Optimising Solar PV Placement in Indonesia: AHP Multi-Criteria Decision Analysis for Ideal Locations

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Abstract. The latest Indonesian Electricity Supply Business Plan (RUPTL 2021-2030) confirms Indonesia's commitment to renewable energy. The government projects electricity generation of 40.6 GW in 2023 and is committed to involving renewable energy, which constitutes 38% of the total electricity generation capacity. Using simple regression analysis, the projected renewable energy capacity requirement is 47 GW, some of which can be met by building solar PV as a power plant. The main obstacle to achieving this goal is securing private investment, which requires identifying optimal locations where protected and conservation areas are not threatened. GIS-based Multi-Criteria Decision Analysis (MCDA) techniques are used in this research to evaluate various constraints. A commonly used method in this framework is AHP (Analytic Hierarchy Process), which uses pairwise comparisons to assign weights based on significance in a hierarchy of objectives. Criteria for determining locations for solar PV development using spatial analysis include prohibited areas, including forest areas and protected habitats, rice fields and peatlands; surface radiance, slope, temperature at 2m; and proximity to highways and power grids. Since the surface radiance spatial data obtained possess missing data, inverse distance weighting (IDW) is utilised to overcome this issue due to its simplicity and fast computation. The location determination process resulted in an estimated 43 solar power plant locations strategically located across all islands in Indonesia to help meet national energy needs.

Keywords: Solar PV; GIS-MCDA; AHP; spatial analysis; IDW.

1 Introduction

The Indonesian government has released a newly approved electricity supply business plan (RUPTL 2021-2030) highlighting that the energy mix needs to be achieved by 2030. RUPTL serves as Indonesia’s state company (PLN) business plan for developing power projects, including power generation, distribution, and transmission project development. The recent launch of RUPTL, revising its predecessor RUPTL 2019-2028, reflects Indonesia’s adjustment in energy growth due to the COVID-19 pandemic, resulting in a 4.9% reduction from the previous RUPTL. Declining development has projected the power generation to be lower from 56.4 GW to 40.6 GW by 2030 [1]. Although the total generation capacity has decreased, the latest RPUTL affirms Indonesia's commitment to renewable energy. It emphasises the crucial role of PLN and IPP (Independent Power Producer) in implementing power generation projects. The anticipated capacity of RNE power plants is expected to reach 20,923 MW by 2030 and is required to attain 23% by 2025 (PLN, 2021). As of 2019, Indonesia's primary energy supply mix consisted of oil 35%, coal 37.3%, gas 18.5%, and renewable energy 9.2% [2].

Dependence on coal has compelled Indonesia to decommission certain power plants by 2030, resulting in a reduction from 39,681 MW to 19,652 MW. Conversely, in developing the NRE sector, Indonesia aims to establish a capacity of 6.5 GW in solar panels by 2025 and 14.2 GW in 2030. The primary obstacle is securing private investment, which requires identifying optimal locations where the protected areas and conservation are not threatened [3]. Additionally, considerations should include factors like grid connectivity and transportation accessibility. This is especially relevant in remote areas with high energy demand and low electrification ratios, leading to increased delivery costs [4]. The process of optimal selection is complex and may involve conflicting criteria, leading to challenging decisions. The GIS-based Multi-Criteria Decision Analysis (MCDA) technique is a framework capable of evaluating multiple constraints. A commonly employed method within this framework is AHP (Analytic Hierarchy Process), which utilises pairwise comparisons to assign weight based on the significance within a goal hierarchy.

Several intensive studies related to solar power development planning through spatial analysis using the MCDA method, assisted by the AHP model, have been carried out [5-7]. As Indonesia increases its share of IPP as part of renewable energy generation plans, this paper assesses the potential location of solar energy by using AHP. The analysis will contribute valuable insights into identifying optimal sites for renewable sources, facilitating informed decision-making and private investors in the evolving energy landscape.

