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Original Article

Techno-Economic Analysis Of Monocrystalline And Polycrystalline PV Module Ratio Variations In Rooftop Solar PV Systems For Self-Consumption Supply At Prabumulih Grid Substation

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ABSTRACT

This study aims to compare the effect of monocrystalline and polycrystalline PV modules on rooftop PV system performance, analyze the economic and environmental feasibility, and determine the optimal rooftop PV system design for energy supply at the Prabumulih Substation. The research was conducted using simulation methods with PVsyst software through five PV module proportion scenarios polycrystalline and monocrystalline, namely 100%:0%, 75%:25%, 50%:50%, 25%:75%, dan 0%:100%. The analyzed parameters include energy production, performance ratio, solar fraction, system losses, economic feasibility, and carbon emission reduction. The results show that increasing the proportion of monocrystalline modules improves energy production, solar fraction, electricity cost savings, and carbon emission reduction potential. However, higher proportions of monocrystalline modules also increase the initial investment cost. From an economic perspective, the 100% polycrystalline scenario provides the best investment feasibility with lower energy costs and a faster payback period compared to other scenarios. Based on technical, economic, and environmental aspects, the 100% polycrystalline scenario is considered the most optimal rooftop PV system design for implementation at the Prabumulih Substation.

Keywords: rooftop power plant, monocrystalline, polycrystalline, PVsyst, electrical substation.

INTRODUCTION

The electricity sector supports the energy transition by targeting a minimum renewable energy mix of 23% by 2025, which is projected to further increase to approximately 25% by 2038. Achieving the renewable energy target in the electricity sector is expected to reduce greenhouse gas (GHG) emissions by 71 million tons of CO_2 by 2030. Moreover, under the optimal implementation of a low-carbon development scenario, the emission reduction potential could reach up to 99 million tons of CO_2 [1]. Indonesia has significant daily solar radiation potential, ranging from 3.8 to 4.6 kWh/m² [2], with a total technical potential reaching 3,294.4 GWp [3]. The substantial solar energy potential positions solar power plants (PLTS) as a priority renewable energy source in Indonesia. This is aligned with the government's target to achieve 6.5 GW of installed solar power capacity across various regions of the country [4]. Limited land availability in several regions has become a major constraint in the development of large-scale solar power plants. Rooftop solar photovoltaic (PV) systems have emerged as an increasingly adopted alternative, as they utilize existing building rooftops without requiring additional land.

Substations are one of the vital infrastructures in the national electricity system, functioning as interconnection points between power generation facilities and the distribution network supplying end consumers [5]. PT PLN Prabumulih Substation in South Sumatra has an operational capacity of 150 MVA with a voltage level of 150/20 kV and is equipped with three power transformers. In its operation, the substation fulfills all internal electricity demand from the PLN grid with a connected load

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

capacity of 100 kVA. Prabumulih Substation also has considerable potential for renewable energy utilization through the installation of a rooftop solar photovoltaic (PV) system. Identification results indicate that approximately 528 m² of concrete rooftop area remains underutilized and could potentially be developed for rooftop PV installation.

To estimate the electricity generation potential of a rooftop solar PV system, an analysis of key parameters affecting system performance is required. One of the primary factors is the type of photovoltaic module used. Based on the silicon crystal structure, PV modules are generally classified into monocrystalline, polycrystalline, and thin-film technologies. Monocrystalline modules have the highest efficiency, followed by polycrystalline and thin-film modules. These differences are mainly attributed to the purity level and crystal structure arrangement, which influence the module's ability to capture and convert solar radiation into electrical energy.

Previous studies have extensively discussed the comparison of electricity generation performance based on different PV module types. A study conducted by Nayan et al. (2016) identified that PV module efficiency is highly dependent on solar irradiation intensity and operating temperature. Under standard test conditions of 1000 W/m², monocrystalline modules achieved an efficiency of 15.27%; however, the efficiency decreased significantly to approximately 9.25% at an operating temperature of 80 °C [6]. Another study from Juaidi et al (2023) also reported that bifacial PV modules are more efficient in electricity generation than monofacial PV modules. However, both studies evaluated the performance of individual PV module types separately [7]. Aribowo et al. (2026) began investigating the configuration of combined PV module and inverter types in rooftop solar PV systems in Central Java. For systems with high self-consumption demand, configurations utilizing higher-efficiency PV modules, such as Longi Solar, were preferred because they produced higher specific yield and greater energy output compared to mixed PV module configurations. [8]. However, the analysis in the study was not integrated with economic feasibility and environmental feasibility assessments, particularly in terms of carbon emission reduction potential.

