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Techno-economic analysis of solar photovoltaic integration as partial substitution of captive coal-fired power in nickel smelters

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Abstract: *The Indonesian nickel processing industry, concentrated in the Morowali (Central Sulawesi) and Obi Island (North Maluku) industrial parks, currently relies on captive coal-fired power plants (PLTU captive) to supply approximately 76% of its electricity demand. This dependency creates a structural barrier to decarbonization and exposes nickel exporters to forthcoming carbon border adjustment mechanisms (CBAM) in major destination markets. This study evaluates the techno-economic feasibility of integrating a 200 MWp ground-mounted photovoltaic (PV) plant coupled with an 80 MWh Battery Energy Storage System (BESS) as a partial substitute for captive coal generation in a representative nickel pyrometallurgical smelter (350,000 ton NPI/year, 132 MW captive load, 1,056 GWh/year electricity demand). The analysis combines solar resource assessment using long-term Global Horizontal Irradiation (GHI) data from the Global Solar Atlas (4.85–4.95 kWh/m²/day for the study locations), Levelized Cost of Energy (LCOE) calculation, and capital budgeting using NPV, IRR and Payback Period. Results show that the proposed configuration generates 279.0 GWh/year (substituting 26.4% of smelter consumption), with a total CAPEX of USD 197.76 million and LCOE of USD 0.0944/kWh (IDR 1,510/kWh). The avoided* CO_2 *emission reaches 237,155 tons/year. Although the project is not feasible under the current Indonesian carbon price (USD 2/ton, NPV negative), feasibility is achieved at carbon prices of USD 50/ton or above (NPV USD 19.84 million, IRR 11.33%) and becomes highly attractive at CBAM-equivalent USD 70/ton (NPV USD 61.34 million, IRR 14.01%, Payback Period 6 years 8 months). Sensitivity analysis identifies carbon price and PV CAPEX as the most influential variables. The study confirms that PV-BESS substitution is a strategically viable decarbonization pathway when supported by carbon pricing reform and ESG-aligned financing.*

Keywords: *Solar PV; Battery Energy Storage System; Captive Coal Power; Nickel Smelter; LCOE; Decarbonization; CBAM*

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INTRODUCTION

Indonesia is the world's largest nickel producer, contributing approximately 55% of the global supply in 2024, supported by laterite nickel reserves of 21 million tons, representing 22% of global reserves (Nuranisa et al., 2023). The implementation of mineral downstream processing policies through Law No. 4 of 2009 has driven massive smelter capacity growth, particularly in two strategic industrial zones: the Indonesia Morowali Industrial Park (IMIP) and the Indonesia Weda Bay Industrial Park (IWIP) in Central Sulawesi and North Maluku, as well as the Harita Group's operations on Obi Island, which focus on High-Pressure Acid Leaching (HPAL) technology for electric vehicle battery materials (Pratiwi & Widodo, 2024).

However, this expansion of the nickel industry has been accompanied by significant environmental consequences. The nickel industry reportedly accounts for approximately 76% of total captive coal-fired power plant (PLTU captive) capacity in Indonesia, where national captive PLTU capacity tripled from 5.5 GW in 2019 to 16.6 GW in 2024, with plans to add 26.7 GW over the subsequent seven years (Reform), 2026). In 2023, the nickel sector was recorded as the largest industrial carbon emitter in Indonesia, contributing approximately 22% of national energy and industrial process emissions, with an emission intensity 7–10 times higher per ton of pure nickel compared to the global average (Wijaya et al., 2024). On Obi Island, the Harita Group's captive PLTU capacity reached 910 MW of the total 1,670 MW planned, while the contribution of renewable energy remained limited to approximately 40 MW of rooftop solar PV (Rahmadina & Hartanto, 2023).

Dependence on coal-fired captive power plants creates three strategic risks for the national nickel industry. First, exposure to the Carbon Border Adjustment Mechanism (CBAM) in the European Union, which will be fully enforced from 2026, with estimated carbon penalties of USD 50–90/ton CO_2 for products with high carbon footprints (Setiawan & Hartono, 2022). Second, pressure from the global electric vehicle supply chain, which increasingly demands low-carbon nickel products to meet Environmental, Social, and Governance (ESG) standards from battery and automotive manufacturers. Third, the risk of stranded assets if domestic carbon prices escalate in accordance with Indonesia's NDC roadmap toward Net Zero Emission 2060 (Pamungkas et al., 2025).

Solar photovoltaic (PV) power generation has emerged as the most commercially and technically mature substitution option. Indonesia has an average Global Horizontal Irradiation (GHI) of 4.3–6.0 kWh/m^2/day, with equatorial areas such as Sulawesi and North Maluku ranging between 4.8–5.2 kWh/m^2/day (Global Solar Atlas, 2024; Silalahi et al., 2021). The steep decline in the global LCOE of solar PV to USD 0.043/kWh in 2024 (Agency), 2025) and the decrease in monocrystalline N-type photovoltaic module prices to the range of USD 0.11–0.13 per Wp in Q4 2025 have made solar substitution of coal-fired power increasingly economically viable. PT Sumber Energi Surya Nusantara commenced construction of a 262 MWp PV + 80 MWh BESS facility in Morowali in September 2025 to supply Nickel Industries' smelters, demonstrating that the technology is already bankable at smelter locations .

