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A Comprehensive Resource Assessment for Wind Power Generation on the Rural Island of Sibuyan, Philippines

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Abstract: Amid rising energy demands in rural areas, thorough resource assessments for initiatives such as wind power are crucial. This study involves a land resource assessment for wind power generation on the rustic Sibuyan Island in the Philippines, which is currently experiencing an electricity shortage. A comprehensive overview of the island's suitability for wind energy projects is performed via evaluation and analysis using geospatial data and multi-criteria decision making (MCDM). The research results indicate that 50.44% (220.68 km^2) of the island's land area is categorized as 'poorly suitable' since it considers protected areas where developments are not allowed. Only 0.08% (0.35 km^2) of the island can be classified as 'marginally suitable', while 9.15% (40.73 km^2), 36.64% (176.39 km^2), and 0.69% (3.05 km^2) are labeled as 'moderately suitable', 'suitable', and 'highly suitable', respectively. This confirms the potential for wind energy exploration on the island. Delineating the suitability levels provides a foundational framework for stakeholders that enables them to identify optimal sites for wind power, sustain the island's resources, and contribute to the renewable energy landscape of this rural location. Overall, this study, underpinned by data analysis, offers invaluable insights for decision making in wind power development, with the presented framework adaptable to other areas of interest.

Keywords: resource assessment; renewable energy; rural energy resources; GIS; multi-criteria decision making; analytical hierarchy process

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1. Introduction

Energy drives countries' economic growth worldwide and is one of the fundamental necessities for assisting scientific and industrial progress [1]. Throughout history, fossil fuels have been the predominant energy source, and their demand has surged since the Industrial Revolution [2–5]. Due to population growth and increasing urbanization, energy demand will continue to rise, with the Energy Information Administration (EIA) predicting a 50% rise in worldwide power usage from 2018 to 2050. Since fossil fuels such as gasoline and coal emit harmful gases that negatively impact the environment and the economy, a growing global and regional focus is on advancing renewable, clean, and affordable energy [6–9]. Wind power has witnessed a global surge in its deployment for electricity generation, now standing as a well-established renewable and eco-friendly energy source [10,11].

Wind energy is highly appealing due to its availability, cost-effectiveness in operations, maintenance, and production, as well as its nominal environmental effect [12,13]. A key challenge in advancing renewable wind energy systems involves identifying optimal locations to erect giant wind turbines, known as wind farms, that maximize electricity production rates with minimal environmental impact [10]. The determination of suitable vicinities for wind farms [1,14–16] requires a meticulous and comprehensive analysis of a range of parameters and constraints related to land suitability, such as wind characteristics, site elevation, topography, and transportation routes such as highways and railways, urban areas, forested regions, and scenic spots [17,18].

Precise resource forecasting is essential to identify optimal site locations for wind farms [2,5,15,18]. Geographic information system (GIS) software programs, such as ArcGIS Pro and QGIS, are widely utilized to analyze attributes with geospatial components. Its ability to process data and develop databases helps provide crucial reference points for decision support systems in various applications related to renewable energy projects [19]. Multi-criteria decision-making (MCDM) tools are operated to identify the optimum outcome by considering more than one criterion in the selection process. GIS and MCDM can be integrated to effectively identify suitable locations for renewable wind energy sources [19–27]. A comprehensive literature review shows that GIS site selection applications predominantly utilize the analytic hierarchy process (AHP), a prominent MCDM method. The AHP is favored for its ease of use, accessibility, and proficiency in solving multi-criteria problems [28]. It involves breaking down design problems into measurable elements, connecting them using key variables, and evaluating options to achieve specific goals. Amjad et al. (2021) [29] utilized GIS-AHP suitability analysis to examine optimal wind farm locations in Alborz Province (Iran), incorporating structural, geographical, and ecological criteria as prioritized and constraint factors for selecting the best sites. Their outcomes showed that only 20% of the examined region was suitable for wind farm installation. In 2021, Tercan [1] employed GIS-AHP to help identify locations for renewable energy farms in Songkhla, Thailand, considering factors such as wind velocity, elevation, proximity to urban/rural areas, wetlands, airports, and roads. Rediske et al. (2021) utilized AHP to evaluate four regions using six criteria, highlighting the significance of mean annual velocity and wind power density in determining the preferred locations for wind farms [30].

Like many countries worldwide, the Philippines is experiencing a significant rise in energy demands. It strives to reduce its dependence on imported fossil fuels and transition toward resilient, low-carbon, and renewable energy systems [31]. The country holds significant potential for wind energy generation thanks to solid and consistent winds in surrounding water bodies such as the South China Sea, the Philippine Sea, and the Celebes Sea [32]. Currently, the Philippines boasts several operational onshore wind farms, including those in Burgos, with a capacity of 150 megawatts (MW), Caparispisan (81 MW), Pililla (54 MW), and San Lorenzo (54 MW). However, the Philippine government aims to achieve 5 gigawatts (GW) of onshore wind power capacity by 2030 [33], motivating the identification of new wind energy sites. Despite good progress, further studies are needed to optimize site selection, particularly in off-grid rural regions.

This research aimed to conduct a land resource analysis for wind power plants on Sibuyan Island (San Fernando, Cajidiocan, and Magdiwang Municipality, Romblon Province, Philippines) and categorize land suitability across the island for wind energy systems. An integrated GIS-AHP approach was employed to consider a range of parameters and criteria. Five criteria, each with particular parameters, were defined, along with four supplementary policy-restricted parameters. The framework presented in this study can be used in other global locations to identify suitable areas for wind energy plant installations related to environmental, social, and technical factors in land resource assessment tailored explicitly to countryside areas.

2. Materials and Methods

2.1. Study Area

Sibuyan Island is situated within the Romblon Province in the Philippines, with a latitude of 12°23′8″ N and longitude of 122°33′41″ E, as shown in Figure 1. Due to its remote location, science experts worldwide have nicknamed Sibuyan Island "the Galápagos of Asia". The landmass has a land area of 445 km^2 and a populace of 62,745, as reported in the 2020 survey by the Philippine Statistics Authority. It comprises the seaside towns of Cajidiocan, Magdiwang, and San Fernando, as shown in Figure 1.

As per the Romblon Energy Plan for 2018–2040 [34], the primary source of power on Sibuyan Island is diesel power, with a small percentage of electricity supplied by a mini-hydro power plant, which is anticipated to witness a significant rise in highest energy demand, escalating from 1.9 MW in 2017 to 5.4 MW in 2040, with an average yearly escalation of 4.6%. The island's electricity consumption is expected to almost triple, surging from 8625 megawatt hours (MWh) in 2017 to 24,859 MWh in 2040, reflecting a mean annual growth of 4.7%. Even before considering this increase, the island already experiences power outages and a shortage of electricity [34,35].

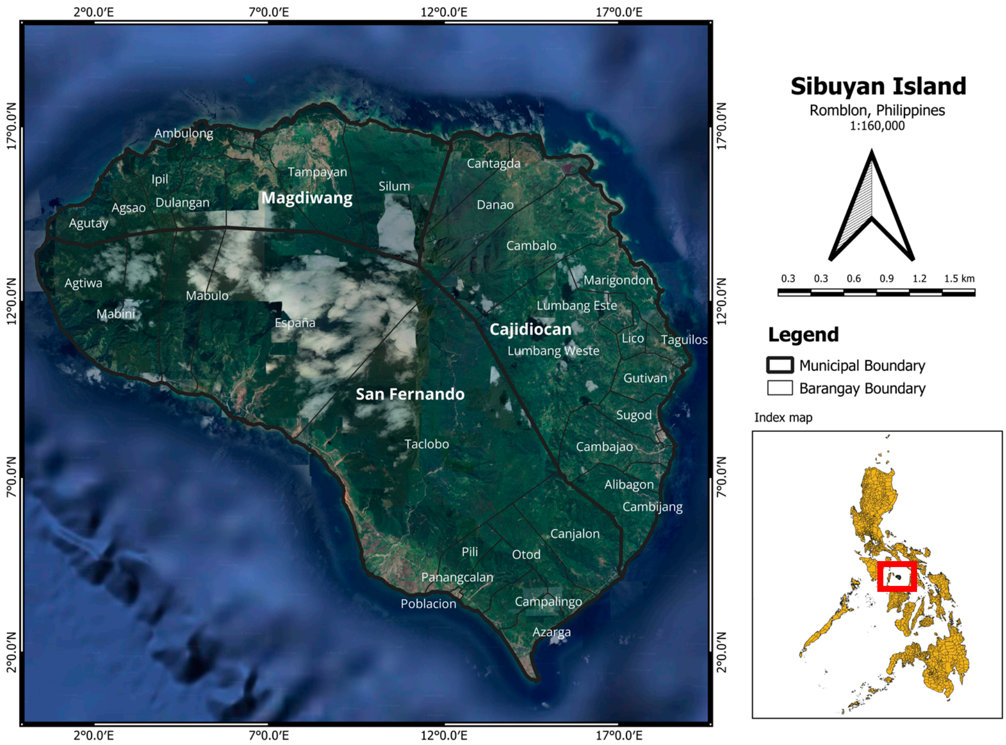


Figure 1. The target study area on Sibuyan Island in Romblon Province in the Philippines. The black lines indicate the municipal boundaries on the island [35].