The research gap identified from previous studies lies in the limited analysis of how PV module selection in rooftop solar PV systems affects energy production performance for self-consumption applications, as well as its implications for economic feasibility and electricity cost savings. Therefore, this study aims to address the following objectives:

1. To compare the effects of monocrystalline and polycrystalline PV modules on the performance of rooftop solar PV system designs.
2. To analyze the economic and environmental feasibility of rooftop solar PV investment planning at the Prabumulih Substation.
3. To recommend the most optimal rooftop solar PV system design for supporting the internal power supply at the Prabumulih Substation.

RESEARCH METHODS :

Research Location

This research was conducted at the Prabumulih Substation, specifically at the operational office building located at Jl. Bukit Lebar 1, PLN Substation Complex, Majasari Village, South Prabumulih District, Prabumulih City, South Sumatra Province, Indonesia. Geographically, the site is located at coordinates 3.4448423° S and 104.2433622° E. The study identified an available rooftop area of 528 m² that can potentially be utilized for a rooftop solar photovoltaic (PV) system to supply the building's self-consumption electricity demand, thereby reducing dependence on the PLN grid. The available rooftop structure consists of a flat concrete roof. Figure 1 illustrates the operational building selected as the research location for the rooftop solar PV installation.

Figure 1. **Operational Building at the Prabumulih Substation.**

To fulfill the electricity demand for operational activities, the building is supplied by the PLN grid with a capacity of 100 kVA as the primary energy source and supported by a 100 kVA diesel generator as a backup power source. The PLN supply is directly distributed to the building through a self-consumption power transformer with a capacity of 100 kVA. Assuming a power factor of 85%, the effective available power for the building's operational self-consumption is approximately 85 kVA. Figure 2 illustrates the existing single-line diagram of the energy distribution system in the operational building of the Prabumulih Substation.

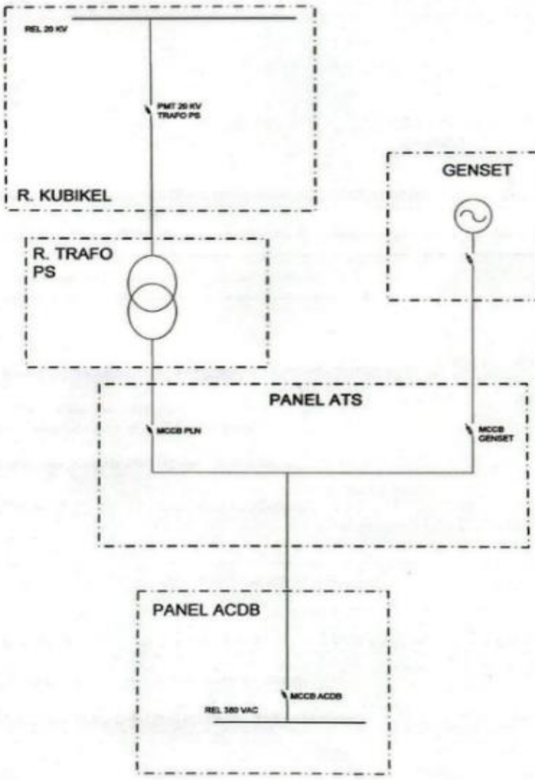

Figure 2. Single-Line Diagram of the Self-Consumption Power System at the Operational Building of the Prabumulih Substation.

Material dan Tools

The analysis of the rooftop solar PV potential at the operational building of the Prabumulih Substation was conducted through simulation using the PVsyst application. The simulation was designed to evaluate the influence of monocrystalline and polycrystalline PV module types on the performance of the rooftop solar PV system. Several scenario combinations were developed to provide a comprehensive assessment of the technical and economic feasibility of the proposed rooftop PV system. In addition, statistical calculations were performed using Microsoft Excel to validate the investment feasibility results and to analyze the impact of the rooftop solar PV system on PLN electricity cost savings.

PVsyst is a software tool used to simulate the performance of solar energy systems [9]. The software is widely recommended for on-grid, standalone, and solar pumping system simulations. The simulation assists in determining the optimal system capacity, estimating annual energy production potential, and evaluating the performance ratio and detailed system loss diagrams [10].

