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Application of GIS in Determining Suitable Locations for Green Industrial Development Based on Renewable Energy in Sumatra

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ABSTRACT

Industry plays a major role in supporting national development. In 2020, the non-oil and gas industrial sector contributed 20% or approximately IDR 19.52–23.01 trillion in domestic investment in Indonesia. The industrial sector also contributed the largest share of Indonesia's exports, accounting for 80.3% of total national exports. On the other hand, rapid industrial growth has negative impacts on the environment, such as global warming. Therefore, Indonesia is committed to minimizing the environmental impact of industry by adopting the green industry concept. In planning the green industry, it is essential first to identify areas suitable for development. This study aims to determine the suitability of green industry areas. This study introduces a new spatial modeling approach to assess industrial suitability by incorporating solar energy potential in Sumatra.The study applies the Multi-Criteria Decision Analysis (MCDA) method, integrating statistical data and remote sensing data based on geospatial approaches. The results show that the solar energy potential across Sumatra varies between 153,772 W/m² at minimum capacity and peaks at 204,382 W/m². The highest green industry suitability is found in the Bangka Belitung Province, covering up to 85% of its total area. It is expected that this research can be used by policymakers in planning green industry development, particularly in Sumatra Island.

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1. INTRODUCTION

Industrial zones play a vital role in Indonesia, especially in the economic sector (Yang and Khan, 2022). According to the Indonesian Budget Study Center, the industrial sector has also supported both Domestic Investment and Foreign Direct Investment in Indonesia (Zahara & Octavia, 2021). In 2020, the non-oil and gas industrial sector contributed between IDR 19.52–23.01 trillion, or around 20% of total Domestic Investment in Indonesia (Ministry of Industry, 2020a). Additionally, the industrial sector accounted for the largest share of Indonesia's exports, reaching 80.30% of total national exports (Ministry of Industry, 2021).

Rapid industrial growth must be held accountable for the decline in air quality over the past 150 years, posing a threat to the surrounding environment (Hosseini & Shahbazi, 2016; Zeng & He, 2019; Zheng et al., 2020; Anggraini et al, 2025). This environmental issue is not only dependent on the emissions or pollutants released but also on the energy consumed (Liu et al., 2020). To minimize these environmental impacts, the Indonesian Ministry of Industry has taken steps to promote green industry through the implementation of renewable energy (Ministry of Industry, 2020a). This initiative also supports the national energy supply, as Indonesia is the largest energy consumer in Southeast Asia, with a consumption of 1033.24 million barrels in 2015 (IRENA, 2017).
One of the renewable energy sources suitable for industry is solar energy (Ashour et al., 2021; Singh et al., 2022; Dhingra et al., 2023). Indonesia has great potential for solar energy due to its location along the equator, resulting in year-round sunlight (Ihsan et al., 2021). According to the Ministry of Energy and Mineral Resources (ESDM, 2023), Indonesia's solar energy potential reaches more than 3200 Giga Watt (GW), yet only 200 Mega Watt (MW) has been utilized. For industrial purposes, Solar Power Plants have advantages over other renewable energy sources because they can be implemented on a micro scale, such as rooftop installations for households (Hong et al., 2017; Ihsan et al., 2021; Sakti et al., 2022).