Previous research on industrial-scale solar PV in Indonesia has generally focused on commercial or institutional buildings (Yunesti & Wardani, 2025), small-capacity rooftop PV installations for residential use (Gumilang, 2025), or analyses of smart greenhouse applications (Febriani & Rani, 2024). Studies on utility-scale PV such as the Tembesi 40 MWp project (Putra & Prabowo, 2025) and leasing-based rooftop PV (Abhirama & Novasani, 2026) provide valuable technical references; however, no research has specifically examined the integration of PV with BESS as partial substitution of captive coal-fired power in nickel pyrometallurgical smelters with high baseload demand. This research gap becomes increasingly critical given the smelter load characteristics of continuous 24-hour operation with a capacity factor approaching 90%, which requires a PV-BESS hybrid design fundamentally different from PV systems for commercial buildings or residential applications.

Based on the above background, this study aims to: (1) analyze the solar resource potential in Morowali and Obi Island as the basis for utility-scale PV system design; (2) design a PV-BESS system configuration suitable for the load profile of a nickel pyrometallurgical smelter with a capacity of 350,000 tons NPI/year; (3) calculate the LCOE of the PV-BESS configuration and compare it with the existing captive coal-fired LCOE; (4) evaluate the financial feasibility of the project using NPV, IRR, and Payback Period parameters incorporating carbon price and CBAM scenarios; and (5) measure the impact of partial substitution on the cost structure of sustainable nickel production. The findings are expected to serve as a decision-making reference for smelter industry stakeholders and regulators in formulating the decarbonization pathway for the nickel processing sector in Indonesia.

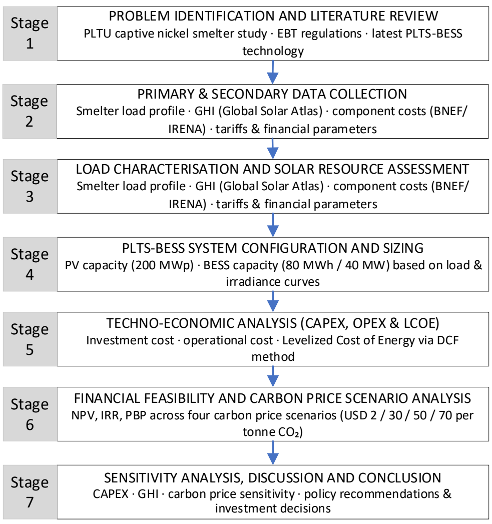
METHOD

Research Object and Location

The research object is a representative nickel pyrometallurgical smelter with a production capacity of 350,000 tons of Nickel Pig Iron (NPI) per year, operating with Rotary Kiln-Electric Furnace (RKEF) technology consisting of four parallel lines, each equipped with a 33 MW electric arc furnace. The case study was designed as a composite smelter profile at two strategic locations: the IMIP Industrial Park, Morowali, Central Sulawesi (coordinates 2°48′ S, 122°08′ E) and the Harita Industrial Park on Obi Island, North Maluku (coordinates 1°30′ S, 127°50′ E). Both locations are major national nickel industry centers with total captive PLTU loads exceeding 5,000 MW.

Research Framework

This study employs a case study approach with a quantitative techno-economic analysis designed through seven systematic stages. The first stage involves the identification of the smelter's electrical load profile, including installed capacity, annual electricity consumption, and operational capacity factor. The second stage conducts a solar resource assessment using long-term GHI data from the Global Solar Atlas (World Bank Group, 2024) for the coordinate points of Morowali and Obi Island. The third stage involves the design of a PV-BESS system configuration with a realistic partial substitution target that accommodates the intermittent characteristics of PV generation and the smelter's baseload requirements. The fourth stage estimates CAPEX and OPEX based on 2024–2025 utility-scale market benchmarks. The fifth stage performs the LCOE calculation using the discounted cash flow method. The sixth stage conducts financial feasibility analysis using NPV, IRR, and Payback Period parameters incorporating carbon price scenarios. The seventh stage comprises a sensitivity analysis of key variables and a discussion of implications for nickel production cost structures.



Source: Author's own elaboration, 2026

Figure 1. Seven-Stage Research Methodology Flow

Research Data

The data used in this study were sourced from: (a) secondary operational data of RKEF smelters from engineering literature from 2021–2026; (b) long-term GHI data from the Global Solar Atlas managed by the World Bank Group and Solargis; (c) pricing data for PV system and BESS components from the IRENA Renewable Power Generation Costs in 2024 report and the BloombergNEF Energy Storage System Cost Survey 2025; (d) industrial electricity tariff data from the Directorate General of Electricity, Ministry of Energy and Mineral Resources (KESDM) for Q3 2025; and (e) commercial specification data for monocrystalline N-type photovoltaic modules rated at 600–700 Wp for 2025–2026. Table 1 presents the operational parameters of the case study smelter and Table 2 presents the solar resource profiles at the study locations.

