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Design and Fabrication of A 100 Wp Solar-Powered Point Indicator Signal for Railway Depot Maintenance Areas

Ach Muhib Zainuri[1], M. M. Rahul Arrahman[2], Pipit Wahyu Nugroho[3], Pondi Udianto[4], Asrori Asrori[5]

[1,2,3,4,5]Department of Mechanical Engineering, Politeknik Negeri Malang

Jl. Soekarno Hatta No.9, Jatimulyo, Lowokwaru, Malang, Indonesia

ABSTRACT: Conventional signalling in railway depots often relies on grid power, which contributes to resource depletion and operational costs. This study presents the design and fabrication of an autonomous, solar-powered point indicator signal to enhance safety and efficiency in nocturnal depot operations. The methodology encompassed electrical load calculation, mechanical design using AutoCAD, and prototype construction employing a 100 Wp monocrystalline panel, a 12V 200Ah battery, a charge controller, and LED arrays. Field testing at the Malang Locomotive Depot validated the system's performance. Results confirmed the prototype successfully illuminated 6-watt LED signals for 7 nightly hours. The battery depth of discharge (DoD) was maintained at 10.5%, promoting longevity. Peak solar irradiance of 851.3 W/m² ensured consistent energy harvesting. The total unit cost was estimated at IDR 8,156,500. This research demonstrates the technical and economic feasibility of a sustainable, off-grid signalling solution for railway maintenance areas, offering a replicable model for reducing carbon footprint and operational dependency.

KEYWORDS: Solar photovoltaic system, Point indicator signal, Railway Signalling, Off-Grid Power System, Depot Maintenance, Renewable Energy Application

I. INTRODUCTION

The global railway sector, a critical component of transportation infrastructure, faces mounting pressure to enhance operational efficiency while simultaneously reducing its environmental footprint (International Energy Agency [IEA], 2023). Railway depots, where rolling stock undergoes maintenance, inspection, and parking, operate continuously and require reliable systems for safety and coordination. A fundamental element of this infrastructure is the point indicator signal, also known as a switch or turnout signal. This device provides visual cues to ground personnel, indicating the alignment status of railway tracks and authorizing the movement or parking of locomotives in designated areas (Petersen et al., 2019; Samsonkin et al., 2022). Conventionally, these signals are powered by the main electrical grid, leading to ongoing operational costs, dependency on fossil-fuel-based energy, and significant logistical and financial challenges when extending infrastructure to remote or new depot areas (Vukovic et al., 2023). In Indonesia, this reliance on conventional power also contradicts the nation's vast solar energy potential, given its tropical location with high average solar irradiance (MEMR, 2022).

The imperative to transition toward sustainable energy solutions is now central to infrastructure development. Solar photovoltaic (PV) technology presents a compelling alternative, offering a clean, renewable, and increasingly cost-effective source of power. Indonesia's geographical position along the equator affords it abundant solar insolation, averaging 4.8 kWh/m²/day, making it an ideal candidate for widespread solar adoption (Susilo et al., 2022). Despite this potential, the application of solar PV in Indonesia's railway infrastructure remains nascent, often limited to small-scale station amenities rather than integrated into core operational systems like signalling (Yogi & Birla, 2025). This gap represents a significant opportunity for innovation, aligning with national energy transition goals and the global push for greener transportation.

The implementation of solar energy solutions, including streetlights, traffic signals, and railway point indicators, offers substantial benefits in both energy conservation and environmental protection (Gumono et al., 2021; Asrori et al., 2022). Despite the expanding use of solar technology, significant opportunities remain for system optimization, especially within railway depot maintenance zones. In these areas, the energy demands of essential signaling systems, such as point indicators, are frequently underestimated or neglected, with current solar applications often confined to non-critical uses like station lighting. For instance, at the Malang Locomotive Depot, night-time operations including locomotive maneuvering and maintenance depend on clear, reliable visual signals, yet a truly efficient, economical, and sustainable power solution for these tasks remains an ongoing challenge.