The first study by Bathrellos et al. (2011) aimed to determine the best industrial locations by considering disaster and geographical parameters. Its strength lies in the use of the Analytical Hierarchy Process (AHP) for weighting each parameter, combined with GIS. The second study is by Ziaei et al. (2012), which examined industrial suitability areas in Birjand, Iran. The strength of Ziaei et al. (2012) lies in the integration of the Fuzzy Multi Criteria Decision Analysis (FMCDA) method and Geographic Information Systems (GIS), enabling the identification of the most suitable locations for industry. Ziaei et al. (2012) focuses solely on geographical aspects, such as slope, land cover, agricultural land, faults, soil type, and others. The third study by Liu et al. (2020) analyzed environmental and economic impacts on industrial areas. Liu et al. (2020) study's strength is the consideration of environmental emissions by integrating Gross Domestic Product (GDP), energy consumption, and pollutants (solid waste, water pollution, and air pollution) using a Computable General Equilibrium (CGE) model. The fourth is a study by Adil et al., 2021, which modeled industrial zone suitability using a GIS-based method, namely Boolean Maps. This research has the advantage of considering both environmental and socio-economic factors. The fifth study is by Nuhu et al. (2022), which modeled the suitability of eco-industrial park locations using several Integrated Multi-Criteria Decision-Making (IMCDM) methods. Nuhu et al. (2022) used data on roads, residential areas, industries, water boundaries, land cover, land surface temperature (LST), slope, and existing

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industries. In general, no studies have modeled suitable industrial zones while considering renewable energy potential to support green industries. Therefore, based on the three studies mentioned above, this research aims to integrate spatial analysis methods to determine suitable industrial zones in Sumatra, Indonesia, by considering renewable energy potential.

The objective of this study is to identify suitable industrial locations in Sumatra Island, Indonesia, by considering geographical, disaster-related, and renewable energy aspects. Indonesia's abundant renewable energy potential serves as a motivation in this study to support the green industry. It is expected that this study will contribute to the development of environmentally friendly green industries through the use of renewable energy.

2. LITERATURE REVIEW

Geospatial technology continues to evolve alongside the advancement of time. With geospatial technologies or GIS, spatial analysis can be easily conducted to generate geospatial information (Nuhu et al., 2021). Geospatial information refers to any form of spatial-based data, including location, shape, and the content of features both above, below, and on the Earth's surface (Rahim, 2020). In this study, the primary technology used is remote sensing. Remote sensing is a space-based technology that utilizes electromagnetic energy to acquire data from the Earth's surface and its surrounding atmosphere through a distant sensing system (Li et al., 2008; Elachi & Van, 2021).

According to regulations by the Ministry of Industry (2020b) of the Republic of Indonesia, industry is defined as an economic activity that processes raw materials into other products with higher value. Furthermore, the regulation (Ministry of Industry, 2020b) states that the selection of industrial estate locations must consider several principles: spatial plan suitability, availability of industrial infrastructure access, environmental friendliness, efficiency, business security and comfort, and acceleration of industrial development distribution and equity. Based on these criteria, industrial site suitability modeling can be carried out using geospatial technology.

Several previous studies have determined industrial site suitability using spatial analysis. These include studies by Bathrellos et al. (2011) in urban areas of Central Greece, Ziaei et al. (2012) in Iran, Liu et al. (2020) in China, Adil et al. (2021) in Iraq, and Nuhu et al. (2022) in Malaysia, among others, which integrated geospatial data to determine optimal locations for industrial development. In general, these studies considered geographical factors for industrial accessibility and disaster-related factors to minimize potential losses from natural hazards. In this study, the concept of the green industrial site suitability is developed by integrating the spatial distribution of renewable energy sources as an energy supply for industries, particularly in Sumatra Island.

Green industry originates from the green economy concept, which serves as a pathway toward sustainability (Barbier, 2012). Green industries offer various benefits: socially, they can improve the local economy; economically, they can enhance business performance by adopting environmentally friendly systems; and environmentally, they can reduce pollutants released into the surrounding ecosystem (Reza et al., 2017).

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3. METHOD

3.1 Data

The data used in this study are presented in Table 1. In general, based on its stages, the data can be divided into three categories: data for industrial suitability modeling, data for Solar Power Plant suitability modeling, and data for green industry suitability modeling. The method to be used is Multi-Criteria Decision Analysis (MCDA) with equal weights assigned to each parameter. This study considers the site suitability for industry (by integrating the geographics and disaster risk analysis) and solar potential energy.