2.2. Selection of Parameters and Data Gathering

Several methodologies were developed to identify potential rural sites for harnessing wind energy on the island, with a schematic of the process presented in Figure 2. The relevant criteria parameters and essential factors were first defined, followed by an extensive search and collection of data and information from the relevant literature and preceding studies.

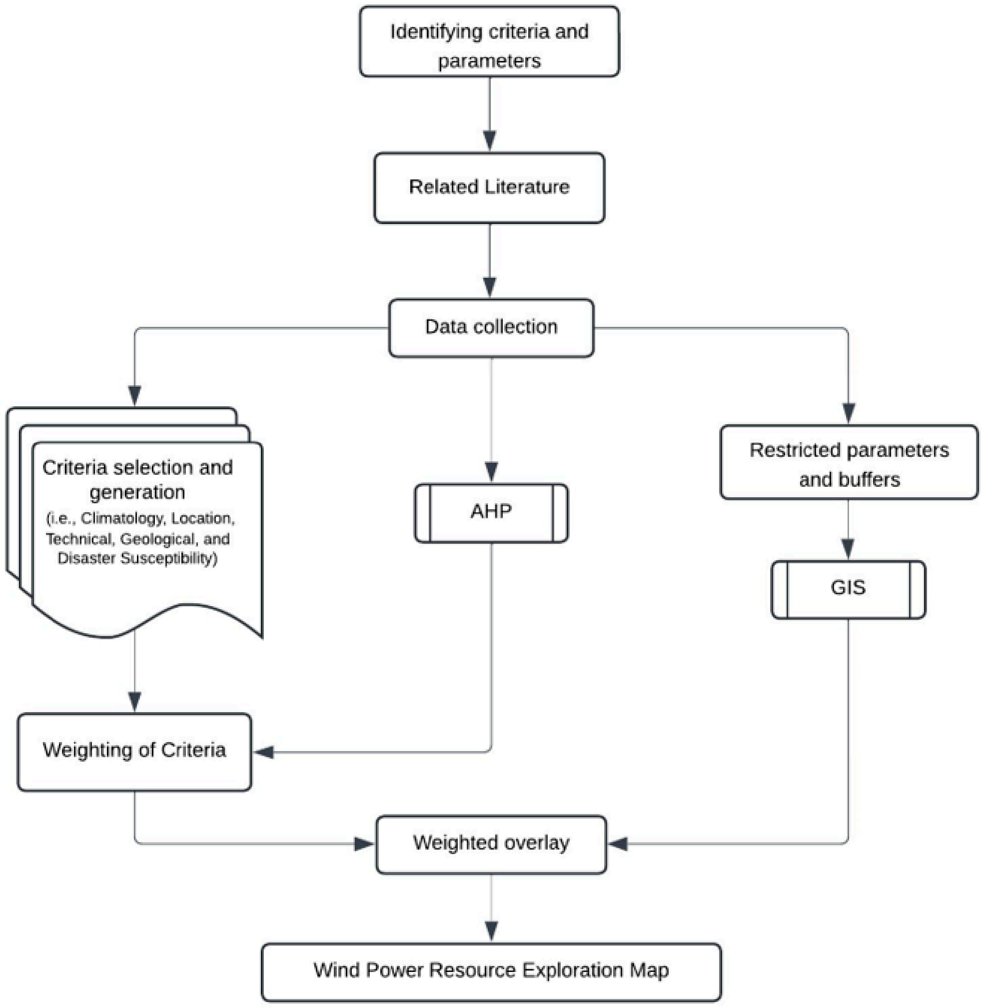


Figure 2. Schematic diagram illustrating the various steps of the methodology used in this study.

The criteria were analytically categorized into five core aspects: (1) climatic conditions, (2) location, (3) geographical features, (4) technical factors, and (5) disaster vulnerability. Certain constraints were cogitated to discount areas that are protected by legal regulations or naturally unsuitable for constructing wind turbines, including proximity to protected areas, ancestral domains, distance from earthquake faults, and locations within bodies of water. Table 1 presents the criteria parameters and the various sources used to obtain them, including data and maps sourced from online platforms, local records, government agencies, satellite imagery, and on-site observations.

Establishing criteria is crucial in identifying areas for wind power plants. These criteria were established with input from experts, including college and university professors, field experts, and researchers, and they are summarized in Table A1 in Appendix A. A group of experts were gathered to examine economic, environmental, technical, and legal frameworks, ensuring a thorough evaluation. The following subsections will discuss each of the five categories of criteria.

2.2.1. Climatology (C1)

Wind speed and wind power density (WPD) are critical parameters for assessing wind resources. Wind speed, expressed in meters per second (m/s), refers to the speed of air movement at a particular area of interest, with variations influenced by altitude and geography [30]. Areas with high wind speeds indicate abundant resources that can foster high wind power generation [36]. In a study by Zahid et al. (2021) [37], areas with mean wind speeds below 3 m/s were insufficient for potential wind farms. According to

EIA, desirable locations for wind turbines exist where the annual mean wind velocity is at least 4.0 m/s for small-scale and 5.8 m/s for industrial-scale turbines. Areas with high wind speeds, typically above 3 m/s, indicate abundant resources suitable for wind power generation at 50–100 m in height. However, small-scale wind energy portable turbines are recommended for low-velocity areas.

Table 1. Identified parameters for spatial planning of wind power plants.

Code	Identified Parameters	Sources of Information	Year	Related Studies
C1		**Climatology Criteria**		
P1	Mean wind speed	Raster Data from Global Wind Atlas Website (https://globalwindatlas.info/en accessed on 5 December 2023)	2023	[2,3,10–12,15,19]
P2	Mean wind power density			[18,19]
C2		**Location Criteria**		
P3	Distance from the road network	Vector file from the Department of Public Works and Highway (DPWH)	2020	[1,5,18,38,39]
P4	Distance from river	Shapefile digitized from Google Earth	2019	[15]
C3		**Geographical Criteria**		
P5	Elevation	Digital elevation model (DEM) with 5 m × 5 m pixels from National Mapping and Resource Information Authority (NAMRIA)	2013	[3,8,12,18,39]
P6	Slope			[1–3,5,8,11,12,38]
P7	Land cover	Vector file form NAMRIA	2020	[1–3,10,11,18]
C4		**Technical Criteria**		
P8	Distance from transmission lines	Spreadsheet file of coordinates from ROMELCO	2022	[2,5,11,12,15,39]
P9	Distance from antenna, radars, and telecoms	Spreadsheet from the Department of Information and Communications Technology (DICT)		[9,15]
C5		**Disaster Susceptibility Criteria**		
P10	Flood susceptibility	Vector file requested from DENR—Mines and Geosciences Bureau (MGB)	2019	[35,40,41]
P11	Landslide susceptibility			[35,41,42]
R		**Restricted Criteria**		
R1	Distance from protected areas	Vector file of NIPAS Map on Geoportal PH (https://www.geoportal.gov.ph/ accessed on 6 September 2023)	2018	[30,35,43,44]
R2	Distance from ancestral domains	Vector file from the National Commission on Indigenous Peoples (NCIP)	2015	[11,15,35]
R3	Distance to faults	Traced from the Map of the National Oceanic and Atmospheric Administration (NOAA)	2017	[45]
R4	Bodies of inside water	Vector file form NAMRIA	2019	[2]

WPD quantifies the wind energy available per square meter (W/m^2) of a turbine's swept area and is calculated by wind velocity and air density at various heights from the ground. Turbines placed in areas with higher WPD will generate more electricity, making it a vital parameter in selecting suitable site factors in evaluating different locations [46]. Ayodele et al. (2018) [47] utilized WPD as a criterion, categorizing sites as 'unsuitable' when the WPD is less than 100 W/m^2, and 'extremely suitable' when the WPD is more significant than 300 W/m^2.

2.2.2. Location (C2)

Some of the most crucial factors to consider for wind farm planning and development include: (i) accessible roadways for turbine transportation [3], (ii) the ecological and economic significance of bodies of water, and (iii) ensuring wind farms are installed away from riverbeds due to safety concerns [2]. While minimizing the construction of new access roads will reduce costs, the proximity of wind farms to established roads can cause noise disturbances and poor aesthetics. As a result, a 500 m buffer zone from major roads is typically maintained [13,16,30,48]. Regarding water bodies, developers have suggested a buffer range of 40–60 m to protect watercourses, including heritage rivers [20].

2.2.3. Geography (C3)

Critical geographic criteria for assessing land resources for wind energy include ground slope, elevation, and land cover, as they all affect installation and accessibility. Lightly sloped terrain is usually preferable [16], and while elevated terrain can capture higher wind speeds, it will also pose construction challenges. The existing land cover influences accessibility, construction, and environmental impact [38]. These criteria are pivotal in guiding effective site selection for wind energy projects.

