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Techno-Economic Assessment Using LCOE for a Centralized Solar Power Plant Design at the PLN UIP3B Kalimantan

Agus Tego Santoso[1], Achmad Syamsu Hidayat[2], Kissinger[3], Abdul Ghofur[4]

[1]Natural Resources and Environmental Management Study Program, Lambung Mangkurat University
[2]Fisheries Socio-Economic Study Program, Lambung Mangkurat University
[3]Forestry, Lambung Mangkurat University
[4]Mechanical Engineering Study Program, Lambung Mangkurat University

Corresponding Author: Agus Tego Santoso

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ABSTRACT

The transition toward low-carbon energy systems requires accelerated deployment of renewable generation technologies, including photovoltaic (PV) systems. This study evaluates the techno-economic feasibility of a proposed 809 kWp centralized off-grid solar PV installation for the PLN UIP3B Kalimantan operational facility in Banjarbaru, Indonesia. Annual energy demand was quantified using historical consumption data, resulting in a required annual energy production of 284,323.32 kWh. The economic assessment employed a Life Cycle Cost (LCC) framework, Levelized Cost of Electricity (LCOE), and financial feasibility indicators including Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR). LCOE values ranged between IDR 432.26/kWh and IDR 465.04/kWh across sensitivity scenarios, reflecting O&M cost variation of 1.0–2.0% of total capital cost. The financial assessment produced negative NPV and IRR values below the discount rate when externalities were excluded, indicating that the project is not financially viable under conventional economic assumptions. However, when environmental and public health externalities, quantified using the Social Cost of Carbon and pollution-related health damage coefficients, were integrated into the analysis, NPV and BCR values shifted significantly into viable ranges, demonstrating strong socio-economic feasibility. The findings conclude that while the centralized PV system is not commercially feasible under traditional investment criteria, it becomes economically justified when external benefits are monetized, supporting its deployment as a strategic clean-energy intervention aligned with Indonesia's energy transition and emission-reduction objectives.

Keywords: LCOE, techno-economic analysis, off-grid photovoltaic power plant, externality valuation, Indonesia, renewable energy policy

INTRODUCTION

The global imperative to mitigate anthropogenic climate change and reduce greenhouse gas emissions has accelerated the adoption of renewable energy technologies, particularly solar photovoltaic (PV) systems (Ebhota & Jen, 2020). PV technology has become one of the most widely deployed renewable energy solutions due to its modularity, scalability, declining investment cost, and minimal operational emissions

(Panagoda et al., 2023). Despite such developments, the energy sector in numerous emerging economies remains heavily reliant on fossil fuels. Indonesia, as the largest archipelagic nation, continues to experience structural challenges in its energy transition, where coal-fired power plants account for the majority of power generation capacity (Khaddafi et al., 2025). National policy frameworks, including the National Energy Plan (RUEN) and the Net Zero Emission Roadmap, outline renewable energy penetration targets; however, their implementation remains constrained by investment risks, regulatory uncertainties, and infrastructural limitations.

PLN, as Indonesia's state-owned electricity utility, plays a central role in operationalizing nationwide renewable energy programs and achieving national decarbonization targets (Apriliyanti et al., 2024). One critical facility under PLN's operational hierarchy is UIP3B Kalimantan, which manages transmission networks and real-time load dispatch for the Kalimantan grid system. Given its continuous and strategically important operational loads, the facility represents a suitable candidate for on-site renewable energy generation to reduce long-term operating costs, carbon emissions, and dependency on the interconnected power grid.

Conducting a techno-economic feasibility study for large-scale PV deployment is essential not only to determine energy performance outcomes but also to evaluate cost competitiveness through the Levelized Cost of Electricity (LCOE) metric. LCOE is widely recognized as one of the most comprehensive indicators for techno-economic evaluation, as it incorporates capital investment, operation and maintenance costs, and discounted lifetime energy production over the entire system lifespan (Khan et al., 2025). Several studies have demonstrated that PV systems can achieve economic viability when supported by favorable financing mechanisms, low-interest green loans, or when environmental and social externalities are internalized into economic assessments (Short et al., 1995). However, feasibility outcomes vary significantly depending on system configuration, installed capacity, capacity factor, technology selection, and financial boundary conditions.