Table 1. Data used in this study

No.	Stage	Data	Sources	Spatial Resolution	Temporal	Reference
1.	Industrial Suitability	Land Cover	ESA	10 m	2021	(ESA, 2021)
2.		River	Digital Chart of the World	Vector	2022	(DCW, 2022)
3.		Road	Digital Chart of the World	Vector	2022	(DCW, n.d.)
4.		Flood Risk	National Agency for Disaster Countermeasure	100 m	2021	(BNPB, 2021)
5.		Earthquake Risk	National Agency for Disaster Countermeasure	100 m	2021	(BNPB, 2021)
6.		Landslide Risk	National Agency for Disaster Countermeasure	100 m	2021	(BNPB, 2021)
7.		DEM	USGS	30 m	2000	(Farr dkk., 2007)
8.		Administrative Data	Geospatial Information Agency	-	2020	(GIA, 2020)
9	Solar Power Plant Potential	Shortwave Radiation	Terra Climate	~4 Km	2021	(Abatzoglou dkk., 2018)
10		Aerosol Optical Depth	Terra & Aqua MAIAC	1 Km	2021	(Lyapustin dkk., 2018)
11		Precipitation	Terra Climate	~ 4 Km	2021	(Funk dkk., 2015)
12		Land Surface Temperature	Modis	1 Km	2021	(Wan dkk., 2021)
13	Comparison	Industrial Area	OSM	vector	2021	OSM, 2021

3.2 Method

The overall methodology used in this research is illustrated in the flowchart shown in Figure 1. The research process is divided into three main stages: industrial suitability modeling based on geographic, economic, and disaster aspects; solar power potential suitability modeling; and green industry suitability modeling.

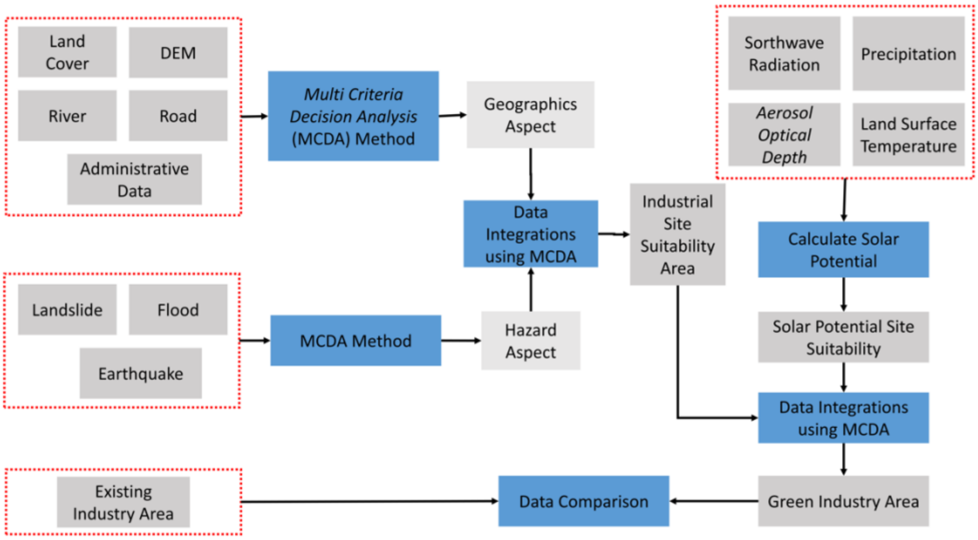

Figure 1. Flowchart in this study

1. Industrial Suitability Modelling

In the initial stage, a model is developed to determine suitable locations for industrial development. The parameters used to assess industrial suitability are divided into two categories: physical aspects and disaster risk aspects. Parameters used to evaluate physical aspects include land cover, elevation, slope, distance from the road network, distance from river networks, and distance from urban centers. Disaster risk assessment is carried out using earthquake, flood, and landslide indices obtained from the disaster risk index calculations by Indonesia's National Disaster Management Authority. After identifying the parameters used for assessing industrial suitability areas, a classification and weighting process is applied to all parameters based on Table 2.