Choosing suitable wind farm locations is crucial. Difficult accessibility on steep slopes raises costs, with flat areas preferred [16]. Elevated terrain can capture higher wind speeds, but it also has construction challenges. Furthermore, elevations above 2000 m altitude reduce turbine efficiency in line with lower air density [30,49]. Land cover with minimal vegetation is favored to lessen the effect of alterations on the ecosystem [30,50].

2.2.4. Technical (C4)

Technical considerations for selecting wind farm sites include the distance of proposed wind turbines to transmission lines, antennas, radars, and telecommunication towers. Maintaining a safe distance is essential to prevent electromagnetic interference and ensure efficient energy transmission. Previous studies have suggested a minimum distance of 500 m to power transmission lines [15,16], and 600 m to antennas, radars, and telecommunication stations [15].

2.2.5. Disaster Susceptibility (C5)

Land resource analysis for wind farms should exclude areas prone to natural disasters such as cyclones, hurricanes, floods, and landslides [30,51]. Assessing the potential of earthquakes is vital to avoid long-term damage to wind farms and turbines. Landslide susceptibility is equally crucial, as it can significantly affect or destroy the infrastructure installed at wind farms.

2.2.6. Restrictive Parameters (R)

Several crucial restrictive parameters should be carefully considered to preserve the natural and cultural environment. Firstly, safeguarding protected areas is imperative for environmental conservation, with buffer distances to areas of ecological sensitivity and/or cultural heritage [44]. Cultural and religious sites, such as monasteries, churches, and archaeological monuments, should be preserved, with specific safety distances used to ensure the tranquility of sacred areas and the aesthetics for tourism investments [15].

In this study, ancestral domain spaces certified by the government were excluded. Additionally, an optimal distance of 150 m from earthquake fault lines was deployed to mitigate potential damage to the site, with areas having low earthquake risk preferred for wind farms [45]. Maintaining biodiversity and protecting surface water bodies is essential, with buffer zones of 600 m established around rivers and lakes that will also conserve flora and fauna [15]. Addressing these restrictive parameters by minimizing visual, acoustic, and aesthetic impacts will ensure environmental preservation and promote public acceptance.

2.3. MCDM

The AHP is widely employed to develop frameworks that systematically evaluate options to aid decision-makers in complex decision-making processes [26,36,44,52–57]. Within the AHP structure, the main objective is arranged at the topmost of the hierarchy, symbolizing the most appropriate option. Criteria that are best positioned at inferior ranks enable a thorough examination of pertinent particulars for each decision rule. Alternatives or indicators for opinion formers are placed at the lowermost level. In this procedure, each criterion goes through pairwise comparisons to designate weights. Experts engage in these comparisons to assess each option. The outcomes are displayed in a matrix style, and the necessary quantity of comparisons is calculated using a specific formula, which is shown in Equation (1):

$$\text{Number of comparisons} = \text{n}\ (\text{n} - 1)/2 \tag{1}$$

Ten experts in renewable energy, which are listed in Table A1, assessed these comparisons using a pairwise comparison questionnaire to evaluate all elements. The results were computed using geometric means on a Ten-Point Intensity of Importance Scale, guaranteeing a comprehensive assessment of each parameter.

After creating pairwise comparison templates for criteria and alternatives, the next step involved evaluating objective attainment and the relative significance of choices. This stage computes normalized outcomes for each criterion and prospect, leading to normalized vital significant vectors or relative weights. Normalized values for each criterion and option are obtained by distributing each cell by its equivalent column, ensuring a sum of 1 for each criterion and alternative. Obtaining the mean of each row of criteria determines weights, providing relative weights for criteria regarding the optimum objective and alternatives concerning the criteria. These values allow decision-makers to choose the best based on overall weighing, assuming consistency in expert assessments.

$$C = \left\{ C_j \middle|\ j = 1, 2, \ldots,\ n \right\} \tag{2}$$

To expand the pairwise comparison process to multiple criteria (n), an assessment matrix (A) is utilized.

$$A = \begin{bmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & . & a_{nn} \end{bmatrix},\ a_{ii} = 1,\ a_{ji} = \frac{1}{a_{ji}},\ a_{ij} \neq 0 \tag{3}$$

Ensuring the accuracy of AHP results depends on the consistency of pairwise comparisons. Assessing this consistency is crucial prior to making decisions, which can be achieved by estimating the consistency ratio (CR). This step identifies possible problems in the selection procedure. CRs for both criteria and alternative matrices are calculated to guarantee consistency. Successively, essential values such as eigenvalue, consistency index (CI), CR, and normalized values are computed for each criterion or alternative. In the last step of the mathematical process, the relative weights of each matrix were normalized and determined. These relative weights (w) conforming to the maximum eigenvalues (λ_{max}) are determined using Equation (4):

$$A_w = \lambda_{max} \tag{4}$$

Weights can be derived by normalizing any row or column of matrix A, provided the pairwise comparisons are coherent, and A's rank is at most n. The relationships between the matrix entries gauge the consistency of these comparisons. The CI is used to evaluate this consistency, as given in Equation (5):

$$CI = (\lambda_{max} - n)/(n - 1) \tag{5}$$

To measure the consistency of the calculations, the decision-maker can compute the *CR* by dividing the *CI* by the Random Index (*RI*), as demonstrated in Equation (6). This calculation gauges the coherence of the assessments.

$$CR = CI/RI \quad (6)$$

2.4. Overlaying of Maps

The following methodology includes utilizing GIS tools to overlay the resulting maps in an analytical procedure: maps resulting from spatial analysis of different parameters mentioned in Table 1 were further processed and used to create new maps emphasizing significant information in the suitability assessment. This method produced a computation matrix, classifying the site into five suitability levels: 'highly suitable', 'suitable', 'moderately suitable', 'marginally suitable', and 'poorly suitable'. During the weighted overlay analysis, equal intervals with the five levels were used to obtain clear and actionable wind power resource assessment results.

In the context of wind power projects, different suitability levels indicate varying degrees of feasibility for development. 'Poorly suitable' areas are strictly restricted or unsuitable for wind farm installations due to various constraints or regulations. These areas pose significant challenges and are not viable options for constructing wind energy facilities. Moving up the scale, 'marginally suitable' areas indicate minimal potential, with limited feasibility for wind power projects. These locations might have certain limitations or constraints, making them marginally viable for development. 'Moderately suitable' areas show moderate feasibility, suggesting that wind farms could be established here with careful planning and consideration of certain factors. 'Suitable' areas signify good feasibility, indicating that these locations are well suited for wind energy projects, requiring standard planning and implementation measures. Finally, 'highly suitable' zones represent the optimum state for wind farm installations, showcasing the highest level of feasibility and suitability. These areas are ideal for harnessing wind power, offering the most favorable conditions for successful and practical wind energy production projects.

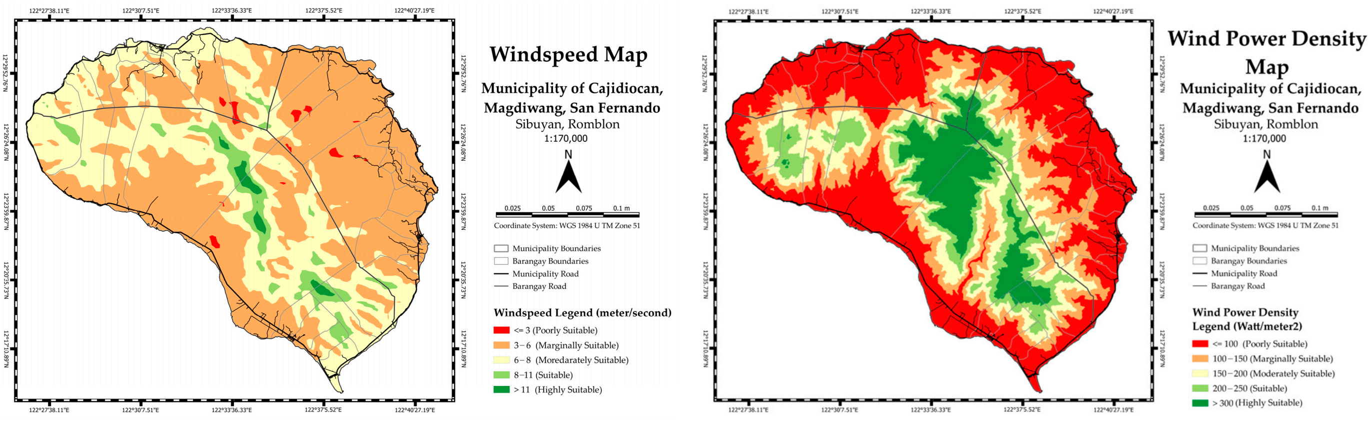
In the final step of the methodology used in this study, a wind energy suitability map was generated by overlapping the parameters and criteria obtained from AHP scores for wind resource assessment. This step integrated the weighted factors and criteria identified through AHP evaluation. Moreover, it incorporated unsuitable regions where wind exploration is not feasible. The maps underwent classification through weighted overlay generation in QGIS. This integrated approach facilitates the classification of suitable areas for wind power plant systems related to environmental, social, and technical factors in land resource assessment tailored to rural areas.

