83%. And then at a 10° tilt angle, the system can generate 248,012 kWh per year with a PR of 82%. Based on the simulation results, other tilt angles also produced higher energy outputs but yielded lower PR values. This study provides practical recommendations for designing RPV systems in regions with similar weather conditions.

This is an open access article under the CC BY-SA license.

Corresponding Author:

Nurhalim Dani Ali
Basic Electricity Laboratory, Department of Electrical Engineering, Faculty of Engineering
University of Riau
HR. Subrantas Street KM 12,5, Pekanbaru 28293, Riau, Indonesia
Email: nurhalim@lecturer.unri.ac.id

1. INTRODUCTION

Solar energy, as one of the most abundant energy resources on Earth, provides an estimated potential of 3.9×10^6 EJ annually (1 EJ=10^{18} J). Globally, the power of solar energy is estimated to reach around 160,000 TW, with solar radiation intensity of approximately 1 kW/m^2 on a clear day [1]. The sun's irradiation and temperature energy generation of solar photovoltaic (PV) [2]-[4]. Indonesia possesses significant renewable energy potential to support its primary energy mix targets. This potential includes approximately 94.3 GW from hydropower, 28.5 GW from geothermal resources, 207.8 GWp from solar energy, 60.6 GW from wind power, and 17.9 GW from ocean energy [5], [6]. Solar energy is one of the options considering the huge energy potential in Indonesia. PT PLN has the potential to increase the use of rooftop photovoltaic (RPV) in Indonesia [7]. The National Energy Policy (KEN) based on Government Regulation No. 79 of 2014 has a target by 2025 the achievement of primary energy of renewable energy of 23%, oil <25%, coal at least 30% and natural gas at least 22%, and then in 2050 has a target as much as 31% renewable energy, oil <20%, coal at least 25% and natural gas at least 24%. Based on the the roadmap on renewable energy development in Indonesia by 2028 is the total installed PV capacity reached 908 MWp, where in 2019 it only reached 63 MWp [8]. PV development in Indonesia is developed by State Electricity

Company (PT PLN) for areas that have access constraints or power grid expansion and transportation access difficulties [9], [10]. The negative relationship between cost and installed capacity highlights that the small-scale renewable energy scheme subsidy provided at the outset effectively encouraged solar energy development [11]. Renewable energy sources are gaining increasing attention due to the depletion of fossil fuels, growing concerns over energy security, rising electricity demand, and heightened awareness of environmental challenges [12], [13].

At present, the use of conventional energy sources, such as coal and oil, will decrease because they generate air pollution, and these reserves are non-renewable. One source of energy that is always available every day is energy from the sun. In addition, solar power generation does not bring air pollution to the atmospher [14]. Global climate change, driven by the excessive consumption of fossil fuels such as coal, petroleum products, and natural gas in sectors including power generation, transportation, and industry, has led to the release of billions of tons of carbon into the atmosphere [15]-[17]. Global surveys confirm that Indonesia is among the world's largest contributors to climate change, of 18% [18]. Economically, under current conditions, investment in rooftop on-grid PV systems will provide a payback period of about 9-10 years. Statistical data indicate that daily solar irradiation in Indonesia could generate more than 500 GW of solar energy potential. Nevertheless, the development and monitoring of the solar PV sector in Indonesia remain limited. It is noted that since 2013, the Indonesian government through the Directorate General of New Renewable Energy and Energy Conservation of the Ministry of Energy and Mineral Resources has started to regulate the solar energy sector in Indonesia. The first policy issued was Regulation No. 17/2013. In the early years, solar technology was still considered expensive and relatively unreliable. Based on this regulation has resulted in a lack of market for solar energy. In the course of time, there have been regulatory changes. The latest Ministry of Energy and Mineral Resources Regulation No. 49/2018 has also been socialized. To accelerate the increase in the utilization of new and renewable energy as a tangible manifestation of the government's encouragement in its utilization, the Minister of Energy and Mineral Resources Regulation No. 49/2018 has been issued. The regulation specifically regulates the utilization of rooftop solar power generation systems [19].

The green campus concept emphasizes environmental conservation, energy efficiency, and the integration of renewable energy as a pathway toward sustainability [20]. In this regard, a grid-connected rooftop solar PV system has been proposed and evaluated using PVsyst software with NASA meteorological data for feasibility analysis [21]. Furthermore, assessing and comparing greenhouse gas (GHG) emissions from power generation technologies supports global initiatives to mitigate climate change by reducing reliance on fossil fuels [22], [23].

Moreover, several studies have demonstrated that the efficiency of PV systems can be significantly improved through solar tracking technologies. For instance, a dual-axis tracker utilizing GPS and Arduino achieved an energy yield increase of 33–38% compared to a fixed system [24]. Similarly, single-axis and dual-axis systems demonstrated 24.37% and 32.25% higher outputs, respectively, with reduced payback periods [25]. In addition, a low-cost single-direction tracker based on photodiode sensors improved energy output by approximately 20% [26], while an optimized dual-axis system yielded an annual energy gain of about 42% [27].

Consequently, based on these findings, the rooftops of campus buildings can be strategically utilized as renewable energy harvesters to address existing energy demands. To maximize PV array performance, solar panels should be positioned perpendicularly to the sun at optimal angles in order to minimize shading losses. Therefore, this paper introduces the design of a rooftop solar PV system for the Faculty of Engineering, University of Riau, developed and simulated using PVsyst software.

2. ENERGY EVALUATION

The main factors to consider for rooftop solar power systems are the total installation cost, the amount of electricity generated as well as government policy support on solar energy development. The nominal output of the PV plant in Wp can be computed using (1) [28].

$$P_{PV,required} = N_{panel,required} \; x \; P_{panel,rate} \tag{1}$$

$P_{PV,required}$ is the required PV system capacity (Wp). This value represents the total nominal power that must be installed to meet a specific energy demand. $N_{panel,required}$ is the number of solar panels required (Pcs). This value is obtained by dividing the total PV system capacity by the nominal power of each panel. $P_{panel,rate}$ is the nominal power of a single solar panel (Wp), as specified in the manufacturer's datasheet, determined under standard test conditions (STC) (STC: irradiance 1000 W/m² and cell temperature 25 °C).