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Table 2. Classification and Weighting

No	Parameter	Class	Score	Weight
1.	Slope	<2	4	0.079
		2-5	3	
		5-8	2	
		8-10	1	
		>10	0	
2.	Elevation	<300	4	0.044
		700–300	2	
		>700	0	
3.	Distance from the River Network	>800	4	0.027
		600–800	3	
		400–600	2	
		200–400	1	
		0–200	0	
4.	Land Cover	Barrens Area	4	0.052
		Paddy Field / Plantation	3	
		Forest	2	
		Built-up Area	1	
		Water Bodies	0	
5.	Landslide Risk	Low	4	0.159
		Medium	2	
		High	1	
6.	Earthquake Risk	Low	4	0.219
		Medium	2	
		High	1	
7.	Flood Risk	Low	4	0.229
		Medium	2	
		High	1	
8.	Distance from the Road Network	<200	4	0.105
		200–500	3	
		>500	2	
9.	Distance from the Urban Center	>8000	4	0.086
		6000–8000	3	
		4000–6000	2	
		2000–4000	1	
		<2000	0	

Source: Bathrellos et al. (2011)

2. Solar Energy Site Suitability Modelling

To model suitable locations for Solar Power Plant installations, the solar energy potential of the area must first be calculated. The potential is determined using a meteorological approach, incorporating solar radiation, precipitation, Aerosol Optical Depth (AOD), and Land Surface Temperature (LST) data. The solar energy potential is calculated using equations 1–4 (Principe & Takeuchi, 2019; Sakti et al., 2022), where: Pv (W/m^2) is the hourly potential, R is solar radiation, η_t is the correction factor for LST, η_p is the correction factor for the number of rainy days, η_{AOD} is the correction factor for dust, n is the number of days analyzed, LST (°C) is Land Surface Temperature, NOCTmax is the efficiency threshold temperature for solar cells, Rain is the number of rainy days, and, dan AOD is the amount of dust. The resulting potential represents the average hourly solar energy potential for the year 2021. Once the potential at each

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location is obtained, it is classified into five suitability classes using the natural breaks method. This method is chosen because it categorizes data based on naturally occurring groupings in the results (Jenks, 1967; Sakti et al, 2023).

$$Pv = R\ (1 - \eta_t - \eta_p - \eta_{AOD}) \quad (1)$$

$$\eta_t = 0{,}094\ x\ \frac{\sum_{i=1}^{n}(LST_i - NOCT_{max})}{n} \quad (2)$$

$$\eta_p = 0{,}035\ x\ \frac{\sum_{i=1}^{n} Rain_i}{n} \quad (3)$$

$$\eta_{AOD} = 0{,}035\ x\ \frac{\sum_{i=1}^{n} AOD_i}{n} \quad (4)$$

3. Green Industry Suitability Modeling

The final stage involves integrating the industrial suitability results, based on geographic, economic, and disaster factors, with the solar power potential suitability results. After data integration, the final suitability data is reclassified into five classes using the natural breaks method. This method is chosen for its ability to group data into natural clusters (Jenks, 1967; Sakti et al, 2023). This research will also be verified by comparing the industrial suitability data with existing industrial zone data.

4. RESULTS AND DISCUSSION

4.1 Industrial Suitability Locations

Based on the results of the industrial suitability analysis, the island of Sumatra generally exhibits high to very high industrial suitability. The largest land area falls under the "high" suitability category, covering approximately 156,848 km², followed by the "very high" category with around 116,733 km². Specifically, the provinces with the largest areas in the "very high" category are Riau (34,274 km²), South Sumatra (24,943 km²), and Jambi (16,303 km²). Areas with low suitability are typically those with high elevation or mountainous regions, where access is more difficult, making them less favorable for industrial development. To provide further recommendations for green industrial development, the suitability of Solar Power Plant locations will be assessed to evaluate the energy potential of these regions.