3. Results

3.1. Land Resource Mapping for Identified Criteria

3.1.1. Climatology

The mean wind speed (P1) and mean WPD (P2) are essential parameters within the climatology criteria; they were acquired from the Global Wind Atlas (https://globalwindatlas.info/en, accessed on 5 December 2023) by the Technical University of Denmark (DTU). Site maps of Sibuyan Island illustrating the distribution of each parameter are presented in Figure 3. The mean wind speed map (Figure 3a) classifies the results into the five levels: <3 m/s, 3–6 m/s, 6–8 m/s, 8–11 m/s, and >11 m/s (poorly suitable to highly suitable) at a height of 50 m. On the other hand, based on the map, 13 m/s is the maximum velocity observed in the area. Most of the land falls within the marginally to moderately suitable range, conducive for constructing low-speed wind turbines. Similarly, the mean WPD (Figure 3b) is categorized into five levels from poorly suitable to highly suitable, namely ≤100 W/m^2, 100–150 W/m^2, 150–200 W/m^2, 200–250 W/m^2, and >300 W/m^2, which were utilized by Ayodele et al. (2018) [47]. Suitable and highly suitable zones with WPD values higher than 200 W/m^2 (green) are identified within certain barangays, along with unsuitable regions, with a WPD index less than 100 W/m^2, which is shown in red.

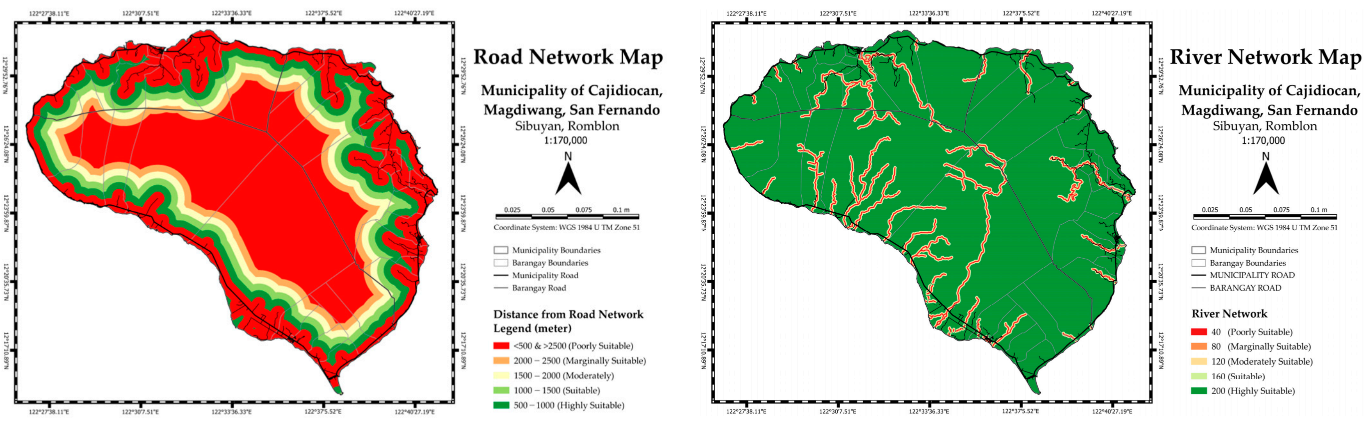


(**a**) (**b**)

Figure 3. Site maps showing the climatology parameters: (**a**) wind speed, and (**b**) wind power density, sourced from the Global Wind Atlas for Sibuyan Island.

3.1.2. Location-Related Criteria

Location-related criteria for Sibuyan Island include road (P3) and river (P4) networks buffered at acceptable distances suitable for wind resource utilization. Figure 4a illustrates the entire island's road networks (around the island's perimeter), with a minimum length of 500 m required between wind farm locations and significant roads. The distances can be classified as follows: <500 m and >2500 m are designated as poorly suitable (red), 2000–2500 m as marginally suitable (orange), 1500–2000 m as moderately suitable (yellow), 1000–1500 m as suitable (light green), and 500–1000 m as highly suitable (green). Figure 4b displays the island's river network, with a proposed buffer distance of 40 m to protect watercourses, including heritage rivers [20]. Distances in the range of 0–40 m are poorly suitable (red), 41–80 m as marginally suitable (orange), 81–120 m as moderately suitable (yellow), 121–160 m as suitable (yellow-green), and over 161 m as highly suitable (green).

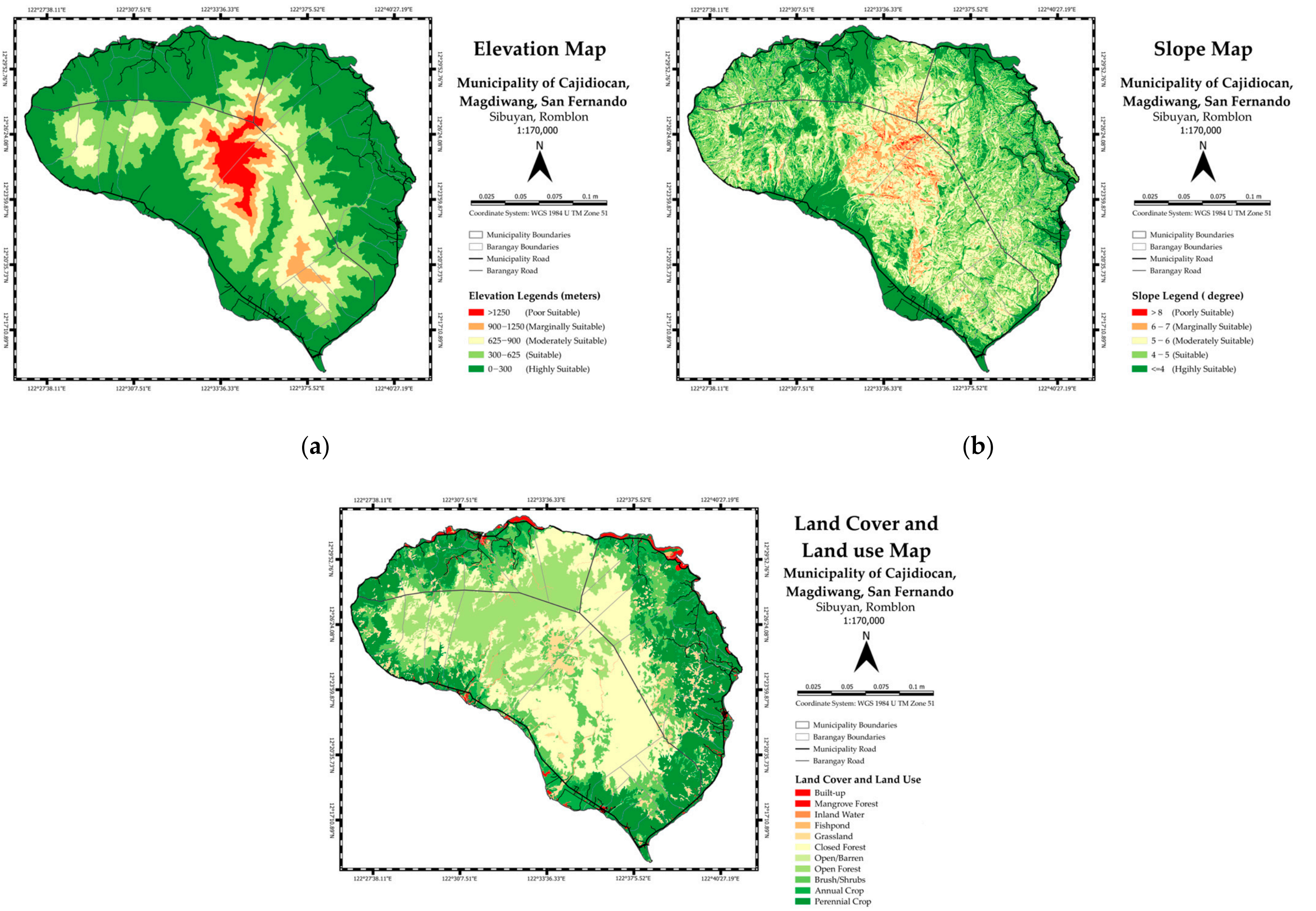


(**a**) (**b**)

Figure 4. Site map showing the location-related parameters analyzed with potential buffer distances: (**a**) road network, and (**b**) river network.