Table 1. Operational Parameters of the Case Study Smelter

No.	Parameter	Value	Unit
1	NPI production capacity	350,000	tons/year
2	Number of RKEF lines	4	lines
3	Electric furnace power per line	33	MW
4	Total smelter captive load	132	MW
5	Operating hours per year	8,000	hours
6	Smelter capacity factor	91.3	%
7	Annual electricity consumption	1,056	GWh/year
8	Specific consumption per ton NPI	3,017	kWh/ton NPI
9	Captive coal PLTU LCOE	0.060	USD/kWh
10	PLN industrial tariff I-4	996.74	Rp/kWh
11	Coal PLTU grid emission factor	0.85	ton CO_2/MWh

Source: Compiled from IESR (2026), KESDM (2025), Pratiwi & Widodo (2024), Wijaya et al. (2024)

Table 2. Solar Resource Profile at Study Locations

Parameter	Morowali	Obi Island	Unit
Latitude	2°48′ S	1°30′ S	—
Longitude	122°08′ E	127°50′ E	—
Average daily GHI	4.85	4.95	kWh/m²/day
Annual GHI	1,770	1,807	kWh/m²/year
Annual DNI	1,480	1,520	kWh/m²/year
Optimal tilt angle	3°	2°	degrees
PVOUT (specific energy)	1,420	1,450	kWh/kWp
Seasonal GHI variation	±15	±12	%
Average air temperature	27.8	27.2	°C
Annual rainfall	2,150	2,480	mm

Source: Global Solar Atlas (World Bank Group & Solargis, 2024); BMKG Morowali and Ternate Stations (2024)

Table 3. Specifications of Monocrystalline N-type Photovoltaic Modules 2025–2026

Parameter	Typical Value	Premium (TOPCon/HJT)	Unit
Nominal power (Pmax)	600	700–750	Wp
Module efficiency	21.5	23.0–24.5	%
Operating voltage (Vmp)	41.8	44.2	V
Operating current (Imp)	14.35	15.84	A
Temperature coefficient Pmax	−0.34	−0.28	%/°C
Annual linear degradation	0.45	0.28	%/year
25-year output (warranty)	87	92.5	%
FOB price (Q4 2025)	0.11–0.13	0.14–0.17	USD/Wp

Source: Compiled from Trina Solar Vertex N, JA Solar DeepBlue 4.0, Longi Hi-MO 7, Jinko Tiger Neo (2025–2026); SolarTech Online (2025); IRENA (2025)

Mathematical Formulation

The annual electrical energy generated by the PV system is calculated using the specific yield approach, as expressed in Equation (Silalahi et al., 2021; Yunesti & Wardani, 2025) (1):

$$E_{PV} = P_{inst}\ x\ GHI\ x\ PR\ x\ (1-d)^{(t-1)} \qquad (1)$$

where E_{PV} = annual PV electricity generation in year t (kWh/year); P_{inst} = installed PV capacity (kWp); GHI = annual Global Horizontal Irradiation (kWh/m^2/year); PR = Performance Ratio (0.75–0.82 for ground-mounted systems in tropical climates); d = annual module degradation rate (0.005 for N-type); t = year t (Silalahi et al., 2021; Yunesti & Wardani, 2025).

The partial substitution rate (SR) of smelter electricity consumption is calculated using Equation (Silalahi et al., 2021; Yunesti & Wardani, 2025) (2):

$$SR = \left({E_{PV}}/{E_{smelter}}\right)\ x\ 100\% \qquad (2)$$

where SR = substitution rate (%); E_smelter = annual smelter electricity consumption (kWh/year).

The Levelized Cost of Energy (LCOE) is calculated as the ratio of the present value of total project costs over the economic lifetime to the present value of total energy produced, in accordance with Equation (3) (Agency), 2025; Sokolov, 2023):

$$LCOE = \left[I_o + \sum \frac{(OPEX_t + R_t)}{(1+r)^t}\right] / \sum[E_t/(1+r)^t] \qquad (3)$$

where I_0 = initial CAPEX investment (USD); OPEX_t = operational cost in year t (USD); R_t = component replacement cost in year t (primarily BESS in year 12, USD); E_t = energy generated in year t (kWh); r = discount rate (10%); t = year (1–25).

The blended energy cost following PV implementation is calculated using Equation (4):

$$C_{blended} = (1-SR)\ x\ C_{PLTU} + SR\ x\ LCOE_{PV} \qquad (4)$$

where C_blended = weighted average energy cost after substitution (USD/kWh); C_PLTU = existing captive coal PLTU LCOE (USD/kWh).

Annual avoided CO_2 emissions resulting from PV substitution are calculated using Equation (5):

$$CO2_{avoided} = E_{PV}\ x\ EF_{grid} \qquad (5)$$

where $CO2_{avoided}$ = annual emission reduction (ton CO_2/year); EF_{grid} = emission factor of the substituted source grid, 0.85 ton CO_2/MWh for captive coal PLTU in Indonesia (KESDM, 2024).