In this context, the present study investigates the techno-economic viability of an 809 kWp centralized off-grid PV system for the PLN UIP3B Kalimantan office. The research objectives are threefold: (i) to estimate the potential annual energy output based on regional solar resource availability and system sizing; (ii) to calculate the LCOE of the proposed system using a Life Cycle Cost (LCC) methodology; and (iii) to evaluate financial feasibility using Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit–Cost Ratio (BCR) under both conventional and externality-inclusive scenarios. This study contributes to the existing literature by highlighting the significance of externality valuation in institutional-scale renewable energy investments, particularly within public-sector infrastructure in developing economies.

MATERIALS & METHODS

This study was conducted at the PLN Unit Induk Penyaluran dan Pusat Pengatur Beban (UIP3B) Kalimantan located in Banjarbaru, South Kalimantan, Indonesia. The building operates continuously as a regional supervisory and control facility for the Kalimantan power transmission network, resulting in a relatively constant daily electricity demand. Historical monthly electricity consumption data obtained from utility billing records and internal monitoring systems were evaluated to determine the representative average daily electrical energy requirement.

The annual electrical energy demand was calculated using:

$$P = \frac{E_L}{PGF}$$

Description,

P : equired installed capacity of the solar PV system (kWp)
E_L : annual electrical energy demand/load (kWh)
PGF : photovoltaic generation factor (kWh/kWp/year)

The resulting annual load serves as the basis for determining the required solar photovoltaic (PV) plant capacity to fully supply the building under an off-grid system configuration (Duffie & Beckman, 2013).

The Levelized Cost of Electricity (LCOE) was evaluated using:

$$LCOE = \frac{LCC \times CRF}{A_{kWh}}$$

Description,
$LCOE$: life cycle cost (IDR)
CRF : cost recovery factor (%)
A_{kWh} : annual electrical energy production generated by the PV system (kWh/year).

The LCOE formulation represents a widely adopted approach for techno-economic assessment of renewable energy systems, incorporating capital investment, operating costs, and lifetime energy production into a single economic metric (Haghi, 2024).

NPV was derived as the present value of net annual cash flows minus the project life cycle cost (Boardman et al., 2020):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} - C_0$$

Description,
C_t : net benefit (IDR)
r : discount rate (%)
t : project lifetime or economic useful life (years)

BCR was calculated to compare discounted benefits to discounted costs (Boardman et al., 2020):

$$BCR = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}$$

Description,
r : discount rate (%)
t : project lifetime or economic useful life (years)
B_t : the annual benefit or revenue obtained (year-t)
C_t : the annual cost incurred (year-t)

The Internal Rate of Return (IRR) was employed as a key financial indicator to assess the economic feasibility of the proposed photovoltaic (PV) system investment (Boardman et al., 2020):

$$IRR = r_1 + \frac{NPV_1}{NPV_1 - NPV_2} - (r_2 - r_1)$$

t : project lifetime or economic useful life (years)
NPV : net present value

Tabe l 1. Economic and Technical Input Parameters for Calculation

Parameters	Unit	Value
Total Capital Cost (TCC)	IDR	13,979,754,545
Annual Energy Production (A_{kWh})	kWh/year	284,323.32
Annual Operation & Maintenace Cost (A)	IDR (in 11 sensitivities level)	1% to 2% of TCC
Discount Rate (i)	%	8,7
Project Lifetime (n)	years	15
Cost Recovery Factor (CRF)	%	12,19
Electricity Tariff (PLN Tariff)	IDR	1.444,7
Social Cost Of Carbon (SCC)	IDR	198,17
Public Health Damage Cost	IDR	6.528,00

RESULTS

Annual O&M costs for photovoltaic systems generally range between 1%–2% of the initial capital expenditure (Kaltschmitt et al., 2007). These costs typically include routine inspection, module cleaning, performance monitoring, replacement of minor components, and costs associated with maintaining battery health and inverter reliability (Walker, 2018). Although photovoltaic systems are considered low-maintenance compared to fossil-based power plants, the O&M component remains economically relevant due to long-term system reliability requirements and the presence of energy-storage components such as batteries, which are subject to gradual degradation (Schmidt et al., 2017).

In this study, a sensitivity-based O&M cost estimation approach was applied using incremental cost scenarios ranging from A0 to A10, representing annual O&M expenses corresponding to 1% and gradually increasing up to 2% of total capital investment. The annual O&M cost values utilized as financial input for further life-cycle calculations are shown in Table below.

