

Article

# A Geospatial Approach to Energy Planning in Aid of Just Energy Transition in Small Island Communities in the Philippines

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**Abstract:** Providing electricity in off-grid island communities is a big challenge, exacerbated by the high cost of transporting fossil fuels and the non-viability of extending grid connections. Installing renewable energy systems in these areas is deemed a practical solution, especially supporting just energy transitions in these communities. However, the lack of information about resource availability and the most suitable locations hinders effective planning. This paper aims to determine the sufficiency of available renewable energy sources to meet the electricity demand of off-grid island communities. It is achieved through a three-phased approach: (1) an assessment stage; (2) geospatial analysis; and (3) technical potential estimation. The approach is applied in three island communities in Palawan, namely Araceli, Balabac, and Cuyo, where a diesel power plant currently provides electricity to its households and commercial/institutional establishments. The results indicate that the three islands can be powered by 3, 1.5, and 11 MW solar photovoltaic farms, respectively, which is sufficient to meet the projected demand until 2030. The approach can be helpful, especially for off-grid island communities, as they plan to provide universal electricity access using renewable energy sources.



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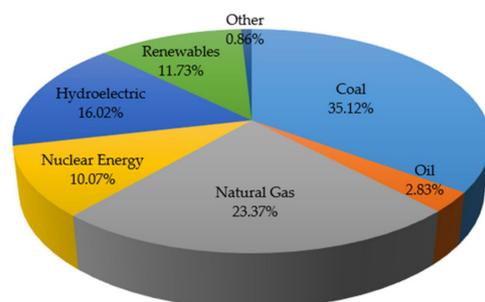
**Keywords:** energy access; load forecasting; renewable energy; resource mapping; GIS; multicriteria decision analysis; analytic hierarchy process

## 1. Introduction

### 1.1. Background

Since its commercialization, electricity has become a necessity, from lighting a small light bulb to cooling air conditioners during summer, heating electric heaters during winter, and powering industrial machinery. It plays a vital role when it comes to global economic development. The development of one country may become fast-paced because of its availability or may slow down due to the lack of it. There are various electricity generation sources, from non-renewable (coal, gas, nuclear, and oil) to renewable energy (RE) such as solar PV, hydro, and wind. Figure 1 shows the latest electricity generation mix worldwide [1], indicating that non-renewable resources are still the dominant sources of electricity. When these fuels are burned, they release carbon dioxide (CO<sub>2</sub>) and other greenhouse gases (GHGs) that may trap heat in the atmosphere, resulting in climate change and global warming [2]. This prompted the United Nations to adopt the Sustainable Development Goals (SDG) in 2015, which provides a roadmap for climate actions to reduce GHG emissions and build climate resilience [3]. Since coal-fired power generation is the

biggest emitter of all energy-related CO<sub>2</sub> emissions [4], most countries have already started using renewable energy technologies (RETs), which helped to decrease the global CO<sub>2</sub> emissions by almost 8% in 2019. The share of renewables in the electricity generation mix rose considerably with the additional output of new wind and solar projects completed over the past year [5].



**Figure 1.** World electricity generation mix by source.

The archipelagic nature of the Philippines proves to be a challenge in achieving universal electricity access and just transition, especially in off-grid communities, where grid extension is unviable, and diesel generator sets are the typical sources of energy. The Department of Energy (DOE) created an energy plan to secure the country's energy future and to actively promote the use of indigenous renewable resources [6] to expand energy access for remote and off-grid areas that are not reached by the primary grid and achieve 100% electrification by 2022 [7]. As of the 2018 World Bank report, 94.9% of the country's population has electricity access, with the remaining 5.1% who do not have access living mostly in remote island communities [8]. These island communities do not have grid access and are powered by diesel generators with a time-limited supply, translating to high electricity costs [9]. Solar, biomass, and wind resources are abundantly available as local energy sources on most small islands, making RETs or hybrid renewable energy systems (HRES) a practical approach to electrifying these communities.

Geospatial analysis has gained much attention in the past few years when it comes to identifying RE resources. Typical studies evaluate suitable locations for the development of RETs [10–14], site selection [15], and residential building energy demand and performance [16,17]. RE resource mapping can help the Philippines plan for energy access and just transition, especially in off-grid island communities. However, there is a need to streamline the RE resource mapping approach to consider consumption patterns such that initiatives for a cleaner energy transition ensure that electricity demands are met. The goal of this paper is to determine if renewable energy sources available in off-grid island communities are sufficient to meet the electricity demand not only at the household level but also at the commercial and institutional levels. It is achieved through a three-phased approach, where the first phase is the assessment stage, including site and load profile studies to assess the current energy situation of the research areas and to project the electric load demand for up to the year 2030. The second phase is the geospatial analysis, which involves identifying the factors that affect the choice of suitable locations for installing renewable energy technologies. In this stage, possible locations for RE resources available in the study area were mapped, and the number of possible sites was identified. The third phase is the technical potential estimation to determine the available generated capacity of RE resources and its ability to meet forecasted demand.

The structure of this paper is as follows: Section 1.2 summarizes the literature review, discussing the strategies and plans of different countries, especially the Philippines, in the transition to cleaner energy. It also discusses the role of GIS in renewable energy planning and reviews the literature identifying the relevant and restrictive factors that influence site selection in terms of environmental, technical, technological, and socio-economic impacts. Section 2 illustrates the proposed framework, and Section 3 presents the methodology

showing each stage of the three-phased approach as it is carried out. Section 4 presents the results, and Section 4 presents the discussion, concludes this study, and identifies the gaps for future studies.

### 1.2. Literature Review

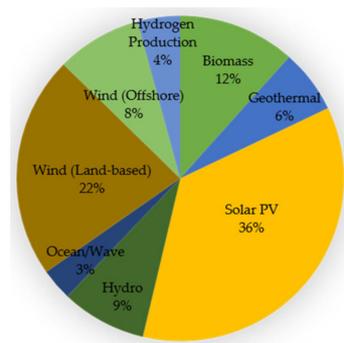
Coal-fired power generation is the largest source of electricity globally and the biggest emitter of all energy-related CO<sub>2</sub> emissions [4]. It prompted countries to adopt the goal of providing affordable, reliable, and clean energy for all [18]. Decarbonizing the power sector aims to achieve a zero-carbon world by increasing the deployment of RE systems to address energy demand [19]. RE is now considered a practical solution for greener energy and sustainable development, prompting most countries to transition from conventional fossil fuels to RE [20–23]. The archipelagic nature of the Philippines makes RE implementation more convenient, where small islands can obtain increased electricity access and cleaner electricity generation with RE implementation. However, the intermittence of RE supply, particularly solar energy resources, is thought to be unable to meet the demand consistently. It necessitates careful planning and resource identification in small island communities to ensure that RE supply is capable of meeting energy demand.

In recent years, the geographic information system (GIS) has grown in popularity as a tool for various site selection studies, particularly renewable energy planning [24]. There are several advantages when GIS is integrated with energy planning. One advantage is using spatial data to analyze demand in a particular location while creating forecasts that consider the location's unique characteristics and related energy access targets [25–27]. Likewise, GIS can assess renewable resource availability and energy potentials [28–30], finding the best suitable location for future energy infrastructure projects [31,32], and mapping out the existing transmission lines, distribution networks, etc. [33,34]. Using GIS in energy planning may help to avoid the sensitive areas that can cause adverse environmental and social impacts [35,36].

GIS plays a significant role in energy planning, from exploring renewable resources and combining them with the existing system to identifying a suitable site for the system installation. Most researchers have proposed integration methods combining GIS with other techniques to improve the potential assessment accuracy and increase site selection precision [37–39]. When combined with multicriteria decision-making (MCDM) methods, these can be among the most effective methods for locating potential renewable energy project sites [12]. They handle the process of making decisions where multiple objectives are considered [40]. The application of MCDM methods used several techniques in many kinds of research [41–43]. Ref. [44] reviewed the previous literature from 2009 to 2018, and among them, the analytic hierarchy process (AHP) ranked first as the most employed MCDM method. It has been used frequently to solve complex decision problems by using pairwise comparisons of criteria to reduce bias in decision-making [45,46].