A notable research void persists concerning the comprehensive design, hands-on fabrication, and real-world validation of a dedicated, off-grid solar-powered point indicator system capable of meeting the stringent reliability, durability, and safety standards of depot environments. This project seeks to close that gap by progressing from theoretical analysis to the development and testing of a fully functional prototype.

Previous research has explored solar applications in railways. For instance, Poompavai and Kowsalya (2019) designed a solar-powered automated level crossing, demonstrating feasibility for safety-critical systems. Ferrari et al. (2018) analyzed solar-based auxiliary power units for trains. However, these studies often focus on mainline crossings or mobile applications, not on fixed, depot-specific point indicators. A study by Sarker et al. (2020) on solar systems for rural station lighting shares similarities but does not address the specific design, fabrication process, and mechanical integration (like the custom-fabricated hollow steel frame detailed in the report's operation plan) required for a robust depot signal. This project integrates electrical engineering principles with mechanical design and fabrication (evidenced by production routing sheets and machining time calculations), providing a holistic case study that bridges the gap between renewable energy theory and practical, deployable railway infrastructure. The functionality of a railway depot relies heavily on points indicator signal, mechanical installations that enable locomotives to divert from one track to another. These points require clear indicators to inform operators of the track's orientation, especially during low-visibility hours (Vukovic et al., 2023).

Solar technology is highly relevant for this application due to Indonesia's tropical climate, which provides abundant solar radiation throughout the year (Witono et al., 2021; Asrori et al., 2023). The foundational technology for this research is the standalone solar PV system, comprising a panel, charge controller, battery storage, and load. For railway applications, reliability is paramount. Studies emphasize the superiority of monocrystalline silicon panels for such uses due to their higher efficiency and better performance consistency in high-temperature climates, which is crucial for tropical regions like Indonesia (Wijaya et al., 2021).

Therefore, the primary objective of this research is to design and fabricate a 100 Wp solar-powered point indicator signal system for railway depot maintenance areas, with a focus on evaluating its energy output and operational performance. The study aims to develop a reliable and sustainable solution that meets the specific energy needs of signaling systems in these settings. The scope of this research is limited to the use of monocrystalline solar panels with a peak power of 100 Wp, battery storage, and solar charge controllers, specifically for railway depots in Indonesia. The project does not address large-scale implementations or the integration of other railway infrastructure and focuses solely on the design, fabrication, and testing of the solar-powered point indicator system.

II. MATERIALS AND METHODS

2.1 Methods

The research methodology was organized into five sequential phases to facilitate the systematic development of the solar-powered point indicator signal. Initially, a thorough literature review was conducted, gathering data and foundational insights from peer-reviewed journals, technical manuals, and credible industry publications on photovoltaic systems and railway signaling. This review directly informed the subsequent design and calculation phase, during which conceptual designs were created using CAD software. Key electrical parameters, such as daily energy demand, solar panel size, battery capacity, and charge controller specifications, were calculated to ensure the system's reliability. These calculations were then translated into precise working drawings, providing detailed dimensional and assembly specifications for all mechanical and electrical components.

The next phase involved fabrication and assembly, where the structural frame was constructed, and the photovoltaic panel, battery, solar charge controller, and LED array were physically integrated into a functional prototype. Finally, a cost analysis based on individual components was conducted to assess the total production expense and determine the economic feasibility of the project. This organized approach ensured that the prototype was both technically robust and practically suitable for deployment in a railway depot environment.

Furthermore, to ensure the precision of the solar energy harvesting model, the local solar irradiance was quantified using a high-precision SPM-1116SD Solar Power Meter, as shown in Figure 1. This specialized instrument is engineered to measure the intensity of solar radiation in Watts per square meter (W/m^2), providing essential empirical data to determine the Peak Sun Hours (PSH) available at the railway depot site.