2 Method & data

This study analysis consists of electricity demand, site suitability, and financial analysis, as described in figure 1. Initially, estimating the population and GDP for 2030 is conducted with a simple regression analysis based on the data from the preceding years. Subsequently, multi-regression analysis is necessary to identify correlations between total energy demand, population, and GDP. According to RUPTL, the shortfall of fossil fuels is essential, and solar capacity acquisition is proposed as an alternative to fossil fuels with the assumption of 38% of total energy from renewable sources.

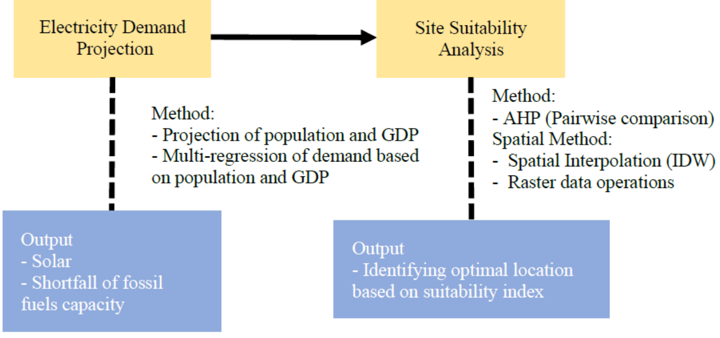

Fig. 1. Schematic of the methodology.

Second, to identify the potential area of solar, the AHP method with a pairwise comparison matrix is employed to ascertain the weight of each criterion. These criteria are established through the combination of literature reviews and expert judgments. Once the requirements and their respective weight are established, the next step involves performing spatial analysis, including interpolation and raster operation. Spatial interpolation is necessary since the solar radiance relies on open-source information from ECMWF, where the available data only represents information at specific points of the weather station. Raster operation is applied to obtain constrained areas using AND logic, ensuring the identification of cells that meet specified criteria. The output would suggest energy makers' policy on applying subsidies or gaining profit using renewable sources as an energy mix of 38% of total energy generation.

2.1 Electricity demand projection

Electricity demand depends on different socioeconomic factors such as population, urbanization, industrialization, and the development of technologies [8], but this study examined energy demand, GDP, and population. Indonesia's historical trends and GDP and population from 1967 to 2021 [9] are analysed, with population displaying a linear relation and GDP exhibiting a quadratic trend. The population uses linear regression with a calculated R-squared of 99% for training and test sets. Subsequently, GDP uses polynomial regression with a degree of 2, resulting in R-squared 89% for the test set and 95% for the training set.

The final electricity demand is obtained through multinomial regression to see the relationship of parameters. GDP and Population to 2030 projection are additional independent variables of the model, resulting in an R-squared 98% for training and test sets. This approach is better than projecting electricity demand yearly without involving GDP and population growth. The overall electricity demand is projected to reach 400 TWh or approximately 45 GW by 2030, a figure closely aligned with the government's estimation outlined in RPUTL. Considering the power factors 0.38 and 0.62 for renewables and fossil fuel sources, the total capacity required amounts to 123,3 GW. If we presume that 38% of this capacity is derived from renewable sources, then the renewable capacity requirement would be 47 GW. Indonesia has achieved 19 GW renewable sources under planning, construction, or existing schemes [10]. Thus, considering existing renewable sources, the total capacity that this study would achieve is 28 GW.

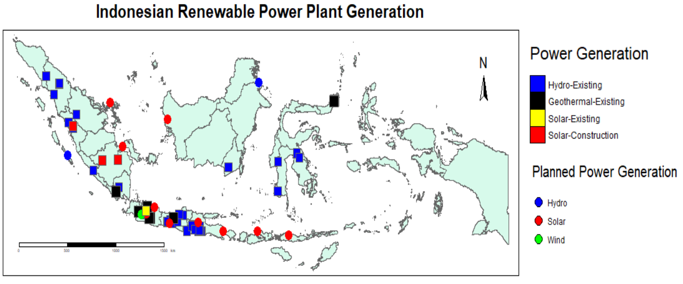

Fig. 2. Existing renewable source's locations.

2.2 GIS Constrained layer

The spatial constraints are based on the geographical and local authorities law summarised in Table 1. This study uses the raster operation by operating AND logic to identify match cells with criteria to get a restricted zone for building solar farms.

