sustainability

Article

Balancing Stakeholders' Perspectives for Sustainability: GIS-MCDM for Onshore Wind Energy Planning

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Abstract: This study supports Jamaica's renewable energy implementation strategies by providing updated wind atlases and identifying suitable locations for future wind farms. Using a GIS-based Analytic Hierarchy Process with multi-criteria decision-making (AHP-MCDM), this research integrates stakeholders' opinions, environmental considerations, and technical factors to assess land suitability for wind energy development. The analysis reveals that Jamaica has the potential to increase its wind power output by 8.99% compared to the current production of 99 MW. This expansion could significantly contribute to offsetting fossil fuel-based energy consumption and reducing carbon dioxide emissions. It identifies sites across several parishes, including Westmoreland, Clarendon, St. Mary, and St. James, as highly suitable for utility-scale wind farm development. By providing detailed spatial information and estimated energy outputs, this research offers valuable insights for energy planners, investors, and policymakers to create sustainable energy policies and advance Jamaica's 50% renewable energy goal by 2030.

Keywords: environmental evaluation; geographic information system (GIS); multi-criteria decision-making (MCDM); carbon dioxide emission reduction; spatial energy systems planning

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1. Introduction

Renewable energy (RE) is one of the fastest-growing power sources worldwide, accounting for the only energy source to see increased demand amidst the pandemic. The year 2020 saw record increases in renewable capacity of 45%, roughly 280 GW. Among the renewable energy sources, solar and wind power marked the highest increases; both realized 50% growth compared to the pre-pandemic era [1]. As onshore wind power becomes increasingly popular, many countries intend to utilize it as an essential energy source since it is globally accessible. The evidence is that, despite the economic decline resulting from the COVID-19 pandemic, wind power has still seen expansion on all continents, as outlined in Renewable Energy Market Update 2021 by the International Energy Agency. By 2020, the global output stood at 743 GW, with onshore accounting for 707.4 GW [2]. Moreover, some countries aiming for carbon neutrality by 2050 see an opportunity to exploit wind power to contribute to decarbonization and climate change-mitigation.

Decreased initial investment costs, with multiple advantages of being environmentally friendly in nature and low social impacts, have led to onshore wind energy's broad appeal to countries with a more than 90% increase in 2020, reaching 114 GW [3,4]. Notwithstanding a downturn, 2021 and 2022 remained higher than the averages of 2017 to 2019 [1]. China continues to dominate expansion, with Europe and the United States trailing behind. While it is difficult to extrapolate the total electrical energy generation from wind for the Caribbean, it is estimated at an average of 10% [5]. On the other hand, Jamaica utilizes 7% of its 19% RE total electricity output from onshore wind farms [6–8]. However, given the gradational growth on 16 October 2018, Jamaica's Prime Minster Andrew Holness advised the government to increase the renewable energy target to 50% while adhering to a regional commitment of 40% with the Caribbean Community (CARICOM) [9].

Consequently, Jamaica's renewable energy is expected to accelerate following global trends driven by the National Development Plan—Vision 2030, which includes the Jamaica National Energy Policy (NEP), the National Renewable Energy Policy, the National Biofuels Policy, and the government's declaration of a 50% goal. Thus, promoting alternative energy sources, including onshore and offshore wind power, is paramount to reducing dependence on fossil fuels. The country spends 7% of its GDP on imported fuel [10], with an average of 5,109,354 barrels of oil imported annually from 2015 to 2019 and 4,487,954 imported in 2019 [11].

Considering the 2018 directives by the Prime Minister, legal framework, and national determination goals, the need arises for expanding RE technologies through coordinated spatial planning. The current legal framework allows for bid procurement, with tenders conducting their environmental impact assessment following the Integrated Resource Plan set by the Ministry of Science, Energy, and Technology, which is then reviewed by the appropriate authorities: the Ministry of Housing, Urban Renewal, Environment, and Climate Change and the Office of Utilities Regulation (OUR) [12].

Several studies have assessed viable wind energy resource development in Jamaica. For instance, Chen et al. (1990) [13] assessed Jamaica's renewable energy potential, including wind energy, and showed appropriate site locations for wind farm installations. Bailey et al. (2013) [14] gave an account of the onshore wind energy installed in Jamaica and the available wind resources. The Petroleum Corporation of Jamaica (2006) carried out a wind resource assessment that led to the development of the Wigton Wind Farm [11]. More recently, in 2017 and 2019, the Ministry of Science, Energy, and Technology plus the Romanian Agency for International Development Cooperation (RoAid) [12,15] evaluated the potential for wind energy in Jamaica using secondary data, which pointed to appropriate spots for installing wind farms, while Chen (2020) [16] explored Jamaica's potential for fossil fuel displacement via on the island. However, these studies neglected to utilize all-island long-term time-series wind threshold with turbines at specific locations for potential wind energy generation. Furthermore, the studies ignored essential environmental considerations in their evaluations, such as excluding protected and unique sites.

Subsequently, this study aims to support Jamaica's current renewable energy implementation strategies by providing spatial information with updated wind atlases to enhance renewable energy output. Furthermore, it will (1) offer options for the suitable locations of future wind farms using current atmospheric, environmental, and geographical data with specific coordinates of potential sites; (2) give a comparative analysis of Jamaican wind studies, considering existing environmental and energy policies—a point lacking in Jamaica's past renewable energy assessments; (3) reflect the opinions of stakeholders and experts on wind farm site suitability; and (4) offer estimated cost reduction of fossil fuel-based energy (FF-BE) provision, with a focus on carbon dioxide emission reduction. The latter addresses the 7.8% reduction in Jamaica's carbon dioxide emissions set for the energy sector present in the Nationally Determined Contribution (NDC) goals under the United Nations Framework Convention on Climate Change (UNFCCC) of 2015 [17,18]. It means instituting unprecedented actions to successfully transition from fossil fuels to renewables by orienting an energy economy fueled by renewables.

This study's approach to wind energy site suitability assessment in Jamaica can be contextualized within the broader landscape of GIS-MCDM applications worldwide. For instance, Latinopoulos and Kechagia (2015) [19] employed a similar methodology in Greece, integrating environmental, technical, and socioeconomic criteria to identify optimal wind farm locations. In Turkey, Aydin et al. (2010) [20] utilized GIS-based AHP to evaluate wind energy potential, considering factors such as wind power, land use, and proximity to roads and power lines. Similarly, Tegou et al. (2010) [21] applied GIS-MCDM techniques in the Greek islands, incorporating unique insular characteristics into their analysis. Additionally, recent studies have continued to refine and apply GIS-MCDM techniques for wind farm-site selection across various geographical contexts. For instance, Gkeka-Serpetsidaki et al. (2021) [22] used this approach to offshore wind farm sites in Greece, considering environmental, techno-economical, and socio-political factors, while Bili et al. (2018) [23] used similar methodologies for onshore wind energy assessment in Poland and Greece, respectively. These studies demonstrate the versatility of the GIS-MCDM approach across diverse geographical and socioeconomic contexts. However, our study distinguishes itself by integrating Jamaica-specific environmental policies, stakeholders' opinions, and long-term wind data series, addressing gaps in previous local assessments. This comprehensive approach not only enhances the applicability of the findings to Jamaica's unique context but also provides a framework that can be adapted to other Caribbean nations facing similar energy challenges and environmental considerations.

An analytical hierarchy process with a multi-criteria decision-making method (AHP-MCDM) has been duly applied to complex environmental schemes requiring vetting socioeconomic, technical, environmental, and supply chain efficiency. The AHP-MCDM approach has been widely accepted and applied in various fields. For example, Afroj (2021) [24] demonstrated its application in municipal services' spatial and functional quality based on citizens' satisfaction. Budak (2019) [25] showed its effectiveness in identifying energy alternatives for a city with ranking preferences. Jato-Espino et al. (2014) [26] demonstrated its application in construction project selection. Rezaei-Moghaddam (2008) [27] used it for ecological risk valuation to select the two competing sustainable agricultural development models. Kiker et al. (2005) [28] presented the available literature and recommended applying multi-criteria decision-making analysis methods in environmental projects [24–29]. The ability of the GIS-based AHP-MCDM to systematically assess RE resources by integrating extensive data, combined with spatial analysis and expert opinion in data analytics, makes it helpful in ranking alternative criteria as a strategy for best results to abet RE development. Thus, it is chosen for modeling onshore wind energy exploration.

This study's integral point is integrating stakeholders' opinions, considering local ecological, geographic, and socioeconomic landscape with real-time and long-term time-series data to derive appropriate land use for further onshore wind development. This approach provides new scientific findings from detailed GIS-based mapping and highlights site-suitable areas for onshore wind energy exploitation compared to all previous works from the research literature in Jamaica. Such detailed site suitability can fast-track the wind energy integration process and aid energy planners, investors, and policymakers in making informed decisions toward creating sustainable energy policies.

While this study focuses on Jamaica's specific needs and context, its methodology and findings have broader implications for the global scientific community. The GIS-based AHP-MCDM approach developed here can be adapted and applied to other regions with different wind climates and geographical characteristics. For instance, similar methodologies have been used to investigate wind energy potential in diverse contexts, from preliminary techno-economic studies of floating offshore wind turbine substructures (Ojo et al., 2024) [30] to evaluating public willingness to pay for floating offshore wind farms in South Korea (Hyun et al., 2024) [31]. Our comprehensive framework, which integrates environmental, technical, and socioeconomic factors with stakeholders' opinions, provides a robust model that can be tailored to various geographical and socioeconomic contexts. Furthermore, the detailed analysis of carbon emission reduction and economic benefits offers valuable insights for policymakers and researchers worldwide, contributing to the global discourse on renewable energy-transition and climate change-mitigation strategies.

The paper has three phases:

1. Firstly, the paper's suitability is explained by outlining AHP-MCDM, utilizing a pairwise comparison matrix with scales of one to nine adopted from Saaty's method [31,32].
2. Secondly, the results are outlined, highlighting the potential for onshore wind energy generation given the available land.
3. Thirdly, it concludes that wind power expansion provides a pathway to aid the mitigation of harmful elements of climate change by increasing wind power output by 8.99% compared to the current production of 99 MW. Consequently, offsetting FF-BE consumption and reducing carbon dioxide (CO_2) emissions are socioeconomic benefits for Jamaica as the country strives to become energy self-sufficient.

2. The Study Area and Onshore Wind Energy

The study focuses on Jamaica, situated in the Caribbean Sea at 18°15′ N and 77°30′ W, covering 10,990 km^2 and comprising 14 parishes. As of 2022, the population stood at 2,961,000 [33]. Despite being categorized as middle-income by the World Bank, a significant portion of the population faces economic challenges [34]. Notably, 99% of the population has access to electricity [8,33], primarily provided by the Jamaica Public Service Company (JPS Co., Kingston, Jamaica) with headquarters at 6 Knutsford Boulevard, Kingston 5, Jamaica, and other suppliers through a comprehensive transmission grid. The transmission system operates at 12 kV and higher, ensuring coordinated and functional power distribution across the island for socioeconomic stability.

Jamaica relies on crude petroleum oil and renewables for its energy needs, accounting for 81% and 19%, respectively. In 2018, the energy demand reached 1,153,885 MWh, resulting in a surplus generation of 4,355,535 MWh, allowing energy exports to neighboring regions [11]. However, the country faces a challenge, as a substantial portion of this energy was derived from imported fossil fuels in 2020 [8,35].

The 2019 electricity generation was 4910 GWh, supplied by 87% non-renewables and 13% renewables. However, the projected increase in demand for 2030 is 9.9% against the business-as-usual (BAU) scenario of 2008, with a generated capacity of 818 MW. Nonetheless, petroleum dependence decreased by 14% from 2008 to 2022, with wind moving in parallel from 1% to 7% within the same period (Richards & Yabar, 2022) [35]. The 2030 expected growth in renewables to 50% means different energy sources are expected to expand, including onshore wind power, which has seen consistent growth since the first installation of 225 kW in 1996 (Figure 1), now amassing nominal and operational capacity of 102 and 99 MW, respectively, by 60 turbines on six wind farms.

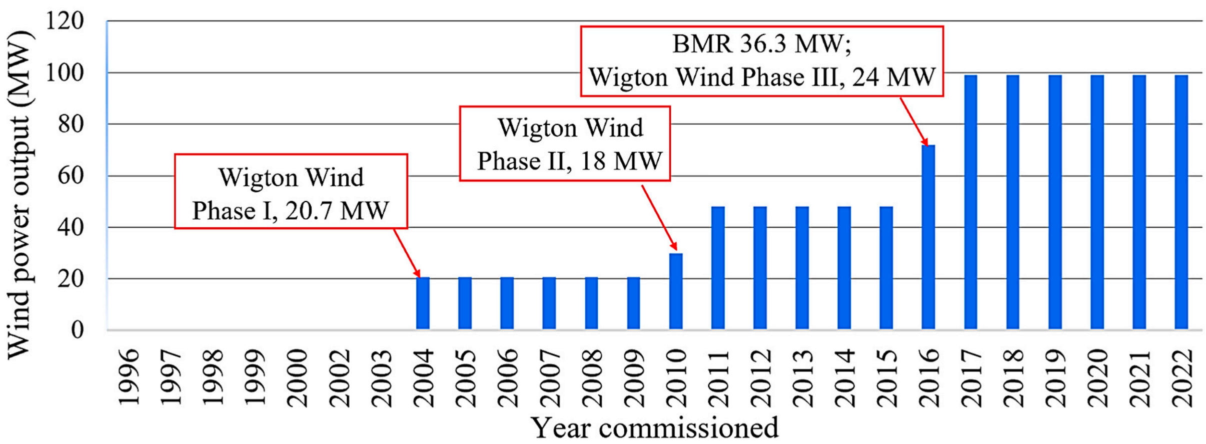

Figure 1. Jamaica's onshore wind power generation capacity since 1996. Information source: THE WIND POWER, 2022 [7].

Jamaica's location in the western part of the Caribbean basin has stable trade winds blowing predominantly northeastern, making it suitable for on- and offshore wind power extrapolation [36,37]. Furthermore, the reduction in production cost of the land-based utility-scale wind farm is encouraging since production cost has fallen from an average of USD 0.068 per kilowatt hour (kWh) in 2001 to USD 0.022/kWh in 2022 [38]. Correspondingly, the global average electricity cost from wind farms is USD 0.051 and USD 0.099/kWh, contingent on location [38]. Thus, the potential expansion of onshore wind power renders opportunities for wind-related technological advances. For example, wind turbine manufacturing and associated parts localize industry resources with spill-over effects of increased job creation in installation, maintenance, marketing, and supporting services, further reducing foreign-based energy procurement.