Annual carbon cost savings, through both domestic carbon trading and CBAM avoidance, are calculated using Equation (6):

$$S_{carbon} = CO2_{avoided}\ x\ P_{carbon} \qquad (6)$$

where S_{carbon} = carbon cost savings (USD/year); P_carbon = carbon price (USD/ton CO_2).

The Net Present Value of the project is calculated using Equation (7):

$$NPV = \sum[CF_t/(1+r)^t] - I_0 \qquad (7)$$

where CF_t = net cash flow in year t, comprising avoided PLTU energy cost savings, carbon cost savings, minus OPEX and BESS replacement cost in year 12 (Sokolov, 2023).

The Internal Rate of Return (IRR) is defined as the discount rate that yields NPV = 0, calculated through Equation (8) using numerical interpolation (Putra & Prabowo, 2025):

$$\sum[CF_t/(1+IRR)^t] - I_0 \qquad (8)$$

The Payback Period with non-uniform cash flows is calculated using Equation (9):

$$PP = a + {(b-c)}/{d} \qquad (9)$$

where a = last year in which cumulative cash flow remains negative; b = initial investment value; c = cumulative cash flow in year a; d = cash flow in year a+1 (Lastina & Alfian, 2022).

Investment Feasibility Criteria

A project is deemed financially feasible when it simultaneously satisfies three criteria: (1) NPV > 0; (2) IRR > MARR set at 10% in accordance with the benchmark interest rate for renewable energy infrastructure projects in Indonesia (Khan et al., 2023); and (3) the PV-BESS LCOE is at a level that provides a blended cost competitive against projected electricity tariffs with carbon internalization. Additionally, a sensitivity analysis of four key variables (PV CAPEX, carbon price, GHI, and benchmark PLTU LCOE) within a ±20% range is conducted to test the robustness of the investment decision.

RESULT AND DISCUSSION

Smelter Electrical Load Characteristics

The case study nickel pyrometallurgical smelter with four RKEF lines operates at a near-constant baseload throughout the year, with a capacity factor of 91.3% (8,000 effective operating hours out of 8,760 total hours). Total annual electricity consumption is 1,056 GWh with a relatively flat load profile between 125–135 MW, except during periodic furnace maintenance shutdowns. At the captive PLTU tariff of USD 0.060/kWh, total annual energy cost prior to PV implementation is USD 63.36 million, representing approximately 13.9% of estimated smelter gross revenue (assuming an NPI price of USD 1,300/ton). The specific electricity consumption per ton of NPI of 3,017 kWh is consistent with RKEF industry benchmarks in the Sulawesi region (Tsukamoto et al., 2023).

Solar Resource Assessment

Data extraction from the Global Solar Atlas (World Bank Group & Solargis, 2024) indicates that both locations possess excellent annual GHI for utility-scale PV, namely 1,770 kWh/m^2/year in Morowali and 1,807 kWh/m^2/year on Obi Island. These values exceed the Indonesian national average of 1,752 kWh/m^2/year (Silalahi et al., 2021). The optimal tilt angle for locations near the equator is nearly zero (2–3°); however, in practical design, a tilt of 10–15° is generally employed for rainwater drainage and maintenance convenience. The PVOUT (Photovoltaic Power Potential) reported by the Global Solar Atlas, namely 1,420 kWh/kWp in Morowali and 1,450 kWh/kWp on Obi Island, already accounts for temperature losses in tropical climates and serves as a conservative reference for energy calculations. For this study, a composite specific yield of 1,395 kWh/kWp/year representing the average condition of both locations with PR = 0.78 is adopted.

PV and BESS System Configuration

The system configuration is designed as a 200 MWp ground-mounted PV plant combined with an 80 MWh / 40 MW BESS (2-hour duration). The capacity selection is based on three considerations: (a) a realistic partial substitution for a high-baseload smelter load profile (target SR ≈ 25–30%); (b) availability of flat land in the industrial zone (estimated land requirement of 3–4 ha per MWp, totaling 600–800 ha for 200 MWp); and (c) BESS sizing sufficient to shift a portion of daytime energy to the high-demand afternoon–evening period without full daily storage (which would disproportionately increase CAPEX). The system employs monocrystalline N-type TOPCon 600 Wp modules (333,333 units), 5 MW central inverters (40 units), and 33/150 kV step-up transformers for connection to the smelter's captive system through a Power Purchase Agreement (PPA). Energy calculations using Equation (1) yield first-year generation of 279.0 GWh, while Equation (2) produces a partial substitution rate of 26.4%.