3.1.3. Geographical Criteria

Figure 5 presents site maps of the geographic criteria, including elevation (P5), slope (P6), and land cover (P7). Figure 5a displays the ground elevations across the island, which are categorized into five levels: above 1250 m are classified as poorly suitable (red), 900–1250 m elevations are marginally suitable (orange), 625–900 m elevations are moderately suitable (yellow), 300–625 m elevations are suitable (yellow-green), and elevations below 300 m are considered highly suitable (green). The island's center, Mount Guiting-Guiting, has elevations above 1250 m, resulting in a significant portion of unsuitable terrain.



(**a**) (**b**) (**c**)

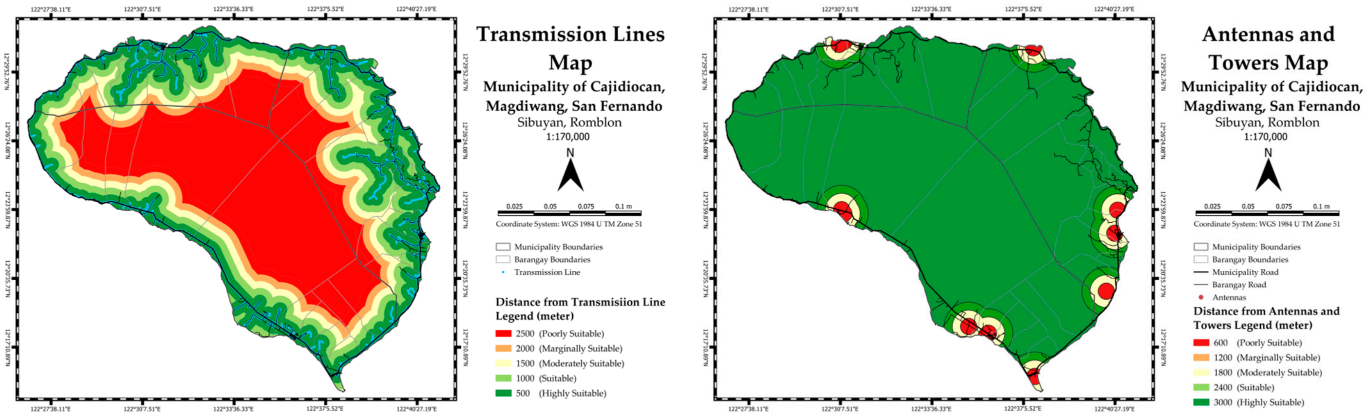
Figure 5. Site maps show the distribution of the parameters for geographical criteria: (**a**) elevation, (**b**) slope, and (**c**) land cover.

Figure 5b presents a map of the slopes across the island, omitting areas with slopes greater than 4.57 degrees (15%) [13]. The categories range from poorly suitable for slopes greater than 8 degrees to highly suitable for slopes less than 4 degrees. Moderately suitable to highly suitable areas are observed on the slope map, indicating favorable conditions for wind farm installation. Figure 5c shows the range of land cover on the island, excluding wetlands, water sources, and settlements [2]. The categorized classes include: built-up areas (poorly suitable; red), mangrove forest (poorly suitable; red), inland water (marginally suitable; orange), grassland (moderately suitable; light orange), closed forest (moderately suitable; yellow), open/barren (suitable; light green), brush/shrubs (suitable; green), annual crop (highly suitable; green), and perennial crop (highly suitable; dark green). Notably, the island's predominant land cover was vegetation, with limited built-up areas, highlighting the island's biodiversity and suitability for wind power projects.

3.1.4. Technical Criteria

Site maps of the critical technical criteria—distances from transmission lines (P8) and distances from antenna, radar, and telecommunication towers (P9)—are shown in

Figure 6. For transmission lines (Figure 6a), a minimum distance of 500 m was maintained to mitigate adverse effects on public health, leading to the following categorization: 2500 m is poorly suitable (red), 2000 m is marginally suitable (orange), 1500 m is moderately suitable (yellow), 1000 m is suitable (yellow-green), and 500 m is highly suitable (green). Areas with high suitability (green) are observed in the island's peripheral regions, coinciding with built-up areas and anticipated electricity distribution. For the island's antennas, radars, and telecommunications infrastructure, a safety distance of 600 m is adopted [15]. As shown in Figure 6b, this criterion was categorized as follows: <600 m is poorly suitable, 1200 m is marginally suitable, 1800 m is moderately suitable, 2400 m is suitable, and 3000 m is highly suitable. Only nine buffered telecommunication towers exist below the safety distance of 600 m with these locations considered poorly suitable.

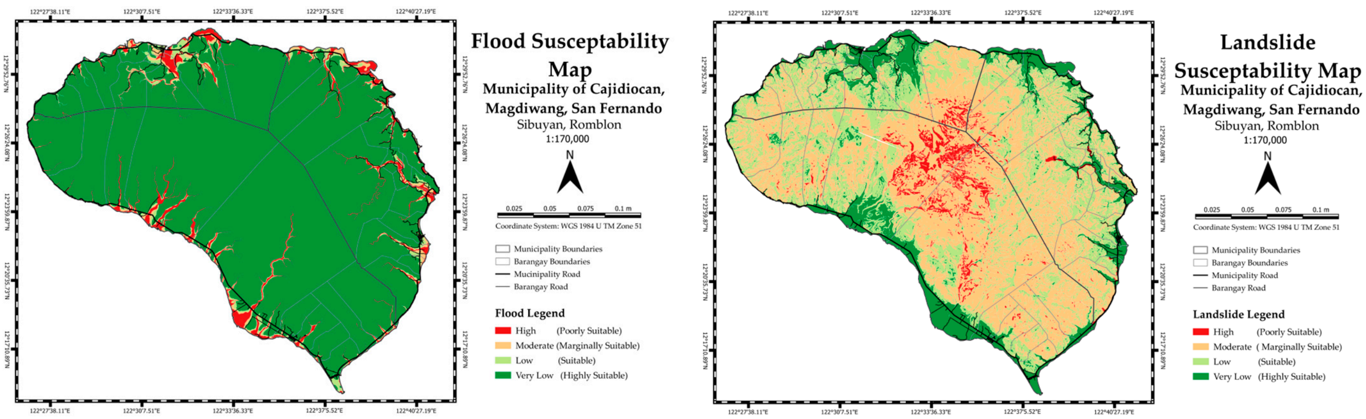


(**a**) (**b**)

Figure 6. Site maps showing the distribution of technical parameters such as distance to (**a**) transmission lines, and (**b**) antennas and towers.

3.1.5. Disaster Susceptibility

Flood (P10) and earthquake (P11) susceptibility were assessed due to multiple past hazard events on the island. Figure 7a illustrates the island's susceptibility to floods, categorized as high (poorly suitable; red), moderate (marginally suitable; orange), low (suitable; light green), and very low (highly suitable; green), which was based on data from Mines and Geoscience Bureau (MGB). Most parts of the island are not susceptible to floods, with poorly suitable areas mainly located in low-lying and/or built-up regions.



(**a**) (**b**)

Figure 7. Site maps showing the distribution of the disaster-related parameters: (**a**) flood, and (**b**) landslide susceptibility.

Figure 7b depicts the island's susceptibility to landslides, categorized as high (poor suitable; red), moderate (marginally suitable; orange), low (suitable; light green), and very low (highly suitable; green). High susceptibility areas are prevalent, especially along road networks, indicating a significant risk of landslides during heavy rains.

3.1.6. Restricted

Figure 8 presents site maps of the restricted areas on the island. Mount Guiting-Guiting Natural Park is located on the island and is recognized as a protected area (R1) according to Republic Act No. 11038, the Expanded NIPAS Act of 2018. A 100 m prohibited area has been established near crucial habitats to safeguard this ecologically sensitive region, creating a development boundary. Figure 8a illustrates the significantly restricted zones associated with Mount Guiting-Guiting. Indigenous communities, specifically the Sibuyan Mangyan Tagabukid, reside within ancestral domains (R2) in Cajidiocan and San Fernando. Due to their cultural significance and legal recognition, these areas were excluded from the land resource assessment for wind power (i.e., red zones in Figure 8b).