The analysis required both primary and secondary data. Primary data were collected directly through field measurements, including rooftop area and orientation, self-consumption electricity demand profiles, and surrounding environmental conditions. Meanwhile, secondary data were obtained from reports published by relevant institutions and previous related studies. Table 1 presents the data requirements and corresponding data sources used in this research.

No.	Type of Secondary Data	Source
1	Monthly electricity load data	Electricity bills/invoices
2	Solar irradiation data	Meteonorm 8.0
3	PV module specification data	Literature review
4	Initial investment cost (CAPEX)	Literature review
5	Operational and maintenance (O&M) costs	Literature review
6	Economic assumptions	Literature review
7	Rooftop solar PV policy and regulations	(Permen ESDM)

Table 1. Secondary Data Requirements

Data Analysis

Pvsyst Simulation

The performance of the proposed rooftop solar PV system was analyzed using PVsyst by incorporating location parameters, meteorological data, environmental conditions, electricity load profiles, as well as technical and investment data of the PV system. The system configuration applied in this study was an on-grid rooftop solar PV system without battery storage. The analysis of the influence of PV module type on system performance was carried out by comparing five different scenarios consisting of combinations of polycrystalline and monocrystalline PV modules. Table 2 presents the five alternative scenarios of polycrystalline and monocrystalline PV module combinations. Apart from the PV module type composition, which was varied across the five scenarios, all other input variables used in the PVsyst simulation were assumed to remain constant. Several of these fixed variables are presented in Table 3.

Scenario	Number of Modules	
	Monocrystalline	Monocrystalline
100:0	200	0
75:25	150	50
50:50	100	100
25:75	50	150
0:100	0	200

Table 2. Combination Scenarios of Polycrystalline and Monocrystalline PV Modules

Variable	Description
Location	-3.44484, 104.24336
Tilt angle	5°
Azimuth	0°
Weather data	Meteonorm 8.0
PV module brand	JA Solar
— Mono PV type	JAM72-S09-380-PR
— Poly PV type	JAP72-S10-350-SC
Inverter	Huawei Technologies
Self-consumption load (LWBP)	832 kWh/day
Average load	34,7 kW

Table 3. Combination Scenarios of Polycrystalline and Monocrystalline PV Modules

The parameters observed in this analysis include the following:

- Rooftop Area (m^2)

The total available rooftop area is referred to as the potential rooftop area. In rooftop solar PV systems, it is necessary to determine the total surface area occupied by the installed PV modules, since electricity generation is highly dependent on the total PV module area. Therefore, the effective rooftop area for PV installation depends on the dimensions of the PV modules, the spacing between PV module rows, and the area required for operational access and maintenance activities. The spacing between PV module rows can be calculated using the following equation.

$$d = \frac{w \,.\, \sin\beta}{\tan\gamma}$$

d represents the spacing distance between PV module rows, β is the tilt angle of the PV modules, and γ is the solar incidence angle, which can be calculated using the following equation: $\gamma = 90^o - tilt^o - 23{,}45^o$. The value of 23,45° represents the maximum solar declination angle caused by the inclination of the earth's rotational axis relative to its orbital plane [11]

- Energy Output (kWh)

Energy output represents the total AC electrical energy generated by the system per unit of installed PV capacity after accounting for system losses. The energy output of the rooftop solar PV system can be calculated using the following equation:

$$E = \frac{Epv}{Po}$$

E is the energy output (kWh/kWp), $E_{PV}$is the electrical energy generated by the PV modules (kWh), and $P_0$is the installed PV system capacity (kWp). The value of $E_{PV}$is strongly influenced by the efficiency of the PV modules, the total effective PV module area, solar irradiation intensity, and the duration of solar exposure [12].

- Performance Ratio (PR) (%)

The Performance Ratio (PR) is a key efficiency parameter that represents the ratio between the actual system output and the theoretical output based on the received solar irradiation. A higher PR value indicates better photovoltaic system performance [13]. The PR value can be calculated using the following equation:

$$PR = \frac{YF}{YR} \times 100\%$$

PR represents the Performance Ratio (%), $Y_F$is the final yield, and $Y_R$is the reference yield. The reference yield (Y_R) is determined by dividing the total daily solar irradiation received on the tilted module surface by the reference solar irradiance under Standard Test Conditions (STC), which is 1,000 W/m²

- System Losses

PVsyst identifies various sources of system losses, including shading effects, module mismatch, high operating temperature, inverter conversion losses, cable losses, and dirt accumulation on PV modules. Higher system loss values indicate lower rooftop solar PV system performance and reduced operational efficiency.

