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Case Report Article

Evaluating Economic Feasibility and Environmental Benefits of Solar Cell Systems in the Mining Industry: A Case Study of the Gunung Mergi Quarry Mining Office

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Abstract. The annual electricity consumption at the Gunung Mergi Mining Office, which reaches ±55,000 kWh, incurs significant operational costs, necessitating a more efficient and sustainable energy supply alternative. To address this need, a technical simulation was conducted using Helioscope software to determine the appropriate rooftop solar power system configuration based on the roof conditions and solar radiation potential at the location. An economic analysis was performed using the Payback Period, Net Present Value (NPV), and Profitability Index (PI) methods to assess the feasibility of the investment. The simulation results show that a roof area of 474.41 m² can accommodate 54 solar modules with a capacity of 550 Wp, with an energy production of ap-proximately ±46,000 kWh per year or capable of meeting 84-85% of the office's electricity needs, and has the potential to save IDR 40-46 million per year. The financial analysis resulted in a positive NPV of IDR 20,076,884, an IRR of 1.078, and a Discounted Payback Period of 22.1 years, which is still within the technical lifespan of solar panels. From an environmental perspective, supplying most of the office's electricity from rooftop solar can substantially reduce Scope 2 emissions associated with PLN electricity use, thereby lowering the carbon footprint of non-productive mining facilities. These findings indicate that the implementation of rooftop solar power plants is feasible and supports cost efficiency and the transition to clean energy in the mining sector.

Keywords: Economic Analysis, Helioscope, NPV, IRR, Solar Cell

1. Introduction

The global energy crisis and increasing carbon emissions have accelerated the utilization of renewable energy, with solar power as the primary choice due to its abundant availability, declining investment costs, and low environmental impact (Hosenuzzaman et al. 2015; Singh, 2021). Beyond its economic advantages, solar energy also plays a crucial role in mitigating greenhouse gas emissions, improving local air quality, and reducing the environmental footprint associated with fossil fuel–based power generation (Yu et al., 2022). The more than 80% reduction in solar power costs over the past decade has made solar cell technology increasingly competitive, including for the mining sector, which has high energy needs (IRENA, 2024; Jaane et al. 2024;). From an environmental sustainability perspective, the adoption of solar power in energy-intensive industries such as mining contributes to decarbonization efforts and aligns with global commitments to climate change mitigation. Importantly, this decarbonization pathway is closely correlated with economic efficiency in mining operations: the same solar investment that lowers lifecycle electricity costs also reduces emissions-related risks and liabilities, such as exposure to carbon pricing, tightening environmental regulations, and ESG-driven financing requirements. Thus, improvements in economic feasibility (e.g., lower LCOE, faster payback, and reduced operating expenditures) tend to coincide with improved environmental performance (e.g., lower CO_2 intensity per ton of material produced), creating a reinforcing relationship between cost efficiency and sustainability outcomes (Avinda & Darjat, 2022; Maka et al., 2024; Iturralde Carrera et al., 2025).

Various studies show that the integration of solar power plants can reduce dependence on diesel generators while accelerating return on investment (Babajide & Brito, 2021; Mohamed et al., 2025). This reduction in diesel usage not only lowers operating costs but also significantly decreases carbon emissions, noise pollution, and the risk of fuel spills in mining environments. In this sense, environmental benefits function as economic value drivers: lower emissions and reduced spill risk can translate into fewer compliance costs, lower remediation and insurance expenses, and stronger stakeholder acceptance that helps protect operational continuity (Mirzehi & Afrapoli, 2024). Meanwhile, Benli and Gürtürk (2021) emphasize the importance of the Payback Period and Cost-Benefit Analysis methods in assessing the feasibility of solar energy investments, especially in sectors that operate sustainably and seek to balance economic performance with environmental responsibility. Therefore, incorporating environmental variables, such as avoided CO_2 emissions, reductions in diesel logistics, and potential carbon cost savings, can strengthen the explanatory link between financial indicators (payback and net benefits) and sustainability performance, highlighting that projects with higher economic efficiency often deliver greater environmental gains.

