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A Multi-Criteria Decision Framework for Optimal Rooftop Solar PV Site Selection in Industrial Zones: An AHP-Based Case Study in Central Java, Indonesia

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A R T I C L E I N F O

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A B S T R A C T

Indonesia targets 23% renewable energy in its mix by 2025 and net-zero emissions by 2060, with rooftop solar PV (PLTS atap) offering strong potential for industrial applications. This study aims to identify the optimal site for rooftop solar installation across four industrial zones in Central Java (Brebes, Tegal, Jepara, and Rembang) using the Analytical Hierarchy Process (AHP). Data from expert stakeholders evaluated four main criteria—installed capacity, project cost, installation time, and quality—along with relevant sub-criteria. Results show installed capacity as the most influential criterion (weight 0.410), followed by cost (0.301), time (0.180), and quality (0.109), with dominant sub-criteria being roof area, EPC cost, installation duration, and safety-health-environment (SHE). The synthesis identifies Jepara as the optimal site (score 0.336), with all consistency ratios below 0.1 confirming result validity. This study provides a systematic decision-support framework for solar developers and policymakers while advancing SDG 7 and SDG 13.

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INTRODUCTION

The global energy landscape is undergoing a profound transformation driven by the urgent need to mitigate climate change and reduce dependence on fossil fuels. The Paris Agreement and the United Nations' Sustainable Development Goals (SDGs) have set ambitious targets for decarbonization, urging nations to accelerate the adoption of renewable energy sources. Indonesia, as the largest economy in Southeast Asia, has pledged to achieve 23% renewable energy in its primary energy mix by 2025 and net-zero emissions by 2060. To meet these targets, a significant shift from coal and gas to cleaner energy sources is essential.

Among the various renewable technologies, solar photovoltaic (PV) systems have emerged as one of the most promising solutions due to their declining costs, scalability, and suitability for distributed generation. Rooftop solar PV systems offer a unique advantage for industrial and commercial sectors, which are major consumers of electricity. In Indonesia, the industrial sector accounts for 42.3% of total electricity consumption, making it a critical target for solar energy deployment.

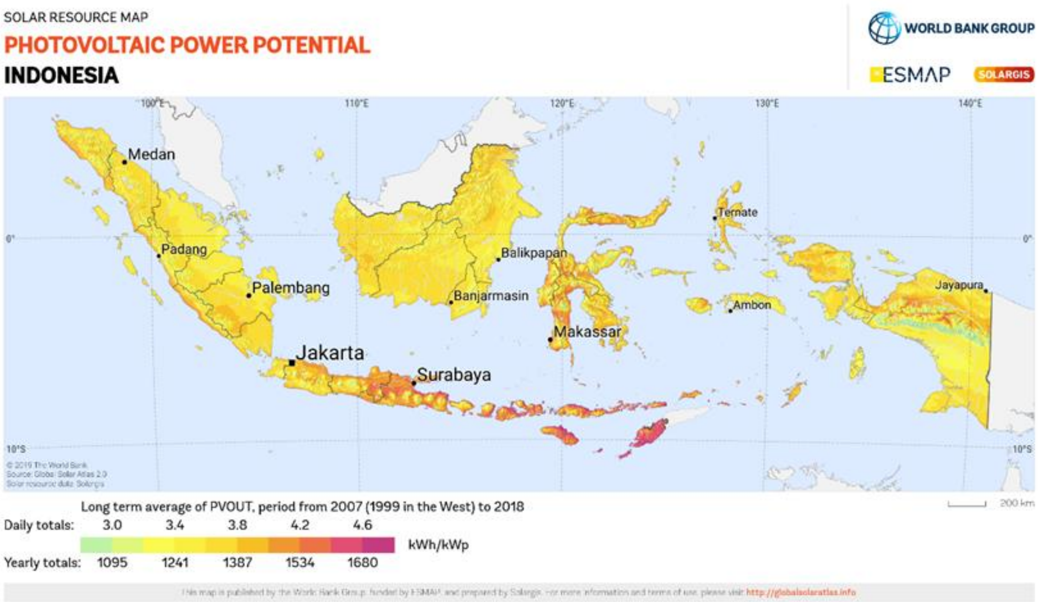

Figure 1. Solar irradiation potential in Indonesia

Source: Global Solar Atlas (http://www.globalsolaratlas.info/)

Despite the vast potential, the adoption of rooftop solar in industrial zones faces several challenges. One of the most significant barriers is the lack of a systematic and objective decision-making framework for site selection. Decisions are often made based on intuition, limited technical assessments, or short-term financial considerations, leading to suboptimal outcomes. This is particularly evident in Central Java, a region with high solar irradiation and a dense concentration of industries, yet relatively low rooftop solar penetration.