AHP can also be combined with other MCDM methods such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [47–49]. The results provided by AHP can be further enhanced by using TOPSIS [50]. It is widely used and can effectively rank feasible sites from best to worst [51]. It proposes an optimal alternative from a series of alternatives with the shortest geometric distance from the positive ideal solution [50]. This hybrid MCDM method enables a more reliable geospatial analysis for electrification planning and site selection.

Table S1 [52–99] summarizes research from 2017 to 2021 using GIS with different RETs and applications used in electrification planning, while Figure 2 shows the percentage of each technology being studied.



**Figure 2.** Percentage of studies based on RETs.

The top three RETs that gained so much attention among researchers worldwide are solar PV (36%), wind power (30%), and biomass (12%). Though solar PV is not the largest contributor among the renewables in the worldwide energy generation mix, the share of solar PV generation rose by 22% in 2019, surpassing bioenergy to become the third-largest renewable energy technology after hydropower and onshore wind [100]. This makes solar energy one of the most important renewable sources today [46], and thus one of the most well-studied resources.

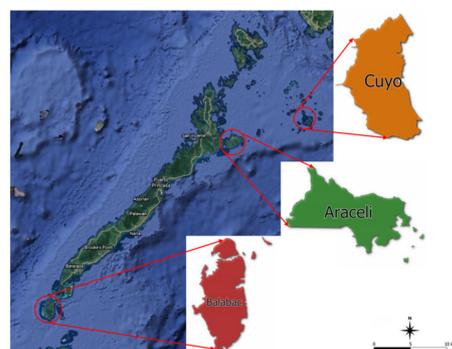
Wind energy potential is also prevalently evaluated. The studies regarding wind energy potential have two application areas. One is onshore, and the other is offshore or floating. While most wind farms today are usually built onshore, research studies shifted their focus to offshore or floating wind turbines. A study in the Canary Islands compared the wind turbine size (5 MW for offshore and 2 MW for onshore), which generates the same amount of annual energy demand, and the total area (180 km<sup>2</sup> for offshore and 500 km<sup>2</sup> for onshore) occupied by offshore and onshore wind farms. The results show that offshore projects require fewer wind turbines and surface area than onshore developments. Offshore wind conditions are far better than onshore wind conditions (i.e., higher wind speed, less turbulence, etc.), but in terms of cost, offshore costs are more than twice the onshore costs [101].

From the literature, most studies focused on RE resource availability and energy potential, suitable locations for the energy infrastructure facility, and electric network design in urban and rural areas. However, few studied the RE potentials in remote islands where energy access is a significant challenge and whether such potentials can efficiently meet demand.

## 2. Materials and Methods

### 2.1. Study Sites

There were three selected areas in this study—two islands located in northern Palawan, Philippines, and one in the southern part (Figure 3).



**Figure 3.** Map of the selected study areas.

The first island is Araceli, a fourth-class municipality, and covers roughly the northern half of Dumaran Island. The second island is Cuyo, a coastal community found in the Sulu Sea 22.3 m above mean sea level [102]. The third study area is Balabac Island, located in the westernmost point in the Philippines. The site descriptions are summarized in Table 1.

**Table 1.** Site description of the selected areas [103,104].

Study Area	Location	Area (km <sup>2</sup> )	Population	No. of Households	Density (Population/km <sup>2</sup> )	No. of Barangay
Araceli	Latitude: 10°33'32" N Longitude: 119°59'40" E	204.30	14,895	3294	73	13
Balabac	Latitude: 07°59' N Longitude: 117°03' E	581.6	22,184	5103	69	20
Cuyo	Latitude: 10°51' N Longitude: 121°01' E	84.95	39,853	8445	263	17

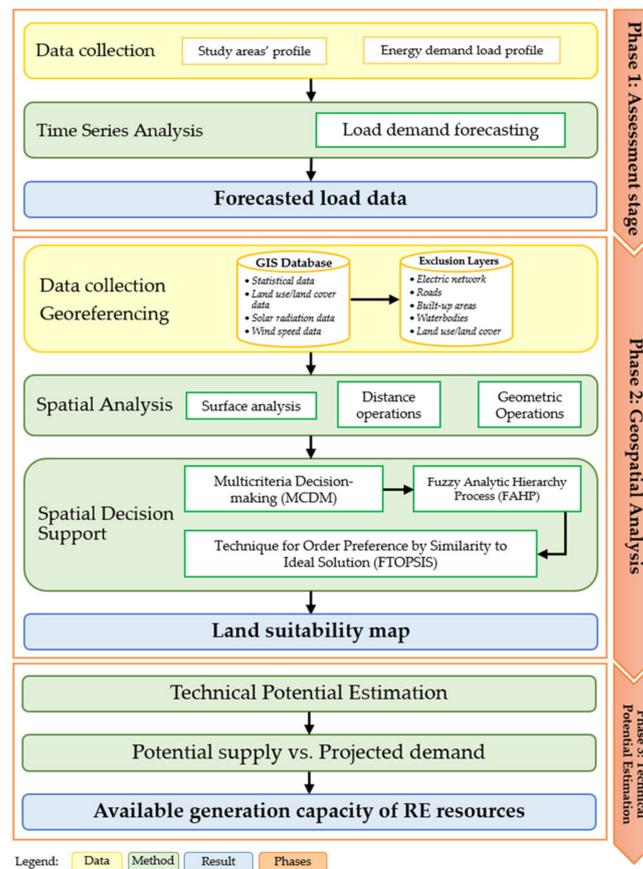
## 2.2. Data Collection and Georeferencing

The data were collected from GIS public databases and local surveys, including exclusion layers, i.e., electric networks, roads, built-up areas, water bodies, and land use/land cover. All layers had their criteria based on the technology being mapped. The collected datasets were used to map solar energy potential. A digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM)—Earthdata (NASA) in a raster format. It was then used to determine the slope and aspects essential in the site suitability analysis of solar energy. The slope and aspect were considered a critical topographical factor that significantly influences land suitability for installing PV systems, where it is best when it faces the south direction [105]. The reason is to avoid the shadow effect on the generation of the PV system [106]. Lands with a slope greater than 5° were not considered [107], because it affects the reception of solar radiation, and the flatter the surface, the more radiation it received [108].

The wind speed is also an important parameter that influences land suitability for installing wind turbines. For the three study areas, the average annual wind speed at the height of 50 m is as follows: for Araceli, it is 5.82 m/s, for Balabac, it is 4.85 m/s, and for Cuyo, it is 6.39 m/s [109]. Since Balabac did not meet the minimum criteria of 5.5 m/s of mean wind speed, it was therefore excluded from the assessment.

## 2.3. Research Framework

The research framework is shown in Figure 4. The framework was developed based on a three-phased approach: (1) an assessment stage; (2) geospatial analysis; and (3) technical potential assessment. The assessment stage included study area investigation, load profile study, and load demand forecasting. The second approach involved the geospatial analysis using the GIS-MCDA method to map the available RE resources in the study areas. It also identified the factors that influence the selection of RE technologies' location. The third and final analysis estimated the technical potential of each RE resource. Then, these resources were evaluated to determine if the generated energy supply will be sufficient to meet the energy demand once it is fully utilized. The paper uses color convention: yellow represents "data", green means the "methods/analysis", blue is the "results of the assessment", and the "research approaches" are in orange.



**Figure 4.** Research framework.

### 2.3.1. Assessment Stage

The assessment stage included (a) the identification of study areas, (b) the load profile study, and (c) load demand forecasting. The data were collected from local surveys and interviews. Other data, such as population and the number of households per barangay, were collected from the local government units. The load profile also came from the local distribution utility. The Holt–Winters exponential smoothing in R software was utilized to determine the forecast the load demand until 2030. It is known to be effective in forecasting seasonal time series, and the smoothing parameters were assumed to be  $\alpha = 0.2$ ,  $\beta = 0.1$ , and  $\gamma = 0.2$ , respectively [110]. While there are many advanced statistical methods to be used in forecasting and many parameters that need to be considered, this study used only one independent variable, i.e., historical load demand data. The forecasted load was compared with the result of resource mapping to determine whether the available generation potential from the available RE resources in the study areas will be sufficient to meet the current load demand until 2030.

