Optimization of Grid-connected PV System for Renewable Energy Utilization in Railways

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***Abstract* — The high electricity demand at railway stations is still largely supplied by fossil-based PLN power plants so its contributing to resulting in carbon emissions. To support the energy transition towards the 2060 Net Zero Emission target, utilizing renewable energy is a strategic solution, one of which is through on-grid solar power plants (PLTS). This study analyzes the implementation of an on-grid solar power plant (PLTS) at Padalarang Station by determining the optimal PV system size using MATLAB simulations with input from load data, solar radiation potential, and Indonesian regulations. Economic feasibility was assessed through Net Present Value (NPV), Return on Investment (ROI), and Payback Period (PP). Results show that a 25 kWp PV system with a 25 kW inverter yields an NPV of Rp378,029,480, ROI of 117.76%, and a payback period of 24 years, proving the system technically and economically feasible to support emission reduction and reduce electricity costs at the station.**

Keywords: Photovoltaic, On-grid, Railway Station, NPV, Renewable Energy

I. INTRODUCTION

Trains are a widely used mode of transportation due to their efficiency, safety, and large capacity. Train stations require significant electricity for lighting, ticketing systems, passenger information, and supporting facilities. Currently, most stations are still supplied by PLN, which is dominated by fossil-fueled power plants, resulting in carbon emissions and potentially increased operational costs due to rising energy prices.

Population growth and economic activity increase energy demand, resulting in increased dependence on fossil fuels and greenhouse gas emissions. The Indonesian government has targeted a clean energy transition through the use of New and Renewable Energy (NRE) with a Net Zero Emission target of 2060. The use of solar energy is a potential solution, particularly at train stations, which have extensive rooftop areas for solar panel installations.

Several studies have shown that on-grid solar power systems can reduce electricity costs and emissions, but their application in railway infrastructure remains limited. This study aims to determine the optimal size of an on-grid solar power plant at Padalarang Station through MATLAB simulations, taking into account electrical load data, potential solar radiation, and energy regulations. The analysis was conducted using investment feasibility parameters in the form of Return on Investment (ROI) and Payback Period (PP), to support the development of sustainable transportation in Indonesia.

II. LITERATURE REVIEW

A. Photovoltaics (PV)

Photovoltaics (PV) is the process of directly converting solar energy into electricity using semiconductor materials, mainly silicon, based on the photoelectric effect [1][8]. PV cells consist of n-type and p-type semiconductor layers forming a p-n junction that generates an electric field. When photons strike the surface, they excite electrons, producing current flow [9][10]. PV modules are commonly fabricated in three types: monocrystalline, polycrystalline, and thin-film. Monocrystalline panels, made from single-crystal silicon, offer the highest efficiency (>15%), while polycrystalline panels are cheaper but less efficient (~12%). Thin-film panels, produced by layering photovoltaic materials, are the most cost-effective though less efficient [8][11].

B. PV Modeling

The performance of PV modules can be mathematically represented using a one-diode equivalent circuit consisting of a current source, diode, series resistance (Rs), and shunt resistance (Rsh) [12]. The output current can be expressed as:

$$I = I_{ph} - \left[I_{o}\left(exp\frac{V + IR_s}{V_t\, a} - 1\right)\right] - \frac{V + IR_s}{R_{sh}}$$

PV characteristics are described using current-voltage (I–V) and power-voltage (P–V) curves, typically measured under Standard Test Conditions (STC: 1000 W/m², 25°C) [13][14]. The maximum power point (MPP) is defined by the product of VmpV_{mp}Vmp and ImpI_{mp}Imp. Other important parameters include open-circuit voltage (Voc) and short-circuit current (Isc). The output power can be estimated as:

$$P_{out} = V_{oc} \times I_{sc} \times FF$$

where FF is the fill factor, calculated by:

$$FF = \frac{Vmp \ x \ Imp}{Voc \ x \ Isc}$$

The conversion efficiency (η) is determined by the ratio of output to input power [11]:

$$P_{in} = G \times A$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

C. Maximum Power Point Tracking (MPPT)

Since the MPP varies with temperature and irradiation, Maximum Power Point Tracking (MPPT) techniques are applied to ensure PV modules operate at optimal efficiency [11][13][15]. MPPT utilizes algorithms and a DC-DC converter to adjust the duty cycle, forcing the PV system to extract maximum available power [15].