Table 1. Spatial Constrained Applied.

Data Layer	**Source**	**Constraint**
Forestry Area	ESA CCI Land cover website [11]	The protected area was protected by law enforcement No. 733/2014 and no. 45/2004
Endangered habitat/Community Forest	Protected planet [12]	Protected area by law enforcement No. 308/MENLHK/2019 Protected area by law enforcement No.21/MENLHK/2019
Rice Field	ESA CCI Land cover website [11]	Law No. 41 of 2009 about the sustainable protection of Food Agricultural lands.
Peatland	Global Forest Watch [13]	Protected area by law enforcement No. 8599/MENLHK/2018

The land protection area and land cover are shown in Figure 3. Following identifying cells that meet specified criteria, approximately 70% of the area is designated as a restricted zone.

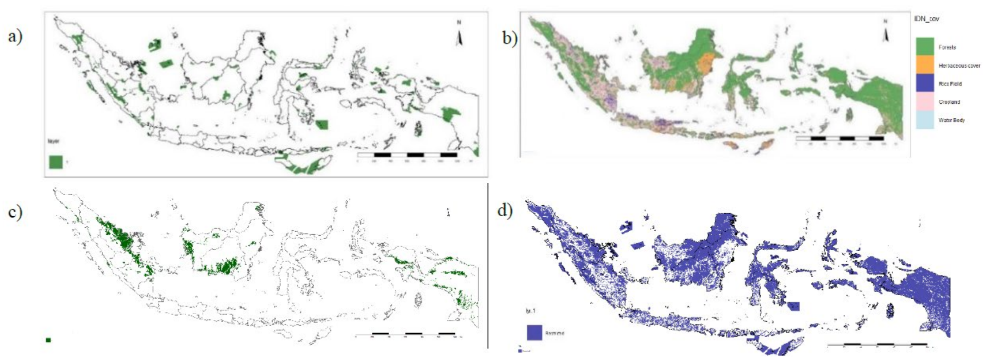

Fig. 3. (a) Land protection area; (b) land cover; (c) peatland area; (d) restricted zone based on GIS-constrained layer 1.

2.3 Geographical potential

Based on the literature reviews, some considerations are considered in determining the optimal location of solar, summarised in Table 2. These layers are used as the criterion for AHP tools.

Table 2. Summary of Criteria for Suitability Assessment of AHP.

Criteria	Source	Sub Criteria	Data References
Surface Radiance	ECMW [14]	1: <1,500 kWh/m^2 2: 1,800 – 2,500 kWh/m^2 3: > 2,500 kWh/m^2	[15]
Slope	Diva GIS [15]	1: >10° 2: 0-10°	[15]
Temperature at 2m	World Bank [16]	1: <20°C 2: 20° – 25°C 3: 25°-30°C	[4]
Road Proximity	Diva GIS [17]	1: 25,000 – 50,000 m 2: 150 – 25,000 m	[18]
Power Grid Proximity	Open Infrastructure Map [19]	1: 5,000 – 10,000 m 2: 1,000 – 5,000 m 3: <1,000 m	[4]

Data on solar surface radiance is sourced from ECMWF 14, and spatial interpolation is crucial to estimate the value from other points using points with known values. Inverse distance weighting (IDW) is the chosen method for this study, assuming the closer values are more closely related than those farther away, following geographical law. IDW method requires adjustment of a tuning parameter, known as weigh exponents, leading to a lower RMSE (Root Mean Square Error). This study uses a k-cross-validation, an iterative way to find the optimum parameter. The weight is tested across a range from 1 to 20 with ten folds. IDP 7 is the optimum point where adding more weight doesn't significantly change RMSE. The radiance data in the Figures 4 corresponds to 08 AM, 10 AM, 12 PM, 2 PM, and 4 PM. The average yearly solar radiance deviation remains relatively stable across three consecutive periods, the same as the World Bank Group [20] observed for the past 11 years. Hence, for the suitability analysis in this study, the criteria rely on the long-term average of yearly solar radiance from 2020 to 2022. Geographical potential of solar farm is shown in the figure 4 below.