To address this gap, this study proposes the use of the Analytical Hierarchy Process (AHP), a well-established multi-criteria decision-making (MCDM) method, to evaluate and rank potential sites for rooftop solar PV installation. AHP allows for the integration of both quantitative and qualitative factors into a structured hierarchy, enabling a comprehensive and transparent evaluation. The method has been successfully applied in various energy-related site selection problems, including wind farms, hydropower plants, and solar parks.

The primary objective of this research is to determine the optimal location for rooftop solar PV installation among four industrial sites in Central Java—Brebes, Tegal, Jepara, and Rembang—using the AHP method. The study evaluates four main criteria: PLTS Installed Capacity, Project Cost, Installation Time, and Quality, each with specific sub-criteria. The results are based on expert judgments from a leading solar developer, ensuring practical relevance and applicability.

This research makes several contributions to the existing literature. First, it integrates AHP with project management principles, considering not only technical and economic factors but also time and quality constraints. Second, it uses real-world data from an industrial developer, enhancing the validity and practicality of the findings. Third, it provides a replicable decision-support model that can be adapted to other regions and contexts. Finally, the study aligns with the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), by promoting the transition to clean energy in the industrial sector.

The remainder of this paper is organized as follows: Section 2 presents a comprehensive literature review on rooftop solar PV, AHP, and related studies. Section 3 details the research methodology, including the AHP framework and data collection process. Section 4 presents and discusses the results. Section 5 outlines the implications and recommendations. Section 6 concludes the paper and suggests directions for future research.

LITERATURE REVIEW

Rooftop Solar Photovoltaic (PLTS Atap)

Rooftop solar PV systems convert sunlight into electricity using photovoltaic panels installed on building rooftops. These systems are typically connected to the grid (on-grid), allowing excess electricity to be fed back into the utility network through a mechanism known as net metering. This setup enables building owners to reduce their electricity bills and, in some cases, earn credits for surplus generation.

The advantages of rooftop solar are numerous. It requires no additional land use, leverages existing infrastructure, and reduces transmission losses by generating power close to the point of consumption. For industries, rooftop solar can significantly lower operational costs, enhance energy security, and improve corporate sustainability credentials.

Indonesia has immense solar energy potential, with an average solar irradiation of 4.5–4.8 kWh/m^2/day across much of the archipelago, particularly in Java, Bali, and Nusa Tenggara. However, this potential remains largely untapped. As of 2023, rooftop solar capacity in Indonesia was less than 1% of its technical potential. The slow adoption is attributed to regulatory hurdles, lack of awareness, and the absence of standardized site evaluation methods.

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty, is a structured technique for organizing and analyzing complex decisions. It breaks down a decision problem into a hierarchy of criteria, sub-criteria, and alternatives, allowing decision-makers to perform pairwise comparisons to derive priority weights.

The AHP process involves the following steps:

1. Define the goal, criteria, and alternatives.
2. Construct a pairwise comparison matrix for each level of the hierarchy using Saaty's 1–9 scale.
3. Calculate the priority weights (eigenvector) for each matrix.
4. Perform a consistency check using the Consistency Ratio (CR). A CR < 0.1 is considered acceptable.
5. Synthesize the results to obtain global priorities for the alternatives.

AHP has been widely used in energy planning and site selection. Çoban (2020) applied a hesitant fuzzy AHP model to select solar energy projects, demonstrating its effectiveness in handling uncertainty. Wang et al. (2023) developed an AHP-based decision-making model for solar plant selection, reinforcing its robustness. In the Indonesian context, Aditya & Suryadi (2021) used AHP to prioritize rooftop solar sites in Central Java, highlighting the importance of roof area and load demand.

