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# TOPOGRAPHICAL AND TECHNO-ECONOMIC ASSESSMENT OF UTILITY-SCALE SOLAR PV DEVELOPMENT IN LEDEK MOUNTAIN, CENTRAL JAVA, INDONESIA

## *AVALIAÇÃO TOPOGRÁFICA E TECNOECONÔMICA DO DESENVOLVIMENTO DE ENERGIA SOLAR FOTOVOLTAICA EM ESCALA UTILITÁRIA NA MONTANHA LEDEK, JAVA CENTRAL, INDONÉSIA*

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**Abstract**

This study conducts an integrated topographical and techno-economic assessment of a proposed utility-scale solar photovoltaic (PV) power plant at Ledek Mountain, Central Java, Indonesia. The research aims to evaluate site feasibility, economic performance, and sustainability potential within the Universitas Negeri Semarang (UNNES) Science and Techno Park, an area promoting conservation-based innovation. A drone-based photogrammetric and GIS survey identified 27 hectares of suitable land, supporting an installed capacity of 18 MWp. The system, optimized for local climatic conditions, produces an annual energy yield of 25,229 MWh with a performance ratio of 80%. The techno-economic analysis estimates a total project cost of USD 19.09 million and a Levelized Cost of Energy (LCOE) of USD

***Resumo***

*Este estudo realiza uma avaliação integrada topográfica e tecnoeconômica de uma usina de energia solar fotovoltaica (FV) em escala utilitária proposta para a Montanha Ledek, em Java Central, Indonésia. O objetivo é avaliar a viabilidade física, o desempenho econômico e o potencial de sustentabilidade do projeto no Parque de Ciência e Tecnologia da Universidade Negeri de Semarang (UNNES), uma área voltada à inovação com base na conservação ambiental. Um levantamento fotogramétrico com drones e análise geoespacial em SIG identificaram 27 hectares de terreno adequado, correspondendo a uma capacidade instalada de 18 MWp. O sistema, otimizado para as condições climáticas locais, apresenta uma geração anual de 25.229 MWh e uma razão de desempenho de 80%. A análise tecnoeconômica estimou um*

0.030/kWh—well below Indonesia's average tariff. The project is projected to generate USD 31.5 million in revenue with a 65% ROI and a 16.9-year payback period. Sensitivity analysis confirms economic resilience to variations in module cost, electricity price, and discount rate. With an annual output sufficient to power 194,000 households or 25,000 small industries, the project demonstrates significant social and environmental benefits. Beyond its technical merits, the initiative illustrates the pivotal role of universities in accelerating renewable energy integration and advancing the Sustainable Development Goals (SDGs) 7 and 13 through sustainable land-use and institutional planning.

**Keywords:** Solar Photovoltaic (PV). Techno-economic Assessment. Renewable Energy. Energy Transition. Sustainable Development Goal (SDG).

*custo total de USD 19,09 milhões e um Custo Nivelado de Energia (LCOE) de USD 0,030/kWh, valor inferior à tarifa média nacional. O projeto deve gerar USD 31,5 milhões em receitas, com retorno de 65% e período de retorno de 16,9 anos. A análise de sensibilidade confirma a robustez econômica frente a variações de custos e tarifas. Com produção suficiente para atender 194 mil residências ou 25 mil pequenas indústrias, o projeto demonstra benefícios sociais e ambientais e evidencia o papel das universidades na integração das energias renováveis e na promoção dos Objetivos de Desenvolvimento Sustentável (ODS) 7 e 13.*

***Palavras-chave:*** *Energia Solar Fotovoltaica. Avaliação Tecnoeconômica. Energia Renovável. Transição Energética. Objetivo de Desenvolvimento Sustentável (ODS).*

## 1 INTRODUCTION

The global commitment to combat climate change, underscored by the goal of achieving net-zero emissions by mid-century, necessitates a rapid transition to clean energy. Solar Photovoltaic (PV) technology has emerged as a cornerstone of this transition (Ahmed et al., 2025). Its widespread adoption has significantly driven down costs, offering a dependable and economically viable source of electricity, particularly in tropical regions like Indonesia, which benefit from abundant and consistent sunlight. Recognizing this potential, the Indonesian government has established ambitious targets, aiming to source 23% of its energy from renewables by 2025 and 31% by 2050 (Aditya et al., 2025). Consequently, solar PV is a critical enabler of the national strategy to promote cleaner energy across diverse sectors, including urban centers, rural communities, and most importantly, educational institutions.

Educational institutions are uniquely positioned to serve as catalysts for this transition, acting as crucial hubs for research, innovation, and community engagement, while also providing a platform for energy initiatives. Integrating utility-scale renewable energy systems into university campuses serves a dual function, which directly aids the institution in meeting its carbon emission reduction targets while simultaneously enriching the learning environment. These systems transform the campus into a practical, living laboratory, providing students and staff with real-world experiences that enhance their awareness of sustainability, technology, and environmental policy (Lazaroiu et al., 2024). This initiative fundamentally contributes to the United Nations' Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 4 (Quality Education) (Garcia & Pscheidt, 2023). Universitas Negeri Semarang (UNNES) embodies this commitment. Its mission is to be a globally recognized institution that champions conservation, a distinction it has held since being designated a Conservation University in 2010. This status requires a focus on protecting natural resources and integrating sustainable practices into all campus activities (Rahmawati et al., 2020).