### 2.3.2. Geospatial Analysis

The second approach was the geospatial analysis to map RE resources available in the study areas. It assessed environmental, technical, technological, and socio-economic factors. The determinant factors were used to identify the exclusion criteria and constraints for geospatial analysis that affect suitable locations for installing RE technologies. The methodology was based on the concept of the previous research [111].

#### a. Spatial Analysis

The geospatial analysis involves several methods such as surface analysis, geometric operations, and distance operations. As shown in Table 2 below, the exclusion criteria and constraints were applied regarding environmental, technical, technological, and socio-

economic aspects. The specific reclassification values and corresponding suitability ratings for each criterion are provided in Table S2.

**Table 2.** Exclusion criteria and constraints.

Code	Data Layer	Criteria		Restriction Factor	Category	Format	Source	Description	References
		Solar PV	Wind						
C1 <sub>s</sub> C1 <sub>w</sub>	Resource potential	GHI > 3.56 kWh/m <sup>2</sup>	Wind speed < 5.5 m/s at 50 m	–	Technical	Raster	SolarGIS, Global Solar Atlas, Global Wind Atlas	GHI: It is the total amount of microwave radiation absorbed by a horizontal surface on the ground. Wind speed: Average annual wind speed at 50 m above ground in off-grid areas.	[112–115]
C2	Slope	>5°	>15°	Topography	Technical	Raster	Earthdata, NAMRIA	It is the degree of inclination of the surface, usually in degrees or in percent generated from DEM.	[106,107,116]
C3	Aspect	South-facing	–	Topography	Technical	Raster	Earthdata	The orientation of a surface and is considered as the slope direction.	[106–108,117]
C4	Electric networks	<100 m	<100 m	Technology	Technological	Vector	PALECO	Transmission and distribution power lines	[118–120]
C5	Roads	<100 m	<500 m	Infrastructure	Socio-economic	Vector	OpenStreet Map, Google Satellite	Proximity to roads, highways, paved paths, unpaved paths, etc.	[43,117–119,121,122]
C6	Built-up areas	<500 m	<1000 m	Infrastructure	Socio-economic	Vector	OpenStreet Map, Google Satellite	Residential, parking lots, commercial buildings, parks, gardens, etc.	[123,124]
C7	Water bodies	<100 m	<100 m	Hydrology	Environmental	Vector	OpenStreet Map, Google Satellite	Lakes, rivers, reservoirs, etc.	[115,121,125]
C8	Land use/land cover	Avoid	Avoid	Land use, Ecology	Environmental	Vector	PhilGIS	Irrigated areas, forests, agricultural lands, mangrove areas, etc.	[123,126–128]

## b. Spatial Decision Support

MCDM allows for the evaluation and prioritization of alternative decisions, particularly for evaluating siting alternatives [35,128,129]. The most commonly used method is the analytic hierarchy process (AHP), initially developed by Prof. Thomas L. Saaty in 1977 [45]. However, according to [130], a traditional AHP has several limitations, such as (1) dealing with an unbalanced judgmental scale; (2) being unable to deal with the ambiguity and uncertainty associated with one's judgment to a number; (3) imprecise ranking; and (4) subjective judgment, in which the decision maker's preference greatly influences AHP results [131]. With this, [132] introduced the concept of fuzzy sets by using linguistic variables rather than numerical values. The application of a hybrid AHP and TOPSIS can provide reliable geospatial analysis for RE resource site selection. This paper used the fuzzy AHP-TOPSIS model, where the Fuzzy AHP was utilized to find out the weights of the criteria, and TOPSIS was used to rank the possible siting locations for solar PV and wind farms.

- Fuzzy AHP Method

The steps of the fuzzy AHP method are summarized as follows [130,133,134]:

Step 1. Determine the goal, alternatives, and criteria.

Step 2. Create a pairwise comparison matrix (PCM) using Equation (1), where  $n$  is the number of criteria,  $w_i$  denotes the weight for the  $i$  criterion, and  $a_{ij}$  is the ratio of the weight of  $i$  and  $j$  criteria.

$$a_{ij} = \frac{w_i}{w_j} \tag{1}$$

where  $i, j = 1, 2, \dots, n$ .

$$A = a_{ij} \cdot \frac{1}{a_{ij}^T} \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} \tag{2}$$

Step 3. Convert Saaty’s numerical scale into a triangular fuzzy number (TFN). The FAHP scale has three values, the lower limit (l), medium limit (m), and the upper limit (u). Table 3 shows the linguistic values and the TFNs.

Step 4. Calculate the geometric mean using Equation (3), where  $l_{ij}$ ,  $m_{ij}$ ,  $u_{ij}$  are geometric means in the TFN scale, and  $k$  is the number of decision-makers. The TFN matrix is consistent if the value of  $l \leq m \leq u$ .

$$\begin{aligned} l_{ij} &= \left( \prod_{k=1}^K l_{ijk} \right)^{\frac{1}{k}}, \\ m_{ij} &= \left( \prod_{k=1}^K m_{ijk} \right)^{\frac{1}{k}}, \\ u_{ij} &= \left( \prod_{k=1}^K u_{ijk} \right)^{\frac{1}{k}} \end{aligned} \tag{3}$$

Step 5. When the AHP numerical scale has been converted to FAHP scale values, calculate the fuzzy synthesis value ( $S_i$ ) given by Equations (4)–(6):

$$\sum_{i=j}^m M_{gi}^j = \left( \sum_{i=j}^m l_i, \sum_{i=1}^n m_i, \sum_{i=j}^m u_i \right) \tag{4}$$

$$\frac{1}{\left( \sum_{i=j}^m \sum_{i=1}^n M_{gi}^j \right)} = \frac{1}{\sum_{i=1}^n u_i}, \frac{1}{\sum_{i=1}^n m_i}, \frac{1}{\sum_{i=1}^n l_i} \tag{5}$$

$$S_i = \sum_{j=1}^m M_{gi}^j * \frac{1}{\left( \sum_{i=j}^m \sum_{i=1}^n M_{gi}^j \right)} \tag{6}$$

Step 6. The last step is to calculate the crisp weights. It can be obtained through a defuzzification process as defined by:

$$W_j = \frac{l + m + u}{3} \tag{7}$$

Step 7. Calculate the eigenvector, maximum eigenvalue, Consistency Index (CI), and the consistency ratio (CR) using Equations (8)–(10), where  $\lambda_{max}$  is the eigenvalue of paired comparison matrix, and RI is for random index (Table 4).

$$\lambda_{max} = \frac{\sum \text{Ratio}}{n} \tag{8}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{9}$$

$$CR = \frac{CI}{RI} \tag{10}$$

**Table 3.** Linguistic values and triangular fuzzy numbers.

Linguistic Values	AHP Scale	TFN Scale (l, m, u)	Reciprocal TFN
Equal importance	1	(1, 1, 1)	(1, 1, 1)
Intermediate value	2	(1, 2, 3)	(1/3, 1/2, 1)
Moderate importance	3	(2, 3, 4)	(1/4, 1/3, 1/2)
Intermediate value	4	(3, 4, 5)	(1/5, 1/4, 1/3)
Strong importance	5	(4, 5, 6)	(1/6, 1/5, 1/4)
Intermediate value	6	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strong importance	7	(6, 7, 8)	(1/8, 1/7, 1/6)
Intermediate value	8	(7, 8, 9)	(1/9, 1/8, 1/7)
Extreme importance	9	(9, 9, 9)	(1/9, 1/9, 1/9)