Figure 1. Measurement of solar radiation with the SPM-1116SD solar power meter

The SPM-1116SD features a wide spectral response and an integrated data-logging function, which allows for systematic real-time monitoring of variations in light intensity. Technically, the device is equipped with an external sensor probe to minimize interference from the main unit and utilizes a silicon photovoltaic sensor that offers a wide measurement range, typically up to 2000 W/m^2. The data-logging capability, supported by an SD card interface, facilitates the recording of irradiance levels at set intervals (such as every ten minutes), enabling a comprehensive assessment of the site's daily solar potential prior to the fabrication of the point-signal prototype.

A. Preliminary design

The operational principle of the solar-powered railway signal lamp relies on sunlight as the primary source of electrical energy. Incoming solar radiation is captured by the photovoltaic panel, where photons interact with the semiconductor material to generate a Direct-Current (DC) output. This electrical energy is subsequently routed to a Solar Charge Controller (SCC), which regulates the current to prevent battery overcharging (Bhattacharyya et al., 2021; Almaktar et al., 2022; Ballaji & Dash, 2023). During daylight hours, the SCC directs the regulated power to the battery for storage, and once sunlight is no longer available, the battery supplies electricity to the LED signal lamps. When the system functions as intended, the LEDs illuminate to provide the required visual indication. Figure 2 presents the schematic diagram illustrating the configuration of the solar-powered railway signal lamp system.

Figure 2. The schematic diagram of the railway signal lamp using solar panels

B. Basic calculations

In the technical literature, the design of a standalone photovoltaic system for signaling applications requires a proper balance between energy harvesting and consumption to ensure operational reliability. The sizing process begins with determining the daily energy consumption of the load (E_L), measured in watt-hours per day (Wh/day), which is calculated according to Eq. 1 as follows (Masters, 2013),

$$E_L = P_L \times t_L \quad (1)$$

where P_L is the power rating of the LED signal lamps in watts (W) and t_L is the daily operating time in hours (h). To meet this demand, the energy produced by the solar-PV (E_{PV}), also in watt-hours per day (Wh/day), must be estimated using the peak power of the panel (P_{PV}) in watts-peak (Wp), the local Peak Sun Hours (*PSH*) in hours (h), and a dimensionless system efficiency factor (η_{sys}) to account for environmental and electrical losses. The amount of energy produced by solar-PV is shown in Eq.2.

$$E_{PV} = P_{PV} \times PSH \times \eta_{sys} \quad (2)$$

As noted by Masters (2013), the *PSH* value is critical as it simplifies the varying intensity of solar radiation into a usable time constant. Given the critical nature of railway point signals, the battery capacity (C_B), typically expressed in ampere-hours (Ah), must be sized to include "Days of Autonomy" or number of backup days required (D), ensuring the system remains functional during extended periods of low solar irradiance. This capacity is defined by Wenham et al. (2013) through the following relation through the following Eq.3.

$$C_B = \frac{E_L \times D}{DoD \times V_{sys}} \quad (3)$$

In this case, *DoD* represents the maximum depth of discharge (dimensionless), and *Vsys* is the nominal system voltage in volts (V). To determine the suitable charge controller capacity within the distribution assembly, the charging current (*Ic*) in amperes (A) is calculated by dividing the PV peak power by the system voltage, as shown in Eq. 4 (Reddy, 2011).

$$I_c = \frac{P_{PV}}{V_{sys}} \quad (4)$$

These equations together provide the necessary framework for the design and optimization of a solar-powered point indicator signal system, ensuring that it meets technical requirements and operates efficiently in a railway depot environment.

C. Technical configuration of the solar-powered point indicator system

Figure 3 presents a exploded view of a solar-powered point indicator signal system designed for a railway depot maintenance application. The diagram illustrates the spatial arrangement and functional integration of several key components, each of which contributes to the overall system performance and reliability.