In its implementation, PV can be constructed off and on grid, and nowadays RPV systems are also widely used. The following description will explain some commonly used PV system constructions. Then, the quality of system operation is determined by the performance ratio (PR) as shown in (2) [29].

$$PR(\%) = \frac{E_{out,AC}}{E_{STC}} \times 100 \quad (2)$$

PR is the PV system performance factor (0–1 or %). PR indicates the overall efficiency of the system after considering all losses, including temperature effects, shading, inverter conversion losses, soiling, and others. $E_{out,AC}$ is the actual output energy of the PV system (kWh), measured after the inverter conversion into alternating current (AC). E_{STC} is the theoretical energy (kWh) that the PV system would produce if it operated continuously under STC corresponding to the received irradiance.

The PR is defined as the difference in final yield (Y_f) and reference yield (Y_r). The actual energy produced by the solar PV system compares with the expected energy from its nameplate rating. The PR can be calculated using (3), as per IEC 61724 [30].

$$PR = \frac{Y_f}{Y_r} \quad (3)$$

The net AC energy produced by PV systems combined with the installed PV array's peak power at STC during a certain period can be compared to the Y_f results. In (4) shows how to express the Y_f in daily, monthly, and yearly periods.

$$Y_f = \frac{E_{out}}{P_N} \quad (4)$$

The Y_r compares total in-plane irradiance to the reference irradiance of the PV. STC are used to measure the PV reference irradiance, which is 1000 W/m2. In (5) describes the Y_r formula.

$$Y_r = \frac{Total\ in\ plane\ irradiance}{PV\ reference\ irradiance} \quad (5)$$

Y_f is the final yield of the PV system (kWh/kWp), calculated as the ratio of actual output energy to nominal system capacity. It represents how much energy is generated per installed 1 kWp of PV capacity. Y_r is the reference yield (kWh/kWp), calculated as the total in-plane irradiance divided by the reference irradiance of 1 kW/m². This value is equivalent to the number of peak sun hours.

3. PHOTOVOLTAIC STRUCTURE

The proposed solar PV power system comprises a PV array, inverter, cabling, mounting structures, protection devices, and battery storage [31]. Appropriately rated power and control cables are essential for interconnections between modules or panels within an array, between the array and the charge controller, and between the charge controller and the loads. Cable sizing is determined by considering the full-load current and allowable voltage drop, with a maximum permissible drop of 2.5% under full-load conditions. Derating factors must also be taken into account when selecting conductors. For the protection of both equipment and personnel, proper earthing is required. Two main grounding methods are employed: system earth, which involves grounding one leg of the circuit, and equipment earth, where non-current-carrying metal parts are bonded to the ground to prevent electric shock during faults. Junction boxes must be properly rated and capable of withstanding environmental factors such as dust and water. Additionally, fuses of adequate rating should be installed to safeguard solar arrays against short-circuit conditions.

Within the category of distributed systems, PV installations can generally be classified into four types:
- Mall-scale, up to 250 kW;
- Medium-scale, ranging from 250 kW to 1 MW;
- Large-scale, from 1 MW to 100 MW;
- Very large-scale, with capacities exceeding 100 MW.

Utility-scale PV systems typically employ a specialized layout that incorporates multiple transformers, inverters, and PV arrays. In this configuration, each PV string is connected to its own inverter, resulting in a higher number of inverters compared to power plants that utilize a single central inverter (Figure 1).

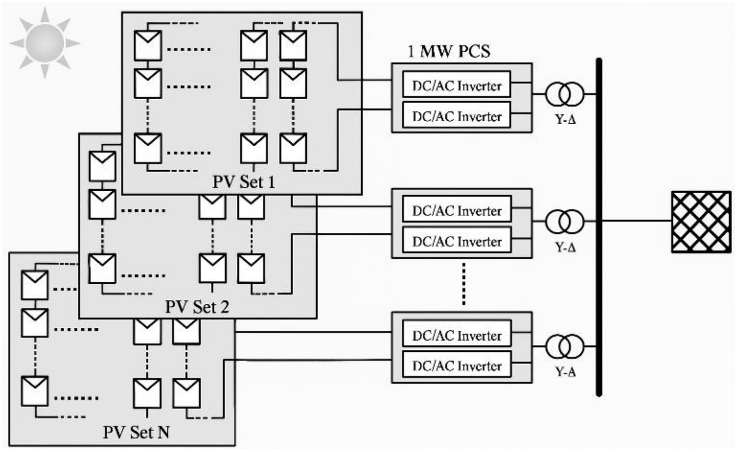


Figure 1. A generating unit that utilizes PV at a grid level [32]

4. METHOD

4.1. Site information and design process

This research is focused on the classroom building of the Building C, Faculty of Engineering, University of Riau. The first step was to measure height and area of the building. And then, the building plan was designed using software application, and then will later be imported into special software to design RPV in specified building. The coordinate of the building is at latitude 0.479994°, longitude 101.376736° and altitude 26 m respectively. Location observation is aimed to determine the position of the building against the position of the sun at any time. In one year, the sun changes its position every month so that the sun's declination point is at 23.45° in every northern and southern part of the earth, where the area of the Faculty of Engineering, University of Riau is ± 84,200 m^2.

The building height was measured with a digital laser meter (LSM), and the roof inclination was measured with an inclinometer meter (IM). These parameters serve as inputs for SketchUp software to design a 3D model of the building. The 3D building model is then imported into PVsyst software to design the RPV system. Meteorological data were collected using an automatic weather station (AWS) installed on the rooftop of the Coversion Energy Laboratory, Department of Electrical Engineering, Faculty of Engineering, University of Riau. The entire process is illustrated in Figure 2.