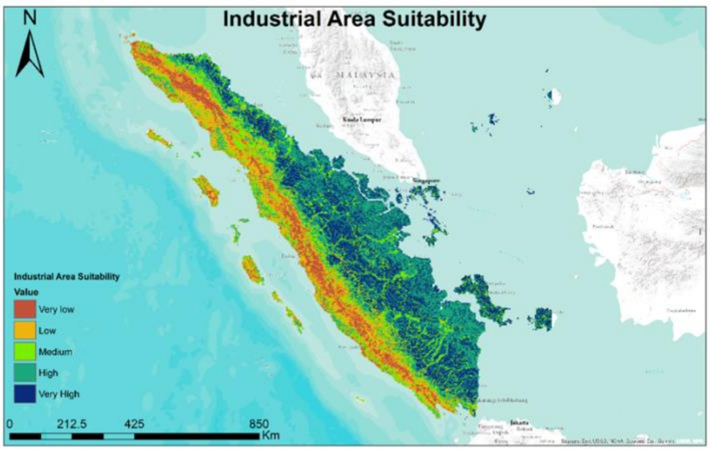

Figure 2. Industrial Area Suitability

4.2 Solar Power Plant Suitability Locations

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The average hourly solar energy potential for the year 2021 is shown in Figure 3. The potential ranges from 153 W/m² to 204 W/m². The lowest potentials are found in mountainous regions due to cloud cover that reduces solar radiation. The highest potential is observed in the eastern part of Sumatra. The province with the highest average potential is Bangka Belitung at 195.322 W/m², while the lowest is in North Sumatra at 171.114 W/m².

The solar energy potential was then classified into five suitability classes, as shown in Figure 4. The results show that South Sumatra has the largest area in the "high" and "very high" suitability classes, covering 81,098 km². Conversely, Riau has the smallest area in the suitable classes, with only 71 km². These suitability results can serve as a reference for identifying areas appropriate for green industrial development.