3. Materials and Methods

3.1. Renewable Energy Multi-Criteria Decision-Making Assessment in Past Studies

Wind turbine-site suitability relies on data collection, geographic characteristics, and technical elements. Advanced technologies like the Global Wind Atlas (GWA) version 1.0 and Geographic Information System-based Analytic Hierarchical Process with multi-criteria decision-making (AHP-MCDM) models expedite precise quantifications for optimal wind power farm locations, incorporating stakeholders' views.

Multi-criteria decision-making (MCDM), extensively applied in research, is crucial in energy-site selection [39]. Previous studies, such as those by Shorabeh et al. (2022) and Charabi and Gastli (2011) [40,41], utilized GIS-based MCDM models for electricity pricing and utility-scale PV farm installation suitability assessment. MCDM defines and rates primary characteristics' weights for site determination [42].

GIS-based onshore wind assessments historically focused on technical, financial, and geological dimensions [43–47]. Tercan (2021) and Guan (2022) [48,49] integrated social dynamics into their analyses, considering environmental, economic, and technical constraints. Notably, this study addresses gaps in existing research by incorporating a comprehensive framework, including factors like land use distance, wake effect, and emission reduction.

Environmental impact concerns, including avian mortality, are addressed with comparisons to other sources [50,51]. Despite the comprehensive factors in previous studies, the inclusion of local experts and community stakeholders is lacking, a gap this study aims to fill. Moreover, this study integrates expert and community opinions, excluding critical ecological areas, to prevent opposition to future projects. Recognizing the pivotal role of local entities, this study calculates theoretical energy potential and greenhouse gas (GHG) emission reduction, aligning with Jamaica's commitment to carbon reduction by 2050.

Using a GIS-MCDM model, this study amalgamates stakeholder and expert opinions on technical, socioeconomic, environmental, and geographical factors. This approach effectively resolves conflicts, considering pros, cons, risks, and rewards. Integrating GIS applications with visual aids ensures a comprehensive decision-making process for renewable energy-site suitability.

Additionally, the study intends to fill a gap in past renewable energy assessments by conducting a comprehensive comparative analysis of Jamaican wind studies, considering existing environmental and energy policies. Furthermore, the study seeks to offer insights into the economic and environmental benefits of wind power expansion, providing an estimated cost reduction of fossil fuel-based energy provision focusing on carbon dioxide emission reduction. The research aims to support Jamaica's renewable energy goals and contribute to sustainable energy policies by addressing these objectives.

3.2. Analytical Hierarchical Process Multi-Criteria Decision-Making Methodology

Caprioli and Bottero (2021) [52] discussed urban-planning challenges and transformations, highlighting multi-criteria techniques for site selection. Notable methods include the Analytic Hierarchy Process (AHP), Weighted Sum Model (WSM), Weighted Product Model (WPM), PROMETHEE, TOPSIS, BWM, and FUCOM [53]. Table 1 outlines these models, detailing their applications and relevance to this study.

Table 1. Description of MCDM models.

Model (Year Invented)	**Primary Tenants of the Model for Decision-Making**	**Applicability and Limitation of the Study**	**Reference**
Analytic Hierarchy Process (AHP) (1970)	The optimal outcome is determined through pairwise comparisons, structured hierarchically to guide solutions logically. This measure utilizes a preference scale from 1 to 9, obtaining ratio scales from discrete and continuous combined comparisons.	AHP is the most appropriate since stakeholders rank the decisions, and it does not demand further influence for weight determination.	[53]
Weighted Sum Model (WSM) (1963)	The methodology takes the optimal solution with the top-weighted sum Nat and uses the less-valued criteria as the minimum.	This model is beneficial when problems share the same criteria. However, with one suitability problem and multiple criteria, the study employs GIS software—ArcGIS 10.8.1. Software for data input to generate images of suitable locations, making it unsuitable for this model.	[53]
Weighted Product Model (WPM) (1922)	This approach finds the optimal solution by multiplying the attribute ratings. The model considers the weight for positive attributes in the multiplying process between attributes, and the attribute score serves as an adverse rank for the cost attribute.	Like WSM, this technique most applies to problems with the same criteria and does not require software.	[54]
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) (1982)	The methodology compares alternatives that outranked each other, considering their variation.	This method is crucial when preference functions have specific definitions but demand multiple tools and restrict the number of GIS-accommodated alternatives—the need for a global comparison results in oversized raster cells. However, decision-making by rank is confined to local stakeholders.	[55,56]
Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS), (1981)	The TOPSIS technique allocates weights and impacts by assigning positive and negative to an ideal solution.	While effective for optimal alternative selection in conflicting criteria, the drawback is the subjective researcher decision and influence of location proximity, which favors economic criteria like road network distance. Stakeholders' input is lacking in other criteria.	[57]
Best-Worst Method (BWM) (2015)	The decision-maker establishes decision criteria through systematic pairwise comparisons of benchmarks. Subsequently, the decision maker selects the best and worst criteria, assigning preferences using a predefined scale from 1 to 9.	The model applies to the study but would alter the decisions or choices of the stakeholders, thereby causing research bias.	[53]
Fuzzy Full Consistency Method (FUCOM) (unknown)	This method evaluates alternatives against criteria, considering weighted importance. It relies on algorithms in pairwise criteria comparisons, with only the necessary $n - 1$ comparisons in the model.	Human thoughts (stakeholders) are constrained in assigning one and zero for ranking alternatives, and the assigned values lack clarity. Alternatives are determined by criteria and attribute ranking, not by assessing alternatives against criteria.	[58]

AHP is a robust arithmetic technique widely acknowledged for criteria comparison and parameter ranking through matrix algebra [59–62]. Employing GIS-based AHP-MCDM, this study determines the relative weights of criteria influencing onshore wind power plant locations in Jamaica. A questionnaire yields responses processed in Microsoft

Excel, with subsequent digitalization and conversion in ArcGIS 10.8.1. Software, producing map layers reflecting defined layers' relative contributions with their weights. The software, version 10.8.1.14362, is from the Environmental Systems Research Institute (Esri), Redlands, CA, USA.

Research design employs two parameter sets: constraint variables (CVs) and suitability factor variables (SFVs). Derived from prior studies and national statutes, CVs include land uses and existing wind farms. SFVs consider visibility impact, slope, resource potential, distance to transmission lines, land cover, resource frequency, existing wind turbines, and stakeholders' attitudes. Table 2 summarizes factors influencing onshore wind farm suitability analyzed in previous GIS models with "X" representing not included and "✓" included, while Table 3 details restrictions in the study's model, while Figure 2 visualizes the AHP-MCDM process. In Figure 2, the red dotted lines form a boundary, representing different data processing segments to derive the suitable areas utilizing the AHP-MCDM technique. Despite methodological pros and cons, GIS-MCDM proves versatile for wind resource suitability in diverse locations [54].

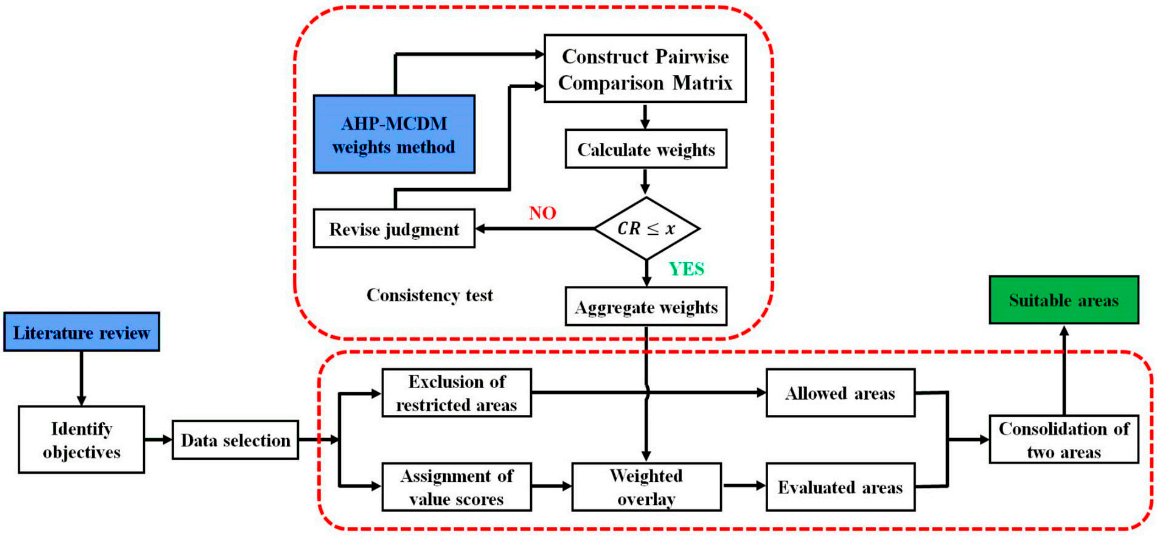

Figure 2. AHP-MCDM process flowchart.

The literature determines SFVs spanning economic, environmental, social, safety, and technical categories (Table 2 and Figure 3). Figure 3's numbers 1–6 show the stages followed in the methodology. This comprehensive analysis involves GIS processing, multi-criteria decision-making (AHP-MCDM), and weighted linear combination for suitability modeling in locating onshore wind farms (OnWF).

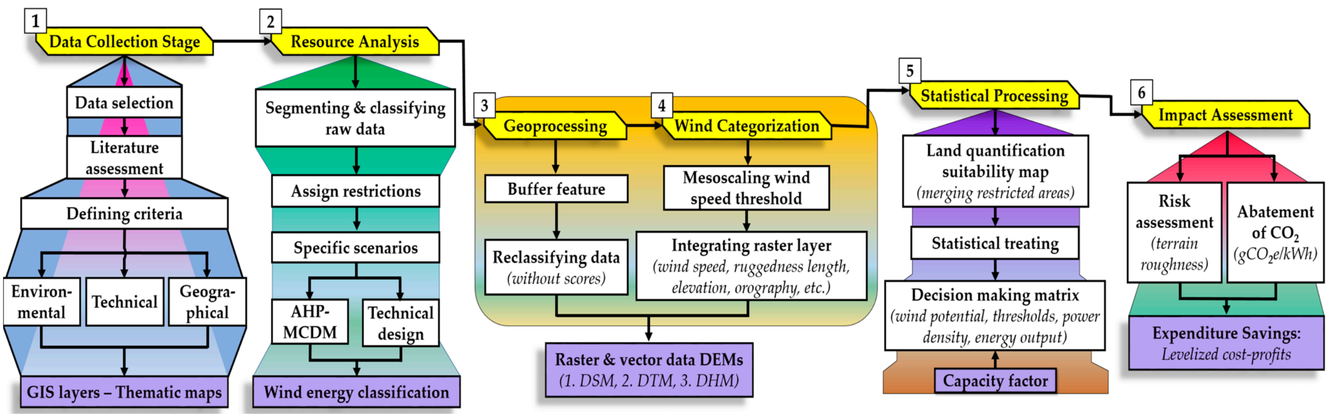

Figure 3. The methodological framework of the study.

Table 2. Parameter references, location, and techniques employed in related studies.

Reference			**This Study**	[44]	[45]	[63]	[64]	[65]	[66]	[67]	[68]	[69]	[69]	**Count**
Variables	**Evaluation Criteria**	**Buffer Distance and Suitability Threshold**	**GIS-MCDM-AHP-LC and WOL**	**GIS-Python Operation of Wind and Solar Resources**	**GIS-MCDM-AHP-WLC**	**GIS Processing of Wind Resource**	**GIS Processing of Wind and Solar Resources**	**GIS Processing of Wind Resource**	**GIS-MCDM**	**GIS-MCDM-AHP**	**GIS Processing of Wind Resource**	**Atmospheric Re-Analysis by Downscaling Wind Climate Data**	**GIS Processing of Wind Resource**	**-**
Constraint variables (*CVs*)	Building (m)	Varies (0–30,000)	✓	✓	✓	✓	X	✓	✓	✓	✓	-	✓	8
	Airport (m)	(1500–10,000)	✓	✓	X	X	X	X	✓	X	X	-	✓	3
	Road (m)	100–10,000	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	9
	Railway (m)	100–500	✓	✓	X	✓	X	✓	X	X	✓	-	-	4
	Waterway (m)	170–200	✓	X	X	✓	X	X	X	X		-	-	1
	Water body (m)	0–200	✓	X	X	X	X	X	X	X	✓	-	-	1
	Land use (m)	200–10,000	✓	✓	✓	x	✓	✓	✓	✓	X	-	-	6
	Special sites (m)	1000–10,000	✓	✓	X	X	X	✓	X	✓	✓	-	✓	5
	Protected area (m)	200–2000	✓	✓	X	X	X	✓	X	✓	✓	-	✓	5
	Existing wind farm (m)	≥170	✓	X	X	✓	X	X	X	X	X	-	-	1
Suitability factor variables (*SFVs*)	Visibility impact (m)	2000–30,000	✓	X	✓	X	✓	X	✓	✓	X	✓	-	5
	Slope (°)	10–30%/10°	✓	✓	✓	X	✓	✓	X	✓	✓	✓	-	7
	Resource potential (GW)	Varies	✓	✓	✓	✓	✓	✓	X	X	✓	X	-	6
	Distance transmission lines (m)	<2000	✓	✓	X	X	✓	X	✓	X	X	X	-	3
	Land cover (terrain roughness) (km)	Varies by location	✓	✓	✓	X	✓	X	✓	✓	✓	✓	-	5
	Resource frequency (wind speed) (m/s)	Varies by location (>3 m/s)	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	-	8
	Population density	Varies by location	X	X	X	✓	X	X	X	X	X	X	-	2
	Wind turbine	Varies by module	✓	✓	✓	✓	x	x	x	x	✓	✓	-	5

Table 2. *Cont.*

Reference			**This Study**	[44]	[45]	[63]	[64]	[65]	[66]	[67]	[68]	[69]	[69]	**Count**
Variables	**Evaluation Criteria**	**Buffer Distance and Suitability Threshold**	**GIS-MCDM-AHP-LC and WOL**	**GIS-Python Operation of Wind and Solar Resources**	**GIS-MCDM-AHP-WLC**	**GIS Processing of Wind Resource**	**GIS Processing of Wind and Solar Resources**	**GIS Processing of Wind Resource**	**GIS-MCDM**	**GIS-MCDM-AHP**	**GIS Processing of Wind Resource**	**Atmospheric Re-Analysis by Downscaling Wind Climate Data**	**GIS Processing of Wind Resource**	**-**
Suitability factor variables (*SFVs*)	Elevation (m)	≥30	✓	X	X	X	✓	X	X	X	✓	✓	-	3
	Road distance (m)	<2000	✓	✓	✓	X	✓	X	✓	✓	X	X	-	5
	Wildlife distance (m)	<1000	✓	X	X	X	X	X	X	✓	X	✓	-	2
	Weibull distribution (a and k)	Varies by location	✓	✓	X	X	X	X	X	X	✓	✓	-	3
	Air density (kg/m^3)	Varies by location	✓	✓	✓	X	X	X	X	X	X	X	X	3
	Stakeholders' opinion	Varies by study	✓	X	X	-	-	-	-	-		X	-	1

Table 3. Restricted areas and buffered distances.