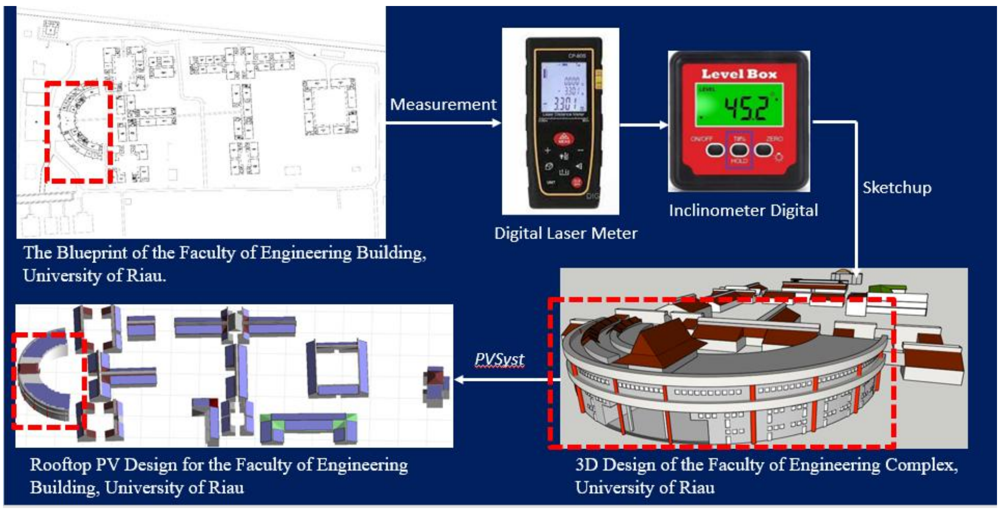
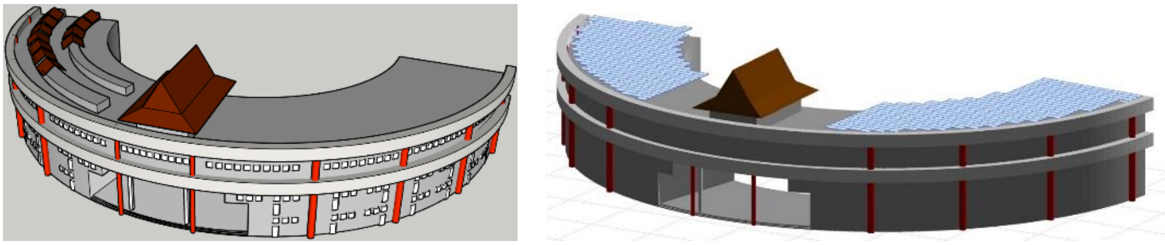


Figure 2. Diagram for designing a RPV system

In this study, the automatic weather station (AWS) records data on solar radiation, humidity, temperature, and other parameters at five minute intervals, producing 12 data points in a hour. The radiation measured by the AWS is global horizontal irradiance (GHI), which represents the total shortwave radiation received by a horizontal surface on a flat plane. This parameter is particularly important for RPV systems that do not employ large solar tracking devices. GHI consists of both direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). In addition, the AWS also records ambient temperature and relative humidity of the surrounding environment.

4.2. Analysis method

The RPV system design requires an actual building design to illustrate the exact roof conditions. Each building in the Building C, Faculty of Engineering, University of Riau has a different roof shape and slope. The design was built is used as a RPV design using a 3DS file type. Based on this figure, from each sides of the roof that can be installed RPV, where the total roof area that can be installed RPV is 1,612.55 m^2. The rooftop code markings as shown in Figures 3(a) and (b) can easily identify the meteonomic position of each rooftop. The azimuth of the building roof is -178°.



(a) (b)

Figure 3. The 3DS and RPV system design of academic building, Building C, Faculty of Engineering, University of Riau: (a) the 3DS design of building and (b) designing an RPV system

Based on the PVSyst software simulation results, the number and area of PV panels that can be installed on each rooftop are shown in Table 1, and the design of the RPV can be seen in Figures 3(a) and (b).

To ensure realistic simulations, key assumptions were applied: monthly cleaning corresponding to ~2% annual soiling loss, module degradation of 0.5%/year, and system availability of 98%. In PVsyst, shading was modelled using the 3-D tool based on rooftop geometry, temperature effects with the normal operating cell temperature (NOCT)-based thermal model and manufacturer's coefficient, mismatch and wiring losses were set to 2% and 1.5%, respectively, and inverter efficiency to 97%. These assumptions are explicitly stated to improve transparency and reproducibility.

Table 1. Number and area of panels on building based on roof angle

Item	Degree				
	5°	10°	15°	20°	25°
Panel (Pcs)	600	612	640	660	680
Panel area (m^2)	1,060.80	1,082.02	1,131.52	1,166.88	1,202.24
Area effective (m^2)	1,116.40	1,138.76	1,190.77	1,228.11	1,265.24

5. RESULT AND DISCUSSION

The panel angle represents the tilt of the solar panel relative to the horizontal. Determining this angle is important as it affects the amount of solar radiation received and the energy output generated by the solar panel. P_{mpp} (Wp) is the maximum power that can be generated by the solar module in Watt peak (Wp). P_{inv} (W) is the maximum power fed into the inverter, measured in watts. This indicates the amount of power converted by the inverter from DC to AC. The inverter (unit) is the number of inverters used to convert power from the solar panels to the electrical system. V_{max} Array (V) is the maximum voltage produced by the solar module array. I_{max} Array (A) is the maximum current produced by the solar module array. Module in Series refers to the number of solar modules arranged in series within the array. The number of strings is the number of solar panel circuits (strings) connected to generate electrical power. Table 2 shows how changes in the solar panel angle affect the power generated and system configuration. The solar panel angle shows the tilt of the PV module relative to the horizontal line. In RPV applications, this angle is crucial as it affects the amount of solar radiation received by the panel surface. The more optimal the angle, the greater the energy that can be generated.

At a 5° angle, the panels are almost flat relative to the ground surface, allowing for good radiation reception in tropical regions. At a 25° angle, the panels are tilted more sharply, suitable for optimal sunlight absorption in locations with varying radiation intensity throughout the year. P_{mpp} (Watt peak) is the maximum power the solar panel can generate under optimal conditions, when the module operates at the maximum power point (MPP). This value varies depending on the installation angle. At a 5° angle, the maximum power generated is 210,000 Wp. At a 25° angle, the maximum power increases to 238,000 Wp, showing that a larger panel angle can generate more energy in certain conditions.

Table 2. Capacity and topology of the RPV system for building

Tilt (°)	Panel (Pcs)	P_{mpp} (kWp)	P_{inv} (kW)	Inverter (unit)	V_{max} array (V)	I_{max} array (A)	Module in series	Number of string
5°	600	210.0	168.0	8	701	324	12	50
10°	612	214.2	171.4	9	701	314	12	51
15°	540	224.0	179.2	9	585	393	10	64
20°	660	231.0	184.8	9	701	338	12	55
25°	680	238.0	190.4	9	585	418	10	68