In the context of the Gunung Mergi Quarry Mine, the geographical conditions with high solar radiation intensity provide a great opportunity for the application of solar power plant in office buildings as a strategic step to reduce operational costs and increase energy efficiency. Environmentally, the implementation of solar power plant in non-productive facilities such as office buildings can serve as an effective measure to reduce indirect (Scope 2) emissions associated with electricity consumption in mining operations (Bayu & Windarta, 2021). This reduction in Scope 2 emissions can also improve economic efficiency indirectly by strengthening ESG ratings, supporting access to green financing or sustainability-linked incentives, and reducing reputational and regulatory risks that may otherwise increase long-term operating costs. However, studies related to the economic feasibility of solar power plant in non-productive buildings in mining areas are still limited, especially those that consider shading factors and actual energy needs. Therefore, this study was conducted to analyze the economic feasibility of using solar cells in the Gunung Mergi Quarry Mine office using the Payback Period and Cost-Benefit Analysis methods, supported by Helioscope simulations to determine the optimal panel configuration, assess the impact of shading on system performance, and con-tribute to more sustainable and environmentally responsible decision-making in the mining sector.

2. Method

2.1. Research Type

This research is a descriptive quantitative study with a case study approach, which aims to analyze the economic efficiency of solar cell implementation in the Gunung Mergi Quarry Mine office area through Payback Period and Cost-Benefit Analysis calculations. A quantitative approach was used because this study involved calculating investment values, estimating the electricity production capacity of the solar cell system, estimating savings in PLN electricity costs, and analyzing the comparison between costs and benefits during the system's operational life (. To support the accuracy of energy demand estimates and system design, this study also used the Helioscope application to simulate the number of solar panels required and identify potential shading from the office building's surroundings.

2.2. Research Location

This research was conducted at the Tambang Quarry Gunung Mergi office building, located in Ungaran District, Semarang Regency (Figure 1). This location was chosen because it is one of the active mining areas with operational activities that have a fairly high electricity demand.



Figure 1. Map of the study area

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2.3. Data Collection Methods

This study used a secondary data collection method, namely data obtained from previously published sources relevant to the focus of the study. The types of data collected and their sources are as follows: Data on office electricity demand was obtained from the General Affairs Department of Gunung Mergi Quarry through interviews and PLN billing documentation, which served to determine the monthly and annual electricity consumption as the basis for simulation. Solar energy potential data at the location was acquired using the HelioScope software simulation to calculate the solar irradiation potential at the office building. Furthermore, PV system simulation data were also generated using HelioScope, providing information such as annual energy output, shading losses, and overall system efficiency. In addition, data on the investment cost of the solar cell system were collected from local market estimates through a market study, covering component prices such as solar panels, inverters, mounting structures, and installation costs.

2.4. Helioscope Simulation

Information on solar radiation intensity in Ungaran District was obtained from the Global Solar Atlas database and the results are shown in Figure 2. The average annual solar radiation intensity in Bayung Lencir District was recorded at 828.6 kWh/m². To optimize solar panel performance while minimizing the potential for shadows that reduce efficiency, the Ministry of Energy and Mineral Resources recommends installing modules at a 20° tilt facing north.

System Metrics

Design	PLTS Rooftop Kantor Quarry Mining
Module DC Nameplate	29.70 kW
Inverter AC Nameplate	30.00 kW Load Ratio: 0.99
Annual Production	43.51 MWh
Performance Ratio	80.8%
kWh/kWp	1,464.8
Weather Dataset	TMY, 10km Grid, Meteonorm 8 (meteonorm_v8)
Simulator Version	790938a89d-304d66aefc-44b0cc6ec0-ffb11a48fd