**Table 4.** Random consistency values [45,50].

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

- TOPSIS Method

After getting the relative weights from FAHP, the TOPSIS method will rank the number of alternatives based on the criteria. TOPSIS is one of the classical MCDM methods initially developed by [135]. It is based on the concept that a chosen alternative has the shortest distance from the positive ideal solution. The one with the farthest distance is the negative ideal solution [131]. The steps of the TOPSIS method [49,107,136,137] are as follows:

- Step 1. Create a decision matrix (D) containing all the criteria, alternatives, and criteria weights.
- Step 2. Calculate the normalized decision matrix ( $X_{ij}$ ) using the following equation:

$$X_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, i = 1, 2, \dots, m, j = 1, 2, \dots, n \tag{11}$$

- Step 3. Calculate the weighted normalized decision matrix ( $X_{ij}$ ) by multiplying the normalized decision matrix ( $X_{ij}$ ) by the weight ( $w_j$ ) of the indicator that came from the fuzzy AHP.

$$V_{ij} = X_{ij} * w_j \tag{12}$$

- Step 4. Determine the positive and negative ideal solution. The positive ideal solution ( $A^+$ ) is the maximum value of  $V_{ij}$ , and the negative ideal solution ( $A^-$ ) is the minimum value.

$$A^+ = [v_1^+, \dots, v_n^+], v_j^+ = \max \{v_{ij}\} \tag{13}$$

$$A^- = [v_1^-, \dots, v_n^-], v_j^- = \min \{v_{ij}\} \tag{14}$$

- Step 5. Calculate the Euclidean distance of each alternative from positive and negative ideal solutions ( $A^+, A^-$ ).

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \tag{15}$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \tag{16}$$

Step 6. Calculate the performance score (CP) of each alternative to the positive ideal solution ( $A^+$ ).

$$CP_i = \frac{d_i^-}{(d_i^+ + d_i^-)} \quad (17)$$

Step 7. Rank the alternatives according to the performance score, where the shortest distance is the positive ideal solution, and the farthest distance is the negative ideal solution.

### 2.3.3. Technical Potential Estimation

The goal of the technical potential estimation is to determine the generation capacity of each RE resource for energy access. Based on the calculated area from GIS and with the aid of HelioScope, the actual solar PV panels installation area can be simulated, and the annual electricity generation capacity will be obtained. This is then fed to HOMER Pro to determine whether the system is feasible or not. Viable power systems as well as battery storage size are obtained, and the monthly power generation is determined.

The forecasted demand from the first phase and the projected supply from renewable energy sources in this stage will be compared to determine if the full utilization of these resources can meet the energy demand, and as a result, support the global and national transition to cleaner energy sources.

## 3. Results

### 3.1. Assessment Stage

#### 3.1.1. Current Energy Profile of the Case Areas

The island communities have residential dwellings, public buildings (municipal hall, essential health services facilities, churches, schools), and commercial establishments (resorts and transient houses, small restaurants, construction hardware, grocery, dry good stores). The Palawan Electric Cooperative (PALECO) manages and operates the islands' power supply, stand-alone diesel power plants, which are not connected to the primary grid of Palawan. Only the island of Cuyo has a 24 h supply of electricity. In Araceli, only 2 out of 13 barangays have a 24 h electricity supply and in Balabac, only 6 out of 20 barangays. Those who do not have continuous access use generators from the local village for 4–5 h daily. The electric load profile from 2017 to 2021 was obtained from NPC and is shown in Table 5.

**Table 5.** Annual electric load demand of the study areas.

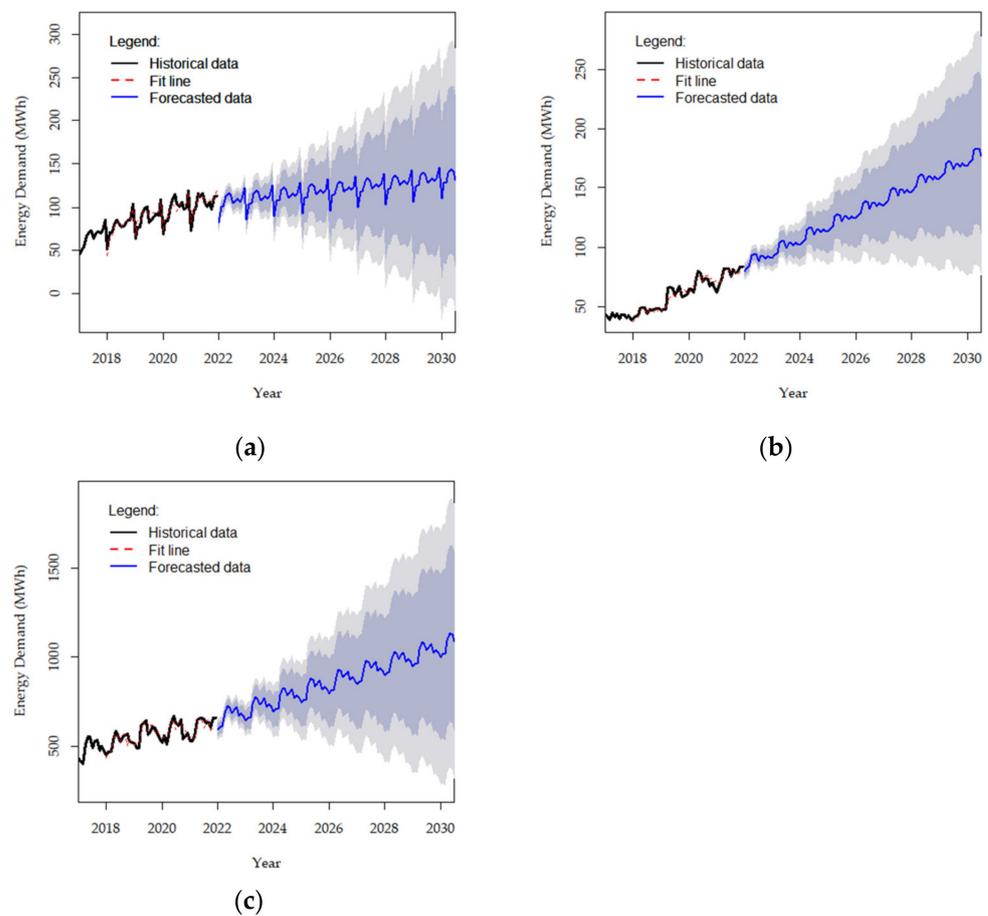
Year	Energy Demand (MWh)		
	Araceli	Balabac	Cuyo
2017	790.850	499.404	5855.638
2018	949.633	552.387	6337.064
2019	1054.212	705.619	6848.156
2020	1186.260	843.871	7406.970
2021	1242.335	931.602	7407.427

#### 3.1.2. Load Forecasting

The energy load demand was predicted until 2030 (see Table S3). It was summed up to obtain the yearly projected load demand, as presented in Table 6, followed by the smoothing trend line of the Holt–Winters method plot as shown in Figure 5 with confidence intervals of 80% and 95%. The predicted energy demand in Araceli for the year 2030 is 1612.724 MWh, an increase of 30% from the 2021 data. In Balabac, there is a 131% of forecasted demand from 931.602 to 2147.121 MWh. The current energy demand of 7407.427 MWh in Cuyo is expected to increase by 75% by 2030, which gives a predicted load demand of 12,958.001. With confidence intervals of 80% and 95%, it is expected that the expected value may fall on those intervals.

**Table 6.** Forecasted energy demand.

Year	Energy Demand (MWh)		
	Araceli	Balabac	Cuyo
2022	1285.385	1075.364	8065.971
2023	1326.303	1209.334	8677.474
2024	1367.220	1343.303	9288.978
2025	1408.137	1477.273	9900.482
2026	1449.055	1611.242	10,511.986
2027	1489.972	1745.212	11,123.489
2028	1530.889	1879.182	11,734.993
2029	1571.807	2013.151	12,346.497
2030	1612.724	2147.121	12,958.001



**Figure 5.** Holt-Winters method plot for (a) Araceli, (b) Balabac, and (c) Cuyo.

### 3.2. Geospatial Analysis

The study areas were defined using GIS data for the region of Palawan, the Philippines. The boundaries of the three off-grid island communities (Araceli, Balabac, and Cuyo Islands) were extracted for use as a mask for all criteria. The data were uploaded to QGIS, including base criteria such as DEM, solar radiation, wind speed, aspect, and slope. Then, the application of the qualifiers layer was implemented to assess the land quality of the areas being investigated. The preparation of the maps before the exclusion criteria and constraints were implemented is presented in Figure S1.