While contemporary studies have explored the technical and economic viability of solar PV in various contexts, ranging from rural electrification (Kassem et al., 2024) to campus microgrids (Adriana et al., 2025) and large-scale farms in Southeast Asia (Govindarajan et al., 2023), a notable gap persists. The existing literature often overlooks projects situated within dedicated Science and Techno Parks (STP) linked to universities, which represent a vital nexus for policy, technology, and community development. Furthermore, comprehensive site-specific topographical surveys, which are crucial determinants of land-use efficiency and overall project cost, are frequently treated superficially in purely economic or technical assessments (Noorollahi et al., 2016). Addressing these research gaps is essential for informing sustainable investment and effective land-use planning in Indonesia's educational and semi-urban landscapes.

UNNES is actively tackling this by transforming its Conservation Park into a Science and Techno Park (STP) in Ledek Mountain, Gunungpati District, Central Java. This strategic area, characterized by significant land area, excellent solar potential, and its symbolic role as a center for innovation rooted in conservation (Mukhlisin et al., 2023), is the ideal location for showcasing a utility-scale solar PV farm. The resulting project is designed to be more than an energy source. It will function as a practical research and learning center, directly contributing to regional carbon reduction goals and potentially supplying reliable, low-cost electricity to surrounding communities. Crucially, the establishment of this project within the STP framework provides a tangible case study in environmental planning and sustainable policy implementation on institution-owned land.

This study performs an integrated topographical, techno-economic, and policy-contextual evaluation of a large-scale solar PV project in Ledek Mountain. The analysis first involves a site-specific topographical assessment to optimize panel orientation and land-use efficiency. This is followed by a detailed design of the PV system and estimation of its performance under a fixed-tilt configuration. Finally, a rigorous techno-economic analysis is conducted, featuring calculations for Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE), including a comprehensive sensitivity analysis. By validating the project's robustness across various technical and economic scenarios, this study offers critical evidence and guidance to decision-makers, policymakers, and academic researchers on how to successfully implement sustainable energy infrastructure in sensitive educational and semi-urban areas, thereby advancing Indonesia's overarching clean energy and sustainable development mandate. The remainder of this paper is structured as follows: Section 2 describes the research methodology, Section 3 presents the results and discussion, and Section 4 provides the main conclusions.

## 2 METHOD

### 2.1 Study area and data collection

The study was conducted at Ledek Mountain, located in Gunungpati District, Semarang City, Central Java, Indonesia. The location is approximately at 7° 2' 29.242" south latitude and 110° 23' 0.532" east longitude, with an elevation between 86 and 121 meters above sea level. The area is situated within the Universitas Negeri Semarang (UNNES) Conservation Park, which is undergoing a strategic transformation into a Science and Techno Park (STP). This site represents a unique combination of optimal solar resources, ample open land for utility-scale development, and significant symbolic importance as a locus for UNNES's conservation-based innovation agenda. The decision to place a clean energy project here is a direct reflection of the institution's policy commitment to blending environmental conservation with technological advancement as a model for regional sustainable development. Due to its position near the equator, the area receives consistent, high-intensity sunlight throughout the year, making it exceptionally well-suited for large-scale solar power generation.

The meteorological data were gathered to assess the potential for solar energy and to aid in the techno-economic evaluation. The solar radiation, ambient temperature, and wind speed data from 2014 to 2023 were obtained from NASA's Prediction of Worldwide Energy Resources (POWER) database. These long-term datasets were used to calculate annual averages and monthly variations, which are essential for predicting the energy output of solar PV systems, determining the performance ratio (PR), and modeling economic viability. Table 1 presents the annual averages, while Figures 1–3 show the monthly trends of solar radiation, temperature, and wind speed, offering a detailed insight into the solar resources and climatic conditions at Ledek Mountain.

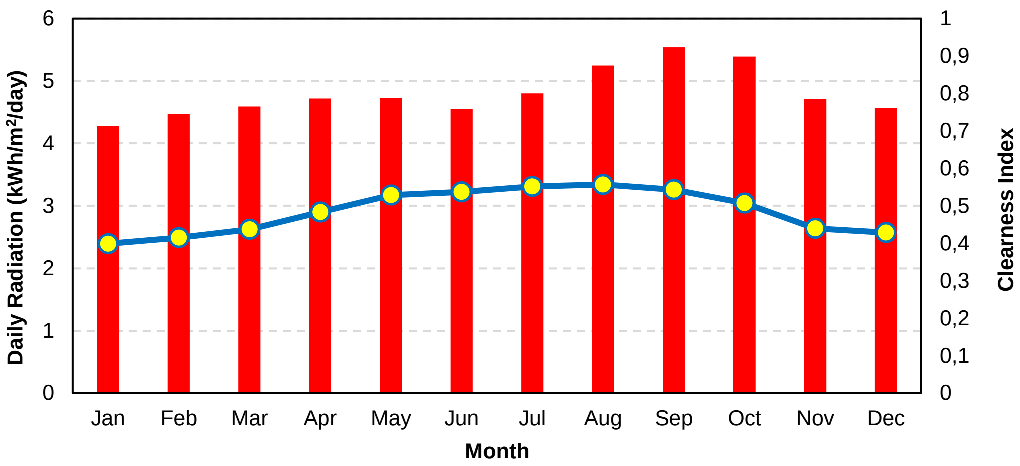
**Table 1**

*The annual averages of meteorological data.*

| Parameters | Annual Average | Unit |
|---|---|---|
| Solar Radiation | 4.8 | kW/m2/day |
| Daily Temperature | 24.82 | °C |
| Wind Speed | 3.41 | m/s |