Figure 2. System Metrics

3. Result and Discussion

3.1. Solar Irradiation Data

Information on solar radiation intensity in Ungaran District was obtained from the Global Solar Atlas database and the results are shown in Figure 3. This database provides long-term, satellite-based solar resource data that are widely used to support preliminary feasibility assessments and reduce uncertainty in solar energy planning. The use of reliable solar resource data is also important from an environmental standpoint, as it helps ensure that photovoltaic systems are deployed in locations where renewable energy harvesting is most effective, thereby maximizing environmental benefits. The average annual solar radiation intensity in Bayung Lencir District was recorded at 828.6 kWh/m². This level of solar irradiation indicates a favorable renewable energy potential that can support stable electricity generation throughout the year, particularly for grid-connected photovoltaic systems in non-productive facilities. Consistent solar energy generation contributes to the displacement of fossil fuel–based electricity, leading to reductions in greenhouse gas emissions and air pollutants. To optimize solar panel performance while minimizing the potential for shadows that reduce efficiency, the Ministry of Energy and Mineral Resources recommends installing modules at a 20° tilt facing north. Such an orientation not only enhances annual energy yield but also contributes to more efficient land and material use, which is important from an environmental sustainability perspective. By maximizing energy output per installed panel, the system can reduce the overall number of modules required, thereby lowering material consumption and lifecycle environmental impacts associated with photovoltaic deployment.

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Map data			Per year
Specific photovoltaic power output	PVOUT specific	1297.5	kWh/kWp
Direct normal irradiation	DNI	828.6	kWh/m²
Global horizontal irradiation	GHI	1635.2	kWh/m²
Diffuse horizontal irradiation	DIF	986.2	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1640.9	kWh/m²
Optimum tilt of PV modules	OPTA	20 / 0	°
Air temperature	TEMP	27.0	°C
Terrain elevation	ELE	7	m

Figure 3. Solar Irradiation Data for Ungaran District

3.3. Helioscope Simulation Results

(a) Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,779.6	
	POA Irradiance	1,812.0	1.8%
	Shaded Irradiance	1,756.0	-3.1%
	Irradiance after Reflection	1,703.9	-3.0%
	Irradiance after Soiling	1,669.9	-2.0%
	Total Collector Irradiance	**1,669.8**	**0.0%**
Energy (kWh)	Nameplate	49,600.7	
	Output at Irradiance Levels	49,360.4	-0.5%
	Output at Cell Temperature Derate	46,108.5	-6.6%
	Output after Electrical Mismatch	44,588.7	-3.3%
	Optimal DC Output	44,435.5	-0.3%
	Constrained DC Output	44,435.4	0.0%
	Inverter Output	43,724.4	-1.6%
	Energy to Grid	**43,505.8**	**-0.5%**
Temperature Metrics			
	Avg. Operating Ambient Temp		26.0 °C
	Avg. Operating Cell Temp		35.9 °C
Simulation Metrics			
	Operating Hours		4686
	Solved Hours		4686

(b) Condition Set

Description	Condition Set 1											
Weather Dataset	TMY, 10km Grid, Meteonorm 8 (meteonorm_v8)											
Solar Angle Location	Meteo Lat/Lng											
Transposition Model	Perez Model											
Temperature Model	Sandia Model											
Temperature Model Parameters	Rack Type		a		b		Temperature Delta					
	Fixed Tilt		-3.56		-0.075		3°C					
	Flush Mount		-2.81		-0.0455		0°C					
	East-West		-3.56		-0.075		3°C					
	Carport		-3.56		-0.075		3°C					
Soiling (%)	J	F	M	A	M	J	J	A	S	O	N	D
	2	2	2	2	2	2	2	2	2	2	2	2
Albedo	J	F	M	A	M	J	J	A	S	O	N	D
	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Rear Mismatch Loss	10%				Rear Shading Factor		5%					
Module Transparency	0%											
Irradiation Variance	5%											
Cell Temperature Spread	4° C											
Module Binning Range	-2.5% to 2.5%											
AC System Derate	0.50%											
Module & Component Characterizations	Type	Component					Characterization					Bifacial
	Module	JKM550M-72HL4 (Jinko Solar)					Spec Sheet Characterization, PAN					False
	Inverter	SUN2000-30KTL-M3 (480V) (2022) (Huawei)					Spec Sheet					N/A