Economic Analysis

The economic analysis was conducted to evaluate the financial feasibility of the rooftop solar PV system based on investment costs, operational costs, energy production costs, and investment return over the system's operational lifetime. This analysis aims to determine the most economically and financially optimal PV module configuration. The economic parameters evaluated in this study include Capital Expenditure (CAPEX), Operational Expenditure (OPEX), Levelized Cost of Energy (LCOE), Payback Period (PBP), Net Present Value (NPV), and Return on Investment (ROI).

- Technical Assumption

The proposed rooftop solar PV system is designed as an on-grid configuration without battery storage to supply electricity for the operational activities of the Prabumulih Substation during the Off-Peak Load Period (*Luar Waktu Beban Puncak*/LWBP). Historical electricity consumption data indicate that the average energy demand of the operational building over the last six months during the LWBP period was approximately 832 kWh/day, corresponding to an average load of 34,7 kW.

Since the proposed system operates as a grid-connected PV installation without battery storage and the latest regulations issued by the Ministry of Energy and Mineral Resources (*Energi dan Sumber Daya Mineral*/ESDM) do not provide a feed-in tariff mechanism, the PV system capacity should be designed to closely match the actual load profile. This approach is intended to optimize investment efficiency and minimize excess energy generation that cannot be utilized by the facility. Consequently, the electricity generated by the rooftop solar PV system can be consumed directly on-site, maximizing self-consumption and reducing energy curtailment.

- Financial Assumption

The financial assumptions applied in this study include the initial system investment cost, annual operation and maintenance (O&M) expenses, project lifetime, inflation rate, electricity tariff, and discount rate. These assumptions serve as the basis for evaluating the economic feasibility and financial performance of the proposed rooftop solar PV system under different PV module configurations. The financial assumptions are presented in Table 4.

Parameter	Value	Unit	Source
Source of capital	Equity financing (no loan)		–
Project lifetime	20	years	Estimation
Discount rate	10	%/year	[14]
Inflation rate	1	%/year	Estimation
Electricity tariff	1,444.7	IDR/kWh	[15]
Inverter Cost			
- Sun2000-40 kWac	59.798.700	Rp	[16]
- Sun2000-30 kWac	45.498.700	Rp	
- Sun2000-36 kWac	51.348.700	Rp	
- Sun2000-20 kWac	42.898.700	Rp	
- Sun2000-70 kWac	85.000.000	Rp	[17]
PV Module Cost			
- JA Solar monokristalin	3.000.000	Rp	[18]
- JA Solar polykristalin	2.500.000	Rp	[19]
Installation Components			Estimation
- Installation accessories	20.000.000	Rp	
- Combiner box	1.000.000	Rp	
- Wiring	1.000.000	Rp	
Installation Cost			
- Installation per module	50.000	Rp	
- Installation per inverter	1.000.000	Rp	
- Setting system	150000	Rp/day	
Operation and Maintenance (O&M)			
- Personnel salary	6.000.000	Rp/year	
- Spare part repair	10.000.000	Rp/year	
- Maintenance equipment	2.000.000	Rp/year	

Table 4. Financial Assumptions

In addition to the investment feasibility indicators, the economic analysis also evaluates the total energy cost savings achieved through the implementation of the rooftop solar PV system for supplying the operational building's electricity demand. Energy cost savings are calculated based on the amount of electricity generated by the PV system that offsets electricity consumption from the PLN grid. Consequently, the reduction in grid electricity purchases translates directly into operational cost savings. The energy cost savings can be calculated using the following equation:

$$E_{cover}(\%) = \frac{E_{Pv}}{E_{LWBP}} \times 100\%$$

Where: E_{cover} represents the proportion of PLN electricity consumption that can be supplied by the rooftop solar PV system (%), $E_{PV}$is the electrical energy generated by the PV system, and $E_{LWBP}$is the total electricity consumption of the operational building during the Off-Peak Load Period (LWBP).The E_{cover}value indicates the extent to which the rooftop solar PV system can meet the building's electricity demand and reduce dependence on grid-supplied electricity. If the savings are expressed in terms of electricity expenditure, the annual electricity cost savings can be calculated using the following equation:

$$B_{cover}(Rp) = E_{PV} \times tariflistrik$$

Where: B_{cover} represents the electricity cost savings achieved through the utilization of the rooftop solar PV system, while $Tariff_{electricity}$denotes the electricity tariff paid to PLN, expressed in Indonesian Rupiah per kilowatt-hour (IDR/kWh). The value of B_{cover}reflects the reduction in electricity expenditures resulting from the substitution of grid-supplied electricity with electricity generated by the rooftop solar PV system. In this study, the electricity tariff is based on the prevailing non-subsidized PLN tariff applicable to the customer category under consideration.