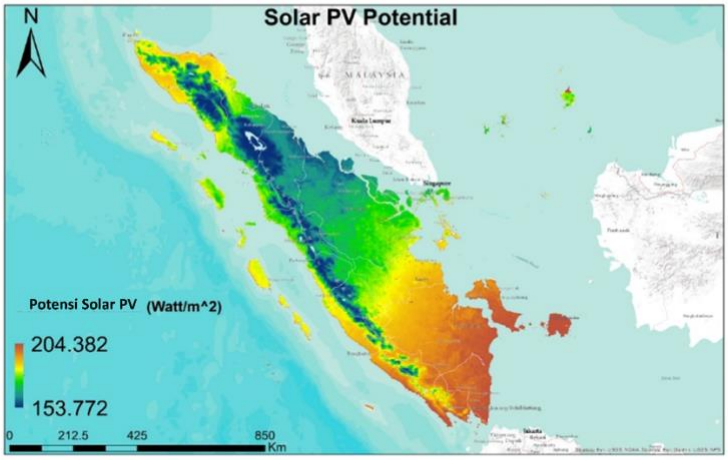

Figure 3. Solar Energy Potential

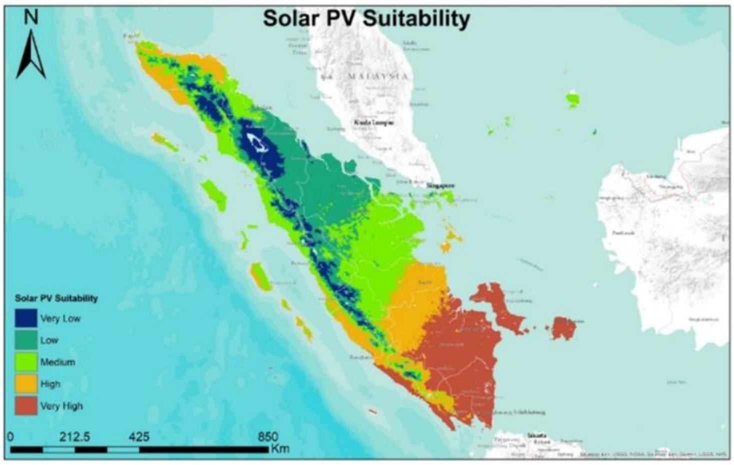

Figure 4. Solar Power Plant Site Suitability

4.3 Green Industry Suitability Locations

The green industry suitability map is presented in Figure 5. As shown, the highest suitability areas are located in the southeastern part of Sumatra, particularly in the provinces of Bangka Belitung, Lampung, and South Sumatra. This is also confirmed by Figure 6, which shows the percentage of land area falling under each suitability class. The provinces of Bangka Belitung, Lampung, and South Sumatra have the highest proportions in the "very high" suitability class, at 85.16%, 61.85%, and 60.69%, respectively.

These three provinces can be prioritized for green industrial development in Sumatra, as they exhibit both high industrial suitability and high potential for solar power. Industries in

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these regions are recommended to install Solar Poower Plant on rooftop systems on their buildings to maximize the use of renewable energy.

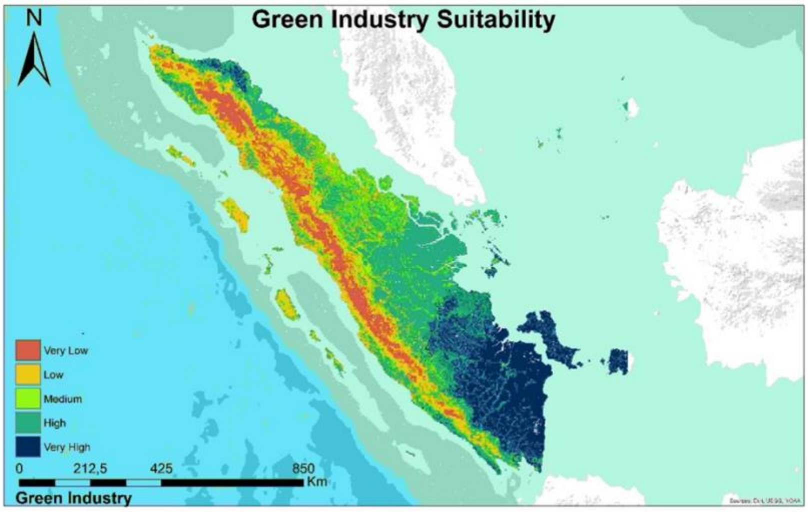

Figure 5. Green Industrial Site Suitability

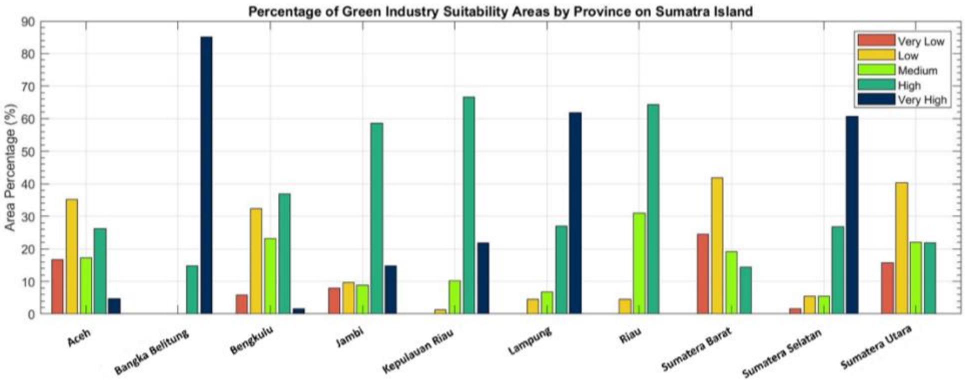

Figure 6. Area Percentage for Green Industrial Site Suitability Based on the Province Area