Figure 4. (a) Annual Production, (b) Condition Set

Solar radiation data and roof dimensions were entered into the system to run the design simulation. This input approach ensures that the photovoltaic system design reflects actual site conditions, allowing a more realistic estimation of energy output and system performance. With a 40.0 kW inverter, the planning results showed a potential daily electricity production of 29.7 kW. Such a level of electricity generation is sufficient to offset a significant portion of conventional grid electricity consumption, thereby contributing to reductions in carbon emissions associated with fossil fuel–based power generation. Annually, the system is projected to be able to produce approximately 44.51 MWh of energy, with a performance level of 80.8% (Figure 4a). A performance ratio above 80% indicates an efficient system operation and supports the long-term environmental benefits of the installation through consistent clean energy delivery (Figure 4b). The simulation using Helioscope software shows that the annual solar radiation potential at the research site reaches 1,669.8 kWh/m². This design uses 54 solar modules with a capacity of 550 Wp, which together are capable of generating approximately 29.70 kW of power per day (Figure 5). By optimizing the number and capacity of modules, the system minimizes material usage while maximizing energy yield, which is favorable from a lifecycle environmental impact perspective. The system configuration employs Fixed Tilt Racking with a module tilt of 20° and a landscape orientation toward the north, which serves as the basis for determining the layout of the solar panels in the simulation.

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Wiring Zones

Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone	-	18-18	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Field Segment 1	Fixed Tilt	Landscape (Horizontal)	Module: 20°	Module: 12.98°	0.5 m	1x1	54	54	29.70 kW

Figure 5. Writing Zones and Field Segments

3.3.1 Monthly Production

The amount of solar radiation received by a horizontal surface per square meter is known as Global Horizontal Irradiance (GHI), while the Plane of Array (POA) represents the combination of diffuse radiation, direct sunlight, and irradiance falling on the solar module surface. Understanding the relationship between GHI and POA is essential for accurately estimating photovoltaic performance and ensuring that solar energy systems are designed to maximize clean energy capture. From the simulation results in Table 1, the potential electrical energy that can be generated by the system in a year reaches 44,505.7 kWh.

Table 1. Monthly Production

Month	GHI (kWh/m²)	POA (kWh/m²)	Shaded (kWh/m²)	Nameplate (kWh)	Grid (kWh)
January	125.7	113.5	109.9	3077.3	2722.0
February	121.2	114.0	110.3	3101.5	2739.4
March	138.9	137.0	132.8	3745.1	3282.7
April	147.0	155.5	150.8	4268.4	3738.1
May	151.8	170.3	164.7	4669.3	4081.5
June	147.1	170.6	164.7	4679.1	4091.1
July	158.6	182.3	175.9	4998.5	4380.4
August	167.8	182.9	177.6	5040.6	4409.6
September	168.4	170.7	166.3	4706.1	4102.4
October	168.3	159.8	155.2	4372.0	3831.8
November	142.1	128.6	124.7	3501.1	3079.2
Desember	142.8	127.0	123.0	3441.9	3046.5

This level of annual energy production indicates a substantial contribution to renewable electricity supply, which can significantly reduce reliance on fossil fuel–based power sources and associated greenhouse gas emissions. The highest monthly production occurs in August, which is around 4,409.6 kWh, while the lowest output is recorded in January at 2,722 kWh (Table 1). Seasonal variations in energy output reflect changes in solar irradiation patterns and highlight the importance of system design optimization to maintain environmental benefits throughout the year. The peak radiation was also recorded in August with a value of 177.6 kWh/m², before experiencing a decline due to certain factors. Despite these fluctuations, the overall radiation profile supports consistent renewable energy generation with positive implications for long-term emission reduction. The visualization of the system design in the form of 4D solar power planT modeling can be seen in Figure 6.

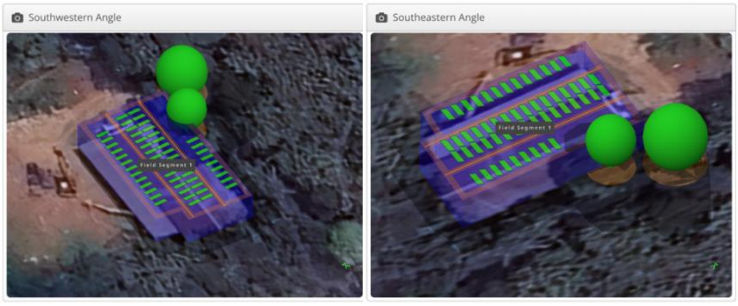

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Figure 6. 4D solar power plant visualization Southwestern Angle and 4D solar power plant visualization South-eastern Angle