D. Types of PV System

PV modules are interconnected to form a system that is categorized into three configurations, namely off-grid, on-grid, and hybrid [9][10][16][17]. In this study, an on-grid system will be used at Padalarang station. Connected to the grid (On-grid): A PV system that is connected directly to the utility grid through an inverter. Excess energy is exported to the grid, reducing electricity bills. This system does not require batteries.

E. PV Regulation Indonesia

There are significant differences between the Regulation of the Minister of Energy and Mineral Resources No. 49 of 2018 and the Regulation of the Minister of Energy and Mineral Resources No. 2 of 2024. The Regulation of the Minister of Energy and Mineral Resources No. 49 of 2018 provides the regulating the electricity import-export mechanism meanwhile the Regulation of the Minister of Energy and Mineral Resources No. 2 of 2024 removes several regulations such as the removal of the export-import of electrical energy.

F. Investment Feasibility Analysis

a. Net Present Value (NPV)

Net Present Value is the difference between the present value of all cash inflows and cash outflows over a specified period of time [20]. The NPV value can be calculated with the following equation ():

$$NVP = \sum_{t=0}^{n} \left(\frac{C_t}{(1+r)^t} \right) - C_o$$

b. Return on Investment

Return on Investment is an indicator used to measure the profitability of an investment. If the ROI shows negative results, the project will be considered unprofitable [24]. The average ROI for installing rooftop solar panels is 13.73% for commercial [25]. Mathematically, it can be written in the equation:

$$ROI = \frac{Net \ Profit \ from \ Investment}{Initial \ Investment} \times 100\%$$

c. Payback Periode

Payback Period (PP) is a method used to determine the period of time needed to return the value of capital investment in a project [23]. This calculation is expressed in equation ():

$$PP = project \ year - \frac{Initial \ Investment}{Cash \ Saving \ per \ Year}$$

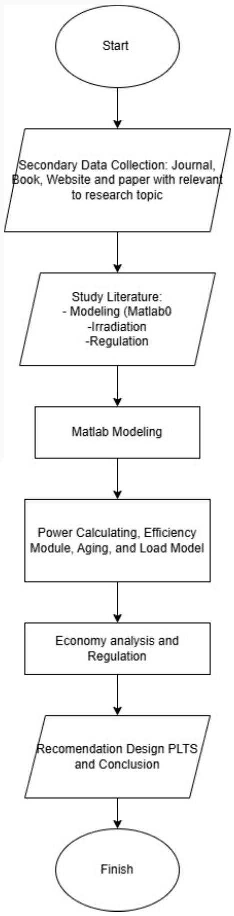
G. Monte Carlo Simulation

Monte Carlo simulation is a statistical technique used to predict outcomes based on probability estimates. This method works by using data distributions that are performed repeatedly using random values to get efficient results [26].This technique is very useful in assessing risk and analyzing uncertainty so as to make the right decision based on existing data.

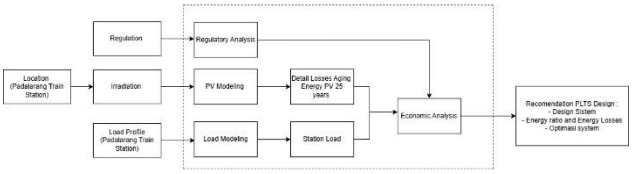
III. SYSTEM DESIGN

A. Design System

This research produces a mathematical modeling of several inputs, processes and outputs which then perform a series of processes. The flow of this research is listed in the figure below.



B. Block Diagram



C. Research Location

The location targeted for this study is Padalarang Station (PDL). Padalrang Station is located in Kertajaya, Padalarang, West Bandung. Geographically, this station is located at 6°50′34.89″ South Latitude and 107°29′50.38″ East Longitude.