Study Criteria	Variables	Buffered Distances or Thresholds (m)	References
Constraint variables (CVs)	CV_1: Buildings	1000	[63,65,67,68,70]
	CV_2: Airports	1500	[66,71,72]
	CV_3: Roads (major and minor)	500	[63,70,72]
	CV_4: Railways	500	[65,71]
	CV_5: Waterways	200	[71]
	CV_6: Water bodies	200	[72]
	CV_7: Land use	1000	[64,71]
	CV_8: Sensitive sites	1000	[65,67,71]
	CV_9: Protected areas	1000	[65,68]
	CV_{10}: Existing wind farms	200 m times the rotor diameter of the selected wind turbine	[63,72]

3.3. Restriction Criteria

To pinpoint suitable locations for onshore wind farms, the initial step involves excluding areas conflicting with renewable energy exploitation due to infrastructure, ecological significance, or unsuitability. Figure 4 illustrates the cumulative isolation of such locations, primarily infrastructure hubs, culturally significant places, and conservation-designated sensitive sites, according to Jamaica's National Environment and Planning Agency (NEPA). These areas, comprising national parks, bird sanctuaries, and Ramsar Convention and UNESCO sites, account for 24% (2867.5 km^2) of the total land mass (10,990 km^2) and are potential areas for onshore wind expansion. While Jamaica lacks federal land management laws for wind farm development, developers must adhere to NEPA rules post-permit acquisition. Compliance details are available on the agency's website, albeit without specific boundaries. Buffered zone restrictions from similar past studies are applied (Tables 1 and 2).

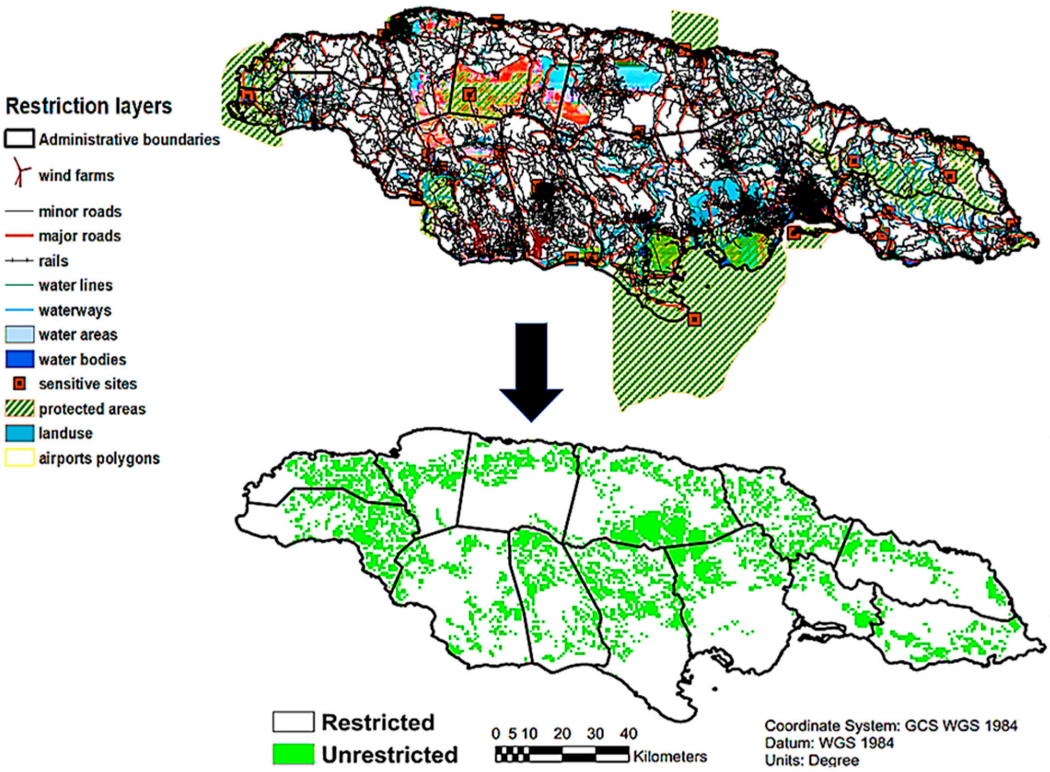

Figure 4. The exclusion zones and unprohibited areas.

This study, for example, emphasizes adherence to environmental impact assessment before renewable energy project installation. The turbine placements are confined to identified areas with favorable wind regimes ≥6 m/s. Limited onshore wind farm studies in the Caribbean, such as those conducted by Costoya et al. (2019) and Sterl et al. (2020) [5,72], employ Weibull distribution for wind speed characterization. This study aligns with Sterl's simulation using Vestas V80 and Vestas V112 turbines. Weibull distribution aids in estimating energy-viable production by assessing historical wind speed distribution.

3.4. Suitability Criteria

The onshore wind power farm (WPF)-site suitability model aims to minimize socioeconomic, technical, and environmental impacts. GIS-MCDM analyzes suitability with constraint and suitability factor variables. *SFV* weights, determined by the analytic hierarchy process (AHP) and multi-criteria decision-making technique, are calculated through pairwise comparisons, utilizing a scale from 1 to 9 [40]. The questionnaire, administered to over fifty participants, incorporates responses from 50 experts and stakeholders, reducing biases in decision-making. Addressing potential conflicts among stakeholders primarily relied on the geometric mean of individual judgments to synthesize a group decision, as Saaty (2008) recommended for AHP applications with multiple decision-makers [67]. This approach allowed for the incorporation of diverse perspectives while mathematically balancing differing opinions. The geometric mean proved particularly useful in cases where initial discussions could not achieve complete consensus. A sensitivity analysis also assessed how stakeholders' preference variations affected the overall suitability rankings. This analysis involved systematically adjusting the weights of different criteria and observing the resulting changes in site suitability scores. The process helped identify which criteria were most influential in determining site suitability and how robust the results were to changes in stakeholders' choices. Combining the geometric mean approach with sensitivity analyses ensured that the final suitability rankings represented the collective stakeholder input and remained resilient to potential disagreements or variations in individual judgments.

The model follows the five steps outlined in the appendix, Figures A1 and A2:

1. Decide on the objective.
2. State criteria based on objectives.
3. Compare alternatives in a comparison matrix.
4. Normalize the matrix by summation.
5. Calculate the average of the attributes in the row of the normalized matrix as components of the largest eigenvalue of the comparison matrices.

The inconsistency index (*CI*) from the Eigen method is determined by Equation (1):

$$CI = \frac{\lambda - n}{n - 1} \tag{1}$$

where λ is the maximum eigenvalue, and n is determined by the number of rows or columns in the decision matrix. Meanwhile, the coherence of the pairwise comparison is determined by the consistency ratio (*CR*), generated as follows:

$$CR = \frac{CI}{RI} \tag{2}$$

where RI assesses the adaptability of the judgments defined by the consistency index of a randomly generated reciprocal from a 10-point scale; see Figure A2. This CR is acceptable when it is less than 10%.

The weighted linear combination (WLC) evaluates AHP-weighted factors from Table 4 using the suitability function in Equation (3) to identify the most suitable sites. Economic, environmental, social, safety, and technical variables are considered. After reclassification (Figure A3), rasterized factor layers undergo formatting with weighted overlay tools in

ArcGIS 10.8.1. The factors are combined by summing all suitability factor layers with their weights. The result is integrated with the restriction map using the Times Tool in ArcGIS. WLC, a reliable statistical analysis method, quantifies factor significance through bivariate discriminant operation [73–75], as seen in Equation (3). This method finds application in various disciplines.

$$SWPF_i = \sum_{j=1}^{n} W_j \times W_{ij} \quad (3)$$

where $SWPF$ is the wind power suitability index of area i, W_j is the comparative importance of weights of criteria j, W_{ij} is the normalized value of the region i under criteria j, and n is the sum of the criteria.

Table 4. Criteria, sub-criteria, and weight of each evaluation index for onshore wind farm site suitability.

Category A	**Category B (Criteria)**	**Weight (%)**	**Category C (Sub-Criteria)**	**Assigned Number**	**Weight**
Level 1	Level 2		Level 3		
	Economic	17.6	Distance to roads and highways	SFV_1	0.060
			Distance to railroads	SFV_2	0.040
			Distance to transmission lines	SFV_3	0.076
Wind	Environmental	28.1	Distance to sensitive sites	SFV_4	0.126
			Distance to protected areas	SFV_5	0.155
	Social and safety	24.5	Distance to airports	SFV_6	0.090
			Distance to land use	SFV_7	0.155
	Technical	29.8	Distance to existing wind farm	SFV_8	0.090
			Mean wind speed	SFV_9	0.168
			Slope	SFV_{10}	0.040

Furthermore, suitability scores were assigned within the suitability model to generate boundary classification with ranks from 1 to 5, low (1), moderate (2), good (3), very good (4), and excellent suitability (5), as seen in Table 5.

Table 5. Criteria used in boundary classification.

	Suitability Score				
Criteria 1–10	**5 (Excellent Suitability)**	**4 (Very Good Suitability)**	**3 (Good Suitability)**	**2 (Moderate Suitability)**	**1 (Low Suitability)**
Distance to roads and highways (m)	500–2000	2000–4000	4000–6000	6000–8000	8000–10,000
Distance to railroads (m)	500–2000	2000–4000	4000–6000	6000–8000	8000–10,000
Distance to transmission lines (m)	<2000	2000–4000	4000–6000	6000–8000	8000–10,000
Distance to sensitive and protected areas (m)	8000–10,000	6000–8000	4000–6000	2000–4000	1000–2000
Distance to airports (m)	8000–10,000	6000–8000	4000–6000	2000–4000	1000–2000
Land use proximity (m)	8000–10,000	6000–8000	4000–6000	2000–4000	1000–2000

Table 5. *Cont.*

Criteria 1–10	Suitability Score				
	5 (Excellent Suitability)	**4 (Very Good Suitability)**	**3 (Good Suitability)**	**2 (Moderate Suitability)**	**1 (Low Suitability)**
Distance to existing wind farms (m)	8000–10,000	6000–8000	4000–6000	2000–4000	1000–2000
Annual mean wind speed (m/s)	>6	6–5.7	5.7–5.5	5.5–5.3	5.3–5
Weibull distribution: precisian wind speed distribution		a = 7.648 (median value)		k = 2 (recommended value)	

3.5. Stakeholders' Opinion

Onshore wind power generation has been integral to Jamaica's landscape since 1996, becoming part of its cultural identity. AHP questionnaire responses indicated favorability toward wind power farm (WPF) electricity production. While not addressing preferences among renewable energy sources, the limited sample size (less than one hundred respondents) might affect generalizability. Opposition to wind turbines often centers on size, noise, shadow, and the absence of legal statutes for compensation [76]. Unaddressed in the questionnaire, these concerns underscore the importance of involving stakeholders in wind energy planning to manage perceptions and attitudes.

The study incorporates stakeholders' opinions quantitatively, focusing on socioeconomic, environmental, and technical aspects. Wind turbine placements consider distances from airports and infrastructure and address noise and visibility concerns (Tables 2 and 3). Turbines are spaced in square arrays of six rotor diameters in areas with high wind regimes ($\geq$6 m/s) to address concerns [68]. A buffered distance of 1000 m is implemented to safeguard wildlife habitats and culturally significant sites. Additionally, the method avoids wake effects from neighboring turbines or areas occupied by turbines (AOT), spaced in square arrays of six rotor diameters. $\left(D_z^2\right)$ represents areas of high wind regimes $\geq$6 m/s, represented by Equation (4) [68], which can impact power density. The outcome is then distributed across available land areas based on suitability results.

$$AOT = 6D_z \times 6D_z = 36D_z^2 \quad (4)$$

3.6. Data Characterization

Social, safety, environmental, technical, and economic data were sourced from metServiceJA, GWA, DIVA-GIS, NASA, and Geofabrik portals. Rasterization in ArcGIS 10.8.1 was performed on files from these sources, including shape files from Geofabrik for roads, railways, waterways, water bodies, buildings, and land use. Some data were created by converting data logged in Excel 2021 to shape files. Administrative boundaries for Jamaica were obtained from DIVA-GIS, while electrical grid network files were drawn in ArcGIS based on images from JPS's website. The accuracy of these drawings is limited because they were not directly obtained from the company for security reasons. The country's raster elevation DEM file was acquired from DIVA-GIS and sourced from NASA's Shuttle Radar Topography Mission SRTM at a three-to-thirty-second resolution. Wind resource data were obtained from GWA, an open web-based system aiding wind power planners globally [70], and the Meteorological Service of Jamaica. Detailed information on GIS format and content is available in materials by Ramm et al. (2014) [77].

3.7. Wind Resource Analysis and Technical Potential

Jamaica lacks comprehensive non-commercial digital wind speed information for potential energy assessment. Previous wind energy studies, such as Chen et al. (1990) and

Daniel and Chen (1991) [13,78], utilized anemometer data and stochastic modeling, with the Petroleum Corporation (PCJ) (located at 36 Trafalgar Rd, Kingston, Jamaica) compiling a wind resource map in the JAMAICA ENERGY INVESTOR GUIDE [12]. The current study enhances previous research by utilizing an extensive dataset for wind resource assessment, including the following:

1. Eight years (2009–2017) of wind speed and direction data at 50 and 100 m above ground level.
2. Wind speed data were collected from 19 automatic weather stations (AWSs) across the island, operated by the Meteorological Service Jamaica.
3. Data from the Geostationary Operational Environmental Satellite, managed by the United States National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service Division.
4. Orographic (terrain-related) data and air density were collected from the Global Wind Atlas.

These datasets were analyzed using the Wind Atlas Analysis and Application Program (WAsP) method. The combination of long-term data, multiple data-collection points, and advanced analysis techniques provides a comprehensive assessment of Jamaica's wind resources, surpassing the scope of previous regional studies.

The 19 AWSs adhere to the World Meteorological Organization (WMO)'s standards of data quality and measurement practices. Each AWS is equipped with anemometers installed at a standard height of 10 m above ground level, strategically located to represent diverse topographical conditions across Jamaica, including coastal areas, inland plains, and hilly regions.