Table 4. Capital Expenditure (CAPEX) Breakdown for the 200 MWp PV + 80 MWh BESS System

No.	Investment Component	Unit Cost	Total (USD million)	%
1	PV monocrystalline 600 Wp modules (333,333 units)	USD 0.12/Wp	24.00	12.1
2	Central inverters 5 MW (40 units)	USD 0.06/Wac	12.00	6.1
3	Mounting structure & single-axis tracker	USD 0.10/Wp	20.00	10.1
4	Cable, combiner box, BoS DC-AC	USD 0.08/Wp	16.00	8.1
5	Step-up transformer 33/150 kV & switchgear	Lump sum	18.00	9.1
6	Civil works (foundation, roads, fencing)	USD 0.18/Wp	36.00	18.2
7	SCADA, monitoring, security	Lump sum	8.00	4.0
8	EPC fee & engineering design	4% of equipment	8.00	4.0
9	Land acquisition (700 ha)	USD 11,500/ha	8.00	4.0
10	Subtotal PV 200 MWp	—	160.00	80.9
11	BESS LFP 80 MWh	USD 200/kWh	16.00	8.1
12	Power Conversion System BESS (40 MW)	Included in No. 11	—	—
13	Contingency 3%	3% of subtotal	5.76	2.9
	Total CAPEX	—	197.76	100.0

Source: Authors' estimation based on IRENA (2025), BloombergNEF (2025), and Ember Energy (2025) benchmarks

The resulting specific investment cost is USD 197.76 million / 200,000 kW = USD 988/kW of installed PV (excluding BESS), or USD 880/kW for PV components alone. This figure falls within the reasonable range for the Indonesian market in 2025–2026, as reported by IRENA (USD 700–1,000/kW for utility-scale in Southeast Asia). The relatively large share of civil works (18.2%) reflects typical conditions of post-mining or industrial land in the IMIP and Obi Island areas, which require significant grading and site preparation.

Table 5. Annual Operation and Maintenance Expenditure (OPEX) Breakdown

No.	Cost Component	USD/year	% of CAPEX
1	PV O&M (cleaning, inspection, repair)	1,920,000	0.97
2	BESS O&M (HVAC, cell balancing)	400,000	0.20
3	Operations personnel (15 persons)	450,000	0.23
4	Asset insurance	395,000	0.20
5	Land lease & utilities	143,800	0.07
	Total Annual OPEX	3,308,800	1.67

Source: Authors' estimation based on Khan et al. (2023) and IRENA (2025) benchmarks

In addition to routine OPEX, a BESS replacement cost of 50% of the initial BESS value is allocated in year 12 (USD 8 million nominal, USD 2.55 million in present value at r = 10%), assuming an LFP battery cycle life of 4,000–6,000 cycles or approximately 11–13 years at one daily cycle (Ember Energy, 2025).

LCOE Calculation

The LCOE calculation uses Equation (3) with the following parameters: discount rate of 10%, economic lifetime of 25 years, module degradation of 0.5%/year, and BESS replacement in year 12. The present value of total project costs comprises USD 197.76 million CAPEX + USD 30.03 million present value of cumulative OPEX + USD 2.55 million present value of BESS replacement = USD 230.34 million. Total discounted energy produced over 25 years is 2,440.8 GWh (per Equation 1 with degradation). Substituting these values yields:

$$LCOE = USD\ 230.34\ million\ /\ 2{,}440.8\ GWh = USD\ 0.0944/kWh \qquad (3)$$

The LCOE equivalent of IDR 1,510/kWh (at USD 1 = IDR 16,000) is consistent with the LCOE range of utility-scale PV+BESS reported for Indonesia, namely USD 0.063–0.155/kWh for PV with 25%–100% storage capacity (BloombergNEF, 2025). This value is higher than the existing captive coal PLTU LCOE (USD 0.060/kWh) but lower than the PLN industrial tariff I-3 (Rp 1,114.74/kWh ≈ USD 0.070/kWh) when measured without carbon internalization.

Table 6. LCOE Decomposition of the PV-BESS System

Cost Component (Present Value)	Value (USD million)	Contribution (%)
Initial CAPEX (PV + BESS)	197.76	85.9
PV OPEX over 25 years	30.03	13.0
PV BESS replacement (year 12)	2.55	1.1
Total Discounted Cost	230.34	100.0
Total Discounted Energy (GWh)	2,440.8	—
LCOE	USD 0.0944/kWh	IDR 1,510/kWh

Source: Authors' calculations using Equation (3); discount rate r = 10%, n = 25 years

Partial Substitution Analysis and Energy Impact

Based on Equation (4), the blended energy cost after PV-BESS implementation is:

$$C\_blended = (1 - 0.264) \times 0.060 + 0.264 \times 0.0944 = USD\ 0.0691/kWh \qquad ()$$

The 26.4% partial substitution results in an increase of the smelter's average energy cost by USD 0.00908/kWh or 15.1% relative to the existing captive PLTU LCOE. Table 7 presents the comparison of energy costs before and after PV-BESS implementation.

Table 7. Comparison of Smelter Energy Costs Before and After PV Implementation

Indicator	Baseline (100% PLTU)	PV 26.4% + PLTU 73.6%	Difference
Smelter electricity consumption (GWh/year)	1,056	1,056	0
PV contribution (GWh/year)	0	279.0	+279.0
Average energy tariff (USD/kWh)	0.0600	0.0691	+0.0091
Total energy cost (USD million/year)	63.36	72.95	+9.59
Energy cost per ton NPI (USD/ton)	181.03	208.43	+27.40
CO_2 emissions (tons/year)	897,600	660,445	−237,155
Emission intensity per ton NPI (kg CO_2/ton)	2,564	1,887	−677 (−26.4%)

Source: Authors' calculations based on Equations (4) and (5)

These results reveal a critical trade-off: PV substitution directly increases energy costs by USD 9.59 million/year (15.1%), while simultaneously reducing the carbon emission intensity per ton of NPI by 26.4% (from 2,564 kg to 1,887 kg CO_2/ton). This reduction in emission intensity is the key to the project's economic value when carbon pricing is incorporated into the analysis.