RESULT AND DISCUSSION

Rooftop Area and Site Conditions

Based on direct field measurements, the operational building of the Prabumulih Substation has a potential rooftop area of 528 m² available for rooftop solar PV installation. The flat concrete roof provides flexibility in determining the optimal orientation and layout of the PV modules. In this study, the PV modules were designed to face north (0°) with a tilt angle of 5°. This orientation was selected according to the geographical location of the building, which is situated south of the equator. For locations in the Southern Hemisphere, north-facing PV modules generally maximize solar energy capture by increasing the duration and intensity of solar irradiation received throughout the year [20]. No surrounding buildings, trees, or other physical obstructions were identified that could cast significant shadows on the rooftop area. The PV modules are expected to receive solar radiation with minimal shading losses, thereby enhancing the overall energy generation potential of the rooftop solar PV system. Figure 3 illustrates the horizon profile of the rooftop site.

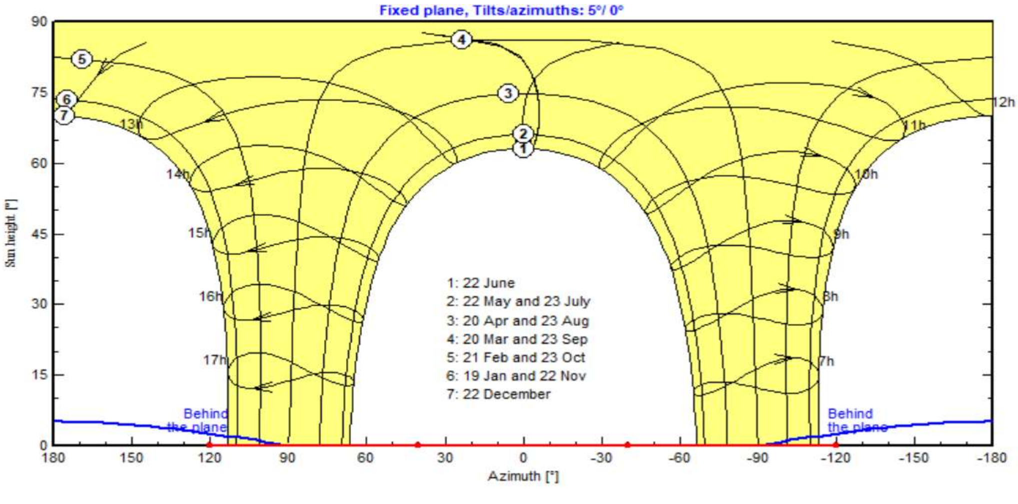

Figure 3. Horizon Line Profile

The yellow area in the horizon diagram represents the solar path that remains unobstructed and accessible to the PV modules throughout the year. This condition indicates that the potential energy losses caused by external shading are negligible, as no significant obstacles or shading sources are present around the rooftop area. To fully utilize this favorable solar exposure, the installation layout of the PV modules must be carefully designed to prevent inter-row shading between adjacent PV module arrays. Adequate spacing between module rows is required to ensure that one row does not cast shadows on another, particularly during periods of low solar elevation angles.Table 5 presents the differences in the required row spacing between monocrystalline and polycrystalline PV modules.

Parameter	Unit	Polycrystalline	Monocrystalline
PV module length	m	2.015	1.979
PV module width	m	0,996	0,996
PV module area	m²	2.007	1.971
Row spacing	m	0,562	0,552

Table 5. PV Module Dimensions and Row Spacing

The results indicate that PV module length influences the required spacing between module rows. The slightly longer polycrystalline modules require a wider inter-row distance than monocrystalline modules to avoid mutual shading. The building has a total usable rooftop area of 528 m², with dimensions of approximately 33 m × 16 m. Based on the selected north-facing orientation, the rooftop can accommodate a maximum arrangement of 16 rows and 13 columns of PV modules. Considering the available rooftop area and the required row spacing, up to 200 PV modules can be installed on the operational building of the Prabumulih Substation. Figure 4 illustrates the detailed layout and maximum allocation of PV modules on the rooftop.