Raw wind speed data underwent a rigorous correction process to account for local terrain effects and extrapolate wind speeds to turbine hub heights (50 and 100 m) using the WAsP method. WAsP utilizes detailed topographical maps and roughness length data to model wind flow over complex terrain. The roughness length for each site was determined based on land cover classification derived from high-resolution satellite imagery incorporated in the Global Wind Atlas model. The software applies the logarithmic wind profile law, adjusted for atmospheric stability, to extrapolate wind speeds from the measurement height to the desired hub heights.

The data consider nearby obstacles, roughness, and digitized maps with a 1:927,890 scale, providing a detailed analysis. Wind speed corrections to 80 and 100 m align with modern wind farm hub heights, addressing limitations of pre-2000s estimates, usually below 50 m. The study offers a dual assessment at 50 and 100 m, aligning with current Jamaican wind farm hub heights [35]. The wind atlases depict annual average wind speeds $\geq$6 m/s at both altitudes, guided by the economic advantage of reference turbines at 100 m hub heights [79]. The wind-derived motion statistics inform site suitability, emphasizing areas with high frequency and power density on a digital map defined by color distribution, with a threshold of wind speed $\geq$6 m/s.

Moreover, energy generation is distinguished from wind power density (WPD), which is crucial for wind turbine power production, defined by the cube of wind velocity. WPD at 50 and 100 m was extrapolated for recommended sites using the Raster Calculator option in ArcGIS, utilizing wind speed and roughness index raster data from the Meteorological Service of Jamaica and the Technical University of Denmark (DTU). WPD calculations involve Weibull parameters, air density, temperature, and wind speed at different hub heights. The formula in Equation (5), adopted from EDUCYPEDIA (2011) [80], was employed for computation. The mean values for all parameters from the eight-year data were then applied.

$$\mathrm{WPD} = 0.5 \times \mathrm{p} \times \mathrm{K} \times \mathrm{V}_3 \quad (5)$$

In the formula, p represents air density (1.1541 kg/m^3 and 0.3462 kg/m^3 at 100 and 50 m above ground level (AGL), respectively), k is the Weibull parameter (2), and V is the average wind speed in m/s. Weibull k values ranged from 0.80 to 2.865 at 50 m and from 0.90 to 3.30 at 100 m, with the study adopting a recommended value of 2 within the data range (Figure 5). An average wind speed of ≥6 m/s was utilized. These parameters were then simulated by utilizing the Swiss Federal Office of Energy's wind power software, assessing selected wind turbines based on the current island version (Table A1), and upgrading turbines of the same brand with increased capacity factors [81].

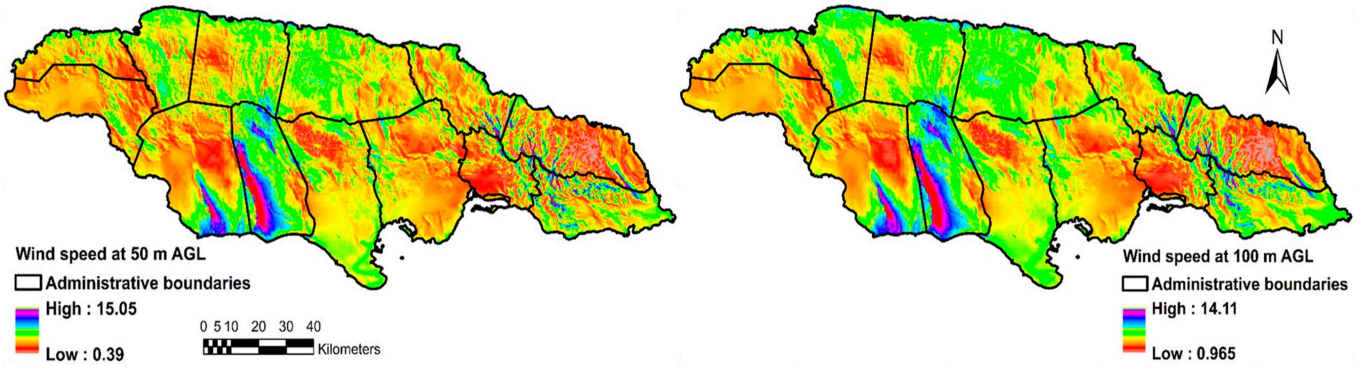

Figure 5. The mean wind threshold at 50 and 100 m above ground level from 2009 to 2017.

For this study, the Weibull k parameter was set to 2 across the entire study area. This value is generally accepted in potential wind site analyses and was chosen to simplify calculations while maintaining a reasonable representation of wind speed distributions. The decision to use a constant k value of 2 is based on its widespread use in wind energy assessments and its ability to approximate wind speed distributions in many locations.

The wind speed maps in Figure 5 were derived through the following process:

1. Wind speed data from the 19 automatic weather stations were input for the Wind Atlas Analysis and Application Program (WAsP) model.
2. WAsP performed a statistical wind data analysis using the fixed Weibull k parameter of 2 for all locations.
3. ArcGIS software then used this parameter, measured wind speeds, and detailed topographical and roughness data to extrapolate wind conditions across the island.
4. This extrapolation process considered terrain effects, such as speedup over hills, slowdown in valleys, and changes in surface roughness.
5. The resulting wind climate was then interpolated to create a continuous wind speed map at the specified heights (50 m and 100 m).

While using a fixed k value may not capture all local variations in wind speed distributions, it provides a consistent basis for comparison across the entire study area and simplifies the overall analysis process. This revised paragraph clarifies that the Weibull k parameter was set to 2 for the whole study area, addressing the reviewer's comment. It also explains the rationale behind this decision and outlines how the wind speed maps were generated using this fixed k value.

3.8. Emission Reduction Computation

Emission reduction is measured in metric tons of carbon dioxide equivalent (MT CO_{2e}) by calculating barrels of avoided fuel oil consumption. This involves multiplying wind power output generation by the average heat rate for FF-BE electricity production, using values from Jamaica's electricity mix. The avoided tons of carbon dioxide emissions per barrel of crude oil (BOE) are determined by considering heat content, carbon coefficient, fraction oxidized, and the molecular weight of carbon dioxide to carbon. Equations (6) and (7) outline the computation methods. The calculations use USD ($) 64 per BOE for 2019, aligning with Jamaica's 2019 energy generation output. Additionally, the study incorporates the average amount of CO_2 emissions per kilowatt-hour of electricity generated by a wind farm, estimated at 11 g of CO_2 [82].

$$AFF = \frac{PWE}{1700\ \text{kWh}} \quad (6)$$

AFF is BOE's avoided fuel oil consumption, and *PWE* is the potential wind energy generation in kWh.

$$GHG_{ER} = \left(\frac{AHC}{\text{BOE}} \times \frac{20.31\ \text{kg C}}{\text{MMBtu}} \times \frac{44\ \text{kg CO}_2}{12\ \text{kg C}} \times \frac{1\ \text{Metric Ton}}{1000\ \text{kg}} \right) - WP_{EG} \quad (7)$$

where GHG_{ER} is carbon dioxide emission reduction (MT CO_{2e}), *AHC* is the average heat content of the electricity mix from fossil fuel electricity plant (10.768 Btu) equivalent to 1 kWh, and WP_{EG} is wind power emission generation in MT CO_{2e}.

The emission reduction calculation in this study assumes an immediate replacement of fossil fuel-based energy production with wind farm energy production. This assumption simplifies the analysis but does not account for the practical delays associated with wind farm construction and commissioning. Realistically, the transition from fossil fuels to wind energy is a gradual process that involves planning, construction, grid integration, and commissioning phases. These phases can span several years, potentially affecting the achievement of Jamaica's 2030 goals for 50% unconventional electricity generation and CO_2 reduction.

To provide a more accurate projection, future studies should incorporate a time-based model that accounts for the following:

1. The typical timeline for wind farm development and construction in Jamaica;
2. The gradual phase-out of existing fossil fuel power plants;
3. The incremental increase in wind power capacity over time;
4. Potential changes in electricity demand during the transition period.

Such a time-based approach would offer a more realistic assessment of emissions reduction and the feasibility of meeting the 2030 targets. The current calculation should be interpreted as an upper bound of potential emissions reduction, assuming optimal conditions and immediate implementation. This additional paragraph acknowledges the limitation in the current emissions reduction calculation and provides context for interpreting the results. It also suggests improvements for future studies to address this limitation.

3.9. Economic Analysis: A Levelized Cost of Electricity Approach

In recent years, the surge in renewable energy capacity, particularly in wind and solar photovoltaic (PV) systems, coupled with the decreasing costs of utility-scale electrical energy storage, has highlighted the economic viability of these technologies. This section presents a comprehensive methodology for calculating the levelized cost of electricity (*LCOE*) for commercial-scale onshore wind systems, providing policymakers and investors with a standard metric for evaluating different turbine systems [83,84].

LCOE is the total lifetime cost of generating electricity divided by the total. This metric is pivotal for economic comparison across various technologies. This study applies the *LCOE* methodology consistently to compare onshore wind systems with traditional petroleum-based electricity commonly used in Jamaica, focusing on the need for significant initial investments and the declining cost trends of renewable systems.

The *LCOE* calculation is a powerful tool that considers all future costs, discounted to present value, resulting in a current price per unit energy rate (USD/kWh). It integrates energy capacity costs (USD/kWh) and power or fuel costs (USD/kW/year) over the project's operational life, providing a clear picture of the actual energy cost.

3.9.1. Variables Influencing Levelized Cost of Electricity

Considering the variables influencing *LCOE*, the calculation aligns with established methodologies in renewable energy studies. Equations (8) and (9) are central to this process. Equation (8) calculates the *LCOE* for utility electricity (USD/kWh), while Equation (9) determines the simple levelized cost of renewable energy ($sLCOE_{RE}$). Equation (10) provides a detailed economic analysis of the capital recovery factor (CRF).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (8)$$

$$sLCOE_{RE} = \left[\frac{(O_c \times CRF + M_t)}{8760 \times C_f}\right] + (F_t \times H_r) + M_v \quad (9)$$

The capital recovery factor (*CRF*) calculation determined by Equation (10) helps translate the capital costs over the project's lifetime into annual payments.

$$CRF = \frac{i(1+i)^n}{\left(1+i\right)^{n-1}} \quad (10)$$

where i is the interest rate, and n is the number of annuities received. This factor simplifies financial calculations over a project's lifetime, facilitating the determination of $sLCOE_{RE}$ and *LCOE*.

The *LCOE* calculation must consider various uncertainties, including technological innovations, market dynamics, and other factors that affect cost variability. These dynamic elements complicate the prediction of energy system behavior over their operational life. In terms of application, the equations standardize assessing utility electricity costs across diverse renewable energy types. Consequently, the approach is valuable for policymakers, investors, and researchers in evaluating the economic feasibility of various renewable energy projects. Table 6 presents the nomenclature for terms used in the *LCOE* equations, while Table 7 details the parameters used in the *LCOE* calculations, along with their respective values.

Table 6. Nomenclature for *LCOE* equations.

Nomenclature	Definition
Project lifetime	The total duration of the renewable energy project
Electrical energy	The cumulative energy output over the project's lifespan
$sLCOE_{RE}$	Simple levelized cost of renewable energy expressed in USD/kWh
LCOE	Levelized cost of utility electricity, expressed in USD/kWh
LCOE	Levelized costs of electricity
I_t	Investment expenditures or capital costs in the year t
M_t	Fixed operations and maintenance expenses in the year t
F_t	Fuel expenditures in the year t
E_t	The electrical energy produced in the year t
R	Discount rate
N	The expected lifetime of the system or power station
CRF	Capital recovery factor
O_c	Overnight capital cost
M_v	Variable operations and maintenance cost
C_f	Capacity factor
H_r	Heat rate
E_r	Escalation rate

Table 7. Parameters used in levelized cost of electricity for renewable energy projects.

Nomenclature	Definition	Amount (USD)	References
I_t	Funds allocated to capital goods, items utilized to produce other goods or services. Investment expenditures encompass acquisitions like machinery, land, inputs for production, and infrastructure.	Onshore wind: 2213 (USD/kW)	[84,85]
M_t	Fixed operations and maintenance costs are constant expenditures, irrespective of energy generation or supply fluctuations.	Onshore wind: (USD/kW/year)	[84,86]
F_t	Fuel expenditure is the cost of fuel per liter in Jamaica.	The exact rate is applied for all scenarios. (USD/L)	[87]
E_t	The total electrical energy generated by the project depends on the scenario.	The price of electrical energy generated is fixed for scenarios.	Calculations from this study determine it.
r	The interest rate employed to discount all future cash flows of an investment to determine its net present value (*NPV*) is known as the discount rate or the discount factor.	Onshore wind: 6.5	[88]
n	The total lifespan of the RE plant.	Onshore wind: 30	[89]
M_v	Variable operations and maintenance costs fluctuate in proportion to the quantity of energy generated or supplied.	Onshore wind: 0.078 (USD/kWh)	[90]
C_f	The capacity factor is a specific technology's average consumption, output, or throughput over a defined period. The values used are based on the turbines chosen for the computation in the scenarios.	Onshore wind: 34	The capacity factor is based on scenarios that are valued.
H_r	Heat rate is the energy an electrical generator or power plant requires to produce one kilowatt-hour (kWh) of electricity.	The equivalent rate is applied for all scenarios. 10,768 (Btu/kWh)	[91] Value is adopted from the scenarios used.

3.9.2. Payback Period and Net Present Value

Payback period (*PBP*) and net present value (*NPV*) are additional metrics for evaluating renewable energy projects. PBP measures the time required to recoup the initial investment, while *NPV* provides a more comprehensive valuation by considering the time value of money. The *NPV* is derived from Equation (11):

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad (11)$$

where R_t is the net cash inflow–outflow during a period, t; i is the discount rate, and n is the number of periods.

This structured methodology provides a comprehensive approach to evaluating the economic feasibility of renewable energy projects through standardized *LCOE* calculations that offer a valuable tool for policymakers and investors.

4. Results and Discussion

This section highlights the stakeholders' wind model atlases by illustrating the restriction map, wind resource maps, suitability, and site-specific geographic locations for potential wind farms. In addition, the amount of potential electrical energy is shown in varying scenarios with specific turbines and equated carbon emission reduction.