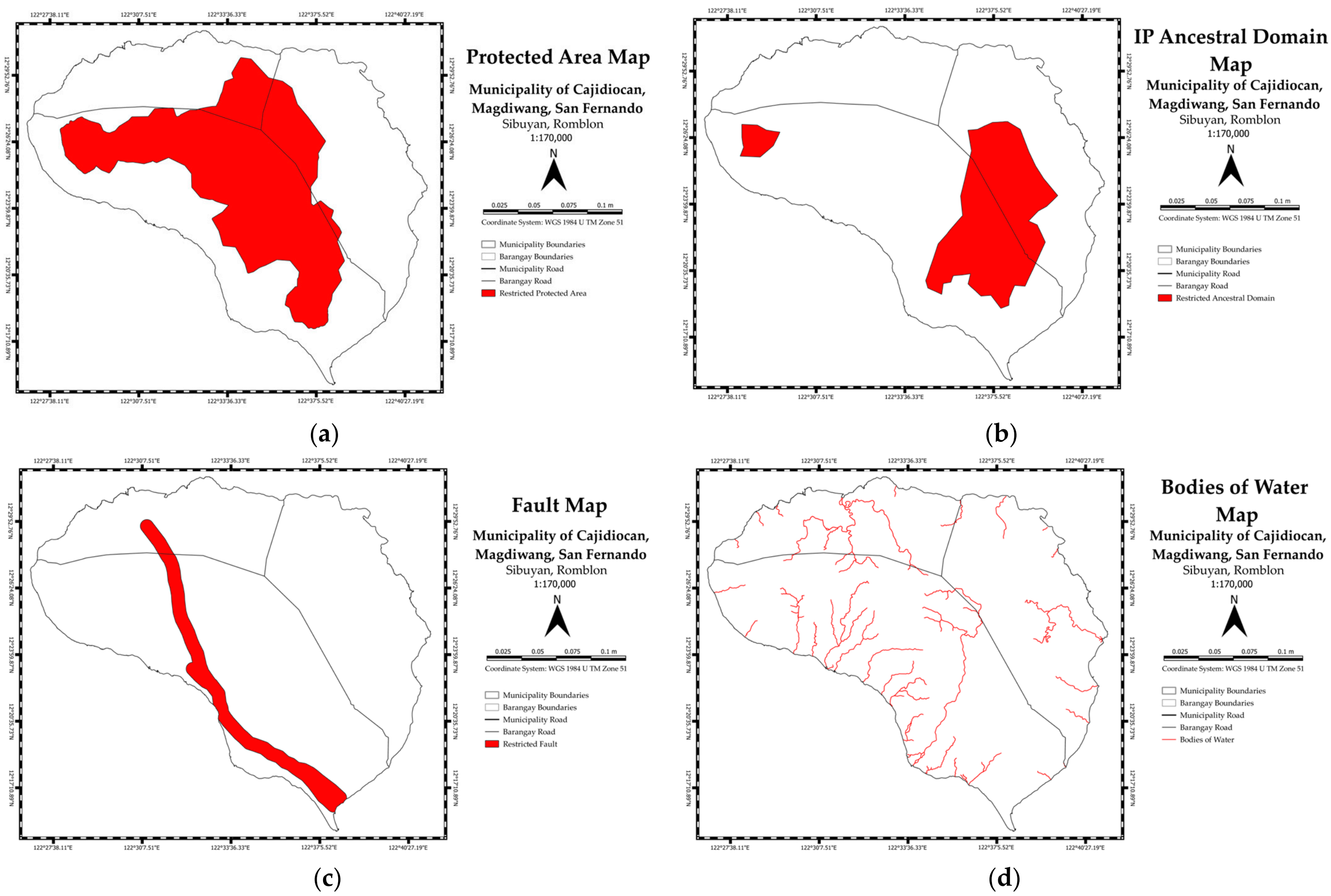


Figure 8. Site maps showing the policy-restricted parameters, including (**a**) protected areas, (**b**) ancestral domains, (**c**) active fault maps, and (**d**) bodies of water.

Another vital consideration is the presence of active faults (R3) in Sibuyan. Using information from the National Oceanic and Atmospheric Administration, a 300 m buffer was applied to pinpoint areas that should be evaded due to their closeness to these faults, as presented in Figure 8c. This precautionary move guarantees the protection and immovability of potential wind power farm systems. Figure 8d presents the river network map (R4) and highlights areas restricted to conserving Sibuyan's intricate river systems, further emphasizing the comprehensive approach to balance sustainable energy initiatives with environmental preservation.

3.2. MCDM-AHP Results

While mapping wind power resources, each parameter underwent a thorough evaluation by assigning feature weights through reclassification and standardization and transforming levels into a scale ranging from one to five indexes. This scale ranged from poor suitability (1) to high suitability (5) for wind power development. The assigned values were determined considering the significance of each level or category. AHP surveys were conducted to ensure precision, involving 10 highly qualified experts specializing in renewable energy and industries. With 5–20 years of experience in energy power plants, these experts contributed to the pairwise comparison process, establishing the relative importance of criteria and assigning relative weights to alternatives.

Following the rigorous pairwise comparison and normalization, the relative significance of each criterion was determined, highlighting their relevance in achieving the whole objective. The consistency of judgments was thoroughly evaluated by employing the CR for alternatives or parameters. The calculations, including CI, CR, and normalized values, were executed to derive the largest eigenvalue, ensuring the quality and accuracy of the AHP's output.

The weights for climatology, location, geology, technical, and disaster susceptibility criteria (Table 2) were then generated using QGIS Desktop (v3.28.10). Utilizing these weights, corresponding index maps for each criterion were generated. This mapping process involved layer clipping, raster conversion, and overlays after calculating criterion weights. The result is a comprehensive assessment of the wind power resource map in the designated area.

Table 2. The corresponding weights for each of the parameters derived from the AHP methodology.

Criteria	Parameters/Factors	Final Weights (%)
C1	P1 P2	80.15 19.85
C2	P3 P4	71.44 28.56
C3	P5 P6 P7	49.00 24.37 26.64
C4	P8 P9	85.51 14.49
C5	P10 P11	26.22 73.78

3.3. Wind Resource Exploration Map

Figure 9 presents site maps following the overlay of parameters associated with (a) climatology, (b) location, (c) environment, (d) meteorology, (e) disaster susceptibility, and (f) restrictions. Each criterion map was classified into five ranks: highly suitable, suitable, moderately suitable, marginally suitable, and poorly suitable. Irrespective of the suitability indexes within other criteria, all areas within restricted zones (Figure 9f) were automatically eliminated from potential site selection due to associated government protocols.

The criteria maps, covering climatology, location, geology, technical aspects, and disaster factors, were assigned equal weights and integrated to generate a wind resource map. The restricted criteria map was then overlain on the other criteria to develop a single site map that is presented in Figure 10, with a classification system ranging from 1 to 5 (with 5 indicating the highest suitability). This combined map comprehensively evaluates wind power resources, offering a respected understanding for decision making and area selection, categorizing areas into highly suitable, suitable, moderately suitable, and not suitable (including restricted parameters).

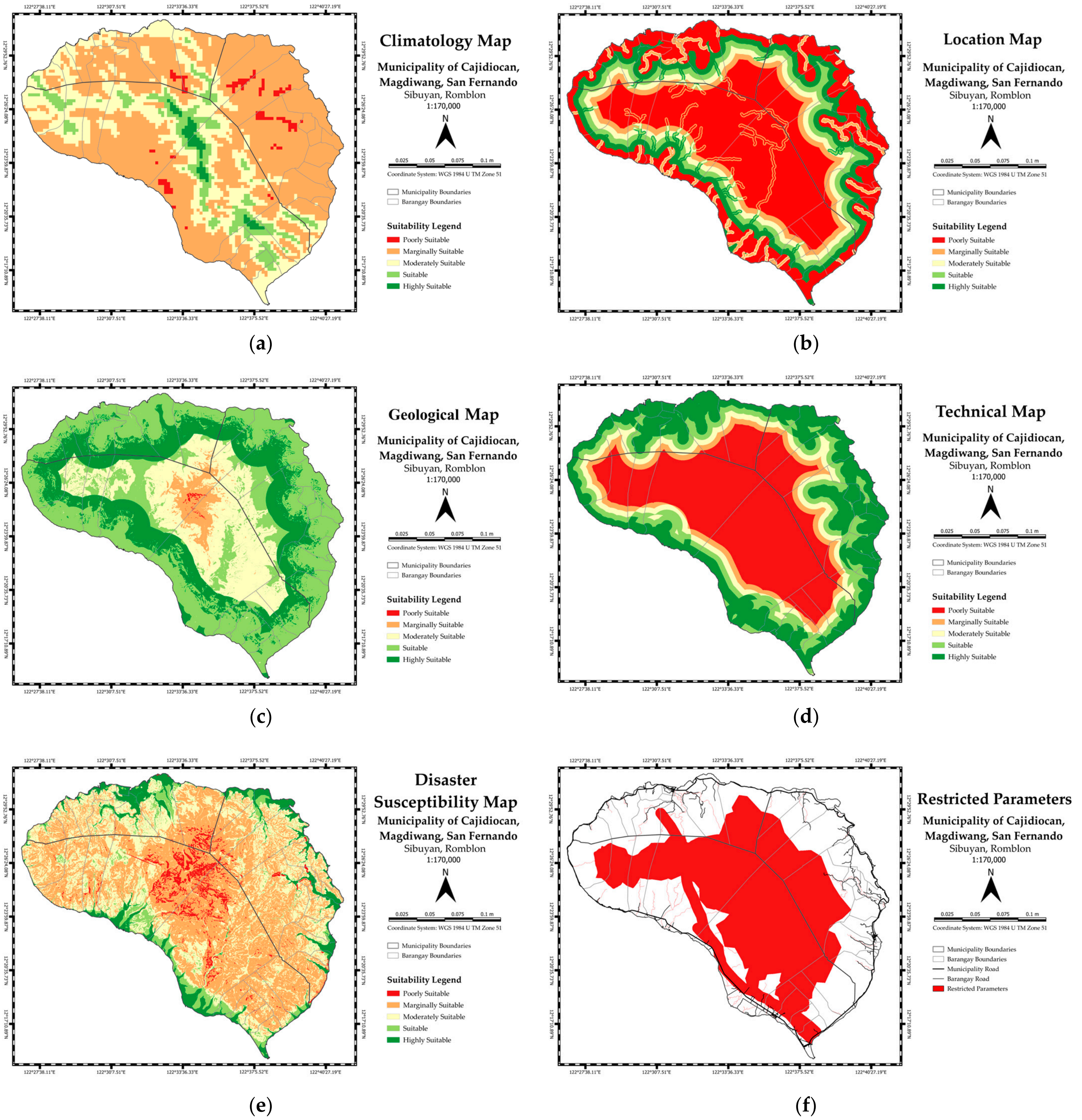


Figure 9. Site maps presenting overlaid parameters within each criterion category: (**a**) climatology, (**b**) location, (**c**) geology, (**d**) technical aspects, (**e**) disaster susceptibility, and (**f**) restricted areas.