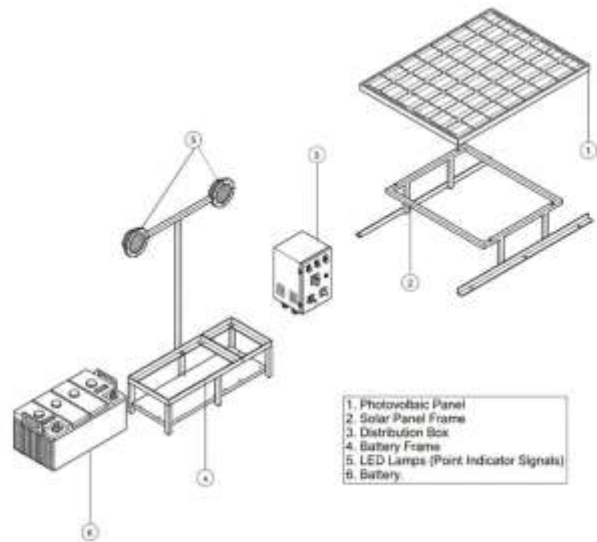

Figure 3. Exploded assembly of the solar-powered point indicator system

At the top of the assembly is the photovoltaic panel (1), which serves as the primary energy source by converting solar radiation into direct current (DC) electricity. The panel is mounted securely on a solar panel frame (2), constructed from corrosion-resistant metal to ensure structural stability and optimal tilt angle for solar capture. Beneath the panel, the distribution box (3) houses the solar charge controller and electrical terminals, regulating the flow of electricity to prevent overcharging and ensure safe energy transfer.

The battery frame (4) supports the energy storage unit and provides mechanical protection against environmental factors. The LED lamps (5), functioning as point indicator signals, are mounted on a horizontal arm and positioned for maximum visibility during depot operations, particularly at night. Finally, the battery (6) stores the electrical energy generated during daylight hours and supplies power to the LED lamps during periods of low solar input.

This configuration reflects a modular and scalable approach to off-grid railway signaling, emphasizing energy efficiency, operational safety, and ease of maintenance. The exploded view aids in understanding the mechanical and electrical relationships among components, which is essential for fabrication, installation, and future system upgrades.

2.2 Materials

The solar-powered railway point indicator signal system was assembled using a combination of electrical and structural components selected for their reliability, efficiency, and suitability for railway depot applications. The primary energy source is a monocrystalline photovoltaic panel rated at 100 Wp, chosen for its high conversion efficiency and durability under tropical conditions. Detailed specifications of the solar panel are presented in Table 1.

Table 1. Technical specifications of solar-PV

Parameters	Value
Type	Monocrystalline
Peak Power (P_{max})	100 W
Current at P_{max} (I_{mp})	5.62 A
Voltage at P_{max} (V_{mp})	17.8 V
Open-Circuit Voltage (V_{oc})	21.8 V
Short-Circuit Current (I_{sc})	6.05 A
Efficiency (E_{FF})	16.93 %
Dimension	910x680x30 mm

To manage the energy flow and protect the storage unit, a Pulse-Width Modulation (PWM) Solar Charge Controller (SCC) was integrated; its critical operational parameters are listed in Table 2.

Table 2. SCC specifications

Parameters	Value
Type	PWM-Kw1210
Battery Voltage	12V/24V
Maximum Charging-Discharging Current	10A
Self Consumption	<10 mA
Operating Temperature	-35 ~ + 60°C
Dimensions	133.5x70x35 mm

The energy storage is handled by a 12V 200Ah sealed lead-acid battery, which provides the necessary backup for nighttime operation, with its specifications detailed in Table 3.

Table 3. Battery specifications

Parameters	Value
Type	Conventional Flooded Lead-Acid
Battery Capacity	12V 200 Ah
Dimensions	505x278x220 mm
Weight	35 Kg

Meanwhile, the structural frame is made of hollow steel profiles that provide the necessary mechanical support and keep the system's weight manageable for installation. The device uses a 12-eye LED strobe light for signal output. This light serves as the primary visual signal for personnel at the locomotive maintenance depot. The LED was chosen for its low power consumption and high luminosity, offering a cost-effective solution for long-term nighttime operation. The use of LED technology ensures the system has sufficient energy for extended periods, even during several consecutive days of low solar radiation. Figure 4 shows the physical configuration of these LED strobes within the signal system.