**Figure 1**

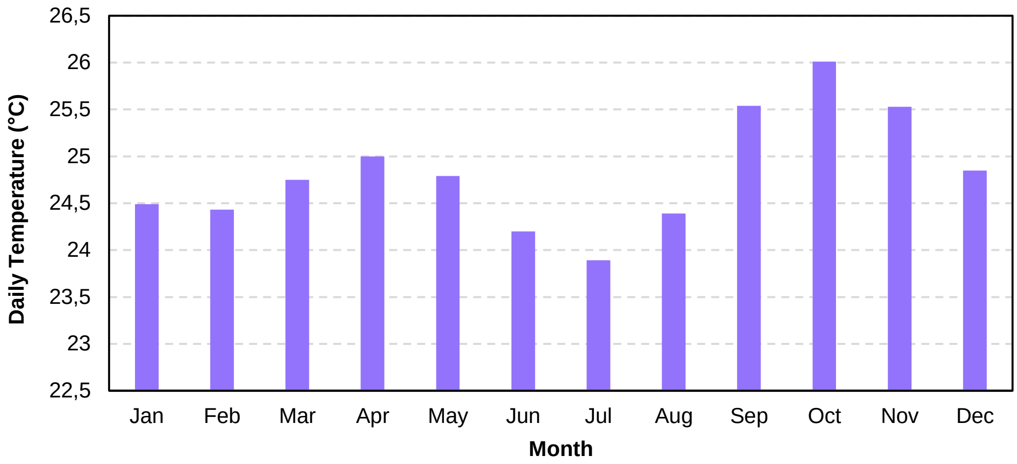
*Solar radiation and clearness index.*




Source: POWER NASA, 2025.

**Figure 2**

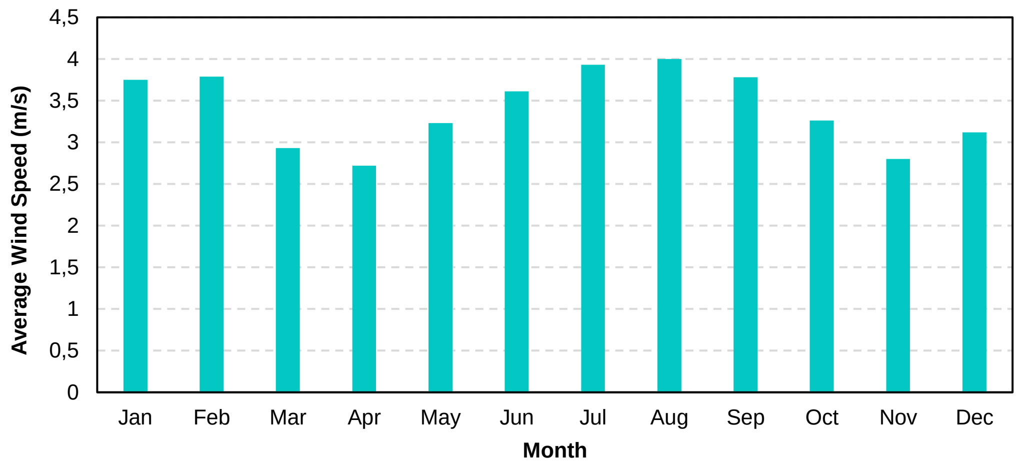
*Daily temperature.*




Source: POWER NASA, 2025.

**Figure 3**

*Average wind speed.*



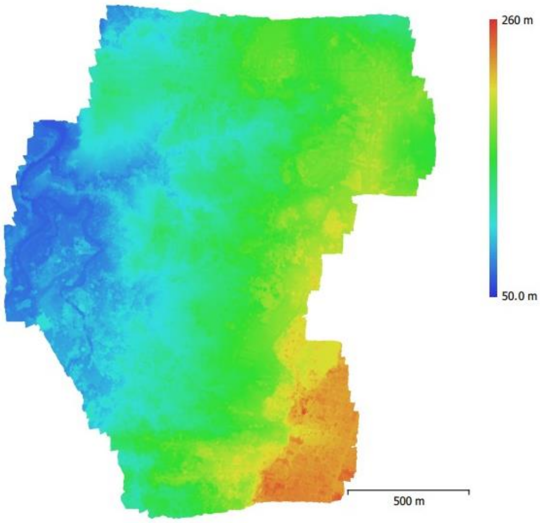

Source: POWER NASA, 2025.