Table 3 summarizes the land resource assessment for wind power exploration using percentages and land area (km^2). It indicates that a substantial portion of the studied area is classified as moderately suitable, encompassing 9.15% of the land. Additionally, 36.64% of the land is suitable for wind power development, while highly suitable regions account for 0.69%. However, areas are marked as poorly suitable and restricted, encompassing 50.44% of the total area.

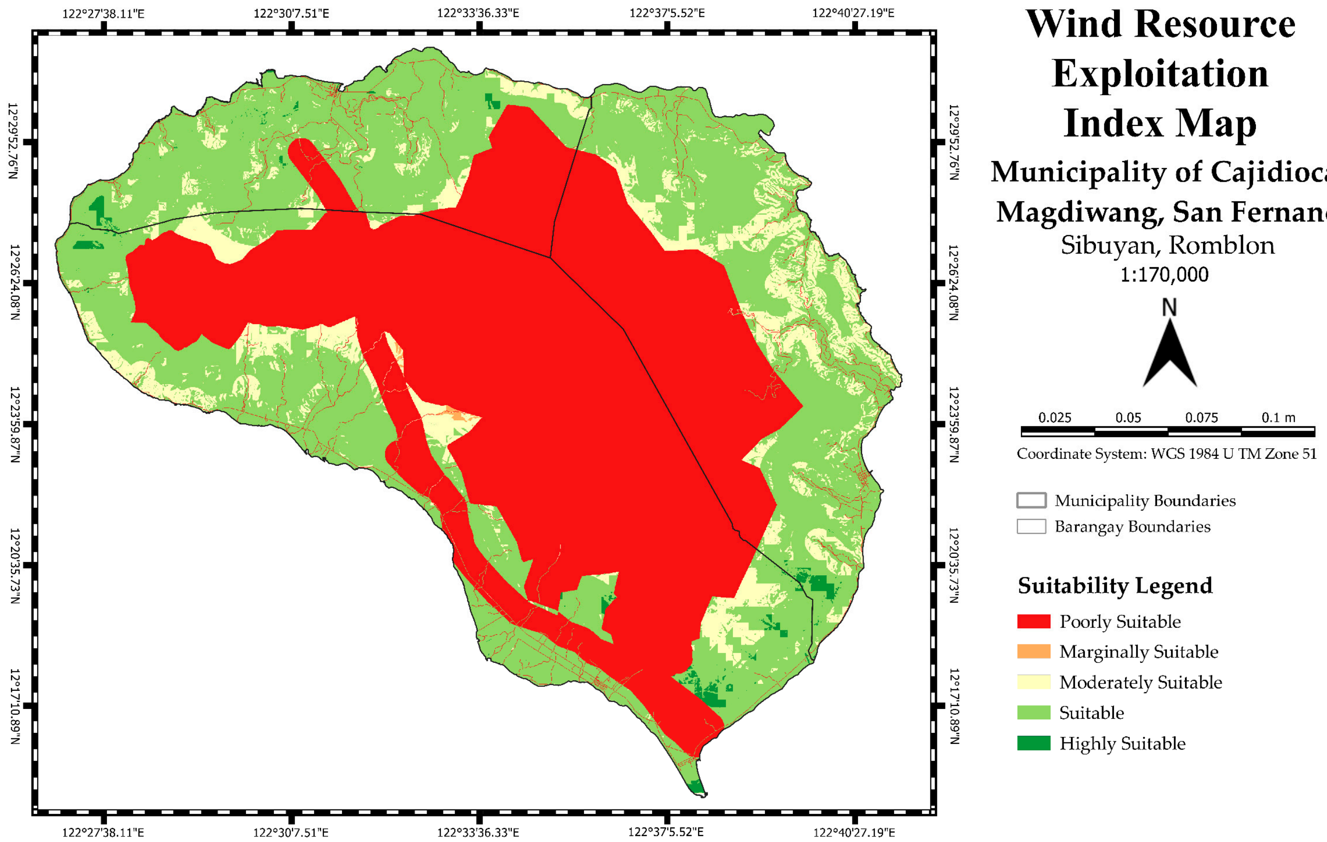


Figure 10. A wind resource map for Sibuyan Island, Romblon, was created with a scale ratio of 1:170,000. This comprehensive map illustrates areas ranging from poorly suitable to highly suitable for wind power assessment.

Table 3. Level of suitability with its percentage and land area for wind power resource assessment.

Level of Suitability and Range of Index Value	Percentage (%)	Land Area (km^2)
Poorly suitable (restricted)	50.44	224.48
Marginally suitable (0–1)	0.08	0.35
Moderately suitable (2–3)	9.15	40.73
Suitable (3–4)	36.64	176.39
Highly suitable (4–5)	0.69	3.05

4. Discussion

The prompt expansion of the global economy has led to a sharp upsurge in energy consumption, resulting in both fossil fuel shortages and environmental pollution. As a result, there is a growing emphasis on developing renewable energy sources. This study focused on Sibuyan Island in the Philippines, which has an inadequate energy capacity, which poses a significant challenge in meeting the increasing future demand, particularly in rural areas. To address this concern, this research utilized GIS and information from government databases and field inspection to assess the suitability of wind energy locations on the island considering criteria such as climatology, location, geology, technical factors, disaster susceptibility, and restricted parameters were considered to understand viable wind energy locations comprehensively.

Several key points emerge when analyzing the results of the land resource assessment for wind power exploration. Most of the area falls under 'poorly suitable' at 50.44%, emphasizing the necessity for strictness concerning environmental protocols. Considering the rich biodiversity and habitats on the island, it is crucial to prioritize policy-restricted areas. Preserving these resources and habitats is vital for the island's conservation efforts.

The 'marginally suitable' areas, while only covering 0.08%, pose challenges and require specialized approaches before being considered suitable. 'Moderately suitable' regions, constituting 9.15%, demand strategic planning and sustainable practices for development. 'Suitable' areas, at 36.64%, offer viable options with great potential but necessitate thorough evaluation and community engagement. Finally, the 'highly suitable' zones, while small at 0.69%, present optimal conditions for wind power generation. These findings underscore the importance of regulatory compliance, targeted investment, and community involvement for successful and sustainable wind power projects.

The categorization of wind turbines according to size, as defined by the National Renewable Energy Laboratory, offers valuable insights into their various applications. Small turbines, with a capacity of up to 100 kW, serve purposes in individual homes, farms, and remote applications such as water pumping and telecommunication sites. Mid-scale turbines, ranging from 100 to 1000 kW, serve purposes such as village power, hybrid systems, and distributed power generation. More giant land-based turbines, with capacities between 1 and 3 MW, are instrumental in utility-scale wind farms and large distributed power setups. Offshore turbines, ranging from 3 to 7 MW, play a significant role in utility-scale wind farms, particularly in shallow coastal waters. Land requirements for onshore wind farms are essential for their successful implementation. Wind farms necessitate vast land areas for turbine spacing, yet the actual land disturbed by these installations remains relatively small. The permanent land requirement is approximately 1 acre per MW (0.00405 km^2/MW), indicating the space needed for the turbines' fixed structures.

Additionally, temporary land requirements for construction and maintenance activities average around 2 acres per MW (0.00810 km^2/MW). The total land requirement for wind farms typically falls within 25–124 acres per MW (0.101 to 0.502 km^2/MW), demonstrating a balance between the extensive spacing needed for optimal wind capture and the limited land area directly affected by the installations. Considering the highly suitable sites for wind power exploration, comprising 0.69% of the total land area (approximately 3.05 km^2), it is estimated that about 753.95 MW of wind power could potentially be generated. However, it is important to emphasize that this estimation is based solely on highly suitable areas and serves as a preliminary calculation. Implementing wind power projects would require a comprehensive feasibility study, considering the temporary land requirements during the construction and maintenance phases and the total land requirements for the entire project. Detailed assessments of environmental impact, local regulations, and community considerations are vital in determining the feasibility and sustainability of harnessing wind power resources in these areas.