#### a. Spatial Analysis

GHI in the country has an annual potential average of 5.1 kWh/m<sup>2</sup>/day [138]. For the three study areas, the GHI values are as follows: Araceli has a GHI of 5.26 kWh/m<sup>2</sup>/day,

Balabac has a GHI of 4.98 kWh/m<sup>2</sup>/day, and Cuyo has a GHI of 5.35 kWh/m<sup>2</sup>/day [139]. The slopes are extracted from DEM in the QGIS slope tool, and a slope of more than 5° was excluded because it affects the reception of solar radiation. The aspect was also extracted from DEM using the aspect tool in QGIS.

The solar and wind farm locations should be near electric networks and road infrastructures to avoid transmission losses and high economic costs [30,140]. The Euclidian distance was utilized to calculate the nearest source based on straight-line distance. Proximity to built-up areas and water bodies were also reclassified using the raster calculator in QGIS.

After applying all of the exclusion criteria and constraints set in Table 2, the result of the spatial analysis is shown in Figure S4.

b. Spatial Decision Support

Fuzzy AHP-TOPSIS was applied to eliminate infeasible areas to map suitable solar PV plant and wind farm locations. A hierarchical structure (Figure 6) was made to show how the criteria are used for evaluation to reach the common goal.

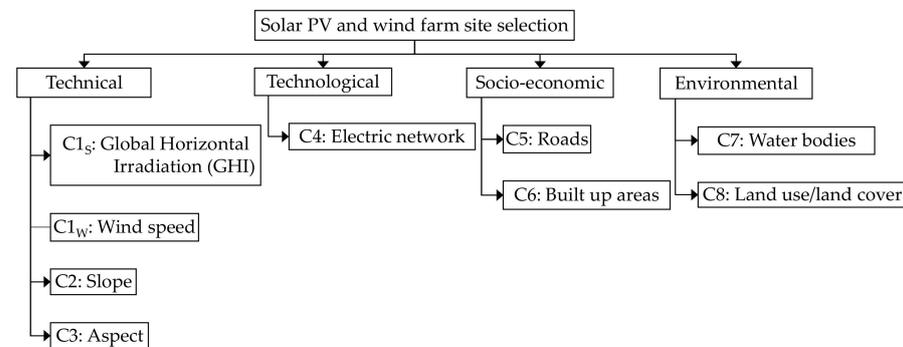


Figure 6. Hierarchical structure for Solar PV and wind farm site selection.

There are eight criteria for solar PV and seven for wind farm mapping. Therefore, the sizes of PCM are 64 (solar PV) and 49 (wind). The comparison matrix of the criteria using a numerical scale was converted into TFNs. The fuzzy weights were obtained using Equations (3)–(6), and through the defuzzification process, the crisp weight was calculated. Then, each crisp weight was divided by the sum of all crisp weights to obtain the normalized matrix. The maximum eigenvalue and Consistency Index (CI) for solar PV were calculated as 8.602 and 0.086, respectively, and 7.428 and 0.071 for wind energy. With that, the CR values for the two RETs are 0.061 and 0.054. Since all the values of CR for both solar PV and wind are less than 0.10, the value judgments are considered acceptable [140]. Table 7 shows the summary of the results for the Fuzzy AHP method.

In QGIS, the final normalized weights were used to identify the degree of importance of each criterion and the rasters of the exclusion criteria and constraints were used as input layers. The final rasters of the suitability map (SM) for solar PV farms (5) and wind farms (6) were calculated using the following expressions:

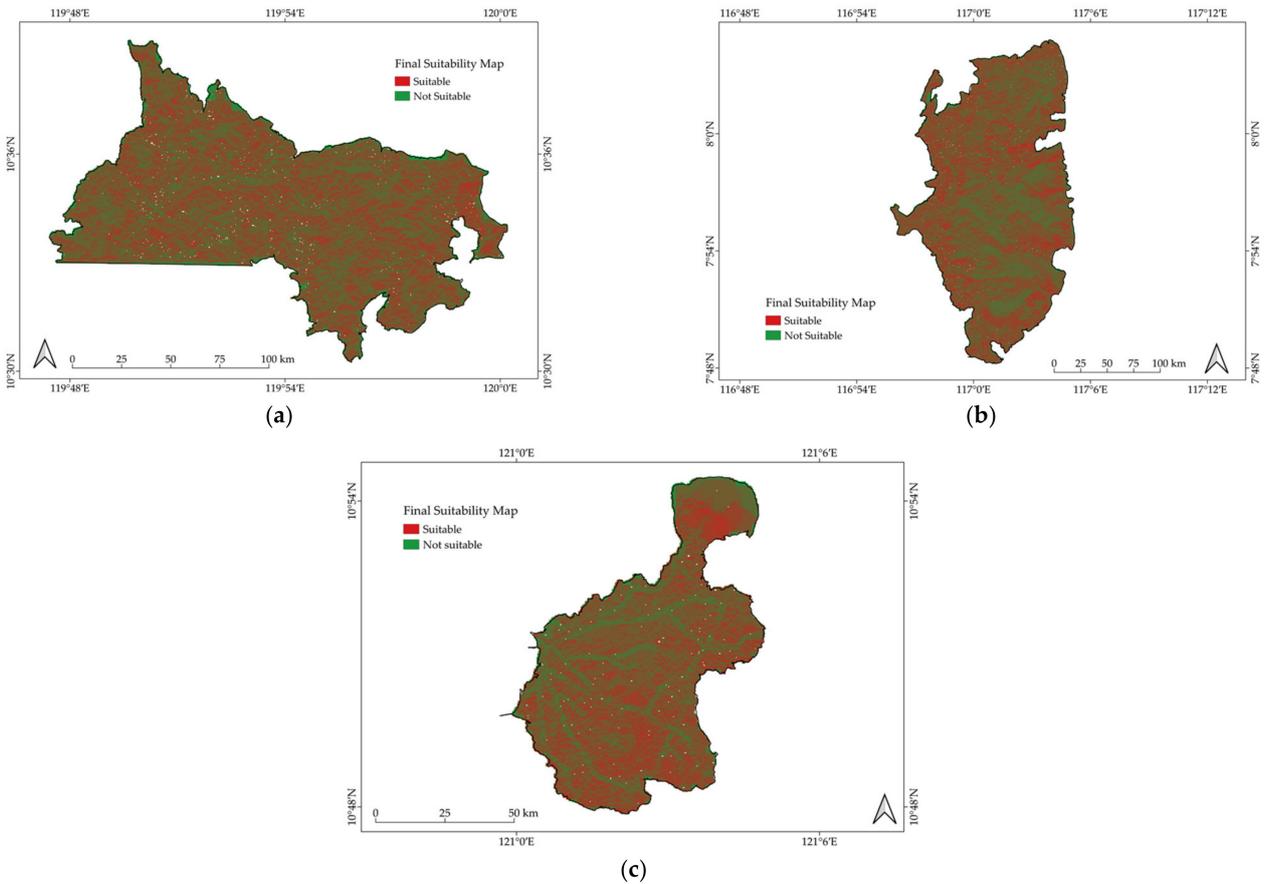
$$SM_S = 0.316C1S + 0.203C2 + 0.189C3 + 0.098C4 + 0.071C5 + 0.055C6 + 0.033C7 + 0.044C8 \quad (18)$$

$$SM_W = 0.327C1 + 0.267C2 + 0.121C4 + 0.105C5 + 0.089C6 + 0.045C7 + 0.046C8 \quad (19)$$