Financial Feasibility Analysis with Carbon Price Scenarios

Since PV substitution increases direct energy costs, the financial feasibility of the project is highly dependent on the internalization of the value of avoided carbon. Indonesia has implemented the Indonesia Emission Trading System (IDX-Carbon) since 2023 with an initial price of approximately USD 2/ton CO_2, while the EU CBAM is fully enforced from 2026 with European ETS carbon prices in the range of USD 70–90/ton CO_2. Table 8 presents the NPV, IRR, and Payback Period analysis for four carbon price scenarios representing domestic and export regulatory pathways.

Table 8. Financial Feasibility Analysis under Four Carbon Price Scenarios

Parameter	Scenario A: USD 2/ton (IDX-Carbon)	Scenario B: USD 30/ton (NDC 2030)	Scenario C: USD 50/ton (Carbon Tax)	Scenario D: USD 70/ton (CBAM EU)
Carbon savings (USD million/year)	0.47	7.11	11.86	16.60
Net annual cash flow (USD million)	13.90	20.53	25.28	30.02
NPV (USD million)	−79.74	−21.65	19.84	61.34
IRR (%)	4.07	8.50	11.33	14.01
Payback Period (years)	15.5	9.9	8.0	6.7
Feasibility Status	NOT FEASIBLE	NOT FEASIBLE	FEASIBLE	HIGHLY FEASIBLE

Source: Authors' calculations using Equations (7), (8), and (9); MARR = 10%

The results in Table 8 demonstrate a critical economic relationship between carbon price and PV substitution financial feasibility. At the current Indonesian carbon price (USD 2/ton), the project is not feasible (NPV = −USD 79.74 million, IRR = 4.07%), as carbon savings amount to only USD 0.47 million/year, far below the energy cost differential of USD 9.59 million/year. Under Scenario B (USD 30/ton, in line with the NDC 2030 roadmap), the project does not reach breakeven (NPV = −USD 21.65 million, IRR = 8.50% < MARR 10%). The feasibility threshold is achieved under Scenario C (USD 50/ton) with a positive NPV of USD 19.84 million and IRR of 11.33%, slightly above the 10% MARR. Under Scenario D (USD 70/ton, approximating the European ETS and CBAM prices), the project becomes highly attractive with an NPV of USD 61.34 million, IRR of 14.01%, and Payback Period of 6 years and 8 months.

Impact on Sustainable Nickel Production Cost Structure

For a smelter with a capacity of 350,000 tons NPI/year and an average NPI selling price of USD 1,300/ton (10% Ni content), the energy cost increases from USD 181.03/ton NPI to USD 208.43/ton NPI (an increase of USD 27.40/ton or 15.1%). However, when CBAM exposure is measured at a penalty level of USD 70/ton CO_2, the smelter prior to PV implementation bears an implicit carbon burden of 2,564 ton CO_2/ton NPI × USD 70/ton CO_2 = USD 179.48/ton NPI. With 26.4% substitution, the emission intensity decreases to 1,887 ton CO_2/ton NPI and the implicit carbon burden becomes USD 132.09/ton NPI, yielding carbon exposure savings of USD 47.39/ton NPI. Table 10 presents the energy-carbon cost structure per ton of NPI.

Table 10. Energy and Carbon Cost Structure per Ton of NPI Before and After PV Implementation

Cost Component per Ton NPI	Baseline (USD/ton)	With PV (USD/ton)	Difference (USD/ton)
Direct energy cost	181.03	208.43	+27.40
Implicit carbon burden (P_carbon = USD 30)	76.92	56.61	−20.31
Implicit carbon burden (P_carbon = USD 50)	128.20	94.35	−33.85
Implicit carbon burden (P_carbon = USD 70 / CBAM)	179.48	132.09	−47.39
Total energy+carbon (P_carbon=30)	257.95	265.04	+7.09
Total energy+carbon (P_carbon=50)	309.23	302.78	−6.45
Total energy+carbon (P_carbon=70 / CBAM)	360.51	340.52	−19.99

Source: Authors' calculations based on emission intensities of 2,564 ton CO_2/ton NPI (baseline) and 1,887 ton CO_2/ton NPI (with PV)

Table 10 reveals the key dynamics for sustainable nickel competitiveness: PV-BESS implementation becomes a project that reduces total cost per ton of NPI (energy + carbon) when the carbon price reaches USD 50/ton or above. Under the CBAM scenario of USD 70/ton, a smelter with PV substitution achieves a cost advantage of USD 19.99/ton NPI compared to competing smelters that remain fully dependent on captive coal-fired power. At a production volume of 350,000 tons NPI/year, this equates to a margin advantage of USD 7.00 million/year in markets that fully implement CBAM.