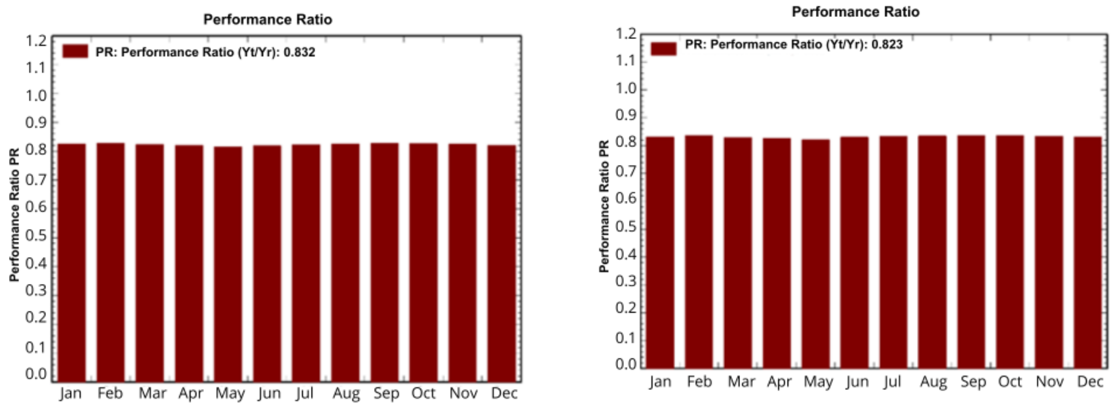
P_{inv} (W) represents the maximum power that can be supplied to the inverter within the system. The inverter functions to convert the direct current (DC) produced by solar panels into AC, making it suitable for use by electrical devices or for distribution to the power grid. At a 5° angle, the inverter receives a power of 168,000 W, while at a 25° angle, the inverter can handle a higher power of 190,400 W. The number of inverters required in the system converts DC power to AC power. More inverters are needed to handle higher power. At a 5° angle, 8 inverter units are required. From angles of 10° to 25°, the number of inverters needed increases to 9 units, as the power generated by the panels rises. V_{max} array is the maximum voltage produced by the solar module array, indicating the voltage level that can be generated from the series configuration of modules. At a 5° angle, the module array produces a maximum voltage of 701 V, which is the same at 10° and 20° angles. However, at 15° and 25° angles, the maximum voltage is lower at 585 V, indicating a different panel arrangement configuration to achieve optimal power. Imax array represents the maximum current generated by the module array in a single string. The higher the current generated, the greater the potential power output. At a 5° angle, the maximum current produced is 324 A, which decreases slightly to 314 A at a 10° angle. At a 25° angle, the maximum current increases to 418 A, indicating a higher energy output at steeper angles.

The number of solar modules connected in series within an array determines the system's total voltage. At a 5° angle, 12 modules are connected in series, as well as at 10° and 20° angles. At 15° and 25° angles, the number of modules connected in series decreases to 10, adjusted to a lower voltage configuration. Number of strings represents the total number of strings or circuits connected within the PV system. Each string contains modules connected in series and parallel to achieve the desired power output. At a 5° angle, there are 50 strings connected, while at a 25° angle, the number of strings increases to 68, indicating adjustments in the number of circuits needed to reach optimal power at larger angles. From the data in Table 2, it is evident that adjusting the panel angle affects various performance aspects of the solar system, including P_{mpp}, P_{inv}, voltage, current, and circuit configuration. A larger angle tends to increase both P_{mpp} and P_{inv} but also requires more strings and modules to optimize energy output. Choosing the optimal angle in RPV installations is crucial to ensure maximum energy efficiency in specific geographic regions.

The PR is a key parameter used to evaluate the overall efficiency of a PV system, as it accounts for the influence of temperature, system losses (Ls), and environmental conditions on energy production. Figure 4(a) describes monthly PR of the PV system over one year. The PR values remain stable across all months, with an annual average of 0.832, reflecting consistent system efficiency under varying environmental conditions. Figure 4(b) presents the monthly PR of the RPV system over a one-year period. The results indicate that the PR values remain relatively uniform throughout the year, ranging closely around the annual average of 0.823.

This stable trend suggests that the PV system consistently converts incident solar energy into usable electrical energy with minimal seasonal variation. The absence of significant fluctuations across the months implies that factors such as shading, dust accumulation, and temperature effects exert only limited influence on the system performance. The relatively high and stable PR also indicates that the system design, installation, and maintenance strategies are effective in mitigating energy losses. For instance, module orientation, tilt angle, and inverter efficiency likely contributed to maintaining reliable energy yield.

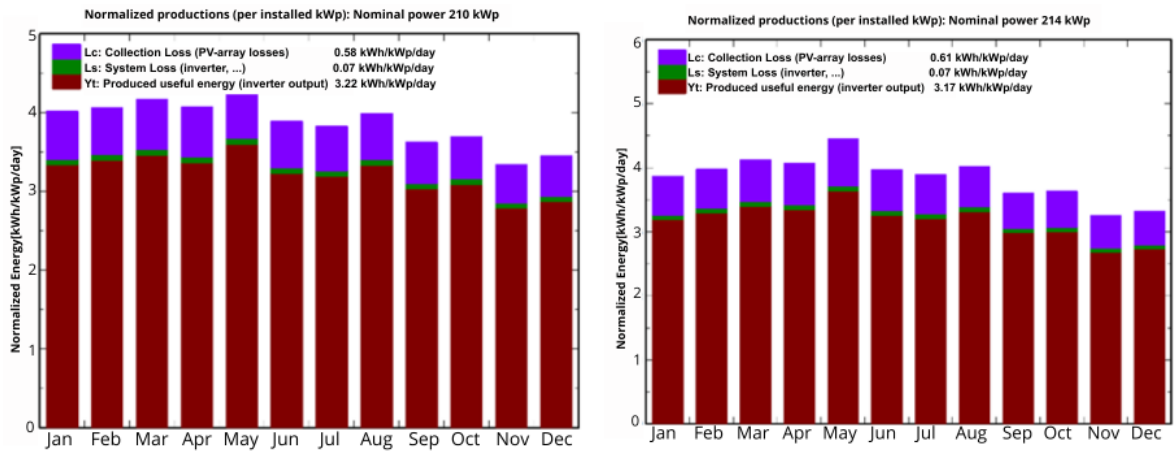
Furthermore, this finding highlights the suitability of RPV systems in achieving consistent energy output throughout the year in equatorial regions, where solar irradiance levels are relatively stable. Overall, the results demonstrate that the installed system performs efficiently and can provide a reliable energy supply for building-scale applications. The high PR achieved further confirms the potential of RPV as a sustainable solution for reducing dependency on conventional energy sources.