D. Software Design

MATLAB (MATrix LABoratory) is a technical computing software developed by MathWorks, designed to support numerical analysis, simulation, and algorithm development. In the context of this research, using MATLAB tools to perform simulation and optimization in obtaining optimal results from an on-grid power generation system, from PLN and Solar PV.

E. Methodology

1. PV Modeling

The PV system was modeled using MATLAB/Simulink based on solar irradiation data obtained from NASA for Padalarang Station. Three models were applied:

a. Power Model, which simulates PV output power under varying irradiance.

b. Efficiency Model, which uses I–V characteristics and the Maximum Power Point Tracking (MPPT) algorithm to optimize performance.

c. Aging Model, which considers module degradation of 0.5% per year over a 25-year lifetime to estimate long-term power output and support economic analysis.

2. Economic Feasibility

Economic assessment was conducted using the Net Present Value (NPV) method to evaluate project profitability over a 25-year operational period. NPV accounts for initial investment, operational costs, and discounted future cash flows. A positive NPV indicates that the project is financially viable.

3. Investment Feasibility

Additional investment indicators analyzed were Return on Investment (ROI) and Payback Period (PP). ROI measures financial benefits relative to investment costs, while PP identifies the time required for cost recovery. A PP shorter than the project lifetime indicates feasibility, whereas a longer PP suggests financial infeasibility.

IV. RESULT AND ANALYSIS

A. Load Profile

Electricity consumption data were collected for one year at hourly intervals (8,760 data points). This data covers all operational needs of the Padalarang Station. The table below shows the electrical load data over a 24-hour period:

Padalarang Station Load Data for 24 hours		
No.	Hours	Load (kW)
1.	1st hour	17.835
2.	2nd hour	22.359
3	3rd hour	20.982
4.	4th hour	21.814
5.	5th hour	20.755
6.	6th hour	20.681
7.	7th hour	16.727
8.	8th hour	17.266
9.	9th hour	16.735
10.	10th hour	15.945
11.	11th hour	15.576
12.	12th hour	15.601
13	13th hour	15.042
14.	14th hour	7.844
15.	15th hour	13.696
16.	16th hour	13.756
17.	17th hour	12.766
18.	18th hour	12.546
19.	19th hour	12.483
20.	20th hour	12.290
21.	21th hour	11.814
22.	22th hour	17.737
23.	23th hour	17.025
24.	24th hour	18.054

The daily average load was 384.34 kWh, with the highest demand of 22.36 kW occurring in the second hour and the lowest of 7.84 kW in the 14th hour. This relatively consistent pattern was used as the station's daily load profile.

B. Solar Irradiation Data

Based on data obtained from NASA (Prediction Of Worldwide Energy Resources, 2021) regarding solar radiation in 2024 at the Padalarang Station in Bandung, which is 4.91 kWh/m2/day. The following are the average monthly solar irradiation values per year at the Padalarang Station:

Month	Solar Radiation (kWh/m^2/bulan)
January	4,63
February	4,86
March	4,52
April	4,86
May	4,75
June	4,54
July	4,97
August	5,54
September	5,69
October	5,81
November	4,67
December	4,11

Solar radiation data is used to process data on the potential for utilizing solar energy to generate solar power at the research site. However, the irradiation data used in this research simulation uses hourly irradiation data for one year.

C. Sensitivity Analysis to Price Variation

Sensitivity analysis was conducted on PV system and inverter price variations within a capacity range of 1–327 kWp and a 25-year project lifetime. In accordance with MEMR Regulation No. 2/2024, excess PV energy cannot be exported to the PLN grid, so the economic value is calculated only from self-consumed electricity. Annual energy degradation of 5% and a discount rate of 5.5% were applied, with savings based on the current PLN tariff of Rp1,444/kWh. Based on simulation results in Matlab, the NPV values for each design variation of on-grid PV system prices and inverter price variations are presented in the following table:

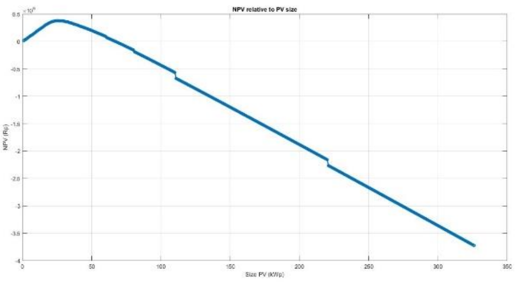
PV System Price per (kW)	Optimal PV Size (kW)	Optimal Inverter Size (kW)	Optimal Inverter Price	NPV
Rp 4.800.000,00	48	50	Rp 57.677.000,00	Rp 597.580.084,62
Rp 12.500.000,00	25	25	Rp 31.620.000,00	Rp 363.008.218,43
Rp 13.000.000,00	25	25	Rp 31.620.000,00	Rp 350.508.218,43
Rp 14.000.000,00	24	25	Rp 31.620.000,00	Rp 325.539.572,72
Rp 14.600.000,00	24	25	Rp 31.620.000,00	Rp 311.139.572,72
Rp 15.500.000,00	23	25	Rp 31.620.000,00	Rp 290.185.586,56

The results show that all scenarios produced positive NPVs, indicating financial feasibility. At the lowest PV price of Rp4.8 million/kWp, the optimal capacity was 48 kWp with an NPV of Rp597.58 million. However, this configuration excluded essential components such as MPPT and mounting. With complete system components, the most feasible option was obtained at Rp12.5 million/kWp, resulting in an optimal capacity of 25 kWp and a positive NPV.

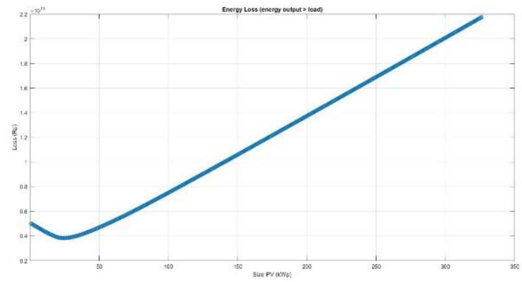
Overall, the analysis indicates that lower PV prices allow for larger installed capacities and higher NPVs, while higher prices reduce the optimal capacity to maintain financial viability. Considering system completeness and investment returns, the PV system cost of Rp12.5 million/kWp is recommended for determining the optimal capacity at Padalarang Station.

D. Optimal PV Size

The optimal PV size is determined when the electricity production per kWp is balanced with the load data. This simulation will use a predetermined system price of IDR 12,500,000. , the simulation results are presented in the graph and table below:



Based on the simulation, in the PV capacity range of 1–25 kWp, the NPV increases significantly along with the growth of PV size. This is because most of the generated energy is effectively utilized to meet the station's electricity demand, while energy losses remain minimal. Consequently, the NPV curve in this range shows a consistent upward trend. In contrast, within the 26–326 kWp range, the NPV begins to decline. Although the project remains feasible up to 67 kWp, further capacity expansion (≥68 kWp) results in negative NPV values. This is due to excessive energy production that exceeds the station's load, leading to a substantial increase in unused energy (energy loss). Hence, despite the technical potential to install up to 327 kWp, an oversized system reduces economic viability. As a result, energy loss increases drastically, as shown in the graph below :

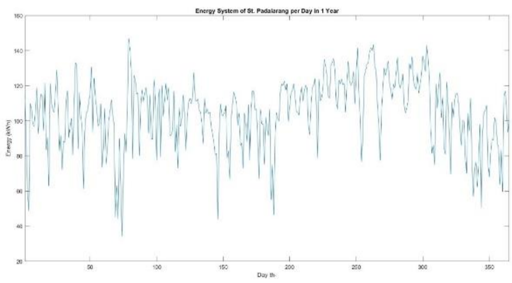


The results indicate that energy loss in the solar PV system increases exponentially once the installed capacity exceeds the optimal point. As illustrated in the analysis, the minimum energy loss occurs at a 25 kW system, with a total loss of 2,654,595 kWh and an average annual waste of 10.62 kWh. In line with the Ministry of Energy and Mineral Resources Regulation No. 2 of 2024, which eliminates the net-metering mechanism for rooftop PV systems, excess electricity can no longer be exported to the PLN grid. Consequently, surplus generation cannot be monetized or utilized, leading to wasted energy and a reduction in the Net Present Value (NPV). This condition implies that oversizing the PV system does not enhance cost savings but instead contributes to greater energy loss due to the mismatch between production and demand.