## 2.2 Topographical survey and land assessment

Topographical data were acquired through a drone-based photogrammetric survey using a DJI Phantom 4 Pro Obsidian, flown at an altitude of 150 meters to achieve an optimal ground sampling distance. The flight mission was designed with four parallel paths, with 70% sidelap and 80% forelap to ensure high-quality 3D reconstruction. The captured aerial images were processed in Agisoft Metashape to produce a Digital Elevation Model (DEM) and orthomosaic map, while additional outputs such as Digital Surface Model (DSM) and Digital Terrain Model (DTM) were also generated. The processed topographical data provided a comprehensive representation of the Ledek Mountain terrain. These are generated from the photogrammetric survey are shown in Figures 4, 5, and 6, respectively, offering a detailed understanding of both surface and ground morphology.

**Figure 4**

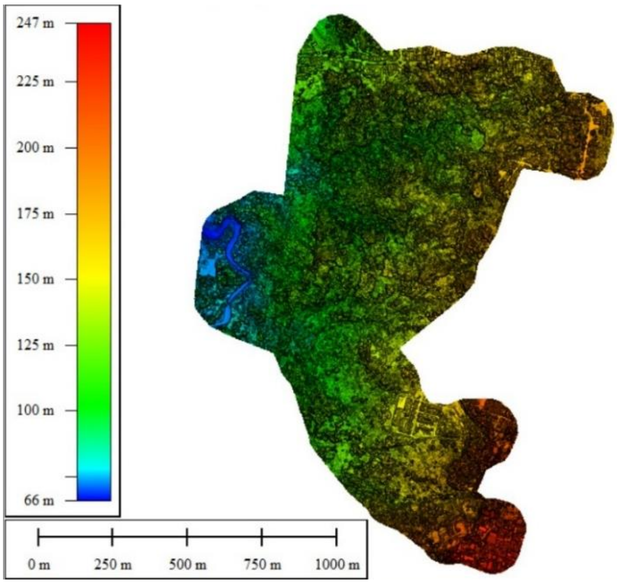
*Digital Elevation Model (DEM).*




Source: Author, 2025.

**Figure 5**

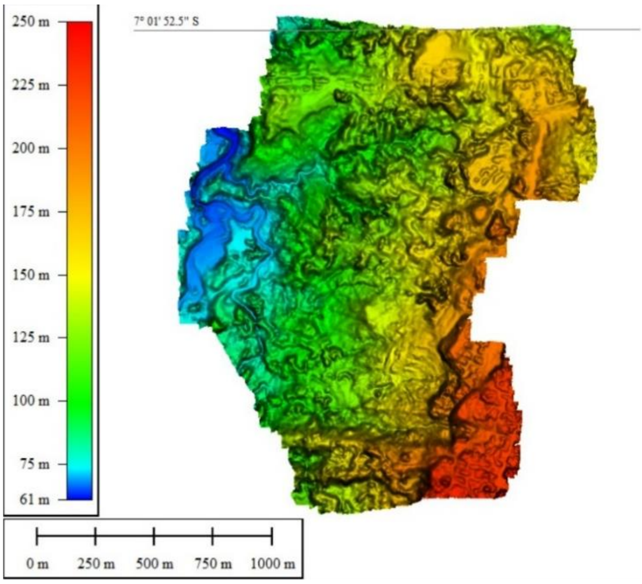
*Digital Surface Model (DSM)*




Source: Author, 2025.

**Figure 6**

*Digital Terrain Model (DTM).*




Source: Author, 2025.

### 2.3 System design and energy yield estimation

The objective of this stage was to configure the solar array layout to achieve optimal solar energy capture while maintaining operational efficiency and reducing losses caused by shading and terrain variations. A ground-mounted, fixed-tilt configuration was selected for its balance between energy performance, structural simplicity, and maintenance efficiency in large-scale applications. Monocrystalline silicon PV modules rated at 550 Wp were chosen for their high conversion efficiency, reliable operation under high temperatures, and durability in tropical climates.

Each module was mounted on galvanized steel support structures with a tilt angle of approximately 7°, corresponding to the site's latitude, to ensure uniform solar exposure throughout the year. The arrays were oriented at an azimuth of 0° (true north), following standard practice in the southern hemisphere to maximize annual solar irradiation. To minimize inter-row shading, the spacing between module rows was determined based on the panel height and tilt angle, ensuring that no shadows are cast on adjacent rows during the winter solstice. The spacing also facilitates maintenance access and natural ventilation to enhance heat dissipation and maintain operational efficiency.

The electrical configuration employs string inverters, selected for their modularity and maintenance flexibility. Each inverter connects multiple PV strings and converts direct current (DC) into alternating current (AC) before feeding it into the step-up transformer and main switchgear. The DC/AC ratio was set between 1.1 and 1.2 to optimize inverter loading and energy output under variable irradiance. A radial cabling layout was implemented to minimize transmission losses and keep the DC voltage drop below 2%, using UV-resistant copper conductors for long-term outdoor durability.