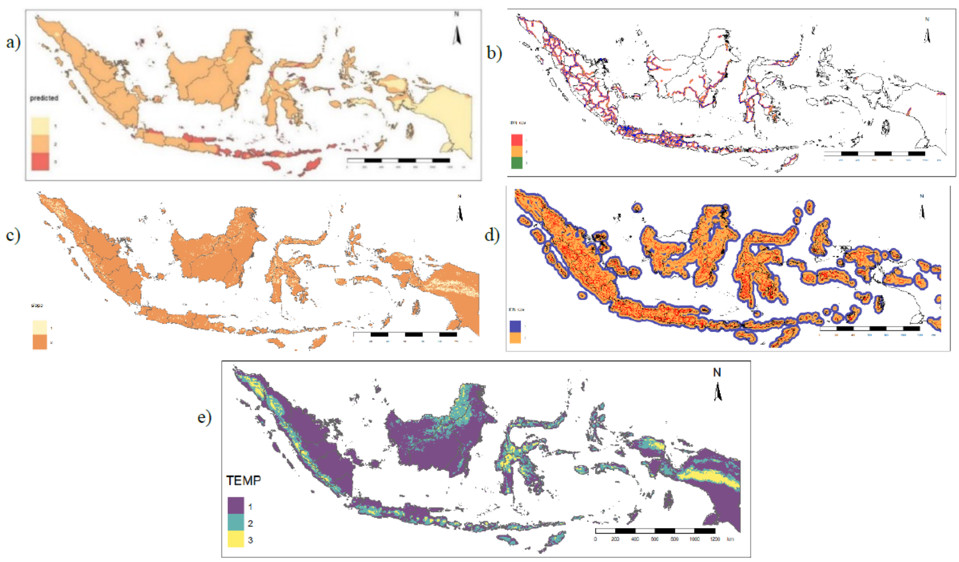

Fig. 4. (a) Long-term yearly average solar radiance; (b) grid network after reclassification; (c) slope after reclassification; (d) road network after reclassification; (e) temperature after reclassification.

3. Results & discussion

3.1 Pairwise matrix of AHP analysis

The initial phase in performing the suitability analysis for potential locations based on individual criteria involves using the AHP toll for multi-criteria decision-making. The AHP process commences by establishing pairwise comparisons to determine the relative importance of each criterion with the others, utilising a level scale. There is no strict protocol for assigning the intensity value, which weighting factors mainly depend on the researchers' decision after doing a literature review. Consequently, weighting factors may vary in each running due to the inherent randomness of choosing a value, necessitating a measure for consistent randomness.

Table **3** represents the weight of each criterion for the suitability analysis. Referring to the pairwise matrix, the Consistency Ratio (CR) outcome is 1% when comparing solar matrices.

Table 3. Pairwise Matrix comparison for solar PV.

Criteria	GHI	Temperature	Slope	Road Proximity	Power Grid Proximity	Criteria Weight
Radiance	0.46	0.35	0.44	0.43	0.50	0.44
Temperature	0.07	0.05	0.05	0.04	0.04	0.05
Slope	0.15	0.15	0.15	0.17	0.13	0.15
Road Proximity	0.09	0.10	0.07	0.09	0.08	0.09
Power Grid Proximity	0.23	0.35	0.29	0.26	0.25	0.28

3.2 Suitability analysis

Referring to Figure 5, regions characterised by proximity to a grid and elevated surface radiance values exhibit a high index. Approximately 30% of the entire land area in Indonesia shows potential for constructing solar farms. Among these, Nusa Tenggara Barat province stands out as the most suitable area.