(a) (b)

Figure 4. The PR change graph at angle variations of: (a) tilt angle 5° and (b) tilt angle 10°

Figure 5(a) illustrates the normalized daily energy yield of the 210 kWp PV system, expressed in kWh/kWp/day. The annual average useful energy (Y_f) is 3.22 kWh/kWp/day, while collection losses (Lc) and Ls account for 0.58 and 0.07 kWh/kWp/day, respectively. The results show that Lc dominate overall Ls, remaining relatively stable throughout the year but slightly higher during months of greater solar radiation (June–August). Ls, mainly from inverter conversion, are minimal and consistent across months, indicating stable inverter performance. Seasonal variations in Y_f are evident, with higher production between April and August and lower values in January and December, likely due to solar radiation differences. Overall, the PV system demonstrates reliable energy production, with Lc identified as the primary area for efficiency improvement. Figure 5(b) presents normalized daily energy production of the 214 kWp PV system, expressed in kWh/kWp/day. The useful energy yield (Y_f) averages 3.17 kWh/kWp/day, while Lc and Ls account for 0.61 and 0.07 kWh/kWp/day, respectively. The results indicate that Lc dominate overall Ls, while Ls remain minimal and stable across months, reflecting consistent inverter performance. Seasonal variations in Yf are observed, with higher production in May and lower output in November–December, mainly influenced by changes in solar irradiance.



(a) (b)

Figure 5. The energy production change graph at angle variations of: (a) tilt angle 5° and (b) tilt angle 10°

Figure 6(a) presents the normalized energy production and loss factors of a 210 kWp PV system. The results show that 83.2% of the available energy is delivered as useful output (Y_f), while 15% is lost through Lc and 1.8% through Ls. Lc, mainly due to dust, shading, or module mismatch, constitute the largest share, whereas Ls from inverter conversion are minimal and stable throughout the year. Then, Figure 6(b) illustrates normalized production and loss factors of the 214 kWp PV system. The results show that 82.3% of the available energy is delivered as useful output, while 15.9% is lost through Lc and 1.8% through Ls. The performance remains stable throughout the year, indicating consistent system efficiency under varying environmental conditions.

Overall, the system demonstrates good efficiency with consistent energy production across all months. Reducing Lc, for instance through panel cleaning or optimal tilt adjustment, could further enhance performance. Simulation results indicate that tilt angles of 5° and 10° provide the most suitable configuration for RPV installation on the Faculty of Engineering building, University of Riau. More details are shown in Table 3.

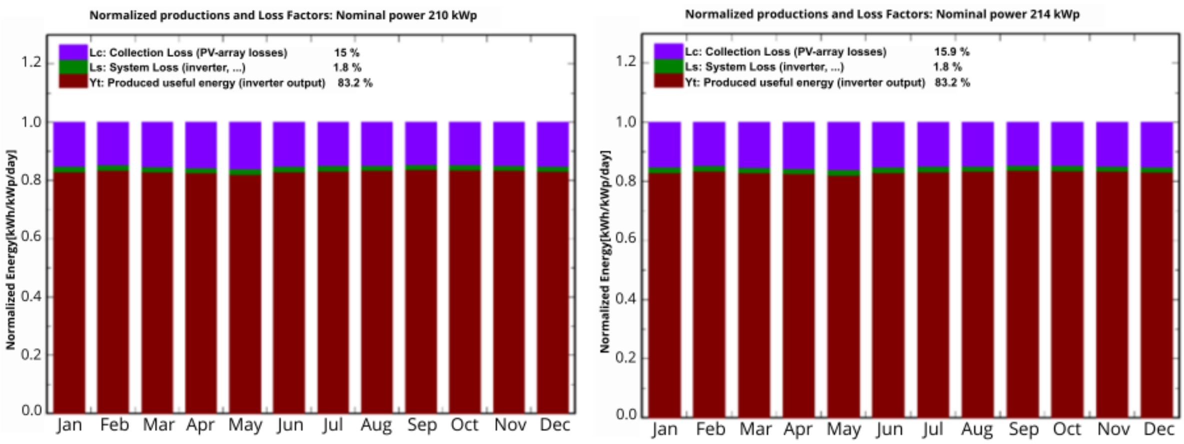


Figure 6. The normalized production and loss factors change graph at angle variations of: (a) tilt angle 5° and (b) tilt angle 10°

Table 3. The effect of tilt angle changes on PR

Tilt (°)	Number of panels (Pcs)	Inverter (Pcs)	E_{Grid} (kWh)	W_{Grid} (kW)	PR
5°	600	8	247,128	28.211	0.83
10°	612	9	248,012	28.312	0.82
15°	640	9	248,856	28.408	0.80
20°	660	9	246,446	28.133	0.78
25°	680	9	240,168	27.416	0.75

Figure 7 presents comparative visualization of PR and annual energy output across different tilt angles (5°–25°). The results show that while differences in PR and energy yield are relatively small, they remain relevant for site-specific RPV optimization. This dual-axis plot highlights the trade-off between PR stability and incremental changes in energy production, providing practical insights for rooftop design decisions in tropical contexts.

Figure 8 presents the trade-off between the number of installed panels and the PR at different tilt angles. The results show that increasing the tilt angle from 5° to 25° allows more panels to be installed (from 600 to 680 Pcs). However, this increase comes at the cost of a lower PR, which decreases from 0.83 to 0.75. This trend suggests that larger tilt angles provide greater installation capacity but reduce the system's ability to capture solar radiation effectively, leading to lower efficiency.

When considering energy delivered to the grid (Egrid), the results confirm that the highest energy output (248,856 kWh) occurs at 15° with 640 panels, despite the PR decreasing to 0.80. Beyond this point, additional panels do not compensate for the reduction in PR, causing Egrid to decline. Therefore, the 15° configuration represents the most balanced option, offering the maximum energy yield while maintaining acceptable efficiency. This trade-off highlights the importance of optimizing tilt angle in RPV system design, where maximizing the number of panels alone does not guarantee higher energy production. Instead, the interplay between PR and installed capacity determines the optimal configuration, which in this case lies at 15°.

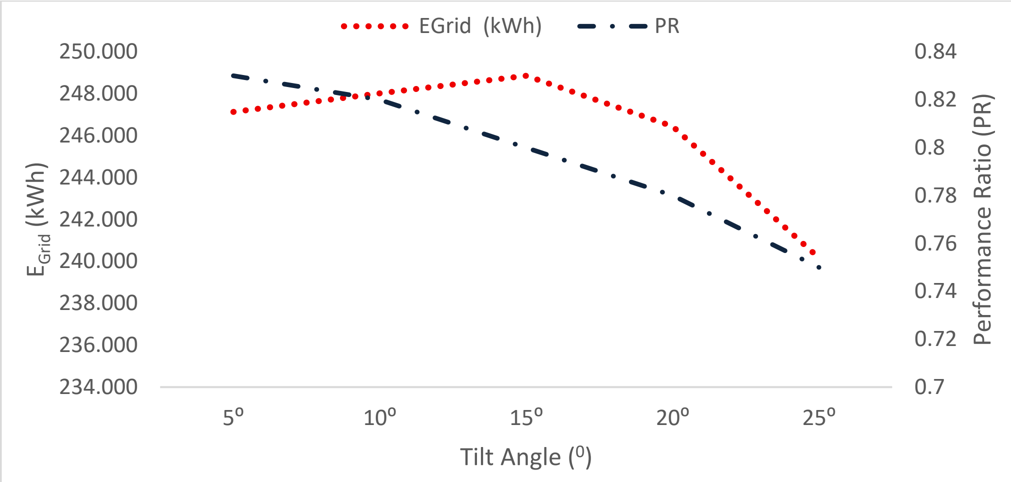


Figure 7. Comparative visualization of the relationship between tilt angle, E_{Grid}, and PR