Meteorological inputs, including Global Horizontal Irradiance (GHI), ambient temperature, and wind speed, were incorporated into the system modeling to simulate PV performance under local climatic conditions. These parameters were used to account for temperature-dependent efficiency variations and to generate hourly energy output profiles. The simulation considered the following primary loss factors:

- Irradiance losses due to shading and surface reflection,
- Temperature losses under elevated ambient conditions,
- Mismatch losses among module strings, and
- System availability losses due to scheduled or unscheduled downtime.

The resulting model produced an annual energy yield ($E_{annual}$), representing the total expected electrical output of the PV system under average climate conditions. This value served as the technical basis for subsequent financial analysis presented in Section 2.4.

## 2.4 Techno-economic assessment

The techno-economic assessment aims to evaluate the financial viability of developing a utility-scale solar PV plant in the Ledek Mountain area by combining technical inputs with economic parameters. Before performing the economic calculations, it is essential to define the key parameters that influence project costs and revenues. Table 2 summarizes the main economic parameters adopted in this study, including the calculation of capital expenditure ($CAPEX$), fixed cost, variable cost, and operational expenditure ($OPEX$).

$CAPEX$ represents the upfront investment required to procure, install, and commission the solar PV plant. Fixed cost refers to the recurring expenses that remain constant regardless of the amount of energy generated (e.g., land lease, administrative costs). Variable cost reflects the operational expenses that vary proportionally with the system's energy output, such as maintenance that depends on production cycles. $OPEX$ is the total annual cost to maintain the plant's operation, including both fixed and variable components. Since a solar PV system does not require fuel input, the fuel cost is zero.

**Table 2**

*The economic aspect parameters.*

| Parameters | Value | Unit | Reference |
|---|---|---|---|
| Capital Expenditure (CAPEX) | 878000 | US$/MWp | (Irbah et al., 2025) |
| Fixed Cost | 7300 | US$/MWp/tahun | (Irbah et al., 2025) |
| Variable Cost | 0.1 | US$/MWp/tahun | (Irbah et al., 2025) |
| Operational Expenditure (OPEX) | 7300.1 | US$/MWp/tahun | (Irbah et al., 2025) |
| Fuel Costs | 0 | US$/tahun | (Irbah et al., 2025) |

For the maximum installed capacity $P_{installed}$, it can be determined by (1), where $A_{Land}$ is the usable land area (ha) and $A_{Req}$ is the land requirement per MWp (ha/MWp).

$$P_{installed} = \frac{A_{Land}}{A_{Req}} \quad (1)$$

The annual energy yield $E_{annual}$ is then estimated by (2), where GHI represents the average daily solar irradiation (kWh/m²/day) and $PR$ is the performance ratio of the PV system.

$$E_{annual} = P_{installed} \times GHI \times 365 \times PR \qquad (2)$$

The total energy production $E_{total}$ over the project lifetime can be determined using (3). $\eta_{year}$ represents the total time of the project.

$$E_{total} = E_{annual} \times \eta_{year} \qquad (3)$$

For the total capital investment $CAPEX_{total}$, total operational expenditure $OPEX_{total}$, annual operation cost $OPEX_{annual}$, and total project cost $TPC$, these are determined by (4)-(7), respectively. Using the total project cost and total energy yield, the LCOE is determined by (8).

$$CAPEX_{total} = P_{installed} \times CAPEX_{unit} \qquad (4)$$

$$OPEX_{total} = P_{installed} \times OPEX_{unit} \times \eta_{year} \qquad (5)$$

$$OPEX_{annual} = \frac{OPEX_{total}}{\eta_{year}} \qquad (6)$$

$$TPC = CAPEX_{total} + OPEX_{total} \qquad (7)$$

$$LCOE = \frac{TPC}{E_{total}} \qquad (8)$$

Meanwhile, total revenue generated over the lifetime of the project can be expressed by (9). $S_{price}$ isthe selling price of electricity (US$/kWh).

$$TR = E_{annual} \times S_{price} \times \eta_{year} \quad (9)$$

The return on investment $ROI$ and net present value (NPV), can be calculated by (10) and (11), respectively.

$$ROI = \frac{TR - TPC}{TPC} \times 100\% \quad (10)$$

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} - TPC \quad (11)$$

where $R_t$ and $C_t$ are the annual cash inflows and outflows, respectively, and $r$ is the discount rate. A positive NPV indicates that the project is financially attractive.

Finally, the payback period, which indicates the number of years required to recover the initial investment, can be computed as (12).

$$PP = \frac{TPC}{R_t - C_t} \quad (12)$$

**2.5 Sensitivity analysis**

A sensitivity analysis was conducted to evaluate how variations in technical and economic parameters influence the financial performance of the proposed solar PV project. This approach helps identify the most critical factors affecting the project's profitability and overall investment risk. The analysis was performed by adjusting one parameter at a time while keeping other variables constant, following a ceteris paribus approach. The parameters selected for sensitivity testing include:

1. PV module price (±20%), representing potential fluctuations in global solar equipment costs.
2. Electricity selling price ($S_{Price}$) (±10% and ±20%), reflecting potential changes in feed-in tariffs or power purchase agreement (PPA) rates.
3. Performance Ratio ($PR$) (±5%), accounting for operational efficiency variations due to weather, maintenance quality, and system degradation. Discount rate ($r$) (±2% and ±3%), to assess the impact of changes in capital cost and financial risk perception.
4. $O\&M$ cost $OPEX$ (±10%), representing possible escalation in operation and maintenance expenses.