4.1. Land Availability and the Best Site Locations

Ten evaluation criteria were highly influential in locating the best wind farm (WF) sites. The markers provided in Table 4, SFV_1 to SFV_{10}, show the ranks according to the weights. Additionally, the pairwise comparison resulted in a consistency ratio of 0.068, within the threshold limit of 0.10. Therefore, the matrix passed the consistency test. The weights obtained are based on the decision matrix's principal eigenvector, 4.18 (Figure A2). The results show that significant weight is attributed to the technical factor of climatology, with the mean wind speed (16.8%) being the most relevant factor in determining the optimum placement for wind farm construction relative to other factor weights in line with past wind studies. Distance from protected areas (15.5%) and land use (15.5%) were regarded as more significant than the distance to sensitive sites (12.6%), existing wind farms (9%), and other determinants.

The suitability map assessment considers the relationship between wind speed and energy production, which is sensitive to the characteristics of wind turbine power curves. This study integrated mean wind speeds and cut-in and cut-out speeds provided by the turbine manufacturing companies into the Swiss Federal Office of Energy's wind power software. The software offers a comprehensive analysis of potential energy production. This study utilized the power curve of the Vestas V80 (2.0 MW), Vestas V112 (3.0 MW), Gamesa G87 (2.0 MW), and Gamesa G114 (2.5 MW) turbine models, a common choice for utility-scale wind farms, selected based on their widespread use and suitability for Jamaica's wind conditions (Table A1 and Figure A5). The approach ensures that the suitability assessment reflects not just mean wind speeds but also the expected energy production based on realistic turbine performance characteristics, including the non-linear relationship between wind speed and power output. By incorporating cut-in and cut-out speeds, the analysis provides a more accurate representation of the turbine's operational range and efficiency under various wind conditions typical to Jamaica.

The final suitability map in Figure 6 and Table 8 both show that the excellently suited area is less than 1% of the total land area, compared to the good suitability area of 15.5%, 5.32% moderately suitable, and 2.82% very good suitability (Table 5). The result shows that the very good and excellently suited locations are primarily concentrated in the parishes of St. Elizabeth, Manchester, Clarendon, St. Andrew, St. Thomas, and St. Ann. However, the one plot of excellently suited land is in Hagley Gap, St. Thomas, as shown in Figure 7.

Most of the grounds identified as suitable are in the coastal and high-elevation regions, mainly due to the strong trade winds and air density [35].

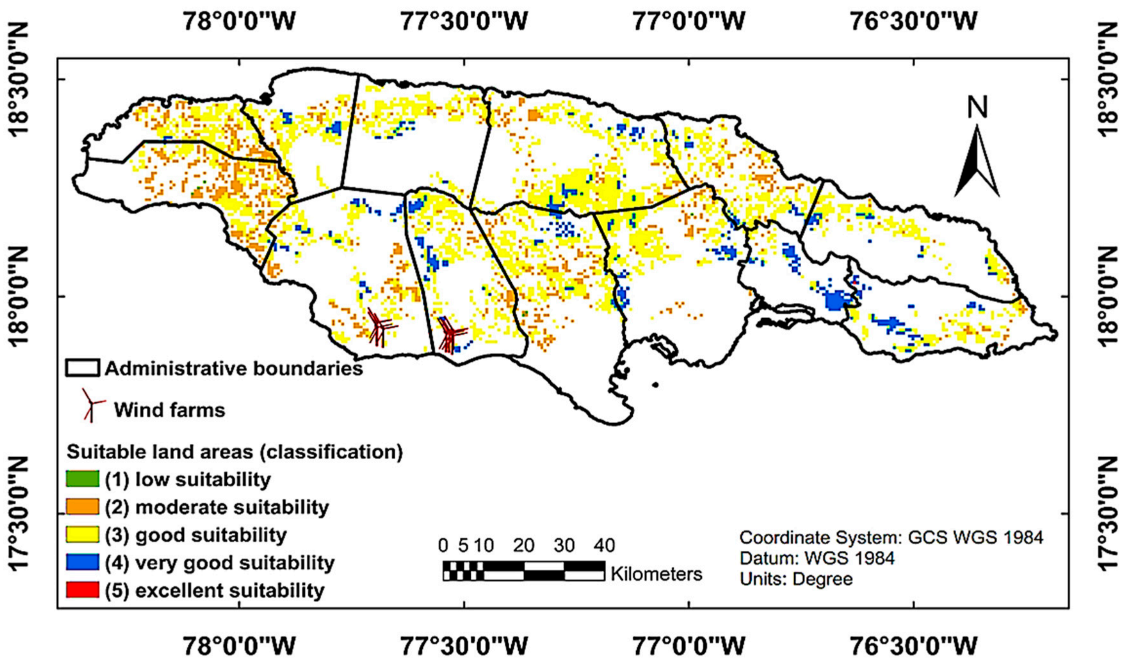

Figure 6. The final suitability map with existing wind farms.

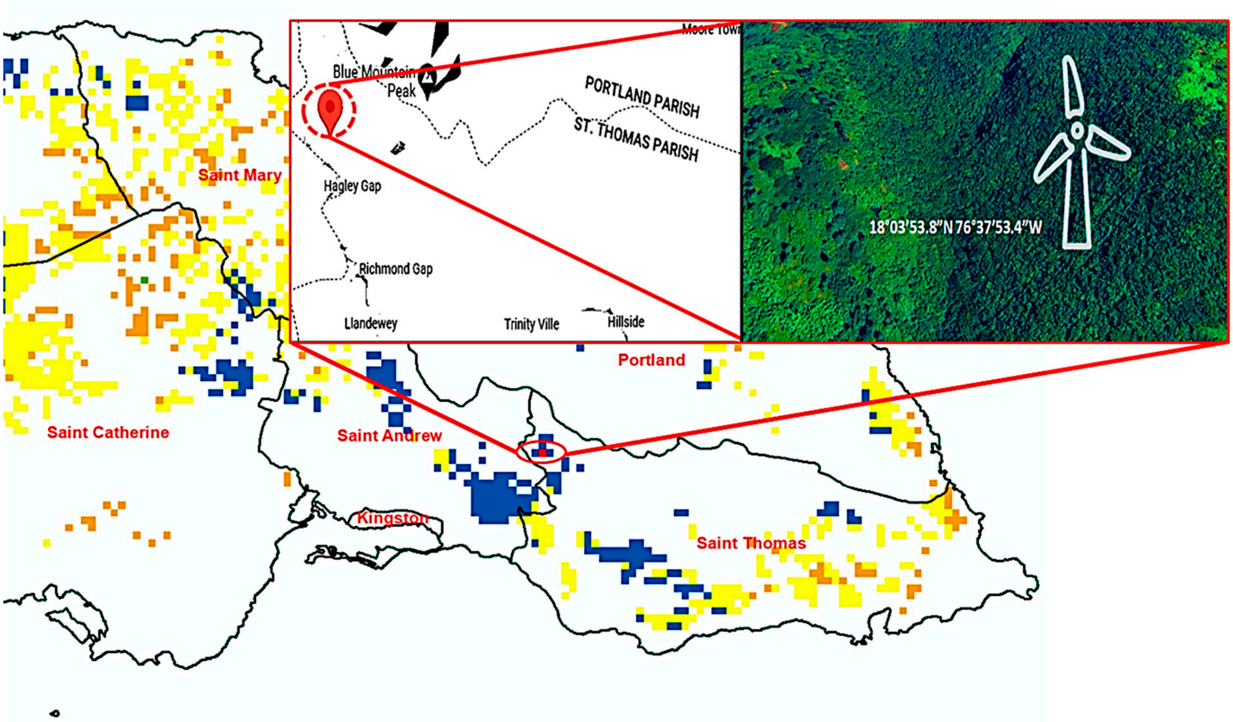

Figure 7. Excellently suited area for wind farm development.

Table 8. Proportional suitable land distribution ranges after reclassification for onshore wind power generation.

Suitability Classification	Land Availability (km^2)	% Total Area
Low suitability	3.833	0.035
Moderate suitability	584.837	5.322
Good suitability	1712.893	15.586
Very good suitability	310.489	2.825
Excellent suitability	0.548	0.005
Total land area	2612.600	23.773

Contrarily, the unsuitability of the conservation areas, topography, and significant settlement in the southern, western, and northwestern regions render it improbable to construct WFs because wind resources are a vital factor influencing the placement of WFs. The study shows that the southern and northern coastal regions are privileged for WF expansion. Nonetheless, the relative importance of other characteristics in the model deems other areas suitable. Moreover, the locations of Jamaica's six wind farms—(1) Munro Wind Farm, Saint Elizabeth (Cornwall), (2) Munro College, Saint Elizabeth (Cornwall), (3) Malvern, Saint Elizabeth (Cornwall), and (4–6) Wigton I, Wigton II, and Wigton III, Manchester (Middlesex), along the south coast—as illustrated in Figure 5, overlap with restricted (Figure 4) and suitable areas to produce the imagery of Figure 6.

The classifications in Table 8 (excellent, very good, good, moderate, and low suitability) are based on a comprehensive set of criteria beyond just wind speed and environmental factors. The classification system incorporates the following elements:

- Wind resource: Mean wind speed at 100 m height, with excellent sites having speeds >7.5 m/s; very good, 6.5–7.5 m/s; good, 5.5–6.5 m/s; moderate, 4.5–5.5 m/s; and low, <4.5 m/s (Archer & Jacobson, 2005) [92].
- Energy production potential: Calculated considering the power curves of the four selected turbines. Excellent sites are expected to achieve capacity factors >35%; very good, 30–35%; good, 25–30%; moderate, 20–25%; and low, <20% (IRENA, 2019) [93].
- Environmental sensitivity: Based on proximity to protected areas, bird sanctuary locations, and sensitive ecosystems. Excellent sites have minimal environmental concerns, while low suitability sites have significant potential impacts.
- Grid accessibility: Distance from existing transmission infrastructure. Excellent sites are within 5 km; very good, 5–10 km; good, 10–15 km; moderate, 15–20 km; and low, >20 km (Tegou et al., 2010) [21].
- Land use compatibility: Consideration of current land use and potential conflicts. Excellent sites have no land use conflicts, while low suitability sites have significant conflicts with existing or planned land uses.
- Topography and accessibility: Slope, elevation, and road access. Excellent sites have optimal conditions for construction and maintenance, while poorly suited sites present significant challenges.
- Social acceptance: This is based on stakeholders' input and proximity to populated areas. The excellent-suited sites (Figure 7) have high community support, while poor sites face significant opposition.

Manchester and St. Elizabeth, on the island's southern coast, encompass the most significant possibilities, with mean wind speeds of 10.08 m/s and 8.26 m/s plus power densities of 956 W/m^2 and 577 W/m^2, respectively [35]. Nonetheless, it is vital to consider other parishes to avoid wake effects and reduce transmission costs for on-grid electricity transmission. Thus, 17 of the most suitable areas, along with their geographic locations and coordinates, are identified in Table 9.

Table 9. The most appropriate site locations for wind power expansion.

Location Number	District/Town	Parish	Latitude	Longitude
1	Hagley Gap	St. Thomas	18°3′54.09″ N	76°37′53.19″ W
2	Santa Cruz	St. Elizabeth	18°1′37.4″ N	77°42′47.5″ W
3	Gutters	Manchester	18°4′10.44″ N	77°34′54.44″ W
4	Gutters	Manchester	18°05′08.9″ N	77°08′43.0″ W
5	Lluidas Vale	St. Catherine	17°55′10.6″ N	76°33′27.6″ W
6	Easington	St. Thomas	17°55′10.6″ N	76°33′27.6″ W
7	Eleven Mile	St. Thomas	17°57′11.6″ N	76°38′21.9″ W
8	Pamphlet	St. Thomas	17°52′30.4″ N	76°30′50.7″ W
9	Easington	St. Thomas	17°55′20.4″ N	76°33′30.9″ W
10	Port Antonio	Portland	18°06′40.5″ N	76°28′53.0″ W
11	Mulleth Hall	Portland	18°11′02.0″ N	76°43′12.9″ W
12	Port Maria	St. Mary	18°21′08.3″ N	76°51′34.9″ W
13	Clarkson Ville	St. Ann	18°12′19.2″ N	77°17′58.7″ W
14	Windsor	Trelawny	18°22′02.9″ N	77°39′49.5″ W
15	Montego Bay	St. James	18°24′19.4″ N	77°53′25.3″ W
16	Montego Bay	St. James	18°24′16.0″ N	77°53′21.9″ W
17	Hertford	Westmoreland	18°15′06.5″ N	78°05′25.6″ W

4.2. Potential Wind Energy Generation

Jamaica encompasses high wind speeds up to 14.11 m/s and 15.05 m/s at 50 m and 100 m AGL, respectively, as illustrated in Figure 5. The wind atlases generated after applying the stakeholder's suitability show that land availability reduced from 2867.45 km^2 (26%) to 2612.59 km^2 (23.77%) of the total land area (Figure 4). It accounts for various constraints to eliminate environmental, economic, technical, social, and safety damages to land use types—roads, protected areas, sensitivity sites, airports, water bodies, railways, and existing WFs. The country's overall mean wind speed is 7.51 m/s. However, at ≥6 m/s, average wind speeds of 6.691 m/s and 7.836 m/s at 50 and 100 m AGL were measured, respectively. The area's power density (W/m^2) varies from 2.52 to 4.1, indicating the feasibility of expanding wind power plants (WPPs) since wind resource viability at 400 watts per hour at greater than or equal to 4 m/s is necessary for utility-scale wind farms [8].

Table 5 and Figure 6 specify specific suitability ranges. However, the final suitability model (Figure A4) elucidates the extraction of polygons ≥47 hectares to facilitate the largest proposed turbine, Gamesa G114, with a rotor diameter of 114 m and rated power capacity of 2500 kW. Subsequently, 578 km^2 (5.25%) of the land area can be used for wind turbine placement. The available space aligns with IRENA's findings, which specify that roughly 5% of Jamaica's total area is probable for onshore wind power expansion [8]. It shows the distribution of Jamaica's wind potential compared to the world's, with credence to available land space and power density, measured in watts per square meter at 100 m at ground level. Another indication of plausibility is the result from a regression analysis showing the possibility of reaching 75.59 MW nominal power by 2030 and 143.19 MW by 2050 (Figure 8).