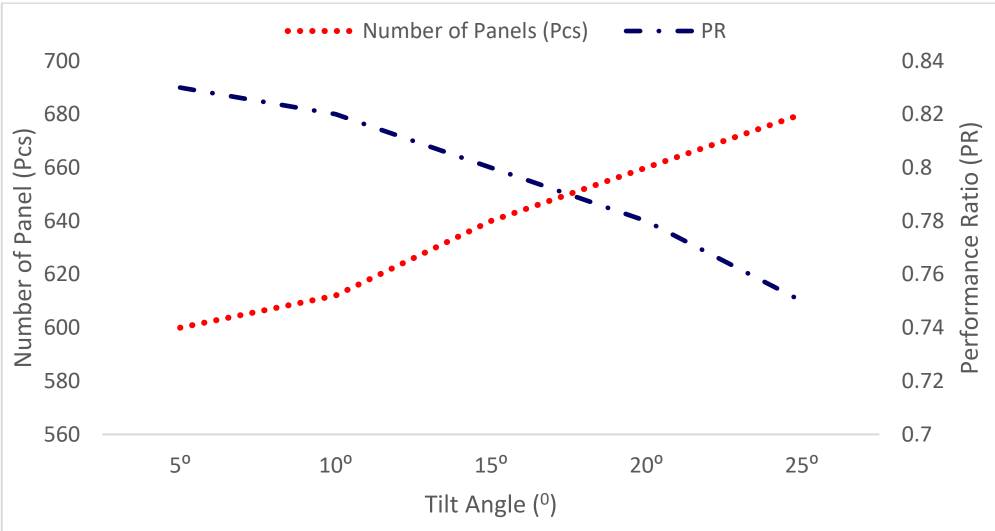


Figure 8. Comparative visualization of tilt angle, number of installed panels and PR

This study assessed the impact of different tilt angles (5°–25°) on the PR and annual energy output of a RPV system at University of Riau using PVsyst simulations. The results indicate that lower tilt angles, consistent with tropical solar geometry, deliver marginally higher PR and energy yield. Although the differences are small, they remain practically relevant for RPV design in constrained urban contexts.

The study's novelty lies in applying a site-specific, rooftop-constrained approach that highlights trade-offs between PR stability and incremental energy gains. Comparative visualizations provide practical insight into how even minor tilt adjustments can influence system performance and economic outcomes. While statistical significance testing, sensitivity analysis, and real-world validation were beyond the present scope, these limitations have been acknowledged and represent important directions for future research.

Beyond site-specific findings, the methodological framework is adaptable to other tropical and urban regions. Tilt optimization contributes not only to improving system efficiency but also to supporting grid integration, off-grid energy reliability, and potential synergies with storage and demand-side management. Thus, this work provides both practical guidance for RPV deployment and a foundation for broader research into scalable, sustainable solar energy strategies in tropical climates.

6. CONCLUSION

This study conducted a comprehensive analysis of the effect of tilt angle on the performance of RPV systems. The results reveal that: i) the tilt angle significantly influences the number of solar panels that can be installed on a given roof area. Larger tilt angles allow for more panels, while smaller tilt angles limit panel installation; ii) an increase in tilt angle reduces the panels' ability to capture direct sunlight, resulting in lower energy output. Conversely, smaller tilt angles enhance the panels' capacity to harness solar radiation, thereby increasing energy generation; iii) the PR is inversely related to the tilt angle; higher tilt angles lead to lower PR values, while lower tilt angles correlate with higher PR values; and iv) based on the results, the optimal tilt angles for the design of RPV systems on the academic building of the Building C, Faculty of Engineering, University of Riau are determined to be 5° and 10°.

These conclusions highlight the importance of selecting the appropriate tilt angle in maximizing the efficiency and energy output of RPV installations. Further optimization of other system components may enhance overall performance.

ACKNOWLEDGMENTS

Thanks to our best team member Abdul Azis, Azis Zamri, Randa Pratama Zulfa, M. Alfaredzi Pranoto, and Omar Wira Maulana for any support provided on this research.

FUNDING INFORMATION

The authors would like to gratefully acknowledge the financial support provided by the Lembaga Penelitian dan Pengabdian kepada Masyarakat (LPPM) of University of Riau through the Riset Unggulan University of Riau (RUUR) research grant scheme, 2024. The contract number: 992/UN19.5.1.3/AL.04/2024.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nurhalim Dani Ali	✓		✓			✓	✓		✓	✓		✓	✓	✓
Syaiful Bahri	✓				✓					✓	✓	✓		
Yusni Ikhwan Siregar		✓			✓			✓		✓		✓		
Suwondo		✓			✓			✓		✓		✓		
Anhar		✓		✓		✓			✓					✓
Noveri Lysbetti Marpaung		✓	✓			✓	✓		✓				✓	
Juandi Muhammad	✓				✓					✓				
Iswadi Hasyim Rosma	✓		✓			✓				✓				

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] D. J. Damiri and A. A. Nugraha, "Technical performance and economic feasibility simulation of 200 kWP rooftop solar photovoltaic on-grid on industrial estate factory building with Helioscope software," *Jurnal Rekayasa Elektrika*, vol. 17, no. 2, pp. 86–93, 2021, doi: 10.17529/jre.v17i2.19578.

[2] A. Jabbari *et al*., "A novel control approach utilizing neural network for efficient microgrid operation with solar PV and energy storage systems," *Advances in Electrical and Computer Engineering*, vol. 24, no. 3, pp. 13–22, 2024, doi: 10.4316/AECE.2024.03002.

[3] N. D. Ali *et al*., "The potential of rooftop solar photovoltaic generation system at the laboratory complex of University of Riau," in *Proceedings of the International Conference on Electrical Engineering and Informatics*, no. 49, pp. 12–16, 2024, doi: 10.1109/IConEEI64414.2024.10748184.