Power loss sources in the solar power plant system consist of shading (4.1%), clipping (0%), wiring (0.4%), mismatch (4.4%), temperature loss (6.6%), reflection (4.0%), inverter losses (1.6%), soiling (2.0%), irradiance loss (0.5%), and AC system loss (0.5%) (Figure 7). These loss components illustrate the combined technical and environmental factors that influence photovoltaic system performance, including site conditions, equipment characteristics, and operational cleanliness. These loss values were obtained from Helioscope simulations. Identifying and quantifying each loss source is important not only for improving system efficiency but also for enhancing environmental performance, as reducing energy losses directly increases net renewable electricity generation and maximizes the displacement of fossil fuel–derived energy over the system's lifetime.

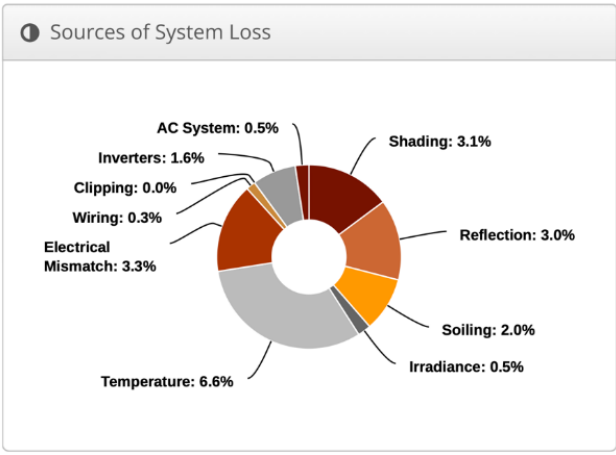
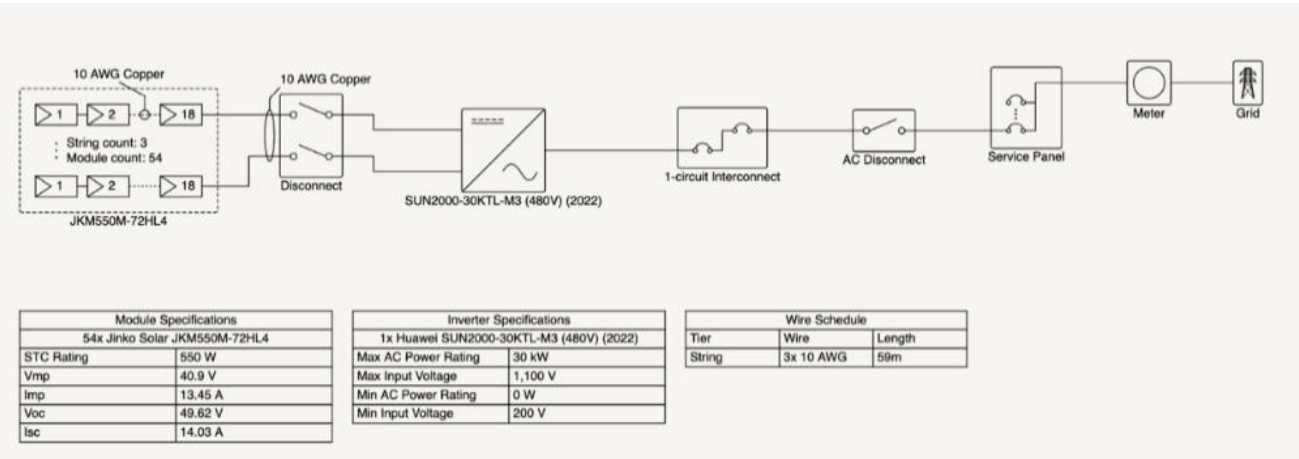


Figure 7. Proportion of Power Losses in solar power plant

3.3.3. Single Line Diagram

The Single Line Diagram in Figure 8 shows the use of the Jinko Solar JKM550M-72HL4 (550 Wp) module with a maximum voltage of 40.9 V and a nominal current of 14.45 A, configured to a Huawei SUN2000-40KTL-M4 inverter with a capacity of 40 kW. This configuration ensures compatibility between the photovoltaic modules and the inverter, enabling efficient energy conversion and stable system operation. The system is equipped with panel box protection, MCCB, and a kWh meter to monitor power export–import. The inclusion of these protection and monitoring components enhances system safety, supports reliable long-term operation, and facilitates accurate tracking of renewable energy generation, which is essential for evaluating environmental benefits such as emission reductions and improved energy management.