As shown in the graph, there is an optimal peak point that yields the maximum NPV. This indicates that the system size at this point provides the best balance between electricity generation and load demand, making it the most economically efficient due to the equilibrium between initial investment and energy savings. However, determining the optimal capacity is not solely based on maximum NPV but also considers minimal energy losses. Based on the simulation results, the optimal size for Padalarang Station is 25 kWp, with an NPV of Rp. 378,029,480 and energy losses of 2,654,595 kWh. Thus, the analysis concludes that the system is economically feasible. The optimal PV system requires a 25 kW inverter priced at Rp. 31,620,000. With this configuration, 72 solar panels with a total capacity of 25 kWp (350 Wp each) are needed, covering an installation area of 120.50 m², along with one 25 kW inverter. Since Padalarang Station has sufficient roof space, the solar panels can be feasibly installed.

E. Analysis of Electricity Production at the Padalarang Station

Based on the simulation results using Matlab software for the optimal size of the Padalarang Station PV system, the result is 25 kW. The amount of energy produced each day by solar power plants will vary, as shown in the simulation data below:



The figure above illustrates the daily energy production fluctuations of the PV system throughout the year. PV energy output varies significantly, ranging from 34.28 kWh to a peak of 149.97 kWh. These variations are caused by changes in solar radiation intensity received by the panel modules, which are influenced by weather conditions, seasonal changes, and the position of the sun.

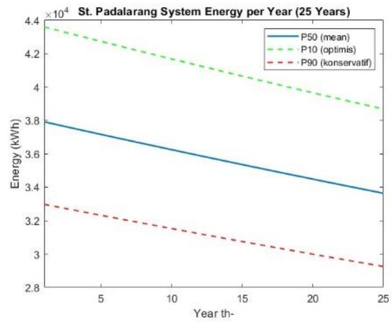
The figure also shows the hourly electricity production over the course of a year, with a total annual generation of 38.10 MWh. On average, the PV system produces 104.39 kWh per day, while the station requires 384.3 kWh per day. This means the PV system is capable of covering 27.16% of the station's energy demand.

Total annual energy production is obtained by summing all daily energy production data based on the simulated PV system capacity. Since this project will last for 25 years, there will be a degradation effect each year. which is calculated using the following exponential formula:

$$E_i = \frac{E_0}{(1+d)^i}$$

Year	Yearly Energy (kWh)
1	37914,87
2	37726,24
3	37538,54
4	37351,79
5	37165,96
6	36981,05
7	36797,07
8	36614,00
9	36431,84
10	36250,58
11	36070,23
12	35890,78
13	35712,22
14	35534,54
15	35357,76
16	35181,85
17	35006,81
18	34832,65
19	34659,35
20	34486,92
21	34315,34
22	34144,62
23	33974,74
24	33805,72
25	33637,53

Thus, from the table above, the total energy that can be produced by a 25 kW PV system over 25 years is 893,38 MWh. The calculation of annual energy production with degradation over 25 years will be presented using the Monte Carlo method, which displays three scenarios (P50, P10, P90).



The figure illustrates the projected annual energy production of a solar power system over 25 years under P10, P50, and P90 scenarios. All curves show a steady decline due to a 0.5% annual degradation rate, resulting in reduced energy output each year. The P50 curve represents the average expected production and serves as the basis for economic feasibility analysis. The P10 curve reflects an optimistic scenario with higher potential output, while the P90 curve shows a pessimistic scenario with lower output. The gap between P10 and P90 highlights the uncertainty in long-term PV energy yield but provides valuable insight for investment risk assessment and decision-making. The 25-year projections yield 1,027,390 kWh (P10), 893,383 kWh (P50), and 776,854 kWh (P90). Among them, the P50 value is considered the most reliable, with a 50% probability and confidence level, as it is neither overly optimistic nor pessimistic.