[4] S. Sundaram, D. Benson, and T. K. Mallick, "Potential environmental impacts from solar energy technologies," in *Solar Photovoltaic Technology Production*, pp. 23–45, 2016, doi: 10.1016/b978-0-12-802953-4.00003-2.

[5] O. S. R. C., J. W., and S. S., "Performance ratio evaluation of rooftop solar power plant 32 kWp on-grid, study case in PT. KPJB Office Jepara Indonesia," *International Journal of Multidisciplinary Research*, vol. 5, no. 1, pp. 1–8, 2023, doi: 10.36948/ijfmr.2023.v05i01.1387.

[6] J. Langer, J. Quist, and K. Blok, "Review of renewable energy potentials in Indonesia and their contribution to a 100% renewable electricity system," *Energies*, vol. 14, no. 21, pp. 1–21, 2021, doi: 10.3390/en14217033.

[7] F. N. Haryadi, A. A. Simaremare, D. F. Hakam, I. A. Aditya, and I. Haryani, "Strategies for increasing the use of rooftop PV in Indonesia," *Journal of Development Economics*, vol. 7, no. 1, pp. 70–83, 2022, doi: 10.20473/jde.v7i1.35679.

[8] Climate Policy Implementation Check 2023, "Policy instrument: General National Electricity Plan (RUKN) 2019–2023," pp. 1–5, 2023.

[9] "Energy transition pathways for the 2030 agenda – SDG 7 roadmap for Indonesia," UNESCAP, 2021.

[10] Republic of Indonesia, "Government Regulation of the Republic of Indonesia Number 79 of 2014 concerning National Energy Policy (in Indonesian: *Peraturan Pemerintah Republik Indonesia Nomor 79 Tahun 2014 tentang Kebijakan Energi Nasional),* pp. 1–60, 2014.

[11] X. Deng, S. Poletti, T. Hazledine, M. Tao, and E. Sbai, "Deploying solar photovoltaic through subsidies: An Australian case," *Journal of Environmental Management*, vol. 372, pp. 1–12, 2024, doi: 10.1016/j.jenvman.2024.123293.

[12] S. Asiaban *et al*., "Wind and solar intermittency and the associated integration challenges: A comprehensive review including the status in the Belgian power system," *Energies*, vol. 14, no. 9, pp. 1–41, 2021, doi: 10.3390/en14092630.

[13] IRENA, "World Energy Transitions Outlook 2023: 1.5 °C Pathway," International Renewable Energy Agency, Abu Dhabi, vol. 1, 2023.

[14] L. A. M. Sijabat and A. Mostavan, "Solar power plant in Indonesia: Economic, policy, and technological challenges to its development and deployment," *IOP Conference Series: Earth and Environmental Science*, vol. 753, no. 1, pp. 1–7, 2021, doi: 10.1088/1755-1315/753/1/012003.

[15] S. Manzoor and M. T. Iqbal, "Dynamic modeling and simulation of the rooftop PV system for the first passive house in Newfoundland," *Journal of Physics: Conference Series*, 2021, pp. 1–10, doi: 10.1088/1742-6596/1803/1/012017.

[16] N. Ali *et al*., "Photovoltaic solar energy as a power source for coal waste measurement equipment," *Journal of Ocean Mechanical and Aerospace Science and Engineering*, vol. 67, no. 2, pp. 58–62, 2023, doi: 10.36842/jomase.v67i2.346.

[17] IEA, "World Energy Outlook 2022," International Energy Agency, Paris, 2022.

[18] Y. Zhang, S. Wang, W. Shao, and J. Hao, "Feasible distributed energy supply options for household energy use in China from a carbon neutral perspective," *International Journal of Environmental Research and Public Health*, vol. 18, no. 24, pp. 1–16, 2021, doi: 10.3390/ijerph182412992.

[19] E. Tarigan, "Rooftop PV system policy and implementation study for a household in Indonesia," *International Journal of Energy Economics and Policy*, vol. 10, no. 5, pp. 110–115, 2020, doi: 10.32479/ijeep.9539.

[20] R. Thaib, M. Amudy, and T. A. Rizal, "Study on implementation of rooftop photovoltaic power plant as an effort to attain a sustainable campus," *European Journal of Engineering and Technology Research*, vol. 4, no. 11, pp. 22–25, 2019, doi: 10.24018/ejeng.2019.4.11.1606.

[21] S. Barua, R. A. Prasath, and D. Boruah, "Rooftop solar photovoltaic system design and assessment for the academic campus using PVsyst software," *International Journal of Electronics and Electrical Engineering*, vol. 5, no. 1, pp. 76–83, 2017, doi: 10.18178/ijeee.5.1.76-83.

[22] R. Leutz, "Carbon footprint estimate from life cycle analysis for hybrid concentrating photovoltaic power generation," in *AIP Conference Proceedings*, 2022, pp. 1–5, doi: 10.1063/5.0099034.

[23] A. Boukhriss, "Active disturbance rejection control applied to a three-phase grid-connected photovoltaic system," *Advances in Electrical and Computer Engineering*, vol. 22, no. 1, pp. 87–94, 2022, doi: 10.4316/AECE.2022.01010.

[24] S. Rustemli, Z. İlcihan, G. Sahin, and W. G. J. H. M. van Sark, "A novel design and simulation of a mechanical coordinate-based photovoltaic solar tracking system," *AIMS Energy*, vol. 11, no. 5, pp. 753–773, 2023, doi: 10.3934/energy.2023037.

[25] T. Demirdelen, H. Alıcı, B. Esenboğa, and M. Güldürek, "Performance and economic analysis of designed different solar tracking systems for Mediterranean climate," *Energies*, vol. 16, no. 10, pp. 1–23, 2023, doi: 10.3390/en16104197.

[26] A. Alshaabani, "Developing the design of single-axis sun sensor solar tracking system," *Energies*, vol. 17, no. 14, pp. 1–14, 2024, doi: 10.3390/en17143442.

[27] C. Alexandru, "Simulation and optimization of a dual-axis solar tracking mechanism," *Mathematics*, vol. 12, no. 7, pp. 1–32, 2024, doi: 10.3390/math12071034.

[28] T. B. Nguyen and P. H. Van, "Design, simulation and economic analysis of a rooftop solar PV system in Vietnam," *EAI Endorsed Transactions on Energy Web*, vol. 8, no. 35, pp. 1–12, 2021, doi: 10.4108/eai.27-1-2021.168504.