Module Specifications	
54x Jinko Solar JKM550M-72HL4	
STC Rating	550 W
Vmp	40.9 V
Imp	13.45 A
Voc	49.62 V
Isc	14.03 A

Inverter Specifications	
1x Huawei SUN2000-30KTL-M3 (480V) (2022)	
Max AC Power Rating	30 kW
Max Input Voltage	1,100 V
Min AC Power Rating	0 W
Min Input Voltage	200 V

Wire Schedule		
Tier	Wire	Length
String	3x 10 AWG	59m

Figure 8. Single Line Diagram of the solar power plant

3.4. Cost Estimate Plan

The total material and component requirements for the rooftop solar power plant include 54 units of Jinko Solar JKM550M-72HL4 photovoltaic modules with a capacity of 550 Wp, amounting to IDR 162,000,000, and one Huawei

SUN2000-40KTL-M4 (480 V) inverter with a capacity of 40 kW, valued at IDR 22,682,686. The system is supported by an aluminum rail mounting structure costing IDR 205,000, along with one panel box unit valued at IDR 4,000,000 and one MCCB unit costing IDR 549. Cable requirements consist of 1,000 meters of DC cable valued at IDR 21,000,000, 40 meters of NYY 4×10 mm² AC cable costing IDR 2,820,000, 10 meters of NYY 4×50 mm² AC cable valued at IDR 4,847,200, 40 meters of NYA 1×16 mm² cable costing IDR 1,050,000, and 100 meters of NYA 4 mm² cable with a total value of IDR 1,485,000. Supporting materials include 400 units of M8×60 mm bolts valued at IDR 425,500 and 200 units of M8×15 mm bolts costing IDR 100,000. Additional components comprise one grounding system set valued at IDR 1,480,000, installation service costs of IDR 4,500,000, Balance of System (BOS) components worth IDR 28,456,000, and certification (SLO) costs of IDR 4,000,000. Overall, the total Bill of Quantities (BoQ) cost for the rooftop solar power plant is IDR 254,447,140.

To ensure long-term system sustainability, annual operation and maintenance (O&M) costs are assumed to be 1% of the initial investment, equivalent to IDR 2,544,471 per year. Assuming a project lifetime of 25 years and using Bank Indonesia's reference interest rate of 4.75% (September 2025), the present value of O&M costs is calculated at IDR 47,149,276. Consequently, the total life cycle cost (LCC) of the rooftop solar power plant amounts to IDR 291,596,416. In the LCC analysis, all project cash flows are converted into equivalent annual values using a capital recovery factor (CRF) of 0.0685. Based on the LCC, annual energy production, and CRF, the cost of energy (COE) is calculated at IDR 459 per kWh.

Cash flow analysis indicates that the solar power plant generates annual revenue of IDR 21,547,450, derived from an electricity production of 44,510 kWh per year at a tariff of IDR 459 per kWh. After accounting for annual O&M costs of IDR 2,544,471, the system yields a stable annual net cash flow of IDR 18,992,979. The financial evaluation is conducted over a 25-year project period using a discount rate of approximately 4.75%. In year 0, the project requires an initial capital investment of IDR 254,447,140. From year 1 to year 25, the annual net cash flows are discounted using discount factors that decline from 0.955 in year 1 to approximately 0.314 in year 25, reflecting the time value of money. The cumulative present value of net cash flow (PVNCF) increases steadily, reaching approximately IDR 276.23 million by the end of the project life.