Figure 4. LED strobe light

III. RESULTS AND DISCUSSION

3.1 Solar irradiance profile at deployment site

The empirical assessment of solar radiation at the railway depot site provides the foundational data necessary to validate the 100 Wp photovoltaic system’s capacity, are visualized in Figure 5. Based on the field measurements conducted using the SPM-1116SD solar power meter, the site exhibits a robust solar profile characterized by high intensity during peak daylight hours. The recorded data, spanning from 09:00 am to 03:00 pm, indicates that solar power reaches its zenith between 11:30 am and 01:30 pm, with values frequently exceeding 800 W/m^2. These results demonstrate that the Malang depot area possesses sufficient solar potential to meet the energy demands of the point-signal lamp, provided that the system efficiency is maintained through the use of high-quality monocrystalline modules.

Figure 5. Temporal distribution of solar irradiance measurements at the project site

The fluctuations in irradiance levels observed in the trend analysis underscore the importance of the integrated energy storage subsystem. Although peak irradiance values were relatively high, periodic decreases in intensity, likely caused by temporary cloud cover, indicated the need for a 200 Ah battery to ensure a stable nighttime signal. When the average hourly solar input was compared to the system's 100 Wp panel capacity, the estimated daily energy yield was sufficient to fully charge the battery before the 10 p.m. operational time. This energy margin provided a significant buffer, even under conditions of continuous unplugging of the 36-watt LED light load during maintenance activities.

The analysis of solar irradiance data indicated that the peak solar hours (PSH) at the study site are highly favorable for off-grid photovoltaic applications. For the railway point indicator signals, the high daytime irradiance enables the Solar Charge Controller (SCC) to operate at optimal charging efficiency, ensuring a reliable energy supply. This consistent energy capture results in a dependable output, with sufficient stored energy to power the 6 Watt LED strobe lights. The core design assumption is that the depot location is well-suited for off-grid solar power applications. It supports the prototype's feasibility in delivering uninterrupted, maintenance-free signaling during nighttime depot operations. Overall, the successful energy harvesting assessment provides strong evidence for the system's technical feasibility.

The technical viability of the solar-powered point indicator signal is established by the synchronization of load requirements with local solar potential. The signaling unit's total operational load consists of six 12-eye LED strobe lamps, each consuming 6 Watts, resulting in a system load of 36 Watts. Given the defined operational time of 10:00 pm to 05:00 am (7 hours), the daily energy consumption is calculated at 252 Wh. When measured against the 2,400 Wh total capacity of the 200 Ah conventional lead-acid battery, the daily depth of discharge (DoD) remains at a conservative ~10.5%. This energy-to-capacity ratio is a deliberate design choice to minimize chemical stress on the battery plates, thereby extending the service life of the energy storage subsystem.

The resulting measured solar profile confirms that the depot location is ideally suited for off-grid deployment, substantiating the prototype's ability to deliver uninterrupted signaling. Furthermore, the configuration provides a robust system autonomy of approximately 6.6 days, guaranteeing operational continuity even during extended periods of low solar radiation. This technical assessment provides empirical evidence of the system's reliability in fulfilling its primary role within the locomotive maintenance environment. The comprehensive comparison between the measured environmental data and the resulting system performance specifications is summarized in Table 4.