Table 2. Annual Cost Operation and Maintenance Calculation

A	Value (IDR)
A 0	139.797.545,45
A 1	153.777.300,00
A 2	167.757.054,54
A 3	181.736.809,09
A 4	195.716.563,63
A 5	209.696.318,18
A 6	223.676.072,72
A 7	237.655.827,27
A 8	251.635.581,81
A 9	265.615.336,36
A 10	279.595.090,90

The Levelized Cost of Electricity (LCOE) calculation, as presented in Table 5, Using a Cost Recovery Factor (CRF) of 12.19% and an annual energy yield (AkWh) of 284,323.32 kWh, the calculated LCOE values ranged from IDR 432.26/kWh to IDR 465.04/kWh across ten O&M cost scenarios (A0–A10), integrates total life-cycle costs-including capitan expenditure, O&M expenses, and system performance degradation-against the total electricity generated over the project lifespan. The resulting LCOE values demonstrate a progressive increase under higher sensitivity assumptions, indicating that cost parameters, particularly long-term O&M and replacement costs, significantly influence the unit cost of electricity generation. These results confirm that while capital expenditure dominates the upfront investment, long-term operational factors materially affect overall economic performance.

Table 3. Present Annual Cost Operation and Maintenance Calculation

POM	Value (IDR)
POM 0	1.147.102.041,54
POM 1	1.261.812.245,70
POM 2	1.376.522.449,85
POM 3	1.491.232.654,00
POM 4	1.605.942.858,16
POM 5	1.720.653.062,31
POM 6	1.835.363.266,47
POM 7	1.950.073.470,62
POM 8	2.064.783.674,77
POM 9	2.179.493.878,93
POM 10	2.294.204.083,08

Table 4. Life Cycle Cost Calculation

LCC	Value (IDR)
LCC 0	15.126.856.586,54
LCC 1	15.241.566.790,70
LCC 2	15.356.276.994,85
LCC 3	15.470.987.199,00
LCC 4	15.585.697.403,16
LCC 5	15.700.407.607,31
LCC 6	15.815.117.811,47
LCC 7	15.929.828.015,62
LCC 8	16.044.538.219,77
LCC 9	16.159.248.423,93
LCC 10	16.273.958.628,08

The Levelized Cost of Electricity (LCOE) calculation, as presented in Table 5, Using a Cost Recovery Factor (CRF) of 12.19% and an annual energy yield (AkWh) of 284,323.32 kWh, the calculated LCOE values ranged from IDR 432.26/kWh to IDR 465.04/kWh across ten O&M cost scenarios (A0–A10), integrates total life-cycle costs-including capitan expenditure, O&M

expenses, and system performance degradation-against the total electricity generated over the project lifespan. The resulting LCOE values demonstrate a progressive increase under higher sensitivity assumptions, indicating that cost parameters, particularly long-term O&M and replacement costs, significantly influence the unit cost of electricity generation. These results confirm that while capital expenditure dominates the upfront investment, long-term operational factors materially affect overall economic performance.

Table 5. Leveraged Cost of Electricity Calculation

LCOE	Value (IDR)
LCOE 0	432,26
LCOE 1	435,54
LCOE 2	438,81
LCOE 3	442,09
LCOE 4	445,37
LCOE 5	448,65
LCOE 6	451,92
LCOE 7	455,20
LCOE 8	458,48
LCOE 9	461,76
LCOE 10	465,04