4.4 Comparison with Existing Industrial Locations

A comparison between the current industrial site data and the suitability model used in this study is presented in Figure 7. Based on the figure, when observing only the industrial suitability, approximately 38.64%, 36.93%, and 21.02% of existing industrial areas fall into the very high, high, and moderate suitability classes, respectively. However, when evaluating the suitability for solar photovoltaic (PV) for Solar Power Plant, the dominant category for existing industrial areas is "low suitability," covering up to 60.33% of the sites. This suggests that while most current industrial areas have considered geographical, economic, and disaster risk factors, they have not yet accounted for renewable energy sources, particularly solar power. Consequently, when looking comprehensively at the green industry suitability map, only 5.95% of the current industrial areas are located within the "very high" suitability class for green industry development.

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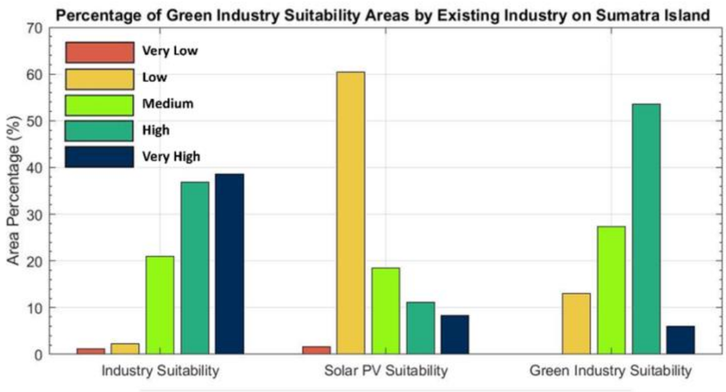

Figure 7. Area Percentage Based on The Existing Industrial Locations

4.5 Limitations and Future Study Recommendations

This study has several limitations. The industrial site suitability was primarily assessed based on physical and disaster-related aspects. Future studies could improve this by incorporating socio-economic factors such as regional income (Utomo, 2016) and population density (Criado et al., 2017), ensuring that new industrial developments contribute to local economic growth and social welfare. Additionally, the solar PV potential assessment in this study was based solely on meteorological factors and did not consider topographic aspects that may cause shading effects (Sakti et al., 2022). Furthermore, the green industry suitability assessment focused only on solar energy as a renewable source. Future research could also explore other renewable energy potentials in Sumatra, such as micro-hydro (Nur et al., 2021), wind energy (Sakti et al., 2023), as well as wave and tidal currents (Ihsan et al., 2021; Anggraini and Santoso, 2023).

5. CONCLUSION

This study identified that the total area of high and very high suitability for industrial development in Sumatra reaches 156,848 km² and 116,733 km², respectively. The province with the largest suitable area is Riau, with 34,374 km². In terms of energy potential, Sumatra's solar energy ranges between 153–204 W/m², with the highest average found in Belitung Province at 195.322 W/m². Based on the classified energy potential, the largest areas suitable for solar PV installation are found in South Sumatra Province, covering 81,098 km².
By integrating industrial suitability with renewable energy potential, Bangka Belitung emerged as the most favorable region for the green industry development, with 85% of its total area classified as highly suitable. The methodology of this research will assist the government and industry in determining potential areas for new industrial development to optimally and effectively utilize solar energy potential. Furthermore, existing industries by considering the solar energy potential modelling. Indirectly, this methodology will also help reduce air pollution and mitigate climate change impacts.

These suitability findings can serve as a valuable reference for planning green industrial development in Sumatra. The government can establish policies to support green industries in Sumatra island. Authorities can create regulations mandating minimum solar energy usage for all industries. The spatial-based analysis provides more detailed information on potential development locations. The study also finds that currently, only 5.95% of existing industries in Sumatra fall within the very high suitability class for green industry, suggesting a

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strong opportunity to designate these sites as pilot projects for green industry development in the region.

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