Table 4. Comparison of Measured Solar Potential and System Design Specification

Parameter	Observed Field Data / Specification	System Design Requirement
Peak Solar Irradiance	≈840 W/m^2 (at 12:00 am)	Min. >500 W/m^2 for efficient charging
Charging Source	100 Wp Monocrystalline PV	Sufficient for 288 Wh daily recovery
Operational Time	10:00 pm– 05:00 am (7 Hours)	Nighttime maintenance duty cycle
Total Operational Load	36 Watts (6× 6W LED Strobes)	High-visibility triple-strobe array
Total Daily Energy Load	288 Wh / day	Must maintain battery health
Energy Storage Capacity	2,400 Wh (12V 200Ah)	Conventional Flooded Lead-Acid
System Autonomy	≈ 6.6 Days	Reliability during low-sunlight periods

3.2 The result of the installation of a solar-powered railway signal light system

The deployment of the photovoltaic (PV) system at the locomotive maintenance depot is executed through a systematic, multi-phase installation procedure. As illustrated in Figure 6, the process initiates with the selection of a shadow-free mounting location on the facility's rooftop to mitigate the impact of transient obstructions and ensure unobstructed irradiance. This is followed by the on-site assembly of the 100 Wp monocrystalline module and its associated supporting framework, which requires precise synchronization of mounting points to ensure structural alignment. Throughout the installation, rigorous safety and security protocols are maintained to integrate the solar infrastructure within the active railway environment without disrupting ongoing maintenance operations.

The final results of the installation process and the spatial distribution of the equipment are shown in Figure 7. As depicted, the 100 Wp solar panel is strategically mounted at the peak of the depot roof to maximize exposure to solar radiation, which empirical data indicates reaches a peak intensity of 851.3 W/m^2. The signaling subsystem consists of three high-intensity 12-eye LED strobe units (LED-1, LED-2, and LED-3) positioned across the entrance of the maintenance bay to provide clear visual indicators for locomotive maneuvers. To ensure system longevity and ease of maintenance, the 12V 200Ah conventional lead-acid battery is situated at ground level, while the distribution panel box containing the switch control and Solar Charge Controller (SCC) is mounted on a primary support pillar.

Figure 6. Installation of photovoltaic panels on the roof of the railway maintenance depot

Figure 7. Spatial distribution and component configuration of the integrated solar-powered signaling system at the maintenance depot

This systematic installation ensures the mechanical stability of the on-site assembly while optimizing energy harvesting. Measured solar profiles confirm that the depot's location is ideal, generating sufficient daily energy to fully charge the battery under bright sunlight conditions.

Figure 8 presents the results of a signal-point test conducted at a railway maintenance depot, demonstrating operation of a three-point LED strobe system along a designated track segment. The image sequence shows the red and green LED indicators functioning as intended, confirming that the signal lights respond appropriately to control inputs.

The 12-eye LED strobe unit demonstrated high visibility in the depot environment, demonstrating that the LED power load of only 6 W provides sufficient light intensity for nighttime locomotive maneuvering. The dual-color signal capability provides clear visual communication for depot personnel during inspection and maintenance activities. Furthermore, the trial integration of the Solar Charge Controller (SCC) and the 200 Ah battery demonstrated that the stored energy is effectively converted into a reliable visual signal.

Figure 8. Functional test of solar-powered LED point signal indicators at the railway maintenance depot

The field test results confirm successful integration of the solar-powered lighting system within the depot's operational framework and demonstrate that stored energy is sufficient to sustain multi-point signaling under practical nighttime conditions (10:00 pm–5:00 am). Collectively, these findings support the system's reliability and suitability for off-grid railway applications that require energy-efficient, low-maintenance signaling solutions.

3.3 Cost analysis

Table 5 summarizes the market prices of the system components, including the photovoltaic panel, charge controller, LED strobe lights, cables, connectors, and structural supports. The most expensive item is the 200 Ah/12 V conventional flooded lead-acid battery, which serves as the primary energy storage unit. The total material cost is estimated at IDR 6,855,000.