Criteria for Rooftop Solar Site Selection

Effective site selection for rooftop solar requires a multi-dimensional evaluation. Based on the literature, the following criteria are commonly considered:

- Technical Factors: Roof area, structural integrity, solar irradiation, and load demand.
- Economic Factors: Capital cost (EPC cost), operational and maintenance (O&M) cost, return on investment (ROI), and payback period.
- Temporal Factors: Project duration, including procurement, construction, and commissioning time.
- Quality and Regulatory Factors: Safety, health, and environment (SHE), quality assurance (QA), and permitting processes.

Saputra & Rahmawati (2022) emphasized that EPC cost and structural reinforcement costs are critical in the financial feasibility of rooftop solar projects in Rembang. Nugroho & Setiawan (2023) highlighted the role of Government Regulation No. 2/2024 (Permen ESDM No. 2 Tahun 2024) in facilitating solar adoption through partnership schemes and online permitting.

Sustainable Development Goals (SDGs)

This research aligns with several Sustainable Development Goals (SDGs). SDG 7 aims to "ensure access to affordable, reliable, sustainable, and modern energy for all". By promoting rooftop solar, this study supports the transition to clean energy. SDG 13 calls for "urgent action to combat climate change and its impacts". Solar energy reduces greenhouse gas emissions from fossil fuel-based power generation. Additionally, the study contributes to SDG 8 (Decent Work and Economic Growth) by creating green jobs in solar installation and maintenance, and SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation in renewable energy deployment.

Project Management and Decision-Making in Energy Projects

The success of energy projects, including rooftop solar installations, is heavily dependent on effective project management. Key factors such as time, cost, and quality must be balanced to ensure project success. Kurniawan et al. (2017) emphasize that project selection in the upstream oil and gas sector requires a structured decision-making framework that integrates technical, economic, and managerial criteria. Their application of the Delphi-AHP method highlights the importance of expert judgment in complex project environments.

Similarly, Nugroho & Pratama (2023) conducted a study on the Semantok Dam Project, analyzing delays in secant pile foundation work using Critical Path Method (CPM) and Project Crashing. They found that delays in procurement and interdependency of activities were major causes of schedule overruns. These findings are highly relevant to rooftop solar projects, where installation time is a key criterion in the AHP model. Delays in procurement or structural reinforcement can significantly impact the project's return on investment (ROI) and overall feasibility.

This study builds on this body of knowledge by integrating project management principles into the AHP framework, ensuring that the decision-making process is not only technically sound but also aligned with best practices in project execution.

METHODOLOGY

Research Design

This study employs a case study design focusing on four industrial sites in Central Java: Factory A Brebes, Factory B Tegal, Factory C Jepara, and Factory D Rembang. The research uses a qualitative and quantitative mixed approach, with data primarily collected through expert interviews and secondary sources.

Analytical Hierarchy Process (AHP) Framework

The AHP model was structured into three levels:

1. Goal: To determine the optimal location for rooftop solar PV installation.
2. Criteria: Four main criteria were identified:
   - PV Installed (PLTS Installed Capacity): Reflects the technical potential.
   - Project Cost (Project Cost): Encompasses financial aspects.
   - Installation Time (Installation Time): Represents project duration.
   - Quality: Includes safety, quality assurance, and permitting.
3. Alternatives: The four industrial sites. Each main criterion was further divided into sub-criteria:
   - PV Installed: Roof Area, Load Demand, Irradiation.
   - Project Cost: EPC Cost, Reinforcement Cost.

- Installation Time: Procurement Time, Reinforcement Time, Installation Time.
- Quality: SHE (Safety, Health, Environment), QA (Quality Assurance), Permitting.