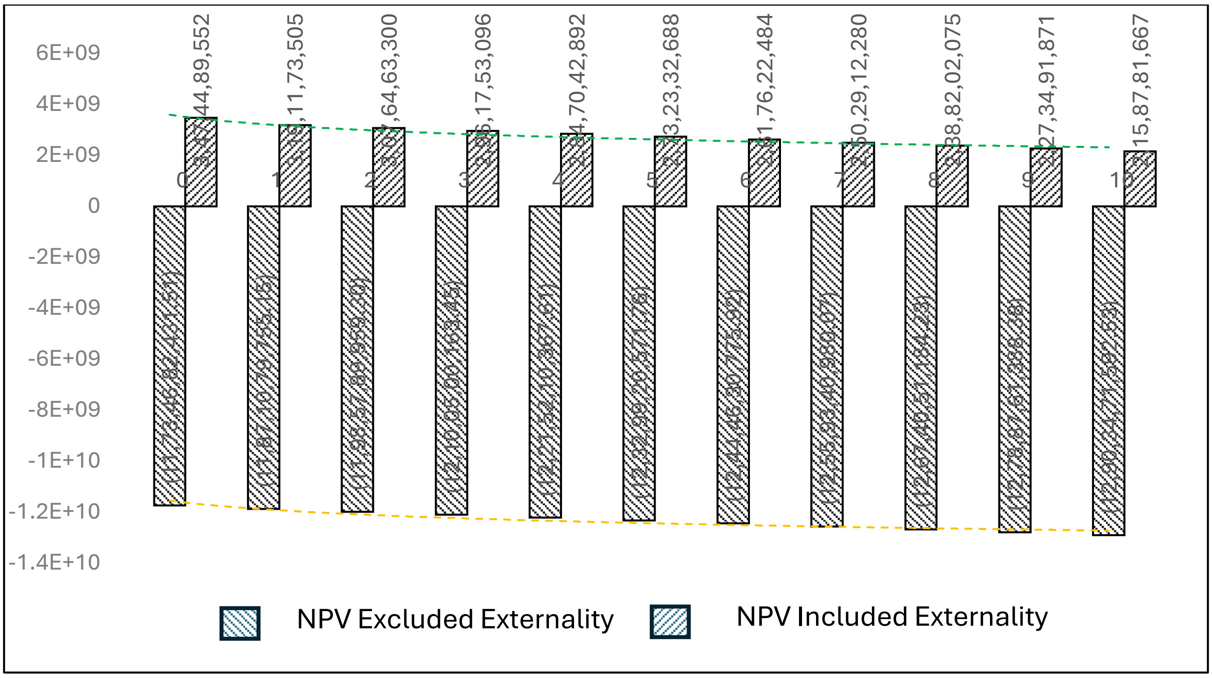

Figure 1. Comparison of NPV with and without accounting for externality costs

The Net Present Value (NPV) analysis was conducted to evaluate the economic feasibility of the centralized solar photovoltaic (PV) system by comparing discounted benefits and costs over the project's operational lifetime. Under a financial-only assessment-excluding environmental and social externalities-the project consistently yielded negative NPV values across all cash-in scenarios. At the baseline condition (Cash In 0), the NPV was recorded at -IDR 11,734,682,431.51, indicating that direct financial benefits derived from electricity cost savings are insufficient to offset the substantial capital investment and long-term operating expenditures.

In contrast, when environmental and public health externalities were monetized and incorporated into the benefit stream, the NPV shifted to a positive value of IDR 3,474,489,552.15 under the same baseline scenario. Although a declining NPV trend was observed from Cash In 0 to Cash In 10, all scenarios remained positive when externalities were included.