Based on the financial feasibility analysis, the Net Present Value (NPV) of the project is IDR 20,076,884, indicating that the investment is financially viable (NPV > 0). The total present value of net cash inflows amounts to IDR 274,524,024, resulting in a Profitability Index (PI) of 1.078, which further confirms the feasibility of the rooftop solar power plant investment at the Gunung Mergi Quarry office building. The discounted payback period (DPP) analysis shows that the cumulative PVNCF exceeds the initial investment in the 22.1st year, which is shorter than the 25-year project lifespan. Therefore, the investment is considered profitable, as the capital costs are fully recovered before the end of the system's operational life.

3.5. Environmental Impact of Solar Power Plants on the Gunung Mergi Quarry Office

The environmental impact assessment focuses on comparing carbon emissions from conventional grid electricity supplied by PLN with emissions associated with electricity generated by the rooftop solar power plant. This analysis aims to quantify potential emission reductions resulting from energy source substitution, without addressing environmental impacts related to panel manufacturing or end-of-life management. Based on an inventory of electrical equipment in the Gunung Mergi Quarry office building, the average daily electricity consumption is recorded at 41.84 kWh, equivalent to an annual demand of 15,272 kWh. This value serves as the baseline for estimating carbon emissions from grid electricity and evaluating the potential emission reductions achieved through the implementation of the solar power system.

3.6 Carbon Emissions from PLN Electricity Use

Carbon emissions generated from PLN electricity consumption originate from the dominance of fossil fuel power plants in the national energy mix. The PLN Indonesia electricity emission factor commonly used in energy and environmental studies is 0.85 kg CO_2/kWh (Handayani & Ariyanti, 2012). The amount of annual carbon emissions resulting from PLN electricity usage is 12.981 kg CO_2/Years. Thus, the use of PLN electricity in the Gunung Mergi Quarry office building produces carbon emissions of 12.98 tons of CO_2 per year. In practical reporting terms, this figure can be interpreted as 12,981 kg CO_2/year, which is equivalent to approximately 12.98 tons CO_2/year, and it represents the indirect (Scope 2) emissions burden attributable to grid electricity consumption. Beyond climate impacts, electricity generated from fossil fuels is typically associated with additional air pollutants such as SO_2, NO_x, and particulate matter, which can contribute to acidification, smog formation, and respiratory health risks—meaning that reducing grid electricity demand can also support local and regional air-quality improvements (Zhang, 2024). Unlike fossil fuel-based power plants, solar power systems do not produce carbon emissions during operation because they do not use fuel and do not involve combustion (Bošnjaković et al., 2023; Tawalbeh et al., 2021). Therefore, operational carbon emissions from solar

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power can be assumed to be close to zero (Kakran et al., 2024). However, from a comprehensive environmental perspective, it is also important to acknowledge that solar PV still has life-cycle impacts (e.g., emissions and resource use from material extraction, manufacturing, transportation, and end-of-life processing), even though these impacts are generally much lower per kWh than fossil-based electricity and are concentrated outside the operational phase (Adiansyah et al., 2025). Accordingly, positioning solar power plant as a sustainable solution is strengthened when the project also includes responsible procurement, durability-oriented design, and end-of-life strategies such as module recycling or take-back programs to minimize waste and support a circular economy.

The potential reduction in carbon emissions from the implementation of a solar power system in the mining office building is calculated as the difference between emissions from PLN electricity and emissions from the solar power system, amounting to approximately 12.98 tons of CO_2 per year. This avoided-emissions value can serve as a measurable environmental performance indicator, enabling the company to track decarbonization progress through transparent monitoring, reporting, and verification (MRV) aligned with widely used frameworks such as the GHG Protocol for Scope 2 accounting. In addition to emissions reduction, solar deployment can lower environmental risks commonly associated with fossil energy supply chains—such as fuel transport hazards, combustion by-products, and upstream extraction impacts—thereby strengthening the overall environmental risk management profile of mining operations. In the long term, assuming a technical lifespan of 20 years for the solar power system, the total potential carbon emission reduction that can be achieved reaches 259.6 tons of CO_2. From a sustainable environment standpoint, long-horizon reductions are particularly meaningful because they contribute to cumulative climate benefits, helping to reduce the long-term probability and severity of climate-related disruptions (e.g., extreme weather events, heat stress, and operational interruptions) that can affect both mining productivity and surrounding communities. Moreover, compared with many conventional thermal power sources, solar PV generally requires minimal water during operation, which is relevant for sustainability in regions where water availability and competing land-water needs may become more pressing over time (Frisvold & Marquez, 2014).