Studies conducted within the Philippines, such as the analysis carried out in 2001 by Conover [53] and the establishment of the Philippines Wind Energy Resource Atlas [54], have established the groundwork for comprehending wind energy resources in the country. The most recent research was carried out in 2014 by Silang et al. [55], focusing on wind energy projection based on climate change modeling. These early studies provided valuable insights into wind farm construction and site selection. Over the past two decades, the landscape has significantly evolved. Changes in land use practices and rapid technological advancements have revolutionized the construction of wind farms, enabling more efficient and sustainable energy generation. In addition, the focus has expanded to offshore wind energy resources. Conducting techno-economic assessments [56] for offshore locations has become crucial. By harnessing wind power from offshore locations, nations can significantly enhance their energy capacities in an environmentally friendly manner. These advancements underscore the continuous efforts to adapt to new technologies and explore diverse geographical locations, ensuring the efficient utilization of wind energy resources for a sustainable future in the Philippines.

Integrating GIS-based and MCDM techniques has become instrumental in spatial analyses, particularly in risk and suitability assessments for renewable energy projects like solar and wind. Numerous MCDM methods, including AHP [8,9,11,15,28,49,57–59], fuzzy AHP [16,47,60], integrated AHP [36], analytical network process (ANP) [18], decision-making trial and evaluation laboratory (DEMATEL) [18], adaptive neuro-fuzzy inference system (ANFIS) [19], density-based clustering [29], best–worst method (BMW) [1], weighted linear combination (WLC) [1,5,8,47,49], data envelopment analysis (DEA) [61], fuzzy complex proportional assessment (COPRAS) [61], preference ranking organization method for enrichment evaluations (PROMETHEE II) [15], and spatial decision support system (SDSS) [4], have been applied in wind power resource assessments. Among these, AHP stands out as a robust and widely utilized technique due to its simplicity and effectiveness in solving complex decision problems within specific case studies. Yet, the advent of artificial intelligence (AI) methodologies, including artificial neural networks (ANN) [62], random forest (RF), support vector machine (SVM), and multi-layer perceptron (MLP) [63], has introduced new avenues in wind farm site selection. Despite their potential, the challenge lies in translating the outcomes of AI-driven analyses into a format understandable by non-researchers, given the inherent complexity of these methods. As renewable energy projects expand, bridging this gap between advanced AI applications and practical, accessible decision-making tools becomes crucial for informed and efficient site assessments.

This study represents a significant leap in optimizing wind power on Sibuyan Island via a comprehensive assessment of its land resources through the use of GIS and AHP methodologies. Integrating the enabling and constraining factors through meticulous analysis provides invaluable guidance for wind power initiatives, particularly in a rural island setup. The generated maps are pivotal in validating and predicting wind energy potential. Given the distinctive geography and environment of the island, these validated maps also contribute to strategically selecting sites for solar installations in rural areas. This comprehensive approach reinforces Sibuyan Island's power resilience by thoughtfully incorporating renewable energy resources in a rustic island context.

The evaluation methods employed in this study, specifically the integration of GIS-based analysis and the MCDM approach, offer distinct advantages compared to traditional wind site assessment methodologies. Unlike conventional methods that rely on broader and less precise assessments due to many assumptions, the GIS-based analysis provides a detailed spatial identification of potential wind power sites by efficiently processing large datasets to map the geographical distribution of wind resources, environmental constraints, and land use compatibility. Moreover, the MCDM approach, mainly the AHP used in this study, allows for a more nuanced evaluation by incorporating various environmental, technical, social, and economic criteria as part of the suitability assessment. This comprehensive evaluation framework contrasts with single-criterion decision-making methods that may overlook the complexities of selecting suitable sites for wind power projects. To contextualize the reliability and effectiveness of this methodology, it is imperative to compare it with other prevalent methods in wind site assessment. Traditional approaches often rely heavily on technical feasibility assessments or economic viability analyses without adequately considering the spatial distribution of wind resources or environmental and social impacts.

In contrast, recent advancements have seen the application of various AI techniques, such as ANN, RF, and SVM, to provide sophisticated predictive capabilities, but they can be opaque and complex for non-experts to interpret. While these AI-driven methods offer valuable insights, particularly in processing complex datasets and predicting wind farm performance, they may not always provide the spatially explicit analysis that GIS offers or the intuitive decision-making framework facilitated by MCDM techniques. The approach employed in this study ensures a detailed spatial analysis by integrating GIS with AHP within the MCDM framework. It encompasses many evaluation criteria, making it a more holistic and stakeholder-friendly methodology. Incorporating these methods enhances transparency, engages stakeholders more effectively, and facilitates a comprehensive understanding of site suitability, affirming the reliability and robustness of our approach in the context of renewable energy project planning. On another note, AI integration into the developed methodology could further enhance the comprehensiveness of the assessment.

This study suggests several vital improvements for land resource assessments in wind power exploration. Firstly, updating mapping data using LiDAR technology with a 1 m resolution is essential for accurate spatial information. Secondly, the on-site validation of identified areas is crucial for ensuring their suitability. Thirdly, incorporating additional parameters like land ownership and financial viability provides an inclusive evaluation. Furthermore, it is essential to assess the capacity of the electrical grid to ensure the smooth integration of wind power. Lastly, recognizing the resource-dependent nature of wind power siting, this study recommends the installation of 3–10 automated weather stations for 1–4 years in the area, as real-time data are fundamental in assessing weather patterns [62]. These stations are pivotal in accurately measuring wind resources, providing invaluable data for well-informed decision-making processes. Implementing these recommendations will refine the study's methodology, resulting in a robust, precise, and all-encompassing assessment of land resource suitability for wind power exploration.

Soon, research is expected to make substantial strides, driven by high-resolution geospatial data and the development of spatial data analysis methods. Integrating GIS technology with diverse empirical, theoretical, and analytical models will continue to propel wind power resource mapping advancements, especially in rural areas. Moreover, the renewable energy landscape is evolving toward decentralized power structures and intelligent grids, underscoring the significance of spatial considerations. Consequently, there is an urgent need for future investigations that focus on optimizing wind energy system design through advanced GIS techniques and considering the potential effects of climate change.

5. Conclusions

In conclusion, this study involved a GIS and AHP-based assessment of rural areas, particularly Sibuyan Island's potential for wind power exploration. The results delineated various suitability levels, with 50.44% of the island falling under 'poorly suitable (restricted)' and 0.69% identified as 'highly suitable'. Highly suitable areas were identified as the optimum location for wind farms and estimated to generate 753.95 MW through wind energy; this number could already supplement the island's energy needs and may potentially supply nearby regions. These findings emphasize the need for strict respect for environmental rules, particularly in policy-restricted areas, to preserve biodiversity and habitats. The study's classifications underscore the significance of regulatory compliance, targeted investment, and community involvement for successful and sustainable wind power projects.

Additionally, this study highlighted the importance of updating spatial data using LiDAR technology, validating identified areas on-site, and incorporating parameters like land ownership and financial viability for comprehensive evaluations. Assessing the electrical grid's capacity and establishing weather stations for accurate wind energy resource measurement are also recommended to enhance the assessment.

Anticipated future research endeavors are poised to harness high-resolution geospatial data and advance spatial data analysis methods, seamlessly integrating GIS technology with diverse models. In the context of the renewable energy landscape gravitating toward decentralized power structures and intelligent grids, continuous investigations are vital for refining wind energy system design through advanced GIS techniques, particularly in rural setups. These advancements will be pivotal in shaping the sustainable future of wind power utilization in Sibuyan Island and other rural areas.

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Appendix A

Table A1. Energy and industry specialists utilized pairwise comparison techniques in their field of renewable energy.

Respondent	Expertise/Projects	Agency/Institution
1	Ph.D., Professor (GIS Expert)	University of the Philippines Diliman (UPD) in the Department of Mechanical Engineering
2	Professor (Electrical Engineer)	Bohol State University
3	Wind Substation Engineer (Operation and Maintenance)	VENA Energy
4	Plant Manager	Alterenergy Wind One Corporation
5	Control Operator (Control and Maintenance)	Catingas Mini Hydro Power Corporation
6	Ph.D., Research Professor	University of Las Palma de Gran Canaria, Department of Electronic and Automation Engineering
7	Ph.D., Candidate	Eindhoven University of Technology, Department of Industrial Engineering and Innovation Sciences
8	Associate Professor (Principal Investigator of Several Research Projects about Offshore Renewable Energies)	University of A Coruña Esteiro Campus, Department of Naval and Industrial Engineering
9	Assistant Professor (Expert in Spatial Planning and Renewable Energy Sources)	School of Spatial Planning and Development, Aristotle University of Thessaloniki, Thessaloniki, Greece
10	Ph.D., Environmental Engineering (GIS Expert)	Mapúa University

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