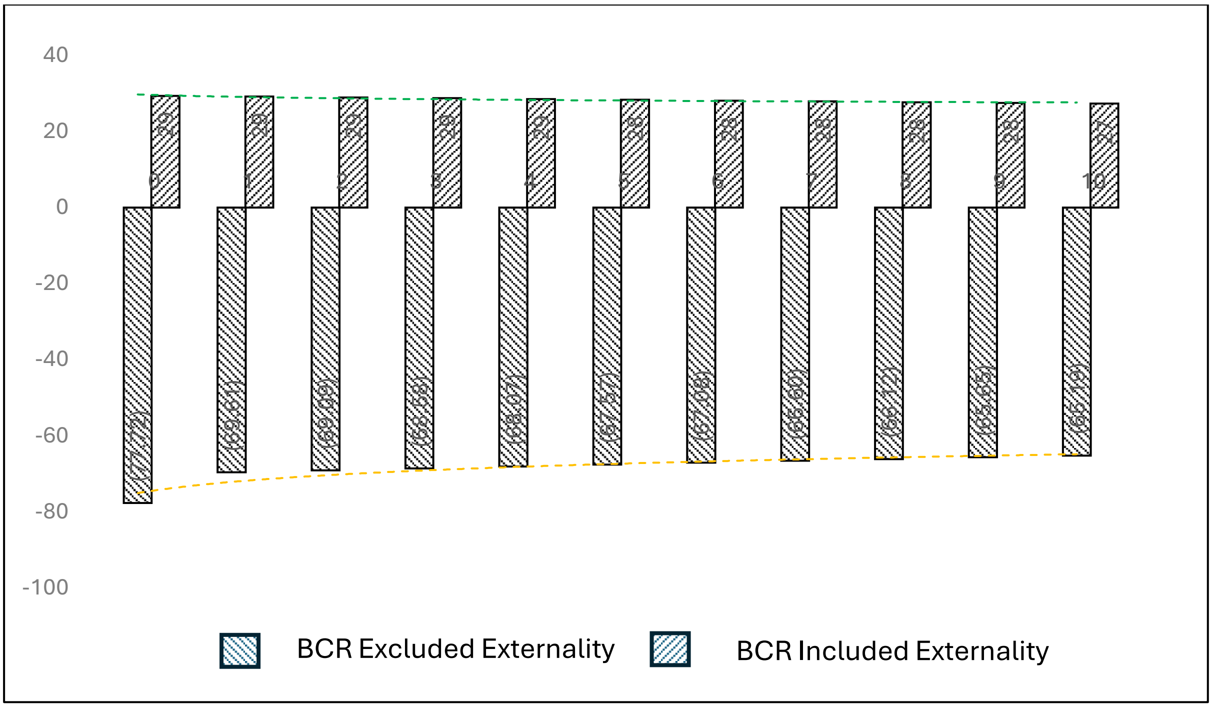

Figure 2. Comparison of BCR with and without accounting for externality costs

The Benefit–Cost Ratio (BCR) analysis reveals a pronounced contrast between financial and socio-economic evaluations. When externalities were excluded, BCR values remained negative across all assessment scenarios, ranging from –77.72 at Cash In 0 to –65.19 at Cash In 10. These results indicate that the direct financial benefits generated by the centralized PV system are insufficient to recover total investment and operational costs.

However, upon incorporating environmental and public health externalities into the benefit calculation, BCR values increased dramatically, reaching a range of 29.44 to 27.36. Although a slight downward trend was observed as cost sensitivity increased, all BCR values remained substantially greater than unity.

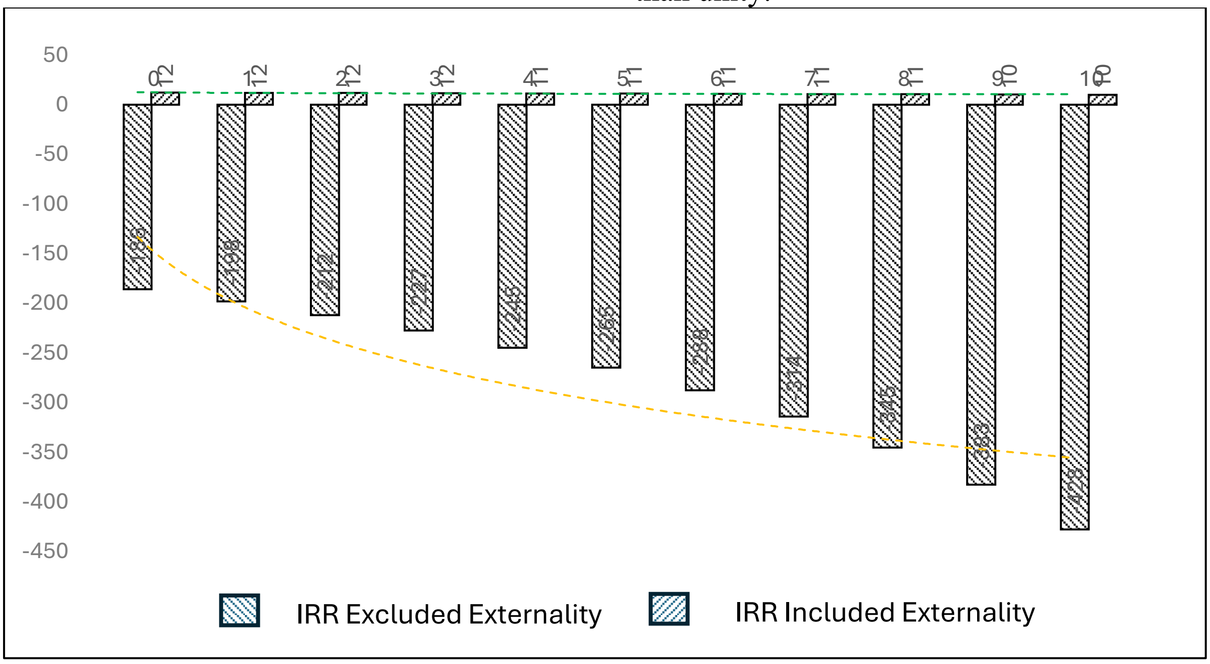

Figure 3. Comparison of IRR with and without accounting for externality costs

The Internal Rate of Return (IRR) analysis further corroborates the findings of the NPV and BCR assessments. Under a financial-only evaluation, the project produced negative IRR values, indicating that the investment fails to meet the required discount rate and does not generate adequate returns to justify capital deployment.