[29] E. Tarigan, "Simulation and feasibility studies of rooftop PV system for university campus buildings in Surabaya, Indonesia," *International Journal of Renewable Energy Research*, vol. 8, no. 2, pp. 895–908, 2018, doi: 10.20508/ijrer.v8i2.7547.g7377.

[30] F. P. H., M. Dachyar, and F. Farizal, "Techno-economic evaluation of solar rooftop photovoltaic systems at factory building in Indonesia," in *12th Annual International Conference on Industrial Engineering and Operations Management*, 2023, pp. 801–811, doi: 10.46254/an12.20220133.

[31] Y. Pradeep Kumar and V. Tejaswitha, "Design and development of solar roof top PV power systems," *International Journal of Engineering and Technology*, vol. 4, no. 1, pp. 8–17, 2018.

[32] E. Rakhshani, K. Rouzbehi, A. J. Sánchez, A. C. Tobar, and E. Pouresmaeil, "Integration of large-scale PV-based generation into power systems: A survey," *Energies*, vol. 12, no. 8, pp. 1–19, 2019, doi: 10.3390/en12081425.

BIOGRAPHIES OF AUTHORS

Nurhalim Dani Ali is a faculty member at the Department of Electrical Engineering, Faculty of Engineering, University of Riau, Pekanbaru, Indonesia. He earned his bachelor's degree in Electrical Engineering from the Medan Institute of Technology in 1998 and completed his master's degree in Electrical Engineering at Universitas Indonesia in 2007. He is currently pursuing a Ph.D. in Environmental Science at University of Riau, with a research focus on sustainable energy. He has published several articles in national and international journals and has received multiple research grants in the field of renewable energy and particularly solar energy. He can be contacted at email: nurhalim@lecturer.unri.ac.id.

Syaiful Bahri is a professor in the Department of Chemical Engineering, Faculty of Engineering, University of Riau, Pekanbaru, Indonesia. He obtained his Master's degree in Inorganic Chemistry from Gadjah Mada University in 1995 and earned his Ph.D. in Chemical Engineering with a specialization in Enhanced Oil Recovery from the University of Salford, United Kingdom, in 2002. His research interests include renewable energy, biomass-based fuels, and catalysis. He has published numerous articles in national and international journals, received multiple research grants, and authored several books. He can be contacted at email: syaifulbahri@eng.unri.ac.id.

Yusni Ikhwan Siregar is a professor in the Department of Marine Science at University of Riau, Pekanbaru, Indonesia. He earned his bachelor's degree in Fish Culture from IPB University in 1983, followed by a master's degree in Aquaculture from Auburn University, Alabama, USA, in 1989. He completed his Ph.D. in Zoophysiology at Arhus University, Denmark, in 1994. His primary research interests include Aquatic Ecotoxicology and Coastal and Marine Conservation. He has published numerous articles in national and international journals, received various research grants, and authored several books. He can be contacted at email: yusni.ikhwan@lecturer.unri.ac.id.

Suwondo is a professor specializing in Ecology and Environmental Sciences at the Faculty of Teacher Training and Education, University of Riau. He earned his Bachelor's degree in 1990 from the Biology Education Study Program, Faculty of Teacher Training and Education, University of Riau. He completed his Master's degree in 1995 in Biology (Ecology) at Gadjah Mada University, Yogyakarta, and obtained his Doctoral degree in 2011 from the Bogor Agricultural Institute, Bogor. Throughout his academic career, he has produced a substantial body of national and international research, along with numerous scientific publications. He has also authored several books that align with his areas of expertise. He can be contacted at email: suwondo@lecturer.unri.ac.id.

Anhar is an Associate Professor in the Department of Electrical Engineering, University of Riau, Indonesia. He earned his Ph.D. in Electrical Engineering from Brunel University London, United Kingdom, in 2019. He has taught a wide range of courses, including data communication, traffic engineering, wireless sensor networks, electrical measurement, and signals and systems. He has published extensively in national and international journals, with research interests in network performance, traffic analysis, antenna design, and IoT systems. In addition, he has received multiple research grants and contributed to the writing of academic books. He can be contacted at email: anhar@lecturer.unri.ac.id.

Noveri Lysbetti Marpaung is an Associate Professor in the Department of Electrical Engineering, University of Riau, Indonesia, where she has been teaching since 1999. She obtained her Bachelor's degree in Electrical Engineering from the University of North Sumatra, Indonesia, and her M.Sc. in Applied Electronics from the University of Newcastle, UK. She has also served in various academic positions, including Secretary of the Diploma-3 Electrical Engineering Program (2004–2008) and Head of the Laboratory of Electrical Engineering (2008–present). Her research interests span control systems, PLC, system reliability, soft computing, artificial intelligence, decision support systems, forecasting systems, internet networks, wireless sensor networks, network security, information systems, Android applications, and IoT. She has published numerous papers in national and international journals, received several research grants, and authored academic books in her field. She can be contacted at email: noveri.marpaung@eng.unri.ac.id.

Juandi Muhammad is professor was born in Lawe Sigalagala on March 26, 1968. He earned his Bachelor's degree in Physics from the Faculty of Mathematics and Natural Sciences, University of Riau, in 1991. He continued his graduate studies in Applied Geophysics at the Bandung Institute of Technology (ITB), completing his Master's degree in 1996, and later received his Doctoral degree in Environmental Science from University of Riau in 2015. He has been a faculty member in the Department of Physics, University of Riau, since 1992, and is actively involved in teaching and supervising doctoral students in the Environmental Science Program. His academic contributions include the authorship of several books—such as *Occupational Safety and Health (K3) from an Islamic Perspective* and *Theory of Groundwater Sustainability*—and numerous publications in reputable international journals indexed by Scopus, where he holds an H-index of 7. He can be contacted at email: juandi@lecturer.unri.ac.id.

Iswadi Hasyim Rosma received his Bachelor's degree in Electrical Engineering from Diponegoro University, Semarang, Indonesia, in 2002, and his Master's degree in Electrical Engineering from the Bandung Institute of Technology, Indonesia, in 2007. He obtained his Ph.D. in Electrical and Electronic Engineering from the School of Electronics, Electrical Engineering, and Computer Science, Queen's University Belfast, Northern Ireland, United Kingdom, in 2016. He is currently an Associate Professor in the Department of Electrical Engineering, Faculty of Engineering, University of Riau, Pekanbaru, Indonesia. His research interests include renewable energy, as well as power system control, stability, and protection. He has published extensively in national and international journals, received numerous research grants, and contributed to several academic books. He can be contacted at email: iswadi.hr@lecturer.unri.ac.id.