For each scenario, the resulting NPV, LCOE, and ROI were recalculated using the same framework described in Section 2.4. The percentage change in these indicators relative to the baseline case provides an understanding of the project’s sensitivity to market and operational uncertainties. The sensitivity of each parameter was analyzed using the following general formulation (13).

$$\Delta P = \frac{P_{scenario} - P_{baseline}}{P_{baseline}} \quad (13)$$

where $\Delta P$ represents the relative percentage change of the financial indicator (NPV, LCOE, or ROI) between the sensitivity scenario ($P_{scenario}$) and the baseline condition ($P_{baseline}$).

## 3 RESULTS AND DISCUSSION

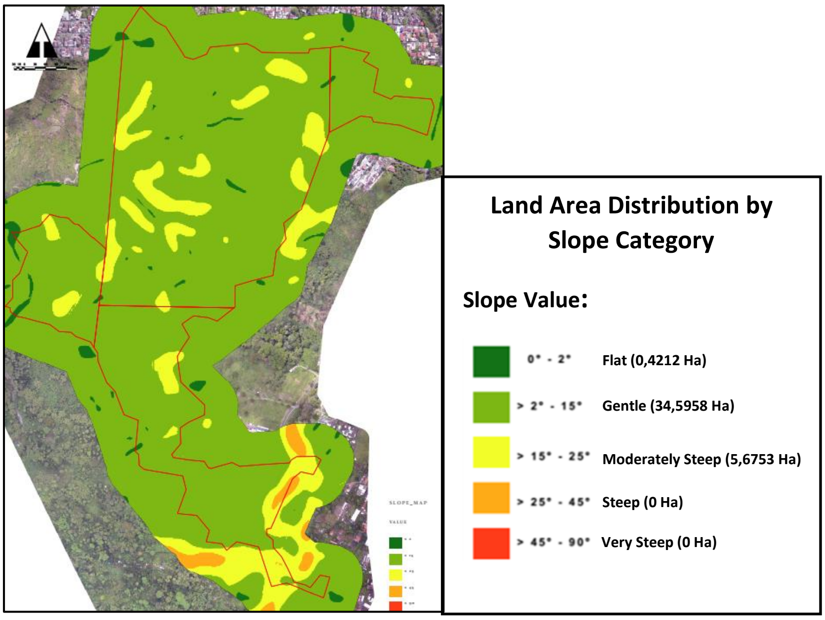
### 3.1 Topographical characteristics

The topographical evaluation of the Ledek Mountain area was conducted using Digital Elevation Model (DEM), Digital Surface Model (DSM), and Digital Terrain

Model (DTM) datasets to determine the physical suitability of the site for large-scale solar PV development. Utilizing ArcGIS Pro, the DEM data were analyzed and classified into five slope categories using planar and equal classification methods: flat (0–8%), gentle (8–15%), moderately steep (15–25%), steep (25–45%), and very steep (>45%). The resulting slope classification maps, presented in Figures 7 and 8, clearly identify areas suitable for PV installation and highlight regions excluded due to steep slopes, shading risks, or construction constraints.

**Figure 7**

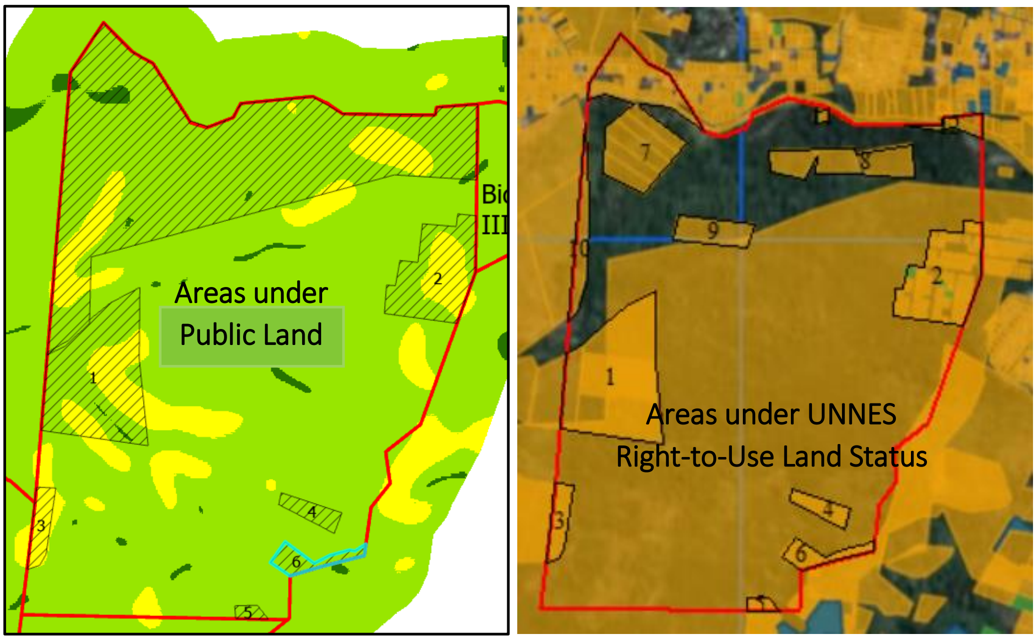
*Land area distribution by slope category.*




Source: Author, 2025.