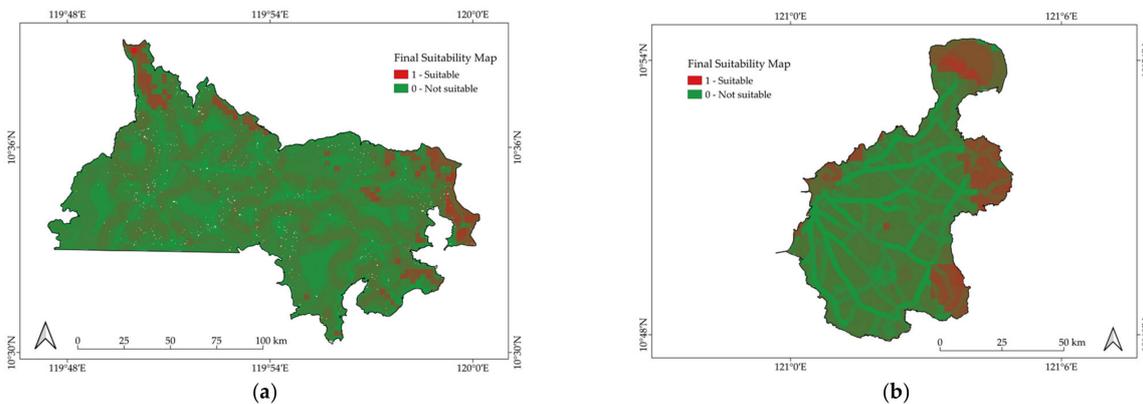
The final suitability map (Figures 7 and 8) is represented by binary values 0 and 1. “0” represents those areas that are not suitable, and “1” shows the best possible location for installing solar PV and wind power farms.

**Table 7.** Comparison matrix sum, final criteria weights, weighted sum value, and ratio.

Criteria	Sub-Criteria	FUZZY Weight		Crisp Weight		Normalized Weight	
		Solar PV	Wind	Solar PV	Wind	Solar PV	Wind
Technical	C1s GHI	(0.201, 0.319, 0.490)	-	0.337	-	0.316	-
	C1w Wind speed	-	(0.192, 0.333, 0.540)	-	0.355	-	0.327
	C2 Slope	(0.135, 0.204, 0.309)	(0.154, 0.265, 0.453)	0.216	0.291	0.203	0.267
Technological	C3 Aspect	(0.124, 0.190, 0.291)	-	0.202	-	0.189	-
	C4 Electric network	(0.064, 0.097, 0.153)	(0.082, 0.122, 0.189)	0.105	0.131	0.098	0.121
Socio-economic	C5 Roads	(0.046, 0.071, 0.111)	(0.064, 0.104, 0.173)	0.076	0.114	0.071	0.105
	C6 Built up areas	(0.035, 0.055, 0.086)	(0.058, 0.092, 0.142)	0.059	0.097	0.055	0.089
Environmental	C7 Water bodies	(0.021, 0.033, 0.053)	(0.027, 0.042, 0.079)	0.035	0.049	0.033	0.045
	C8 Land use/land cover	(0.020, 0.031, 0.058)	(0.025, 0.042, 0.082)	0.036	0.050	0.034	0.046
						CR = 0.061	CR = 0.054



**Figure 7.** Final suitability map of solar PV: (a) Araceli; (b) Balabac; and (c) Cuyo.



**Figure 8.** Final suitability map of wind energy: (a) Araceli; and (b) Cuyo.

To produce 1 MWp, 1–2 hectares (10,000–20,000 m<sup>2</sup>) of land is needed for a solar farm, and 10 hectares (100,000 m<sup>2</sup>) of land is required to install a 1 MW wind farm [141,142]. Areas below 5 hectares (50,000 m<sup>2</sup>) were excluded from the site selection for solar PV farms, and 10 hectares (100,000 m<sup>2</sup>) for wind farms, and those near agricultural farms. Additionally, since this study considered island communities, 500 m from the seashore was considered a buffer zone. Since Cuyo has an airport, a 5000 m buffer zone from the airport was also considered. Then, a visual inspection by georeferencing on Google Earth was performed to obtain the best results of potential sites.

The application of the TOPSIS method ranked the locations based on the given criteria. The weighted normalized decision matrix was calculated using Equation (12) by multiplying the normalized decision matrix by the indicator’s weight from the fuzzy AHP analysis. The Euclidean distance of each alternative from the positive and negative ideal solutions was obtained, and the performance score was calculated. Table 8 presents the summary of the TOPSIS method showing the number of possible locations and the total calculated area in square kilometers and the ranking of feasible selection sites. Figures 9 and 10 show where these possible locations are situated.

The areas stated are for solar PV and wind farm suitability mapping. The ownership of the land and other governmental concerns were not considered.

### 3.3. Technical Potential Estimation

The three islands currently use diesel generators with an installed rated capacity of 1.386, 1.086, and 3.2 MW. Based on the ranked locations from Table 8, the first-ranked locations are chosen as the most feasible locations. These were then simulated in HelioScope to determine the generated potential rated capacity and solar PV’s estimated annual generation potential. Simulation results in HelioScope were used in HOMER Pro to determine the system’s feasibility. The most viable power system was obtained with different technology options and resource availability. Table 9 shows each renewable resource’s demand and production profile and the energy storage needed to replace the existing diesel generator sets, while Figures 11–13 display the time series plots on an hourly basis of the demand, production, and unmet electrical loads of solar PV and wind.

Table 8. Calculated area and performance scores of possible locations.

Study Area and Locations	Total Area (m <sup>2</sup> )		Performance Score								
	Solar PV	Wind	Solar PV				Wind				
			$d_i^+$	$d_i^-$	$CP_i$	Rank	$d_i^+$	$d_i^-$	$CP_i$	Rank	
	Araceli										
L1	131,813	4,563,000	0.048	0.088	0.646	3rd	0.110	0.133	0.546	1st	
L2	182,860	8178,000	0.088	0.059	0.404	5th	0.133	0.110	0.454	2nd	
L3	181,688	–	0.047	0.087	0.649	2nd	–	–	–	–	
L4	51,585	–	0.060	0.086	0.590	4th	–	–	–	–	
L5	238,280	–	0.008	0.101	0.922	1st	–	–	–	–	
	Balabac										
L1	226,891	–	0.054	0.058	0.514	3rd	–	–	–	–	
L2	238,558	–	0.025	0.065	0.723	1st	–	–	–	–	
L3	121,919	–	0.060	0.037	0.381	4th	–	–	–	–	
L4	133,057	–	0.043	0.055	0.563	2nd	–	–	–	–	
	Cuyo										
L1	200,565	4,330,000	0.020	0.025	0.550	2nd	**	**	**	1st	
L2	54,498	–	0.036	0.004	0.092	3rd	–	–	–	–	
L3	225,405	–	0.005	0.035	0.881	1st	–	–	–	–	

\*\* Ranking is not applicable since it has only one alternative.