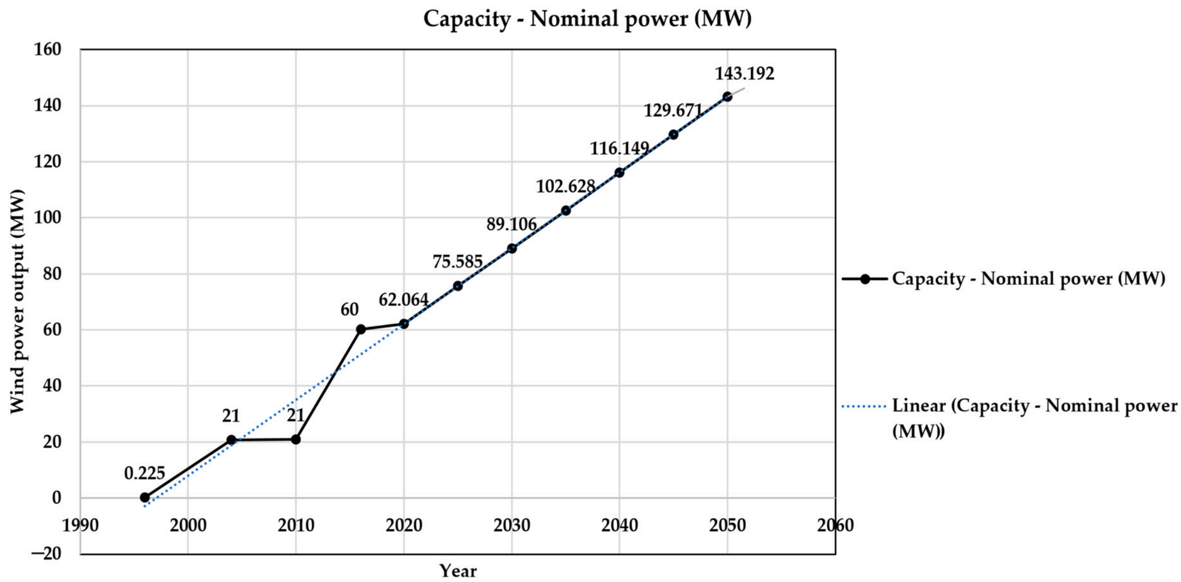

Figure 8. Projected nominal wind power output for 2050.

The linear trend assumed in Figure 8 for the projection of nominal wind power represents an idealized scenario. Wind farm development follows a stepped pattern due to the construction and commissioning phases. Historical data from Jamaica's wind power development demonstrate this stepped growth, as seen before 2010 and 2020. The projection should be interpreted cautiously, considering potential growth plateaus during construction periods. For instance, if new wind farm construction begins in 2024, a plateau might occur from 2024 to 2030, similar to past patterns. These construction and commissioning delays can significantly influence the achievement of Jamaica's 2030 goals for 50% unconventional electricity generation and CO_2 reduction. The linear projection may overestimate short-term growth but could underestimate long-term potential if multiple projects are completed in quick succession. Future studies should incorporate a more detailed time-based model that accounts for specific project timelines, regulatory processes, and historical patterns of wind farm development in Jamaica. This approach would better illustrate wind power capacity growth and its impact on emissions reduction, offering policymakers and investors a clearer picture of the challenges and opportunities in meeting Jamaica's renewable energy targets.

Table 10 indicates the specifications of the four proposed turbines, the electric energy production before the wake effect, and the number of turbine applications. Following simulations with Vestas V80, Vestas V112, Gamesa G87, and Gamesa G114, gross annual electricity yields of 1,964,504 GWh, 3,439,862 GWh, 2,136,397 GWh, and 3,134,487 GWh, correspondingly, were determined at 50 m AGL. Likewise, from 4,915,940 to 8,938,675 GWh was deduced at 100 m AGL. A 20% reduction accounts for the losses from the wake effect, track laying, array loss, maintenance, and turbine availability, resulting in annual net production from 1,571,603.20 to 2,751,889.60 GWh for scenario A at 50 m AGL and 1,964,504–3,439,862 GWh, 20%, in scenario B (Table 11).

Tables 10 and 11 show differences in output from the turbines used. Previous studies multiplied a parameter ranging from 0.71 to 0.90 to derive the net energy production for OnWFs [68]. Consequently, a mid-range value of 0.80 is applied in the evaluation.

Furthermore, a comparison of the turbines' capacity-rated power output shows that Vestas V112 has the most significant capacity output until it reaches a cut-off wind speed of 25 m/s (Figure A6). Consequently, it is the most suitable for wind power expansion among the four turbine models. The individual power curves of each turbine utilizing the same mean wind speed, Weibull k, and air density are also shown in Figure A5.

Table 10. Turbine specification and potential electrical energy output.

Turbine Information Scenarios		Vestas V80 (2000 kW)	Vestas V112 (3000 kW)	Gamesa G87 (2000 kW)	Gamesa G114 (2500 kW)
Rated capacity power (kW)		2000	3000	2000	2500
Rotor diameter (m)		80	112	87	114
Operating hours (hour/year)	Scenario A: 50 m AGL ≥ 6 m/s	7066	7850	7066	7850
	Scenario B: 100 m AGL ≥ 6 m/s	7488	8085	7488	8085
Full load hours (hour/year)	Scenario A: 50 m AGL ≥ 6 m/s	982	1146	1067	1253
	Scenario B: 100 m AGL ≥ 6 m/s	2456	2978	2726	3342
Capacity factor (%)	Scenario A: 50 m AGL ≥ 6 m/s	11.20	13.10	12.20	14.30
	Scenario B: 100 m AGL ≥ 6 m/s	28.00	34.00	31.10	38.20
Energy yield (kWh/year)	Scenario A: 50 m AGL ≥ 6 m/s	1,964,504	3,439,862	2,136,397	3,134,487
	Scenario B: 100 m AGL ≥ 6 m/s	4,915,940	8,938,675	5,456,203	8,361,762

Table 11. Annual generation and loss values of 4 selected wind turbines.

Parameter		Turbine Model and Rated Capacity Power (GW)			
		Vestas V80 (2000 kW)	Vestas V112 (3000 kW)	Gamesa G87 (2000 kW)	Gamesa G114 (2500 kW)
Annual gross energy generation (GWh)	Scenario A: 50 m AGL ≥ 6 m/s	1,964,504	3,439,862	2,136,397	3,134,487
	Scenario B: 100 m AGL ≥ 6 m/s	4,915,940	8,938,675	5,456,203	8,361,762
Annual net energy generation (GWh)	Scenario A: 50 m AGL ≥ 6 m/s	1,571,603.20	2,751,889.60	1,709,117.60	2,507,589.60
	Scenario B: 100 m AGL ≥ 6 m/s	3,932,752	7,150,940	4,364,962.40	6,689,409.60
Wake, track, and other losses (%)	Scenario A: 50 m AGL ≥ 6 m/s; Scenario B: 100 m AGL ≥ 6 m/s	0.80	0.80	0.80	0.80
Number of turbines	Scenario A: 50 m AGL ≥ 6 m/s; Scenario B: 100 m AGL ≥ 6 m/s	2508	1281	2121	1235
Area under turbine (km^2)		578			

The study's findings reveal that variations in wind speed significantly impact energy output across different locations in Jamaica. Areas with mean wind speeds above 7 m/s at 100 m height consistently show higher energy production potential. However, the relationship is not linear. For instance, a 10% increase in mean wind speed, from 7 m/s to 7.7 m/s, can result in approximately a 30% increase in annual energy production, based on the power curve of the Vestas V80-2.0 MW turbine. This non-linear relationship underscores the importance of precise wind speed assessments in site selection, as found in the study by Topaloğlu and Pehlivan in 2018 [94].

Furthermore, the study found that areas with more consistent wind speeds, even if slightly lower on average, may produce more energy annually than areas with higher but more variable wind speeds. This finding suggests that wind farm developers should prioritize locations with steady wind regimes, not just the highest average wind speeds. Additionally, the analysis indicates that Jamaica's coastal areas and elevated regions often offer the most favorable wind conditions for energy production. However, these must be balanced against other suitability criteria, such as grid accessibility and environmental considerations.

4.3. The Economic Potential of Wind Energy from Fossil Fuel-Based Energy Displacement

In addition to environmental and technical considerations, economic savings and CO_2 mitigation play significant roles in wind farm development. Market and policy factors, particularly the Jamaican government's commitment to increasing renewable energy generation to 50%, as outlined in the National Energy Policy 2009–2030 and the NDC agreement under the UNFCCC, provide a solid foundation for wind farm growth. Globally, onshore wind energy is rising, and Jamaica can benefit from expanding wind power to achieve energy autonomy and carbon dioxide reduction goals. In 2019, the global wind energy market reached USD 62.1 billion, projected to grow by USD 127.2 billion by 2027 [95]. The international weighted mean levelized cost of electricity for onshore wind power is USD 0.033/kWh, making it cost-competitive with other energy sources. The efficiency of onshore wind energy systems, reaching 59%, surpasses that of fossil fuel sources, at 35–45%.

Proposed wind power expansions in Jamaica could reduce petroleum consumption for electricity generation, leading to significant cost savings and boosting energy systems transition. For instance, scenarios A1 to A4, with turbines at 50 m AGL, could result in a 4–5.16% decrease in barrels of oil equivalent (BOE) consumed, saving from USD 11.65 to 14.83 million. Alternatively, scenarios B1 to B4 with 100 m hub height turbines could lead to a 10.82–12.92% decrease in BOE expended, saving from USD 31.10 to 37.13 million (Table 12). These scenarios represent a substantial increase in cost savings and GDP injection compared to current energy generation from onshore wind farms.

Table 12. Fossil fuel-based energy displacement, cost savings, and CO_2 reduction.

Scenario Turbine Model (kW)	Potential Wind Energy (GWh)	Number of Barrels of Oil Saved *	Cost Savings (USD Million) *	CO_2 Reduction ($MMTCO_{2e}$)
Current scenario		160,000	10.240	1.250
Scenario A1: Vestas V80 (2000)	3941.580	231,857	14.838	1.811
Scenario A2: Vestas V112 (3000)	3525.170	207,378	13.271	1.620
Scenario A3: Gamesa G87 (2000)	3625.030	213,237	13.647	1.666
Scenario A4: Gamesa G114 (2500)	3096.870	182,169	11.658	1.423
Scenario B1: Vestas V80 (2000)	9863.340	580,196	37.132	4.533
Scenario B2: Vestas V112 (3000)	9160.350	538,844	34.486	4.254
Scenario B3: Gamesa G87 (2000)	9258.085	544,593	34.853	4.356
Scenario B4: Gamesa G114 (2500)	8261.420	485,965	31.101	3.796

* Assuming USD 64 per BOE for 2019.

4.4. Addressing Climate Change and CO_2 Reduction

Wind power is a viable means for Jamaica to achieve CO_2-neutral electricity, ensuring energy security and aligning with climate targets set for a 7.8–25.4% reduction in CO_2 emissions by 2030 [96]. As fuel oil (petroleum) is the primary source of CO_2 emissions, the long-term benefits of CO_2 reduction through wind power will outweigh the gains from net energy tax revenue. Jamaica, facing a challenging 13% energy self-sufficiency rate and lacking fossil fuel deposits, necessitates a transition to alternative energy sources. Scenarios A1–A4 potentially reduce 1.81 million metric tons (MMT) of CO_{2e}, while scenarios B1–B4 could decrease emissions by 4.53 $MMTCO_{2e}$. At the highest level, this equates to 16.9–53.9% of total 2019 emissions, considering 8.41 $MMTCO_2$ generation, with oil contributing 85% [96]. These scenarios, addressing 3 $MMTCO_2$ impacts from electricity and heat, present significant reductions in the energy sector, amounting to 47.43% of total emissions. The study demonstrates the potential for substantial GHG emission reduction with limited environmental impact, aligning with global efforts to transition to cleaner energy sources. The methods employed in this study, leveraging Microsoft Excel, ArcGIS, Global Wind Atlas, stakeholders' choices, AWS data, and various satellites, showcase the potential of wind energy expansion to mitigate GHG emissions, even without using specialized software like RETscreen, MESSAGE, EnergyPLAN, LEAP, POLES, ESME, and MARKAL, commonly utilized for such evaluations [97].

4.5. Economic Analysis of Onshore Wind Power for Electricity Generation

The economic analysis for onshore wind power highlights the financial implications of implementing wind energy projects using the recommended scenarios from the suitability analysis. The study considers capital, operation, and maintenance costs, offering a detailed breakdown of these components.

The total capital cost for the onshore wind project using the Vestas V80 turbines is approximately USD 21.83 billion for a total electricity output of 9863.34 GWh. These metrics provide insights into the cost per unit of electricity generated and the overall project costs, including energy capacity and other associated costs. Despite the relatively high initial investment capital cost, considering the variables and factors listed and discussed above, the levelized cost of utility electricity and the simple-levelized cost of renewable energy are more significant than zero, meaning that the projects cannot operate at a loss. The $LCOE$ for onshore wind is USD 0.11 per kWh, while the $sLCOE_{RE}$ is USD 0.21 per kWh. The higher $sLCOE_{RE}$ indicates that additional factors, such as energy capacity and system costs, significantly influence the overall cost compared to the $LCOE$.

Figure 9 illustrates the NPV of total output for various onshore wind scenarios, highlighting these projects' economic viability and potential profitability in Jamaica. The scenario with the highest NPV involves the Vestas V80 turbines, with a total output of USD 61.64 billion. Furthermore, the NPV of total output for onshore wind energy projects signifies the present value of projected future cash flows, discounted to the present. The scenario involving the Vestas V80 turbines is the most economically viable, suggesting high financial returns. Moreover, the specified NPV of the total cost at USD 1291 denotes the cost per kilowatt-hour utilized in the NPV calculations. These crucial metrics aid in discerning the economic feasibility and profitability.

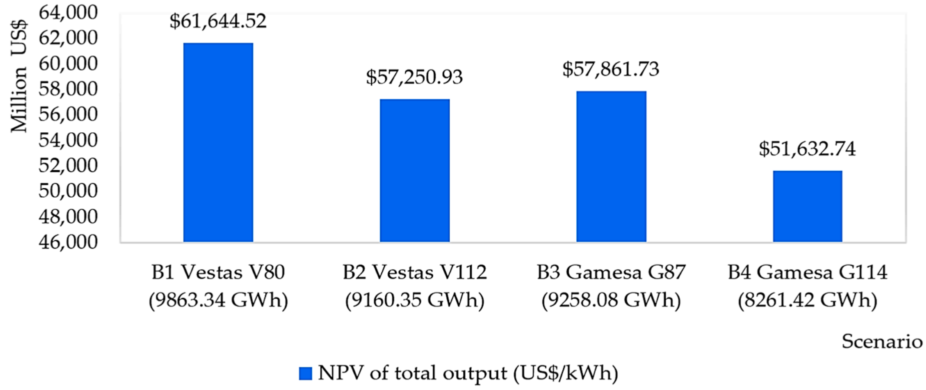

Figure 9. Total NPV output for onshore wind scenarios.