**Figure 8**

*Land ownership classification.*




Source: Author, 2025.

A quantitative summary of the land distribution across slope classes is presented in Table 3. The results indicate that most of the Ledek Mountain area falls within the flat-to-gentle slope range, with approximately 85% of the total land area having gradients below 15%. These conditions are favorable for PV deployment, as they minimize the need for extensive earthwork and reduce construction complexity. Only a small portion of the terrain is moderately steep, and no sections exceed a 25% slope, confirming that the site is technically suitable for a utility-scale solar installation.

**Table 3**

*Distribution of land area by slope category.*

| Slope Category | Slope Range (%) | Area (ha) | Percentage (%) |
|---|---|---|---|
| Flat | 0-8% | 0,4212 | 1,0351 |
| Gentle | 8-15% | 34,5958 | 85,0181 |
| Moderately Steep | 15-25% | 5,67530 | 13,9469 |
| Steep | 25-45% | 0 | 0 |
| Very Steep | >45% | 0 | 0 |
| **Total** | | **40,6923** | **100** |

Following the slope classification, a GIS-based masking process was applied to remove unsuitable areas such as steep terrain, dense vegetation, and regions with limited accessibility. A spatial overlay analysis was also performed to integrate topographic results with land ownership data, ensuring that only publicly owned lands within the flat and gentle slope categories were considered viable for development. Table 4 presents the calculation of the effective land area derived from this overlay process. After excluding non-public and steep-slope regions, approximately 27 ha of land were identified as suitable for the proposed solar farm. This refined estimation provides the foundation for determining the maximum installable capacity and serves as a reference for array layout planning in the subsequent design stage.

**Table 4**

*Calculation of effective land area for solar power plant development at ledek mountain.*

| Parameter | Value (Ha) |
|---|---|
| Total flat and gentle area | **35,0170** |
| Areas under public land ownership status | 11,8070 |
| Areas with public land ownership status outside flat and gentle areas | 8,2950 |
| Total area with solar PV plant potential | 35,0170-8,0170 = 26,722 ≈ 27 |

## 3.2 System capacity and energy performance

Using the effective area and the land-use coefficient of 1.5 ha per MWp, the total installed capacity was estimated at 18 MWp. With an average solar irradiation of 4.8 kWh/m²/day and a performance ratio (PR) of 0.80, the system is expected to generate an annual energy yield of approximately 25,229 MWh, or 630,720 MWh over a 25-year project lifetime. The fixed-tilt array with a 7° tilt and north-facing orientation ensures stable energy production throughout the year, with limited seasonal fluctuation due to the site's equatorial location (Jacobson & Jadhav, 2018). Loss analysis indicates that irradiance and temperature losses account for the largest share of system losses, followed by mismatch and availability effects. Nevertheless, the overall PR of 80% is consistent with benchmark values for tropical utility-scale PV plants reported in Southeast Asia (Taduran & Piao, 2025).

### 3.3 Economic performance

The CAPEX for the 18 MWp installation was estimated at USD 15.8 million, while the annual OPEX amounts to USD 131,400, leading to a total lifetime OPEX of approximately USD 3.28 million. Consequently, the TPC reached USD 19.09 million. Based on the expected lifetime energy output, the LCOE was calculated at USD 0.030 per kWh (equivalent to around IDR 499 per kWh). This value is considerably lower than Indonesia's current average electricity tariff, suggesting that the proposed system can supply electricity at a competitive cost, either to the national grid or for local community consumption. Assuming an electricity selling price of USD 0.05 per kWh (IDR 825 per kWh), the project would generate an annual revenue of approximately USD 1.26 million and a total revenue of USD 31.5 million over 25 years of operation. The ROI is estimated at 65%, which demonstrates strong financial feasibility and places this project within the favorable range of similar solar developments in Southeast Asia, where LCOE values typically range from USD 0.035 to 0.050 per kWh. Benchmark studies in the Asia-Pacific and ASEAN regions report LCOE for utility-scale solar PV in the order of USD 0.038–0.045 /kWh under favorable conditions (Lee et al., 2019).

Further financial assessment through NPV analysis indicates a positive net value of about USD 6.8 million, assuming a discount rate of 5.25%. This result confirms that the project remains profitable throughout its lifetime and is resilient to moderate fluctuations in market or policy conditions. The project's payback period is approximately 16 years and 11 months, the time required to recover the initial investment from annual net cash inflows. After this period, all subsequent revenue represents net profit, ensuring continuous economic return for nearly eight additional years. Such a payback horizon is considered favorable for renewable energy projects, especially given the low operational costs and long service life of photovoltaic systems.