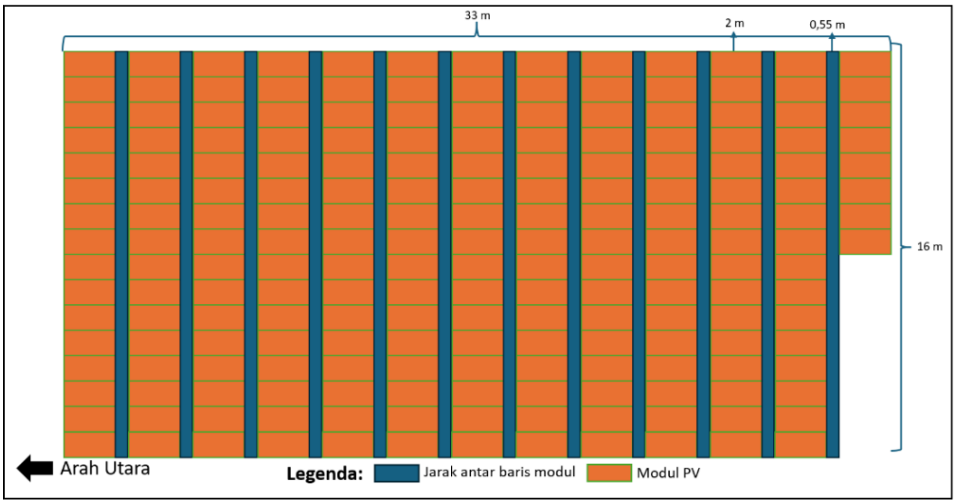

Figure 4. Layout Installation of 200 PV Modules

The spacing between PV module rows serves not only to prevent inter-row shading but also to provide access for operation and maintenance activities. Rooftop solar PV development should consider safety and operational accessibility, particularly when installed on existing buildings, where sufficient space must be allocated for maintenance purposes [21]. After accounting for the required access area, the effective rooftop length available for PV installation is reduced from 33 m to approximately 26,1–26,2 m, resulting in an effective PV installation area of about 417–419 m². This effective area range was used as the basis for subsequent PVsyst simulations. Table 6 presents the effective PV module area for each simulation scenario. The results indicate that scenarios with a higher proportion of polycrystalline modules require a larger installation area due to their larger module dimensions.

Scenario	Potential Rooftop (m²)	Total Row Spacing (m²)	Potential PV Installation (m²)	Effective PV Installation (m²)
Poly:Mono				
100:0	528	107,904	420,096	401
75:25	528	107,424	420,576	400
50:50	528	106,944	421,056	398
25:75	528	106,464	421,536	396
0:100	528	105,984	422,016	394

Table 6. Effective PV Installation Area for Each Simulation Scenario

Energy Production

Simulation results across all scenarios with varying proportions of monocrystalline and polycrystalline PV modules were compared based on the resulting energy output. As presented in Table 7, differences in module composition influence the total electricity generation of the rooftop PV system. The scenario with 100% monocrystalline modules yields the highest energy production, while a gradual decrease in output is observed as the share of polycrystalline modules increases. This trend is consistent with the solar fraction results, which increase with a higher proportion of monocrystalline modules. It indicates that monocrystalline PV technology provides a better contribution in meeting the building's energy demand under the same installation area. The performance ratio across all scenarios remains relatively stable within the range of 73,11–73,87%, indicating consistent system efficiency regardless of module composition. This also suggests that differences in energy output are primarily driven by module efficiency rather than system losses. These results are aligned with Hassaan et al., (2022), who reported that under the same installation area, higher efficiency of monocrystalline modules results in better electricity generation performance compared to polycrystalline modules [22].