The economic analysis highlights Jamaica's substantial potential for onshore wind energy projects. The relatively low $LCOE$ and competitive $sLCOE_{RE}$ indicate cost efficiency in electricity generation. Additionally, the high *NPV* of total output underscores the long-term profitability of these projects, making onshore wind an attractive investment. Moreover, the findings align with other studies, which report similar *LCOE* values for wind energy projects in countries like China and India, ranging from USD 0.06 to USD 0.11 per kWh [98,99]. This consistency suggests that Jamaica's cost structure of onshore wind projects is comparable to global standards, reinforcing their economic viability.

4.6. Suitability Modeling and Implications

This study implemented AHP-MCDM with a weighted linear combination to formulate a suitability model for OnWF locations. The foundation of this model relied on robust wind data collected between 2009 and 2017 at both 50 and 100 m above ground level, obtained through the Wind Atlas Analysis and Application (WAsP) method's mesoscale model. The Weibull parameter, crucial in characterizing wind speed distribution, was determined within ranges at 50 and 100 m, corroborated by studies from Izydorczyk (2019) and Miao et al. (2020) [100,101], which adds reliability and validity to our methodology.

From a sustainability perspective, the study's outcomes are pivotal in fostering cleaner energy policies and aiding regional infrastructure-planning decisions. Environmental assessments and stakeholders' opinions were considered, addressing ecological, social, safety, and economic impacts. These considerations aim to minimize environmental damage associated with commercial wind farms and align with the imperative to integrate ecological factors into cleaner energy policies and regional infrastructure planning, as highlighted by the IPCC (2018) and Rogers et al. (2007) [102,103].

The study emphasizes the influence of technical factors, particularly climatology, in determining optimal wind farm placement. Environmental considerations are also highlighted, including proximity to sensitive and nationally protected sites. This approach aligns with the broader goal of ensuring ecological responsibility in wind energy projects and mitigating risks to local ecosystems, wildlife habitats, and biodiversity [104].

Integrating wind speed and slope analysis is foundational for developing cleaner energy policies. Wind speed analysis aids in estimating potential energy output and selecting optimal turbine placements, ensuring investments in areas with sufficient wind resources [105,106]. Slope evaluation is equally crucial, as it affects wind turbine efficiency, emphasizing the importance of proper site selection for long-term sustainability [107].

Integrating new and existing wind projects and clustering them in regions with favorable conditions emphasize efficient resource utilization and reduced environmental impacts. A collaborative approach involving local communities, energy stakeholders, and environmental experts enhances the efficiency and sustainability of policies and decisions related to wind farm siting.

4.7. Comparing Other Jamaican-Based Onshore Wind Studies

In contrast to prior onshore wind studies in Jamaica, this pioneering research stands out because of its comprehensive eight-year dataset, which provides an in-depth understanding of wind resources across the island. By incorporating a more extended temporal range and modern mesoscale methodology, this study surpasses the earlier studies by the Ministry of Science, Energy, and Technology (2017); Chen et al. (1990), and RoAid (2019) [12,13,15], which contributed valuable insights. The dataset spans longer and offers all-island coverage, ensuring a more nuanced evaluation of wind resources. Moreover, the study employs a holistic approach that integrates critical ecological considerations, current land use patterns, geomorphological features, and hydrological zones (Figure A7).

A distinctive aspect of this study is its emphasis on safety distance measures, aiming to minimize potential ecological and social impacts that might arise from turbine installations. The meticulous attention paid to conflicts such as radio signal interference and wake turbulence near airports and existing wind farms set this study apart regarding environmental responsibility. The study debunks two proposed sites (#1 Port Morant and #2 Stoney Point from RoAid (2019) [15] due to their locations within nationally designated protected areas and bird sanctuaries. It demonstrates the commitment of the research to biodiversity conservation, which was a notable gap in prior studies (Table A2).

Environmental constraints, including the protection of flora and fauna, are seamlessly integrated into the site-selection process. This aspect of the study reflects a commitment to ecological sustainability and a keen awareness of stakeholders' concerns and opinions. Environmental criteria are ranked second (28.1%) among the stakeholders, reinforcing the study's responsiveness to multifaceted considerations.

The study's dedication to surpassing the limitations of previous assessments is evident in its incorporation of stakeholder and expert opinions through AHP-MCDM techniques. This participatory approach enhances the evaluation of potential locations, adding depth and validity to the site selection process. It contrasts with prior studies, such as Chen et al.'s study (2020) [16], which lacked a precise power output assessment for potentially suitable wind turbines.

This study contributes to the growing knowledge of onshore wind energy in Jamaica and sets a new standard in methodology, dataset comprehensiveness, and stakeholder engagement. The meticulous consideration of safety, environmental impact, and stakeholders' perspectives positions it as a valuable guide for future regional wind energy projects.

5. Conclusions

This research advances the literature on wind energy potential in Jamaica by utilizing an all-island long-term time-series wind threshold with turbines at specific locations, addressing a gap identified in Chen's (2020) [16] integrated resource planning. The study's impact on the worldwide literature is significant in several aspects:

- It presents a comprehensive approach integrating ecological considerations, wind speed and slope analyses, and evaluation of existing wind farms to inform cleaner energy policies and facilitate regional infrastructure-planning decisions.
- The methodology addresses limited spatial opportunities for analyzing wind power expansion and assessing the potential land area for onshore wind farm expansion in Jamaica, a model applicable to other regions with similar constraints.
- Integrating geographical distribution, economic, social, safety, and technical parameters minimizes conflicts in spatial energy planning and offers a blueprint for sustainable energy development in other countries.
- The GIS AHP-MCDM technique, incorporating stakeholders' opinions, resulted in 5.25% or 578 km^2 of viable land, aligning with IRENA's assessment of 2019–2020. This approach demonstrates the value of combining technical analysis with local expertise and community input.

The study's findings suggest a high probability of extensive wind farm development in Jamaica, with scenario B1 utilizing Vestas V80, 2 MW turbines, presenting the most compelling investment opportunity. This scenario offers the highest potential wind energy (9863.34 GWh), significant economic savings (USD 37.132 million), and substantial environmental benefits (4.533 MMT CO_2 reduction). This research exemplifies how modern renewable energy models, integrated with expert and stakeholder viewpoints, can efficiently develop wind resources while minimizing negative ecological impacts. The model's relevance extends to similar renewable energy spatial planning globally, accommodating parameter alterations without compromising environmental, socioeconomic, and technical systems in pursuing sustainable renewable energy resource planning.

6. Recommendations and Future Research

This research provides an original and detailed site suitability map through the GIS AHP-MCDM technique. Considering that only six sites have been established in Jamaica (Table A1), localized to St. Elizabeth and Manchester parishes, this research reveals 17 additional sites for expansion (Table 9) and consideration of grid networks and load centers. Although four turbine design scenarios were investigated (Table 10), future research can expand on both the technology type—application of different turbine technology and evaluate the best suit for energy, environmental, and visual impacts through the refinement of the site locations (for example, the examination of the effects of these potential wind farms to nearby housing communities).

Hence, the application of state-of-the-art wind energy software such as WindPro 4.0 can be used to perform in-depth wind resource assessments (analyzing wind data, topography, and other vital parameters) to estimate potential energy production (numerous other turbine technologies beyond the four used in this research can be explored), environmental and visual aspects calculations and mappings of decibel (noise), shadow flickering, Zone of Visual Impact (ZVI), and Photomontage. Therefore, these outlined additions, among others, can provide refined and on-site calculations, adding to specialized resource studies and providing a template for future investments in Jamaica.

Author Contributions: Conceptualization, D.R.; methodology, D.R., H.Y. and T.M.; investigation, D.R. and H.Y.; formal analysis, D.R.; writing—original draft, D.R. and R.K.K.; writing—review and editing, D.R., H.Y., T.M., R.K.K., G.H.T. and Y.E.; visualization, D.R., H.Y., R.K.K. and G.H.T.; supervision, H.Y. and D.R. All authors have read and agreed to the published version of the manuscript.

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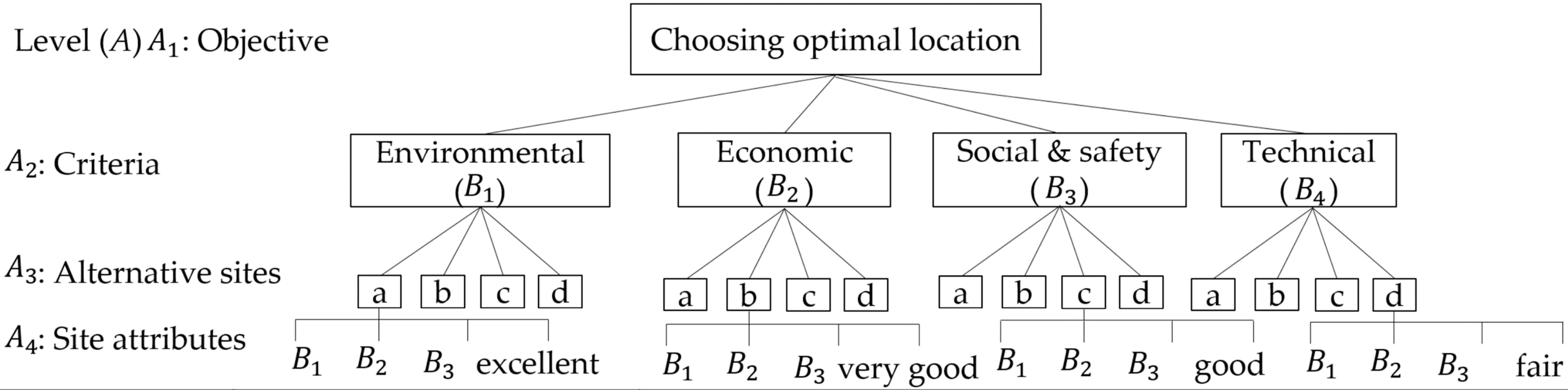
Conflicts of Interest: The authors declare that no conflicts of interest exist.

Appendix A



Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed
Multiplicative inverse	If one activity *i* has one of the above activities assigned to it when compared with activity *j*, then j has the reciprocal value when compared with *i* (i.e., 5 = 1/5 or 0.20)	

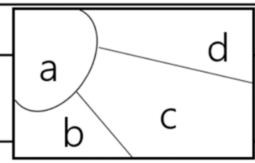


Figure A1. Determining the best alternatives. The AHP pairwise comparison method in the figure above ranks criteria in a hierarchy, with a, b, c, and d representing site alternatives. Criteria are compared using a nine-point scale to normalize and determine weights that determine the most suitable sites.

The normalize pairwise comparison matrix and criteria weights

	Economic (B_1)	Environmental (B_2)	Social and Safety (B_3)	Technical (B_4)	Criteria weights (%)
Economic (B_1)	1.00	0.50	0.50	1.00	17.6
Environmental (B_2)	2.00	1.00	1.00	1.00	28.1
Social & Safety (B_3)	2.00	1.00	1.00	0.50	24.5
Technical (B_4)	1.00	1.00	2.00	1.00	29.8
Λmax = 4.1836	*RI* = 0.90	*CI* = 0.612		*CR* = 0.068	

Size of matrix (*n*)	1	2	3	4	5	6	7	8	9	10
Random consistency index (*RI*)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Λmax = 4.184

Σratio/ratio

RI = 0.90

Referring to the size of the matrix (that is, the no. of factors, *n*, found in the comparison matrix

CI = 0.0612

(Λmax−*n*)/(*n*−1)

CR = 0.068

Consistency ratio (*CR*) computed by *CR*/*RI*

Figure A2. Normalization of pairwise comparison matrix and criteria weights.

Table A1. Current onshore wind farms and specifications in Jamaica.

Name	Location	Developer/ Operator	Hub Height	Swept Area (m^2)	Nominal Power (kW)	Number of Turbines	Land Space Occupied (km^2)	Turbine Manufacturer	Status	Commissioning Date	Specific Area (W/m^2)	Estimated Power per Turbine-Power (kW)	Turbine Type	Turbine Diameter (m)	Altitude (m)
Malvern	Saint Elizabeth (Cornwall)	BMR	Not available (N/A)	9852 m^2	36,300	11	0.34803	Vestas (Danemark)	Operational	2016	2.99 m^2/kW	3300	Vetas V112/3300	112 m	N/A
Munro College	Saint Elizabeth (Cornwall)	Petroleum Corporation of Jamaica	50 m	573 m^2	225	1	N/A	Vestas (Danemark)	Operational	1996	2.55 m^2/kW	225	Vestas V27/225	27 m	N/A
Munro Wind Farm	Saint Elizabeth (Cornwall)	Jamaica Public Service Company (JPS Co.)	50 m	1964 m^2	3000	4	N/A	Unison (Corée du Sud)	Operational	2010	2.62 m^2/kW	750	Unison U50	50 m	700 m
Wigton I	Manchester (Middle-sex)	RES/Wigton Wind Farm Limited/PCJ	50 m	2141 m^2	20,700	23	2 km length and 1 km width	Neg Micon (Denmark)	Operational	2004	2.38 m^2/kW	900	Neg Micon NM52/900	52 m	750 m
Wigton II	Manchester (Middle-sex)	RES/Wigton Wind Farm Limited	N/A	5027 m^2	18,000	9	N/A	Vestas (Danemark)	Operational	2010	2.52 m^2/kW	2000	Vestas V80/2000	80 m	750 m
Wigton III	Manchester (Middle-sex)	RES/Wigton Wind Farm Limited	N/A	5027 m^2	24,000	12	N/A	Gamesa (Espagne)	Operational	N/A	2.52 m^2/kW	2000	G80/2000	80 m	750 m