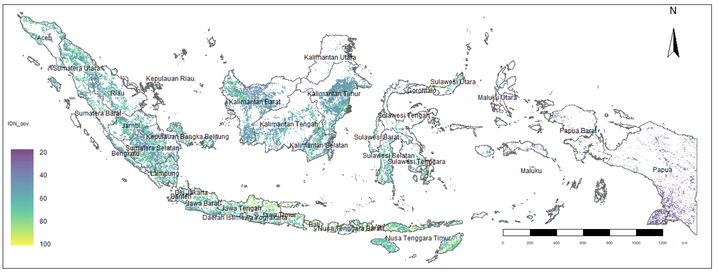

Fig. 5. Overall Suitability Index of Solar Farm Indonesia.

The study assumes that considering the promising areas, solar farms are built in areas with a solar index over 70%. The surface radiance is converted to power generation with the formula: $GP = SR \times CA \times SF \times \eta \times 365$ (1); Where SF = Shading Factor (%); SR = Surface Radiance (kW); CA = Converting Area (m2); GP = Power Generation (kWh/m2); η = Solar PV Efficiency (%). This study assumed a shading factor of 0.7 [21] and average efficiency of commercial silicon PV modules of 16% [6]. Hence, from 30% of the area, 8% is the ultimate region chosen for establishing solar farms within Indonesia's total land area of 1,892,555 km^2. The overall potential is calculated by multiplying the solar farm's average yield by the panels' efficiency and performance ratio, as detailed in Table 4. The solar capacity is taken with the assumption that sun hour is equal to 10 hours per day.

Table 4. Solar Panel Energy in Indonesia.

Power Type	Average Power Generation per day (kWh/m^2)	Average Solar Capacity (MW/km^2)	Geographical Potential (km^2)	Total Generation (GW)
Solar Panel	0.54	54	151,404	6608

Since 8% of Indonesia's overall land area can meet the target of 28 GW, Figure 6 illustrates specific regions suggested for solar farm locations where the matching index exceeds 70%. A total of 43 solar farm sites are distributed across the islands of Indonesia, strategically positioned to help meet the nation's energy demand. Figure 6 shows several areas with high levels of solar radiation (especially in the Sumbawa/Southeast region) have fundamental problems because they are unable to optimize their energy sources due to the lack of electricity network infrastructure in these areas. On the other hand, areas with high electricity needs and better electricity network infrastructure (Sumatra, Java, Kalimantan Island) have lower solar radiation. This can undoubtedly be a consideration for the government in implementing this project.

Solar Power Plant with Grid Lines

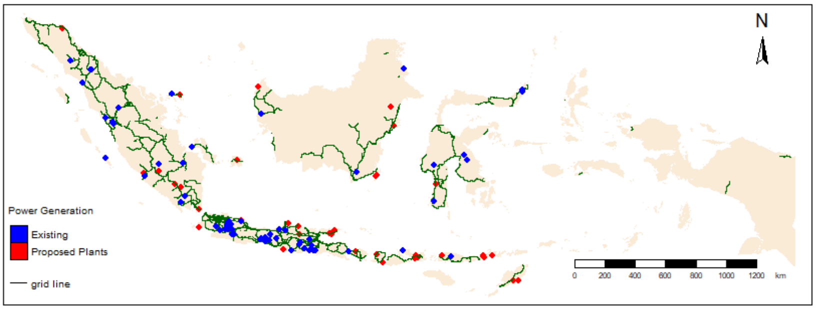

Fig. 6. Proposed and Existing Solar Plants.

4 Conclusion

To meet Indonesia's renewable energy capacity target of 47 GW for electricity generation in 2030, of which 19 GW is existing capacity, an additional 28 GW is needed, which can be met by building 43 solar power plants, with an average power of 0.54 kWh/ m2, at several locations in Indonesia based on constraints and several criteria using the Multi Criteria-Decision Analysis method assisted by AHP (Analytic Hierarchy Process). This process involves spatial data for each criterion with a comparison matrix weighting. For irradiation data, since the spatial data obtained is still missing data, interpolation is needed to overcome this. In this study, Inverse distance weighting or IDW method was used due to its simplicity and fast computation. Future studies are expected to involve more extended history data with computational risks to obtain more accurate heat radiation estimation data. Electricity demand projections can have high flexibility with many influences beyond estimates, such as inflation, pandemics, and changes in consumer behavior.

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