F. Economic Feasibility Analysis

a. NPV

Year	Biaya Investasi	Cashflow
0	Rp 344.120.000,00	
1		Rp 51.029.171,99
2		Rp 48.368.883,40
3		Rp 45.847.282,84
4		Rp 43.457.140,14
5		Rp 41.191.602,02
6		Rp 39.044.172,53
7		Rp 37.008.694,35
8		Rp 35.079.331,13
9		Rp 33.250.550,84
10		Rp 31.517.109,80
11		Rp 29.874.037,72
12		Rp 28.316.623,43
13		Rp 26.840.401,36
14		Rp 25.441.138,73
15		Rp 24.114.823,44
16		Rp 22.857.652,55
17		Rp 21.666.021,37
18		Rp 20.536.513,15
19		Rp 19.465.889,24
20		Rp 18.451.079,85
21		Rp 17.489.175,21
22		Rp 16.577.417,26
23		Rp 15.713.191,72
24		Rp 14.894.020,59
25		Rp 14.117.555,06
Total cash flow for 25 years		Rp 722.149.479,74
NPV		Rp 378.029.479,74

From the table above, the NPV value is calculated by subtracting the initial investment cost of Rp 344.120.000 from the total present value with cash flow over 25 years. The calculation shows that the NPV of the PLTS system is Rp 378.029.479 which indicates that the NPV value is positive. Therefore, it can be concluded that the PLTS investment is considered profitable and economically viable.

$$NPV = Net\ cash\ flow - Investment\ Cost$$

$$NPV = \text{Rp}. 722.149.479{,}74 - \text{Rp}\ 344.120.000$$

$$NPV = Rp\ 378.029.479{,}74$$

b. ROI

The Return on Investment value is calculated from the NPV of all cash flows over 25 years. In this case, it is very relative. Cash flows have been calculated using the interest rate for each year, so there is no need to recalculate the interest rate, therefore:

$$ROI = \frac{\text{Rp}. 722.149.479{,}74 - \text{Rp}\ 344.120.000}{\text{Rp}\ 344.120.000} x100\%$$

$$ROI = 117{,}76\%$$

c. PP

The Payback Period calculation is used to measure how long it takes for the costs incurred for a project investment to be fully recovered. The Payback Period for a photovoltaic solar power plant is calculated as follows.

$$PP = Time\ Project - \frac{Initial\ Investment}{NPV}$$

$$PP = 25 - \frac{\text{Rp}\ 344.120.000}{\text{Rp}\ 378.029.479{,}74}$$

$$PP = 24{,}12 \approx 24\ Year\ 1\ Month$$

V. CONCLUSION

Based on the research on *Optimizing Grid-Connected PV Systems for Renewable Energy Utilization on Railways*, the following conclusions can be drawn:

1. The study at Padalarang Station employed an On-Grid PV system to support renewable energy utilization in line with government policies on reducing greenhouse gas emissions and achieving carbon neutrality by 2060. This system also provides direct benefits by lowering electricity expenses.

2. Sensitivity analysis of PV system pricing determined that the appropriate cost to be used is Rp 12,500,000, as it offers complete system components while maintaining a relatively high NPV.

3. The optimal system size is 25 kWp with a 25 kW inverter, requiring 72 panels of 350 Wp each and an installation area of 120.50 m². The station's roof area is sufficient to accommodate this system.

4. A 25 kWp system generates 38.10 MWh annually, with a total of 893.38 MWh over the 25-year project lifetime.

5. Investment feasibility analysis shows a positive NPV of IDR 378,029,479.74, an ROI of 117%, and a payback period of 24 years and 1 month, confirming that the project is financially viable but categorized as a long-term investment.

6. Regulatory challenges remain, particularly the abolition of the net metering scheme under ESDM Regulation No. 2/2024, which reduces user benefits and extends the payback period. Despite this, the project remains promising, but supportive government reforms are required to sustain investment attractiveness and meet the 2060 carbon neutrality target.

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