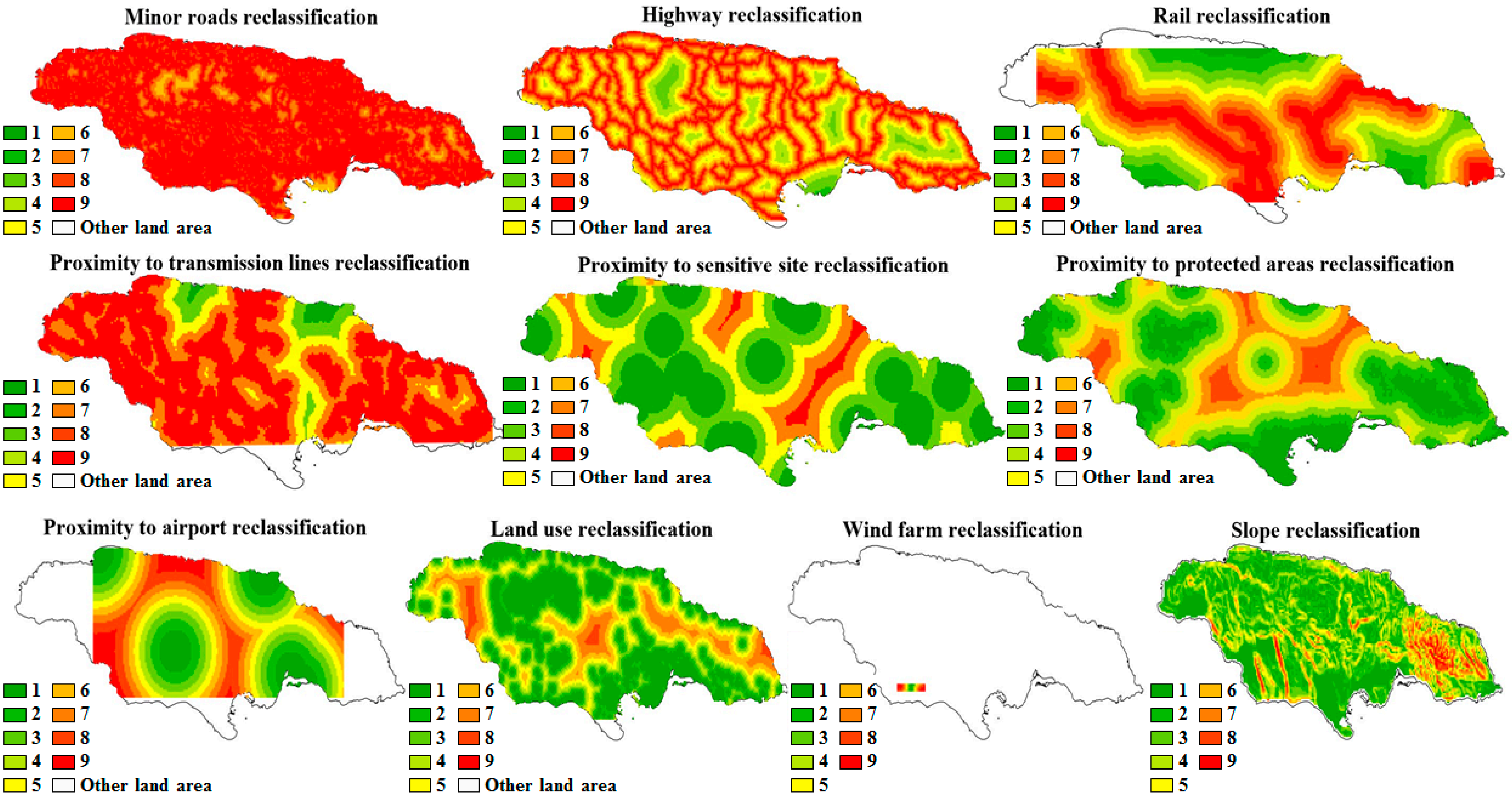


Figure A3. Reclassification of different layers. It includes evaluation criteria for the suitability map, including distance to minor roads, highways, railroads, transmission lines, sensitive sites, protected areas, airports, land use areas, existing wind farms, and slopes.

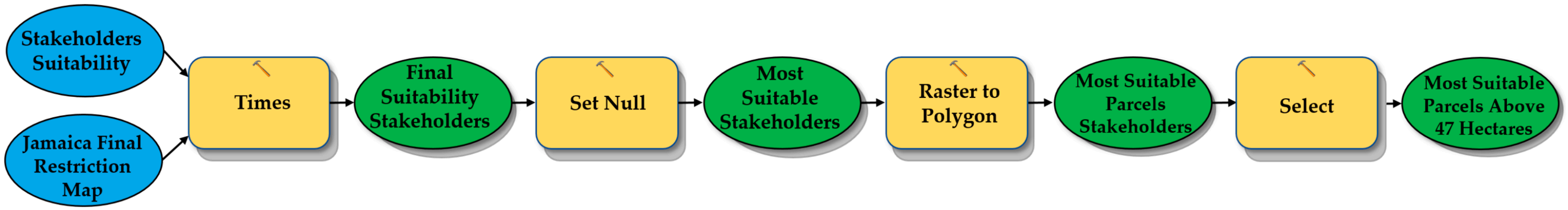


Figure A4. Final suitability model. Accounts for land areas greater than and equal to 47 hectares within the unprohibited and suitable locations for onshore wind power expansion. The model was created with ArcGIS 10.8.1. Software.

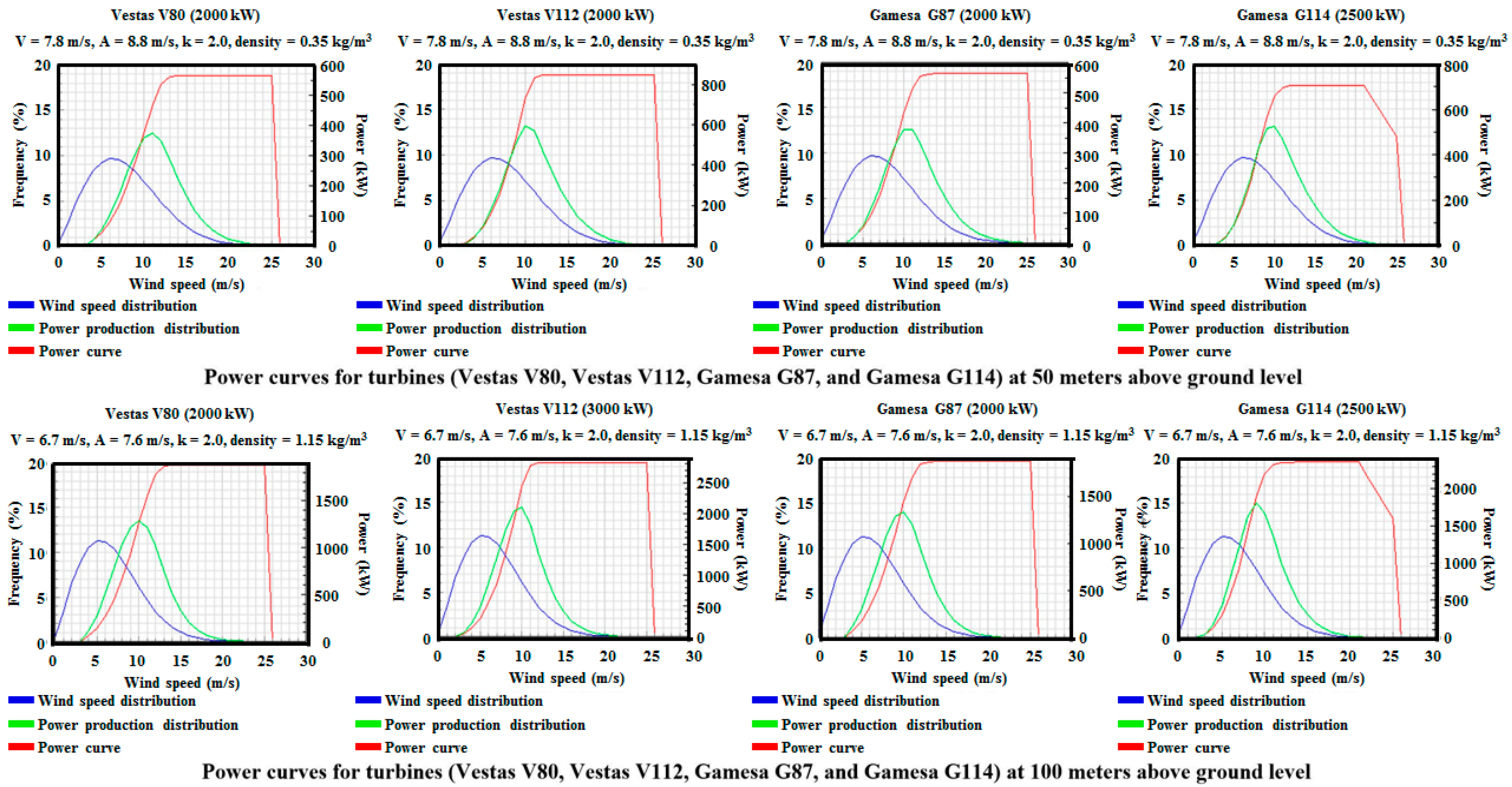


Figure A5. Power curves of suitable wind turbines adopted in the study for scenarios A1 to B4.

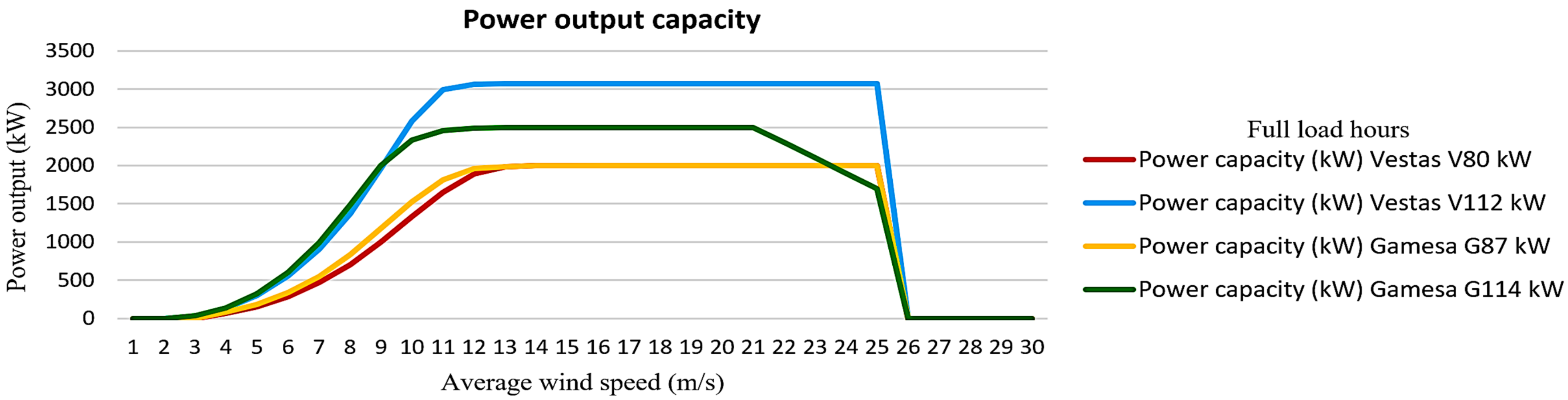


Figure A6. Power output capacity of the four selected turbines.

Table A2. Comparing other studies.

Factors for Wind Farm Allocation	This Study	Chen et al. (1990) [13]	The Ministry of Science, Energy, and Technology (2017) [12]	RoAid (2019) [15]	Chen et al. (2020) [16]
Wind resource	✓	✓	✓	✓	✓
Anemometer data/19 automatic weather stations (AWS)—Primary data	✓	✓	x	x	x
Stakeholders opinion	✓	x	x	x	x
Exclusion of protected areas and sensitive sites	✓	x	x	x	x

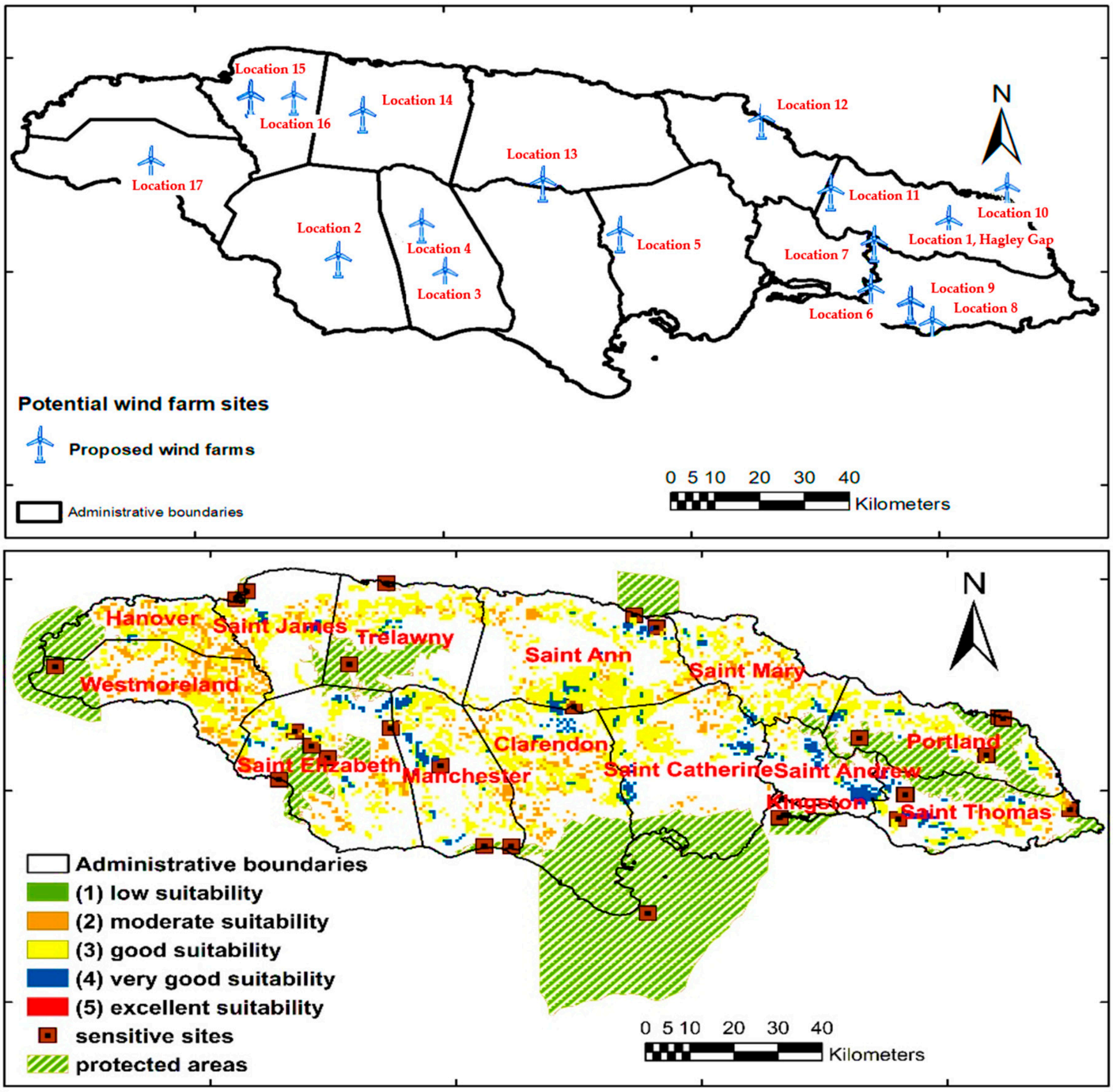


Figure A7. Minimization of ecological and social conflicts.

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