Table 5. Component costs (materials)

No.	Component	Qty.	Unit Price (IDR)	Total Price (IDR)
1	Mono-solar panel 100 Wp	1	1,200,000	1,200,000
2	SCC (10A–20A)	1	150,000	150,000
3	LED strobe light, 6-eye	6	20,000	120,000

4	Solar Cable (PV1-F 4mm²)	7 m	25,000	175,000
5	Panel box (30 × 40cm)	1	200,000	200,000
6	Cable roll (30 m)	1 roll	120,000	120,000
7	MC4 connector socket	1 set	35,000	35,000
8	Electrical plug socket	1	25,000	25,000
9	Battery terminal lug	2 pcs	5,000	10,000
10	Heat Shrink Tubing (4mm)	3 m	10,000	30,000
11	Bolt and nut M8	10 pcs	4,000	40,000
12	Solar panel mounting frame	1	250,000	250,000
13	Astra Premium 200Ah/12V	1	4,500,000	4,500,000
Subtotal materials				6,855,000

Therefore, the economic assessment of this system takes into account material procurement as well as assembly, installation, and design costs. The assembly phase is estimated to require two eight-hour workdays, resulting in labor costs of approximately IDR 560,000. Design and engineering are budgeted at 10% of the combined material and assembly costs, resulting in IDR 741,500. When added to the total material cost of IDR 6,855,000, the overall production cost of the solar-powered point signaling system is estimated at IDR 8,156,500. This cost breakdown clarifies the financial requirements for implementation and demonstrates that this prototype offers a cost-effective solution for railway depot signaling, across materials, labor, and design.

The primary strength of the proposed signaling system is its high operational reliability and energy redundancy, particularly when paired with 100 Wp monocrystalline photovoltaic modules. The system is designed to supply a 36 W load (3 × 12 W LED strobe lights) over a 7-hour nighttime operating window (10:00 pm–5:00 am), corresponding to an energy demand of approximately 252 Wh per cycle. Relative to the 2,400 Wh nominal capacity of the 200 Ah battery storage unit, this requirement limits the daily depth of discharge (DoD) to about 10.5%. Such a low DoD reduces electrochemical and mechanical stress on flooded lead-acid plates, thereby extending service life beyond typical cycle ratings. In addition, the configuration provides an estimated autonomy of approximately 6.6 days, supporting uninterrupted signaling during extended periods of low irradiance or adverse weather conditions that are common in the Malang region.

However, the project also highlights several limitations that define its scope and point to areas for future improvement. The most significant constraint is the high initial capital expenditure, primarily driven by the cost of the 200Ah battery, which represents a substantial investment compared to a grid-tied alternative. Additionally, the reliance on a conventional flooded lead-acid battery introduces a requirement for periodic manual maintenance, including electrolyte level verification and monitoring of the distribution box for proper ventilation to prevent hydrogen gas accumulation. The system's fixed duty cycle also represents an underutilization of energy, as the 100 Wp panel capacity remains idle during the majority of the daylight hours after reaching a full state of charge.

IV. CONCLUSIONS

This study has demonstrated the technical and economic feasibility of a solar-powered indicator signal light system for railway depot applications. The integration of a 100 Wp photovoltaic panel with a 200Ah/12V battery provides sufficient energy storage to reliably power a 36-Watt LED load for seven hours of nocturnal operation (10:00 pm–5:00 am). Performance testing confirmed that the dual-color LED strobe units respond effectively to control inputs, ensuring clear visual communication for depot personnel during inspection and maintenance activities. The cost analysis, which estimated a total production expenditure of IDR 8,156,500, highlights the affordability of the system when compared to conventional grid-dependent signaling solutions.

Beyond its economic viability, the system offers significant advantages, including off-grid independence, reduced maintenance requirements, and enhanced operational safety. However, limitations such as dependence on local solar irradiance and the finite lifespan of conventional batteries must be acknowledged. These constraints suggest opportunities for future improvement, particularly through the adoption of advanced energy storage technologies, smart charge controllers, and hybrid PV–grid configurations to enhance resilience.

Overall, the findings validate the prototype as a reliable, low-maintenance, and energy-efficient solution for railway signaling. The successful implementation underscores the potential of renewable energy integration in railway infrastructure, contributing to sustainable operations and reduced reliance on conventional energy sources.

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