In contrast, when external benefits were internalized, the IRR values increased and approached or exceeded the applied discount rate, thereby classifying the project as feasible from a social return perspective.

DISCUSSION

LCOE

These findings suggest that although initial capital expenditure remains the dominant cost component, O&M contributes significantly to lifetime expenditure and must be carefully managed. This aligns with Kaltschmitt et al. (2007), who reported that PV O&M costs typically range between 1–2% of initial investment and include module cleaning, performance monitoring, routine inspection, and minor component replacement. The increasing LCC trend across sensitivity levels reflects the importance of accurate O&M forecasting, particularly for systems incorporating battery storage and inverter replacement potential (Schmidt et al., 2017).

The gradual increase in LCOE values reflects the system's sensitivity to rising O&M cost assumptions, indicating that maintenance strategy and component reliability are critical drivers in long-term cost performance.

The resulting LCOE range remains within a competitive cost corridor, particularly when considering global trends of decreasing PV module prices and rising fossil fuel electricity generation costs influenced by market volatility and carbon externality considerations.

Overall, these results emphasize that techno-economic assessments of PV systems should not focus solely on initial investment costs but must also incorporate detailed long-term operational considerations to ensure reliable and realistic evaluation outcomes.

NPV

The substantial divergence between the financial-only and socio-economic NPV results highlights the fundamental limitation of conventional financial appraisal methods when applied to renewable energy infrastructure projects. The negative NPV under the financial perspective reflects the capital-intensive nature of centralized PV systems and their relatively modest direct revenue streams (IRENA, 2019).

Conversely, the positive NPV obtained through the inclusion of externalities demonstrates that avoided carbon emissions, reduced pollution-related health costs, and broader environmental benefits contribute significantly to the project's overall economic value. The gradual decline in NPV under sensitivity scenarios further emphasizes the importance of robust and scientifically grounded assumptions in externality valuation (Nordhaus, 2017). Overall, the findings indicate that while the project is financially unviable from a commercial standpoint, it is economically justified under a comprehensive socio-economic evaluation framework aligned with decarbonization and public welfare objectives (Boardman et al., 2020).

BCR

The negative BCR values under the financial-only framework confirm that the project is unattractive from a purely commercial investment perspective. Nevertheless, the exceptionally high BCR values obtained when externalities are included underscore the dominance of socio-environmental benefits in the project's value proposition (Manganelli, 2022).

These results demonstrate that social benefits particularly emissions reduction and health cost avoidance far exceed the associated economic costs, even under conservative assumptions (Markandya et al., 2018). The persistence of BCR values well above one across all scenarios indicates strong socio-economic robustness. This finding supports the argument that renewable energy projects should be evaluated within a broader public value framework rather than solely through private profitability metrics.

IRR

The negative IRR under the financial framework confirms that the centralized PV system does not satisfy conventional investor return requirements. However, the improvement in IRR following the inclusion of externalities highlights the relevance of non-market benefits in renewable energy investment appraisal.

The results suggest that this project is more appropriately positioned as a policy-driven and socially oriented investment, rather than a profit-maximizing commercial venture (IRENA, 2019). Incorporating environmental and health-related benefits enables the project to deliver meaningful social returns, reinforcing its alignment with energy transition strategies, climate mitigation policies, and the Sustainable Development Goals (Arkauti et al., 2024).

CONCLUSION

Based on conventional financial analysis, the investment is not economically feasible when evaluated solely from technical cost–benefit perspectives. However, when environmental externalities, national clean energy policy directives, and emission reduction commitments are incorporated into the evaluation framework, the project becomes feasible and strategically aligned with long-term sustainable energy development objectives. Therefore, the implementation of this centralized solar PV system is recommended as a strategic and environmentally beneficial investment, particularly within the context of Indonesia's energy transition roadmap.

Declaration by Authors

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