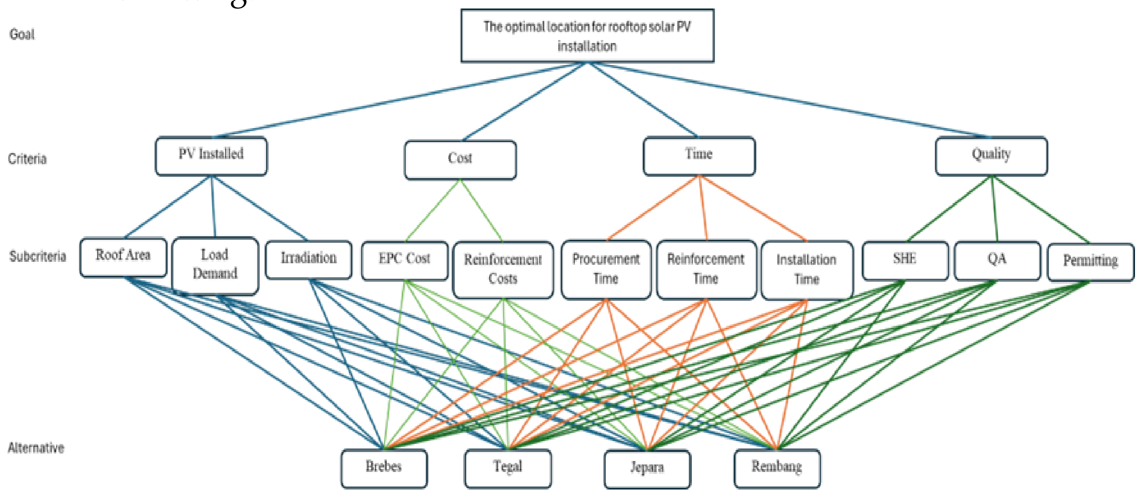

Figure 2. Hierarchical structure of the AHP model for rooftop solar PV site selection.

Source: Author, 2025

Data Collection

Data were collected from six expert stakeholders of a leading solar developer in Indonesia:

1. Project Manager: Provided insights on project timelines, technical challenges, and quality control.
2. Sales Director: Offered perspectives on market potential, customer engagement, and regulatory processes.
3. 2 person BD Manager: Shared data on site feasibility, financial modeling, and strategic planning.
4. O&M Manager: Provided input on operational requirements and maintenance planning.
5. HSE Manager: Contributed expertise on safety and environmental compliance.

The experts were asked to perform pairwise comparisons for each criterion and sub-criterion using Saaty's 1–9 scale. The data were then input into Expert Choice 11.1 software to calculate the priority weights and perform consistency checks.

Data Analysis

The analysis followed the standard AHP procedure:

1. Pairwise Comparison: Experts compared the relative importance of criteria and sub-criteria.
2. Weight Calculation: The software computed the local and global weights.
3. Consistency Check: The Consistency Ratio (CR) was calculated for each matrix. A CR < 0.1 was required for the results to be deemed consistent.
4. Synthesis: The global weights were used to rank the four alternatives.

RESEARCH RESULT

Criteria and Sub-Criteria Weights

The pairwise comparison results are presented in Table 1.

Table 1. Priority Weights of Criteria and Sub-Criteria

Main Criteria	Local Weight	Subcriteria	Local Weight	Global Weight
PV Installed	0.410	Roof Area	0.560	0.230
		Load Demand	0.284	0.116
		Irradiation	0.155	0.064
Project Cost	0.301	EPC Cost	0.750	0.226
		Reinforcement Cost	0.250	0.075
Installation Time	0.180	Procurement Time	0.237	0.043
		Reinforcement Time	0.323	0.058
		Installation Time	0.440	0.079
Quality	0.109	SHE (Safety, Health, Environment)	0.488	0.053
		QA (Quality Assurance)	0.252	0.027
		Permitting	0.260	0.028
Total	1.000			1.000

Figure 3. Priority weights of (a) main criteria and (b) sub-criteria in the AHP model.

Source: Expert Choice Result

The PV Installed criterion received the highest weight (0.410), indicating that technical capacity is the most critical factor in site selection. Within this criterion, Roof Area (0.560) was deemed most important, followed by Load Demand (0.284) and Irradiation (0.155). This finding is consistent with Aditya & Suryadi (2021), who identified roof area as the primary determinant of solar potential in industrial zones.

The Project Cost criterion was the second most important (0.301). EPC Cost (0.750) dominated this category, reflecting its significant impact on project economics. This aligns with Saputra & Rahmawati (2022), who found that EPC cost is a major component of total project cost in Rembang.

The Installation Time criterion (0.180) highlights the importance of project duration. Installation Time (0.440) was the most influential sub-criterion, underscoring the need for efficient project execution. This is in line with Khoiroh (2018), who emphasized the role of time management in project success, and supports the findings of Nugroho & Pratama (2023) on the impact of delays in construction projects.