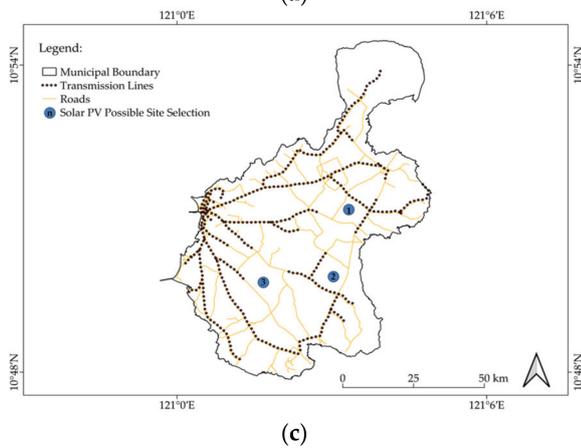
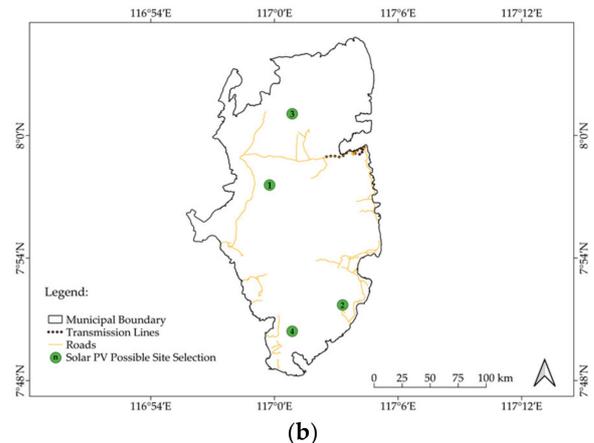
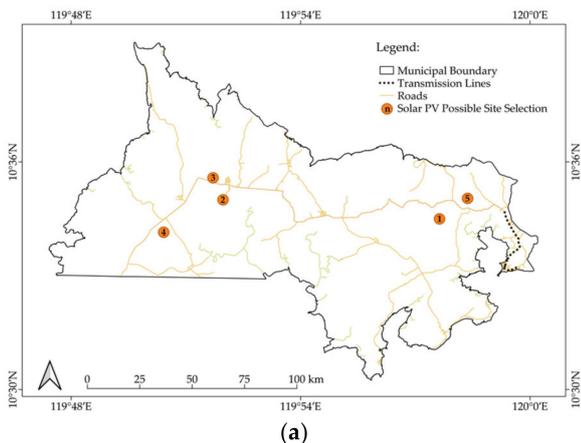


Figure 9. Possible locations for solar PV farms: (a) Araceli; (b) Balabac; and (c) Cuyo.

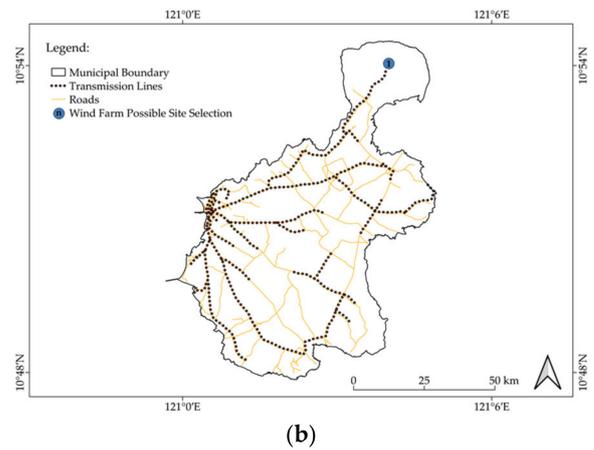
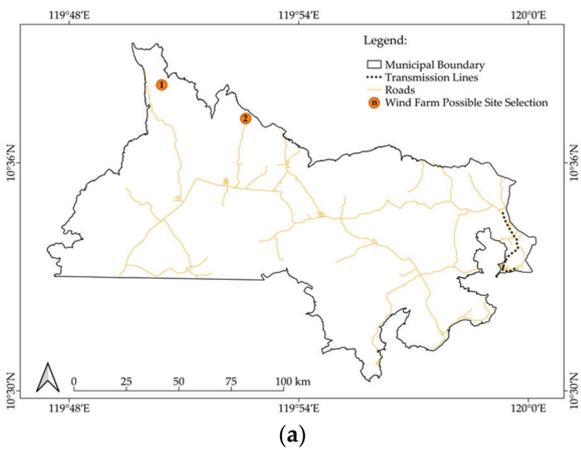
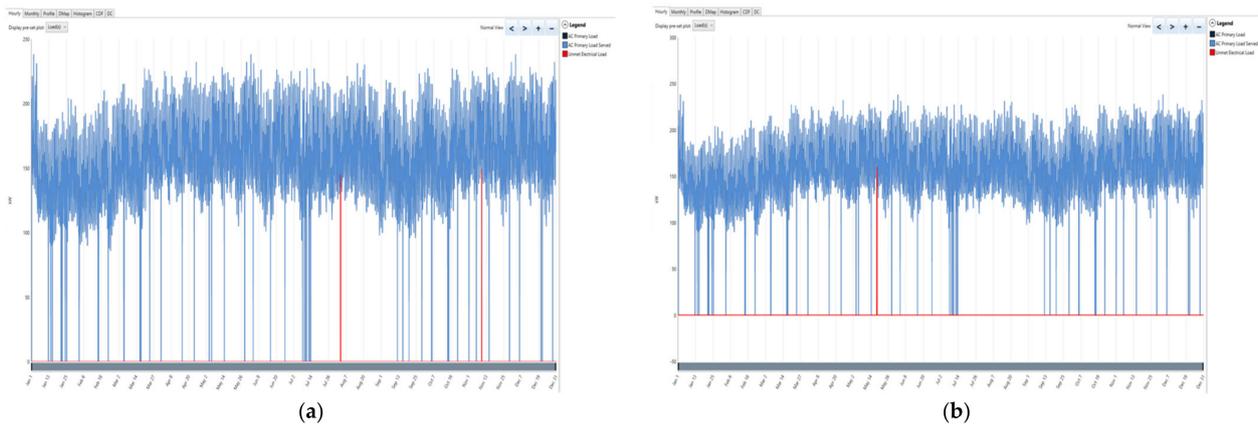


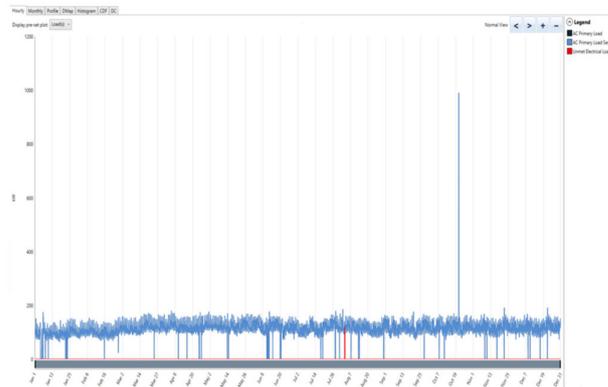
Figure 10. Possible locations for solar PV farms: (a) Araceli; and (b) Cuyo.

**Table 9.** Electricity generation capacity and annual generation potential of solar PV and wind.

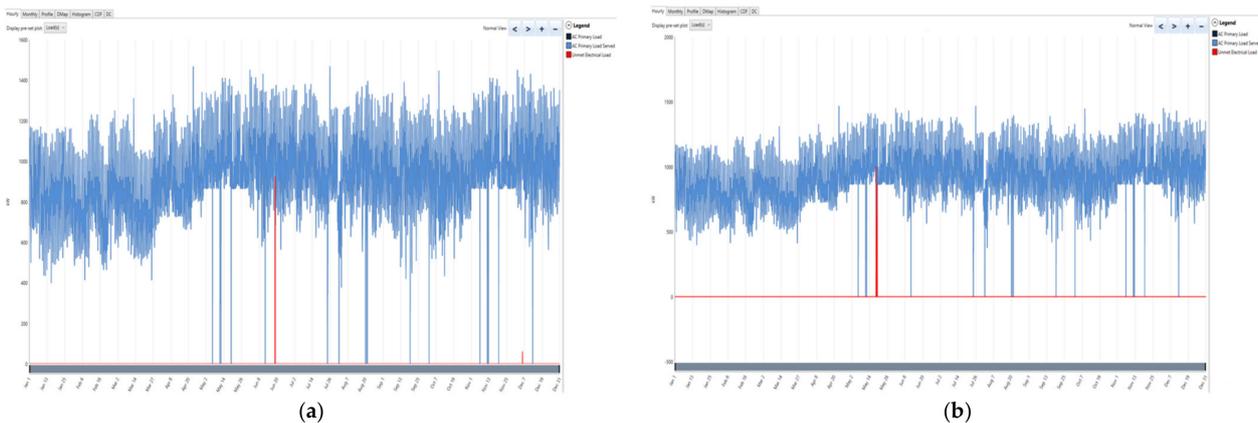
RETs	Current Installed Rated Capacity (MW)	Potential Rated Capacity (MW)	Battery Storage		Annual Generated Potential (MWh)	Load Demand (MWh)	
			Qty	Capacity (Ah)		Present	Forecasted (Year 2030)
Solar PV-battery storage	1.386	2.643	<b>Araceli</b>		3911.569	1242.335	1612.724
Wind-battery storage			437	60			
Solar PV-battery storage	1.086	1.397	<b>Balabac</b>		2201.624	931.602	2147.121
Wind-battery storage			426	60			
Solar PV-battery storage	3.2	11.399	<b>Cuyo</b>		17,676.309	7407.427	12,958.001
Wind-battery storage			3234	60			
Wind-battery storage		8.7	4049	60	31,947.048		