This analysis shows that the implementation of solar power in the Gunung Mergi Quarry office building not only provides economic benefits through electricity cost savings, but also contributes significantly to carbon emission reduction, as shown in Table 2. These benefits can be further interpreted as part of a broader sustainable environment strategy, where decarbonizing office electricity demand reduces the site's environmental footprint and supports more responsible resource use without interfering with core production activities. The reduction of nearly 13 tons of CO_2 per year reflects the strategic role of solar power in supporting the transition to clean energy and the application of sustainability principles in the mining sector (Agung & Maharta Yasa, 2021). In practice, such a transition can enhance environmental stewardship by lowering the emissions intensity of supporting facilities, improving the credibility of sustainability reporting, and demonstrating tangible mitigation actions that complement other environmental programs (e.g., land rehabilitation, biodiversity management, and pollution prevention). Additionally, integrating solar power plant can strengthen energy resilience and sustainability by stabilizing electricity supply for administrative functions, which supports continuity of environmental monitoring systems, digital reporting, and safety-related operations that depend on reliable power. From a managerial perspective, these findings reinforce the argument that investing in solar power is worth considering not only based on financial feasibility, but also as part of the company's commitment to environmental management and the implementation of Environmental, Social, and Governance (ESG) principles. Therefore, the solar power plant initiative can be positioned as a multi-benefit sustainability intervention: it reduces Scope 2 emissions, supports cleaner air outcomes through reduced fossil generation demand, encourages responsible life-cycle management of energy infrastructure, and contributes to stronger long-term environmental governance within mining operations.

Table 2. Summary of Environmental Impact

Parameters	Value
Daily energy consumption	41,84 kWh/day
Annual energy consumption	15.272 kWh/year
Emissions from PLN electricity	12.98 ton CO_2/year
Operational emissions from solar power plant	~0 ton CO_2/year
Potential for emission reduction	12.98 ton CO_2/year

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4. Conclusion

Research on the economic efficiency of applying solar cells at the Gunung Mergi Quarry Mining Office shows that the annual electricity demand of approximately ±55,000 kWh results in significant operational costs, which encourages the adoption of more efficient and sustainable energy alternatives. Through technical simulations using Helioscope, it was found that the solar power system designed for a roof area of 474.41 m² is capable of generating approximately ±46,000 kWh of energy per year, or meeting around 84–85% of the office's electricity needs. This level of energy production not only reduces dependence on PLN supply and generator use, but also contributes to a reduction in carbon emissions associated with fossil fuel–based electricity consumption, thereby supporting environmental sustainability in mining operations. From an economic perspective, this energy production capacity has the potential to save Rp40–46 million per year in electricity costs. The economic feasibility analysis supports these findings, as indicated by a positive Net Present Value (NPV) of IDR 20,076,884 and a Profitability Index (PI) of 1.078, which demonstrate that the project provides financial added value. Meanwhile, the Discounted Payback Period (DPP) of 22.1 years remains within the technical lifespan of solar panels, which is approximately 25 years. Although the investment payback period is relatively long, the system implementation is still considered feasible when evaluated from a long-term cost and sustainability perspective. In addition to economic benefits, the application of solar cells enhances energy supply reliability and strengthens the commitment of the mining sector to the clean energy transition and environmental responsibility. By partially substituting conventional electricity with renewable solar energy, the system contributes to long-term greenhouse gas emission reductions and supports the implementation of Environmental, Social, and Governance (ESG) principles. Future research is recommended to expand this analysis by incorporating more detailed technical evaluations, such as system configuration optimization and panel degradation rates, as well as additional financial indicators including Internal Rate of Return (IRR) and Levelized Cost of Energy (LCOE). Moreover, comprehensive environmental impact and social benefit assessments would further strengthen the applicability and relevance of the research findings.

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