Scenario	PV Capacity (kWp)	*Epv* (MWh/year)	Output Energy (kWh/ kWp/year)	Solar Fraction (SF) (%)	Performance Ratio (PR) (%)
Poly:Mono					
100:0	70,0	91,65	1.309	27,89	73,64
75:25	71,5	92,98	1.300	28,13	73,11
50:50	73,0	95,40	1.307	28,52	73,47
25:75	74,5	97,07	1.303	28,81	73,25
0:100	76,0	104,3	1.313	29,88	73,87

Table 7. Rooftop PV System Energy Production Results for Each Simulation Scenario

Energy losses are primarily driven by temperature effects, contributing an average reduction of approximately 10,5% across all scenarios. The next most significant losses are caused by module degradation (7,8%) and mismatch losses (5,4%), which remain relatively consistent across the simulation cases. Table 8 provides a detailed breakdown of the losses for each scenario. Losses associated with module degradation, ohmic wiring, and the IAM (Incidence Angle Modifier) factor are identical across all scenarios. This is due to the assumption of a uniform degradation rate of 4% per year over a 20-year project lifetime, along with a consistent module performance improvement factor of 0,75% applied in all configurations. Ohmic losses are fixed at 1,03% because the same cable type and electrical configuration are used in every scenario. Similarly, IAM losses remain constant at 3,06%, reflecting uniform angular losses due to the incidence angle of solar irradiation on the PV module surface.

Component	Poly;Mono				
	100;0	75;25	50;50	25;75	0;100
IAM Factor Loss	3,06	3,06	3,06	3,06	3,06
Module Degradation Loss	7,8	7,8	7,8	7,8	7,8
PV Loss due to Irradiance	0,68	0,71	0,68	0,65	0,63
PV Loss due to Temperature	10,51	10,56	10,51	10,46	10,42
Module Quality Loss	-0,75	-0,75	-0,75	-0,75	-0,75
Mismatch Loss	5,38	5,47	5,38	5,45	5,26
Ohmic Wiring Loss	1,03	1,03	1,03	1,03	1,03
Inverter Loss	1,68	2,27	1,68	2,27	1,51
Night Consumption	0,05	0,05	0,05	0,05	0,01
Total Losses	29,44	30,2	29,44	30,02	28,97
Performa Ratio (%)	73,64	73,11	73,47	73,25	73,87

Table 8. Detailed System Losses for Each Scenario

Economic Analysis

The economic analysis shows variations in initial capital expenditure (CAPEX) across different PV module composition scenarios. The scenario with a higher proportion of monocrystalline modules requires the largest initial investment, mainly due to the higher unit price of monocrystalline PV modules compared to polycrystalline modules. However, the operational expenditure (OPEX) is identical across all scenarios, amounting to IDR 19.817.103 per year, which includes maintenance costs and routine cleaning labor, with an assumed annual inflation rate of 1%.

The Levelized Cost of Energy (LCOE) ranges between IDR 1.005 and IDR 1.051 per kWh. The scenario with a 25% polycrystalline and 75% monocrystalline composition results in the highest electricity generation cost, while the lowest LCOE is achieved by the 100% polycrystalline scenario. The lower investment cost in the 100% polycrystalline configuration leads to the best economic performance, with a Net Present Value (NPV) exceeding IDR 196 million, a Return on Investment (ROI) of 28,8%, and a payback period of approximately 11 years. Detailed economic comparisons for all scenarios are presented in Table 9.

Parameter	Unit	Poly:Mono				
		100;0	75;25	50;50	25;75	0;100
CAPEX	Rp	682.330.000	726.197.400	753.797.400	776.197.400	782.330.000
OPEX	Rp	19.817.104	19.817.104	19.817.104	19.817.104	19.817.104
LCOE	Rp/kWh	1.005	1.038	1.039	1.051	1.027
Unused energy	MWh/year	85	86	87	88	89
Surplus Energy	MWh/year	7	8	9	10	11
PBP	tahun	11	12	13	13	13
NPV	Rp	196.838.656	164.284.366	152.436.885	137.704.613	148.852.394
ROI	%	29	23	20	18	19

Tabel 9. Economic Feasibility Comparison

These economic outcomes are strongly influenced by the effective utilization of generated energy for building consumption. With an average load demand of 832 kWh/day, the 100% polycrystalline scenario provides the most efficient configuration, indicated by the lowest unused energy of 85 MWh/year and only 7 MWh/year of excess energy. In contrast, the 100% monocrystalline scenario is the least economically efficient due to its higher investment cost and lower effective utilization of generated electricity. In this case, approximately 11% of the generated energy is exported to the PLN grid but cannot be monetized.