In addition to financial feasibility, the project's energy yield translates into tangible social and economic benefits. With an estimated annual electricity generation of 252 GWh, the proposed solar power plant has the potential to supply electricity to approximately 194,000 residential households, based on the national average consumption of 1,300 kWh per household per year. Alternatively, if directed toward the business and small industrial sector, it could serve about 25,000 small-scale industrial customers, depending on consumption levels. This scale of energy distribution would contribute significantly to regional electrification and the local economy, supporting sustainable industrial growth in Central Java.

Overall, these results confirm that the Ledek Mountain solar farm is not only financially viable but also strategically aligned with Indonesia's clean energy transition agenda. The project's integration within the UNNES Science and Techno Park reinforces its dual role as an energy infrastructure initiative and a living laboratory for sustainability education and research—an approach that bridges academic innovation with practical contributions to national energy security and the achievement of Sustainable Development Goals 7 and 13.

### 3.4 Sensitivity analysis

To assess financial resilience, a sensitivity study was carried out by varying major parameters such as module price, selling price, PR, OPEX, and discount rate. The results show that electricity selling price and PV module cost are the most influential variables affecting profitability. A 20% increase in module price would raise the LCOE by roughly 12% and reduce NPV by about 10%, whereas a 20% increase in selling price would improve ROI by more than 15%. Changes in the discount rate (±3%) moderately affect NPV, while variations in OPEX and PR have smaller impacts, each altering ROI by less than 5%. Overall, the sensitivity analysis confirms that the Ledek Mountain solar farm remains economically viable under a wide range of market scenarios. Even in a pessimistic case (–10% selling price and +10% CAPEX), the project maintains a positive NPV and an LCOE below US $ 0.04/KWh, reinforcing its robustness for long-term investment.

### 3.5 Comparative and contextual discussion

The techno-economic analysis confirms that the proposed solar PV project in Ledek Mountain demonstrates a highly competitive energy generation and cost structure when compared to similar solar initiatives in Central Java and the wider ASEAN region. The LCOE achieved in this study US$ 0.030/kWh is significantly lower, roughly 30–35% below the average generation cost from fossil-fuel power plants in Indonesia. Beyond providing a robust financial benchmark for national decarbonization targets, this LCOE provides critical data to support the acceleration of large-scale solar deployment. From a regulatory perspective, this validates the economic premise underlying key national energy policies, such as Indonesia’s Ministry of Energy and Mineral Resources regulations, by demonstrating the project's ability to offer a highly competitive standardized tariff.

Furthermore, the integration of the solar farm within the UNNES Science and Techno Park is a tangible result of institutional policy and environmental planning, representing a strategic choice to utilize land previously dedicated to a Conservation Park for clean energy infrastructure. This sets a precedent for how academic institutions can legally and effectively implement sustainable land-use policies to meet climate mitigation goals. Crucially, the project is a functional mechanism for advancing Sustainable Development Goals (SDGs), not only aligning with SDG 7 (Affordable and Clean Energy) but also strengthening SDG 4 (Quality Education) by transforming the site into a "living laboratory" that provides real-world learning and innovation opportunities for future policy-makers and engineers.

These findings not only reinforce the economic justification for integrating large-scale solar development within national energy transition plans but also provide evidence-based insights that can inform the formulation of renewable-energy governance frameworks in Indonesia. By demonstrating the feasibility of clean energy deployment within academic and semi-urban environments, the Ledek Mountain project offers a replicable model for sustainable infrastructure planning that aligns with the principles of environmental law, social equity, and long-term policy coherence.

## 4 CONCLUSION

The comprehensive assessment carried out in this study demonstrates that Ledek Mountain possesses highly favorable topographical and economic conditions for the establishment of a utility-scale solar PV plant. The geospatial analysis confirmed that most of the area lies within flat-to-gentle slopes, providing approximately 27 hectares of feasible land with minimal civil work requirements. Based on this available area, the system design supports an installed capacity of 18 MWp and produces a stable annual output exceeding 25 GWh. The techno-economic analysis revealed a competitive Levelized Cost of Energy (LCOE) of USD 0.030/kWh and a total project cost of USD

19.09 million, resulting in a strong Return on Investment of 65%. The project achieves full capital recovery within 16.9 years, ensuring positive net cash flow for the remaining operational life. With a positive Net Present Value (NPV) of USD 6.8 million, the solar farm proves to be both profitable and resilient against fluctuations in market parameters such as module price, electricity selling price, and discount rate. Moreover, the estimated annual generation has the potential to power approximately 194,000 households or 25,000 small industries, thereby enhancing local electrification and promoting sustainable regional growth. Beyond its financial and technical outcomes, this project serves as a model for integrating renewable energy development into academic and institutional frameworks. Its establishment within the UNNES Science and Techno Park exemplifies how educational institutions can lead the transition toward cleaner energy systems while providing practical platforms for research, innovation, and policy learning. In this way, the Ledek Mountain solar farm not only contributes to Indonesia's national renewable energy targets but also advances the broader agenda of sustainable development by linking technological progress, environmental responsibility, and educational empowerment.

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## Authors' Contribution

Both authors contributed equally to the development of this article.

## Data availability

All datasets relevant to this study's findings are fully available within the article.

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