**Figure 11.** Demand, production, and unmet electrical loads in Araceli: (a) solar PV and (b) wind.



**Figure 12.** Demand, production, and unmet electrical loads of solar PV in Balabac.



**Figure 13.** Demand, production, and unmet electrical loads in Cuyo: (a) solar PV and (b) wind.

The best locations for solar PV installations in Araceli, Balabac, and Cuyo have a potential rated capacity of 2.643, 1.397, and 11.399 MW, respectively, and an estimated annual potential generation of 3.912, 2.202, and 17.676 GWh, respectively. For wind renewable technology, Araceli's and Cuyo's best locations for wind turbine installation have an estimated rated capacity of 10.56 and 8.7 MW, respectively with estimated annual potential generation of 34.533 and 31.947 GWh. For all three islands, the solar potential alone can already satisfy the forecasted load demand up to 2030, and it can replace the existing conventional diesel generator sets. However, due to the intermittent characteristics of solar energy, wind power should be installed to back up the energy supply.

#### 4. Discussions and Conclusions

This paper aimed to determine if renewable energy sources available in off-grid island communities are enough to meet the electricity demand at the household, commercial, and institutional levels. In order to do this, a three-phased approach was used: an assessment stage, geospatial analysis, and technical potential estimation. In the assessment stage, the site and load profile analysis was performed to analyze the present energy status of the research areas. Load forecasting was also included to anticipate the demand for electricity until 2030. The Holt–Winters exponential smoothing method in the R package was utilized to forecast the future load using the historical data. The predicted energy demand in Araceli is 1612.724 MWh, 2147.121 MWh in Balabac, and 12,958.001 MWh in Cuyo, with an increase of 30%, 131%, and 75%, respectively, from the current load demand.

The second approach is the geospatial analysis, during which the open-source software QGIS and, among the decision-making techniques, the MCDM Fuzzy AHP-TOPSIS method were used. The aim was to identify the exclusion factors and constraints affecting the choice of suitable locations for installing renewable energy technologies. The potential locations for solar PV and wind energy resources available in the study areas were identified and mapped, and the number of possible sites was determined. There are 12 potential sites for solar PV farms and 3 locations for wind farms among the three study areas. Each location was ranked based on the considerations that it is near the electric networks, roads, and built-up areas but far from water bodies and protected areas.

The technical potential estimation is the last approach used in this study. It aims to determine the available generated capacity of RE resources. Based on the calculation, the annual generation potential was estimated based on the calculated area of each feasible site obtained from the resource mapping. The generation capacity for each RE technology that can be installed in all study sites are as follows: Araceli needs a generation capacity of 3 MW (solar) and 10 MW (wind); Balabac may consider installing a generation capacity of 1.5 MW (solar); and a generation capacity of 11 MW (solar) and 9 MW (wind) is required by Cuyo. If solar PV farms are installed with their generation capacity as stated, they can replace the existing diesel power plant. The expected power generation potential is more than enough to supply the projected demand until 2030. However, there are some areas that the electric network has not yet reached; thus, if there is for a hundred percent energy access, a capacity addition is required.

In conclusion, resource mapping of renewable energy sources using GIS in these communities is of great importance, particularly to those off-grid islands that are not connected to the primary grid. However, in energy planning, it must be done in conjunction with determining whether such available resources can sufficiently supply for the demand of the islands. Furthermore, selecting the appropriate locations of RET implementations must be done. In this paper, the fuzzy AHP-TOPSIS approach was used to rank the alternatives based on set criteria. The estimations of the generation potential helped to obtain the required capacity of each RET to replace the existing diesel power plants in Araceli, Balabac, and Cuyo. The forecasting method applied has contributed significantly to predicting future demand, thus achieving the goal of this study. Therefore, the methodology used contributes to the literature, which can be used in similar studies of RE resource mapping. As a concluding remark, the neglected off-grid areas are the best place to start

in the transition to cleaner energy sources while achieving the goal of universal access to electricity.

Future works include other RE resources, i.e., biomass, geothermal, offshore wind, and hydro, in mapping resources potential. Additionally, it is recommended to consider the economic potential and technical system design, including protection, coordination, and systematic load dispatching if renewables are to be fully utilized in off-grid areas' transition to cleaner energy.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/app112411955/s1>, Table S1: Summary of research studies on energy planning using GIS; Table S2: Reclassification values of exclusion criteria and constraints; Table S3: Result of Holt-Winters Exponential Smoothing Method for Balabac. Figure S1: GIS maps before the application of exclusion criteria and constraints. Araceli: (a) DEM; (b) GHI; (c) wind speed; (d) slope; (e) aspect; (f) electric network; (g) roads; (h) built-ups; (i) water bodies; (j) land use/land cover; Figure S2: Balabac: (a) DEM; (b) GHI; (c) slope; (d) aspect; (e) electric network; (f) roads; (g) built-ups; (h) water bodies; (i) land use/land cover. (j) water bodies; (k) land use/land cover; Figure S3: Cuyo: (a) DEM; (b) GHI; (c) wind speed; (d) slope; (e) aspect; (f) electric network; (g) roads; (h) built-ups; (i) water bodies; (j) land use/land cover; Figure S4: GIS reclassification maps, Reclassification of datasets in Araceli: (a) GHI; (b) wind speed; (c) slope; (d) aspect; (e) electric network; (f) roads; (g) builtups; (h) water bodies; and (i) land use/land cover; Figure S5: Reclassification of datasets in Balabac: (a) GHI; (b) slope; (c) aspect; (d) electric network; (e) roads; (f) built ups; (g) water bodies, and (h) land use/land cover; Figure S6: Reclassification of datasets in Cuyo: (a) GHI; (b) wind speed; (c) slope; (d) aspect; (e) electric network; (f) roads; (g) builtups; (h) water bodies; and (i) land use/land cover.

**Author Contributions:** Conceptualization, K.R.M.S., L.L., I.D.F.T. and E.M.Q.; methodology, K.R.M.S. and L.L.; software, K.R.M.S.; validation, K.R.M.S. and L.L.; formal analysis, K.R.M.S.; investigation, K.R.M.S.; resources, K.R.M.S.; data curation, K.R.M.S.; writing—original draft preparation, K.R.M.S.; writing—review and editing, L.L., I.D.F.T. and E.M.Q.; visualization, K.R.M.S.; supervision, L.L., I.D.F.T. and E.M.Q.; project administration, L.L., I.D.F.T. and E.M.Q.; funding acquisition, E.M.Q. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

MCDM	Multi-criteria decision-making
AHP	Analytic hierarchy process
FAHP	Fuzzy analytic hierarchy process
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
FTOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
MW	Megawatt
MWh	Megawatt-hour
GHI	Global horizontal irradiance
DNI	Direct normal radiation
DHI	Diffuse horizontal irradiance
DEM	Digital elevation model
PCM	Pairwise comparison matrix
TFN	Triangular fuzzy numbers
l, m, u	Lower limit, medium limit, upper limit
CI	Consistency index
CR	Consistency ratio
$\lambda_{\max}$	Maximum eigenvalue
RI	Random index

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