The rooftop solar PV system is designed to supply the electricity demand of the Prabumulih Substation's operational building during the Off-Peak Load Period (LWBP), with an energy consumption of 832 kWh/day or equivalent to 303.680 kWh/year. The results indicate that all rooftop PV scenarios are capable of supplying approximately 30–34% of the electricity demand during the LWBP period. Table 10 presents a comparative analysis of energy savings and electricity cost savings across all PV simulation scenarios.

Skenario	Energy Demand (kWh/year)	PV Energy (kWh/year)	Energy Coverage (%)	Cost Savings (Rp/year)
Poly:Mono				
100;0	303.680	91.650	30%	132.406.755
75;25	303.680	92.980	31%	134.328.206
50;50	303.680	95.400	31%	137.824.380
25;75	303.680	97.070	32%	140.237.029
0;100	303.680	104.300	34%	150.682.210

Tabel 10. Energy Savings and Electricity Cost Reduction

The 100% monocrystalline scenario delivers the highest electricity cost savings from the PLN grid due to its superior energy generation capability compared to all other scenarios. This higher energy yield increases the contribution of the rooftop PV system in supplying the building's load demand and results in greater electricity cost reduction. The investment feasibility analysis indicates that the 100% polycrystalline scenario provides the most favorable financial performance, reflected by a faster PBP, higher NPV, and greater ROI compared to the other configurations.

This condition demonstrates that although the 100% monocrystalline configuration achieves the highest energy and cost savings, its higher capital expenditure reduces overall investment attractiveness. In contrast, polycrystalline modules offer a lower upfront investment cost, resulting in a more balanced trade-off between initial investment and long-term economic benefits. Therefore, from a techno-economic perspective, the 100% monocrystalline scenario is superior in terms of energy production performance, while the 100% polycrystalline scenario is more optimal in terms of financial feasibility for rooftop PV investment.

Environmental Analysis

The environmental analysis focuses on the system's capability to substitute electricity supply that is originally generated from fossil-fuel-based power plants, which produce carbon emissions, with renewable electricity from the rooftop solar PV system. As presented in Table 11, the 100% monocrystalline scenario provides the highest contribution to avoided emissions, reaching 1,469 tons of CO_2. The generated emissions across all scenarios remain constant at 118,42 tCO_2, representing emissions associated with PV module manufacturing, installation activities, and system operation. The net carbon savings are calculated as the difference between avoided emissions and generated emissions.

The 100% monocrystalline scenario results in the highest net emission reduction of 1.219.3 tCO_2, while the 100% polycrystalline scenario have the lowest reduction at 1.106.0 tCO_2. These results indicate that higher PV electricity production directly increases the potential for carbon emission reduction, reinforcing the relationship between system performance and environmental benefits.

Scenario	Total Emissions (tCO_2)	Generated emission (tCO_2)	Replaced Emissions (tCO_2)	Net Carbon Savings (tCO_2)
Poly:Mono				
100;0	1106,0	118,42	1344,8	1226,38
75;25	1124,3	118,42	1364,9	1246,48
50;50	1156,7	118,42	1400,5	1282,08
25;75	1179.0	118,42	1425,0	1306,58
0;100	1219,3	118,42	1469,3	1350,88

Table 11. Emission Balance for Each Scenario

CONCLUSION

The proportion of PV module types has a significant influence on the performance of the rooftop solar PV system designed for the Prabumulih Substation. From a technical perspective, increasing the share of monocrystalline modules improves system performance indicators, including higher electricity generation, solar fraction, carbon emission reduction, and electricity cost savings. This is reflected in the simulation results, where the 100% monocrystalline scenario achieves the highest annual energy production of 104,3 MWh/year and the highest cost savings of IDR 150,68 million/year, compared to

91,65 MWh/year and IDR 132.41 million/year in the 100% polycrystalline scenario. This technical advantage is accompanied by higher capital expenditure due to the higher module cost.

In the other hand, although polycrystalline modules exhibit slightly lower energy performance, they demonstrate stronger economic feasibility under a 20-year project lifetime assumption. The 100% polycrystalline scenario achieves the lowest Levelized Cost of Energy (LCOE) of approximately IDR 1.005/kWh, the highest Net Present Value (NPV) exceeding IDR 196 million, a Return on Investment (ROI) of 28.8%, and a payback period of around 11 years. Despite its lower energy yield, the 100% polycrystalline configuration remains the most optimal scenario, as it delivers the most balanced trade-off between technical performance and economic viability for the rooftop solar PV system at the Prabumulih Substation.

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