Sensitivity Analysis

To test the robustness of the investment decision, a sensitivity analysis of four key variables is conducted using Scenario C (carbon price USD 50/ton) as the feasibility base case. The variables tested are PV CAPEX, carbon price, annual GHI, and benchmark PLTU LCOE. Table 11 presents the results.

Table 11. Sensitivity Analysis of Key Variables (Base case: Carbon USD 50/ton)

Variable	Change	NPV (USD million)	IRR (%)	PP (years)
Base case (Scenario C)	0%	19.84	11.33	8.0
PV CAPEX decrease	−20%	59.40	14.32	6.4
PV CAPEX increase	+20%	−19.72	8.80	9.8
Carbon price decrease	−20%	−1.71	9.80	9.1
Carbon price increase	+20%	41.38	12.77	7.1
GHI decrease (adverse weather)	−10%	−2.87	9.75	9.3
GHI increase (optimal conditions)	+10%	42.57	12.86	7.1
PLTU LCOE increase (carbon tax)	+15%	38.52	12.55	7.4

Source: Authors' calculations using one-at-a-time analysis

The sensitivity analysis confirms three strategic findings. First, the most influential variables are PV CAPEX and carbon price, with an NPV swing of ±USD 38,52 million for ±20% changes. Second, sensitivity to GHI is relatively low because seasonal variation at equatorial locations is only ±12–

15%, and worst-case conditions (GHI −10%) only shift the project to marginal status (NPV approaching zero, IRR declining to 9.75%). Third, the combination of a 20% CAPEX increase and a 20% carbon price decrease would render the project infeasible; however, the probability of this combination is low, as PV CAPEX trends have consistently declined at 8–11% per year (BloombergNEF, 2025)while global carbon pricing policies have been escalating.

Discussion and Strategic Implications

The findings of this study confirm that PV-BESS integration as partial substitution of captive coal-fired power at nickel smelters in Morowali and Obi Island is not financially feasible under current Indonesian carbon prices but becomes highly viable when CBAM exposure and/or domestic carbon price increases are factored in. These findings are consistent with (Wijaya et al., 2024), who found that the decarbonization pathway for the Indonesian nickel industry is uneconomical without carbon internalization and policy support, as well as (Liu et al., 2022)on the Tembesi 40 MWp PV project, which similarly found that the feasibility of utility-scale PV projects is highly dependent on the negotiated PPA tariff.

Three strategic implications can be drawn from this analysis. First, from a policy perspective, reform of Indonesian carbon pricing is the primary prerequisite for PV adoption in nickel smelters. The IDX-Carbon price at USD 2/ton is too low to trigger energy transition in large industries; gradual escalation toward USD 30–50/ton as projected in the NDC roadmap would unlock PV-BESS investment opportunities at the gigawatt scale. Second, from a business perspective, Indonesian nickel exporters targeting the European Union, South Korea, and Japan—markets that implement carbon adjustment mechanisms—need to proactively prepare CBAM mitigation strategies; PV investment at the 200 MWp scale as analyzed herein can provide a margin advantage of USD 19.99/ton NPI, equivalent to USD 7 million/year under a full CBAM scenario. Third, from a financing perspective, the CAPEX requirement of USD 197.76 million can be accessed through blended finance combining green loans from multilateral development banks, ESG-linked financing from commercial banks, and equity from specialist PV developers such as SESNA Group, which is already active in the IMIP area (Gumilang, 2025)

Compared with similar studies in other sectors, the PV-BESS LCOE of USD 0.0944/kWh for smelters remains higher than the average rooftop PV LCOE for institutional applications (Yunesti & Wardani, 2025) and the floating PV LCOE at Tembesi (Putra & Prabowo, 2025), owing to the substantial BESS requirement for the smelter's baseload profile. However, a combination of fiscal tax incentives (tax holiday under Article 31A of the Income Tax Law, Special Economic Zone facilities), accelerated depreciation, and revenue from green NPI sales at a 5–10% premium in premium markets can bridge this economic gap(Pamungkas et al., 2025)further demonstrated that the combination of PV with waste heat recovery technology can generate a synergy effect for mineral processing industry decarbonization, a pathway that warrants further investigation.

Implementation challenges that must be anticipated include: (a) the availability of 600–800 ha of flat land near industrial zones, which generally border conservation areas or protected forests, thereby requiring stringent spatial planning coordination (Liu et al., 2022); (b) more complex grid stabilization requirements when PV penetration exceeds 25%, making BESS sizing and grid-forming inverters critical; (c) a construction period of 18–24 months requiring cross-disciplinary project management among PV EPC contractors, BESS integrators, and smelter operators; and (d) compliance with Domestic Content Level (TKDN) standards, which mandate a minimum of 40% local components in accordance with Ministry of Energy and Mineral Resources Regulation No. 2/2024 for large-scale PV systems.