The Quality criterion (0.109) had the lowest weight, but SHE (0.488) emerged as the most critical sub-criterion, emphasizing the priority of worker safety and environmental protection. This supports the findings of Heizer et al. (2017) and the PMBOK Guide (2017), which stress the importance of safety in project management. The integration of SHE into the decision model reflects a modern approach to project management that prioritizes sustainability and corporate responsibility.

All pairwise comparison matrices had a Consistency Ratio (CR) < 0.1, confirming the reliability of the expert judgments.

Alternative Ranking

The final synthesis of the AHP model produced the following ranking for the four industrial sites:

Table 2. Global Scores and Ranking of Alternatives

Alternative	Global Score	Ranking
Factory C Jepara	0.336	1
Factory D Rembang	0.270	2
Factory A Brebes	0.243	3
Factory B Tegal	0.152	4

Factory C Jepara was identified as the optimal site, with the highest global score of 0.336. Its superiority is attributed to its large roof area (25,000 m^2), high load demand (2,400 kW/day), and favorable EPC cost (Rp 7,500/Wp). These technical and economic advantages outweighed other factors, making it the most viable option.

Factory D Rembang ranked second (0.270), primarily due to its shortest installation time (4.5 months), as it did not require structural reinforcement. This demonstrates that even sites with lower technical capacity can be highly competitive if they offer advantages in time and cost efficiency. The finding is consistent with Oka & Kartikasari (2017), who noted that projects with stable roof structures have shorter durations.

Factory A Brebes ranked third (0.243). Despite having the highest solar irradiation (1,541.9 kWh/m^2/year), its ranking was affected by the high reinforcement cost (Rp 200 million), which significantly impacted the project's economic feasibility.

Factory B Tegal ranked last (0.152) due to the highest reinforcement cost (Rp 600 million) and medium permitting risk, which increased both the financial and operational risks of the project. Susilo & Utomo (2020) previously identified permitting delays as a major barrier in Tegal, validating this finding.

The results of this study are consistent with the broader literature. The dominance of roof area and EPC cost as key criteria is supported by multiple studies. The high ranking of Jepara aligns with Widyastuti & Prasetyo (2021), who identified Jepara as a high-potential location for rooftop solar.

CONCLUSION

This study successfully applied the Analytical Hierarchy Process (AHP) to determine the optimal location for rooftop solar PV installation in four industrial sites in Central Java. The results demonstrate that Factory C Jepara is the most suitable location, followed by Factory D Rembang, Factory A Brebes, and Factory B Tegal. The AHP model effectively integrated technical, economic, temporal, and quality factors, providing a comprehensive and transparent decision-support tool.

The findings highlight the critical importance of roof area, EPC cost, installation time, and SHE in the site selection process. The study also underscores the value of using expert judgment and structured methodologies to overcome the subjectivity often associated with project decisions.

This research contributes to the literature by providing a practical, data-driven framework for rooftop solar site selection in the industrial sector. It supports Indonesia's national energy goals and the global Sustainable Development Goals. Future work should focus on validating the model with additional case studies and exploring more advanced decision-making techniques.

RECOMMENDATION

For Solar Developers

- Adopt the AHP framework as a standard tool for evaluating potential sites. This will ensure a systematic and objective decision-making process.
- Prioritize sites like Factory C Jepara that offer a strong combination of technical and economic advantages.
- Consider sites like Factory D Rembang as secondary options, especially when faster project turnaround is a priority.
- Conduct early structural assessments to avoid unexpected reinforcement costs, as seen in Factory B Tegal.

For Industrial Managers

- Evaluate the feasibility of rooftop solar using a multi-criteria approach, not just on the basis of electricity tariff or initial cost.
- Leverage government incentives such as Permen ESDM No. 2/2024 to implement solar projects without upfront investment.
- Designate a single point of contact to coordinate with the solar developer and PLN, streamlining the permitting process.

For Policymakers (PLN and ESDM)

- Accelerate the verification process on the pltsatap.esdm.go.id portal to reduce project lead times.
- Provide priority review for sites with high technical potential (e.g., roof area > 15,000 m²).
- Enhance outreach and education on net metering and green energy benefits for the industrial sector.

ADVANCED RESEARCH

- Develop hybrid models combining AHP with other MCDM methods (e.g., TOPSIS, Fuzzy AHP) to improve accuracy.
- Expand the geographical scope to include other regions in Indonesia.
- Incorporate social and cultural factors such as management support and employee readiness into the decision model.

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