This study is subject to several limitations that should be acknowledged when interpreting its findings. First, the analysis is built on a composite smelter profile derived from secondary engineering literature and industry benchmarks rather than site-specific operational data from a single operating RKEF facility; actual hourly load fluctuations, unplanned outages, and site-specific grid constraints may therefore differ from the modeled baseload assumption. Second, the solar resource assessment relies on long-term average GHI and PVOUT values from the Global Solar Atlas, which do not capture inter-annual climate variability or extreme weather events that could affect actual PV yield in a given year. Third, the financial model applies a constant discount rate and discrete carbon price scenarios, whereas real-world project economics would also be exposed to exchange rate fluctuations, inflation, and the pace and design of Indonesia's evolving carbon pricing regulation, which remain inherently uncertain. Fourth, the techno-economic scope does not incorporate a full life cycle assessment (LCA) of the PV-BESS system, so embodied emissions from module and battery manufacturing, transport, and end-of-life disposal are not netted against the operational emission reductions reported here. Fifth, land acquisition, spatial planning, and grid interconnection constraints are discussed qualitatively rather than modeled explicitly, so the CAPEX and implementation timeline may be sensitive to site-specific permitting and community factors not captured in this analysis.

These limitations point to several directions for future research. First, subsequent studies could validate and refine the present model using primary operational data from an actual smelter's supervisory control and data acquisition (SCADA) system, enabling hour-by-hour matching of PV-BESS output against real load profiles. Second, replacing the deterministic ±20% sensitivity analysis with probabilistic techniques such as Monte Carlo simulation would allow the joint uncertainty of CAPEX, carbon price, and GHI to be expressed as a distribution of NPV and IRR outcomes rather than discrete scenarios. Third, integrating a full life cycle assessment would allow the net decarbonization benefit of PV-BESS substitution to be verified on a cradle-to-grave basis, consistent with the LCA agenda highlighted by (Pamungkas et al., 2025) for mineral processing decarbonization. Fourth, extending the model to hybrid PV–BESS–Waste Heat Recovery configurations, and to alternative storage chemistries beyond lithium-ion BESS, could reveal additional cost and reliability synergies for continuous smelter operation. Finally, future work could incorporate spatial and land-use modeling of candidate sites around Morowali and Obi Island to move the qualitative implementation-challenge discussion presented here toward a quantitative site-selection framework

CONCLUSIONS

Based on the techno-economic analysis conducted, six key conclusions can be drawn. First, the nickel smelter locations in Morowali and Obi Island possess excellent solar resources for utility-scale PV, with annual GHI of 1,770–1,807 kWh/m^2/year and PVOUT of 1,420–1,450 kWh/kWp, exceeding the Indonesian national average. Second, a 200 MWp PV + 80 MWh BESS system configuration is capable of generating 279.0 GWh/year, representing a 26.4% partial substitution of the electricity demand of a smelter with a capacity of 350,000 tons NPI/year, while avoiding CO_2 emissions of 237,155 tons/year.

Third, the total investment cost is estimated at USD 197.76 million with annual operating costs of USD 3.31 million, yielding a PV-BESS LCOE of USD 0.0944/kWh (IDR 1,510/kWh). This LCOE is higher than the existing captive coal PLTU LCOE (USD 0.060/kWh) but lower than the PLN industrial tariff I-3. Fourth, the financial feasibility of the project is highly sensitive to carbon pricing: at the current Indonesian carbon price of USD 2/ton, the project is not feasible (NPV –USD 79.74 million); at USD 30/ton, the project remains infeasible (NPV –USD 21.65 million); at USD 50/ton, the project is feasible (NPV USD 19.84 million, IRR 11.33%); and at USD 70/ton in line with CBAM, the project becomes highly attractive (NPV USD 61.34 million, IRR 14.01%, Payback Period 6 years 8 months).

Fifth, from the perspective of sustainable nickel production cost structure, PV substitution reduces carbon emission intensity from 2,564 to 1,887 kg CO_2/ton NPI (a 26.4% reduction); under the CBAM scenario of USD 70/ton, a smelter with PV integration achieves a total cost advantage of USD 19.99/ton NPI compared to competitors that remain fully reliant on captive coal-fired power. Sixth, the sensitivity analysis demonstrates that PV CAPEX and carbon price are the most influential variables on NPV; the trend of declining PV CAPEX at 8–11% per year and escalating global carbon prices support a positive medium-term outlook.

This study recommends four strategic actions: (1) gradual reform of the domestic carbon price toward USD 30–50/ton to unlock PV investment opportunities in nickel smelters; (2) development of a green NPI standard with low-carbon certification to capture export market premiums; (3) blended finance schemes combining green loans, ESG-linked finance, and PV developer equity to fund large-scale CAPEX; and (4) further research on hybrid PV–Waste Heat Recovery–BESS configurations for more comprehensive decarbonization, as well as life cycle assessment (LCA) studies to validate end-to-end sustainability claims.

As this study relies on a composite smelter profile, deterministic sensitivity analysis, and secondary techno-economic data, future research is encouraged to validate these findings against primary operational data from an actual RKEF smelter, to apply probabilistic (Monte Carlo) simulation of carbon price and CAPEX uncertainty, and to extend the analysis through a full life cycle assessment and exploration of hybrid PV–BESS–Waste Heat Recovery configurations for a more comprehensive decarbonization pathway in the nickel processing industry.

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