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The significance of clean energy, education, and environmental management in fostering a sustainable future

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ABSTRACT

BACKGROUND AND OBJECTIVES: In Santa Cruz del Islote, an island located in the Colombian Caribbean, the lack of access to reliable electricity significantly affects the quality of life and educational opportunities of its inhabitants. The ongoing dependence on diesel generator-powered polygeneration systems is financially unsustainable, detrimental to the environment, and unstable in operation. The island experiences an average energy autonomy of only 11 hours. Consequently, this study intends to assess the viability of introducing renewable energy systems, particularly solar and wind energy, designed to suit the island's specific climatic and geographic characteristics, with the objective of boosting energy self-sufficiency and encouraging equitable educational access

METHODS: The study focused on the assessment of meteorological and energy data obtained from Santa Cruz del Islote to evaluate the viability of solar and wind energy. Solar irradiance levels were evaluated using historical data and the application of atmospheric transmittance models. Another approach to understanding wind behavior involved examining historical meteorological data, developing wind rose diagrams, performing frequency analysis, and utilizing probability density functions. The study also included an assessment of the island's available renewable energy resources.

FINDINGS: The results indicate that Santa Cruz del Islote receives high levels of solar irradiance throughout the year, with average daily values around 4,290 and peak values exceeding 5,780 watt-hours per square meter. The wind behavior analysis revealed predominant directions toward the north and north-northeast, with average wind speeds ranging from 2.6 to 4.7 meters per second, suggesting the feasibility of harnessing this available renewable resource. Wind energy potential, however, changes with the seasons, experiencing diminished availability between May to November. These findings support the design of hybrid renewable energy systems tailored to local conditions.

CONCLUSION: The findings demonstrate that Santa Cruz del Islote is equipped with enough renewable energy resources to enable a move away from fossil fuels. Implementing clean energy technologies would not only reduce environmental impact and operational costs but also enhance educational infrastructure and digital access. The merging of sustainable practices, technological progress, and social fairness is vital for the enduring resilience and advancement of insular communities including Santa Cruz del Islote.

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INTRODUCTION

Many rural communities in the Colombian Caribbean (CC) face serious development challenges as non-interconnected zones (NIZ), meaning they are not connected to the National Interconnected System (NIS) (Colmenares-Quintero *et al.,* 2022; Fábregas *et al.,* 2024). Historically, this has limited access to vital services, particularly in the fields of education, healthcare, and the economy. In response, the Institute for Planning and Promotion of Energy Solutions for non-interconnected zones (IPSE) has played a crucial role in expanding energy access in Colombia, especially in NIZ areas (Garces *et al.,* 2021; Castro *et al.,* 2023). IPSE advocates for projects centered around solar and wind energy, which substantially elevate living standards in these communities (Eras-Almeida *et al.,* 2023; Zamora-Muñoz *et al.,* 2025). Despite these efforts, many NIZ communities in the CC still lack 24 hours (h) electricity, affecting daily life and limiting progress in education, health, and economic development. Hevia (2021) conducted a study on open government initiatives in Latin America and the Caribbean, underscoring the critical role of connectivity, educational investment, and equity, while also pointing out the limitations of current educational governance models. Pedraza-jiménez *et al.* (2024) emphasize the value of community-based environmental education that fosters identity, respect for diversity, and ecological awareness, recognizing the interdependence between humans and nature. In alignment with this, Bernal *et al.* (2021) recommend an environmental education approach aimed at marginalized Caribbean communities, utilizing self-structuring pedagogical models and active learning techniques. Although the Coronovirus desease 2019 (COVID-19) pandemic disrupted implementation, it helped internalize environmental concepts and spark scientific curiosity (Gidarjati *et al.,* 2024). Manjarres and Salazar (2021) criticize the rigidity and lack of innovation in Colombia's educational model, advocating for public investment in education that strengthens human capital and integrates science and technology into national development. Plasencia-Díaz (2021) provides a critical viewpoint on the consequences of the pandemic, drawing attention to the heightened school dropout rates and the erosion of intellectual and human capital, especially in disadvantaged and poorly connected communities. This situation calls for a paradigm shift in education, enabling the design of resilient and sustainable long-term strategies. Herrera (2020) contributes to this perspective by stressing the necessity of revitalizing schools as hubs of solidarity, democracy, and territorial diversity, fostering public discourse and acknowledging educators and students as key players in driving change. From an institutional standpoint, Galindo (2021) stresses the urgency of reforming the Ministry of Education's management model, moving toward a more innovative, digital, and human rights-centered public administration to reduce inequalities. Acevedo-Tarazona and Lizcano-Herrera (2021) point out that education budgets have historically been insufficient, forcing local communities to assume responsibilities that should fall under the State. Consequently, Blanco *et al.* (2022) highlight the concept of education as an essential right and a continuous process that encourages individual development, honors human rights, and aids in the creation of a more equitable society. In this context, Santa Cruz del Islote (SCDI), a small island in the CC, faces major challenges in both education and energy autonomy. Despite the introduction of innovative strategies such as environmental education, insufficient infrastructure and scarce resources obstruct their sustainability. Another major hurdle is the island's lack of energy self-sufficiency, as it is heavily dependent on pricey external energy supplies, which limits the adoption of educational technologies and curtails school programs. Expanding solar and wind energy offers a sustainable way to improve quality of life (Alazzam *et al.,* 2024). It also strengthens education by ensuring stable and equitable learning conditions. The implementation of renewable energy in non-interconnected insular zones (NIIZ) is a key opportunity for sustainable development and educational improvement. Fábregas Villegas *et al.* (2024) highlight the importance of selecting renewable energy projects through comprehensive life cycle cost analysis to maximize economic, social, and environmental benefits. Jareemit and Srivanit (2024) build upon this idea with innovative solar control systems that improve energy capture by utilizing fuzzy entropy algorithms, which in turn boosts the efficiency of solar panels. Baranitharan *et al.* (2024) emphasize the potential of wind energy as a sustainable source, stressing the importance of accurate wind speed (WS) and direction forecasts to optimize its use. This data is essential for designing reliable energy systems that can be efficiently integrated into local grids. Furthermore, Castro *et al.* (2021) bolster this argument through their analysis of international microgrid case studies, showing that the synergy of solar, wind, and battery storage technologies effectively secures energy supply in isolated communities. The energy transition is key to improving life in vulnerable NIZ. The use of statistical tools, climate modeling, and techno-economic analysis enables more precise and efficient planning of sustainable energy systems. (Trenggono *et al.,* 2025). The evaluation of wind resources via statistical distributions, notably the Weibull distribution, has been thoroughly validated as a reliable approach for estimating wind energy potential. Studies such as those by Ávila *et al.* (2022), Vega-Zuñiga *et al.* (2022), and Souza *et al.* (2024) agree that accurately estimating the shape and scale parameters of this distribution is essential for reliably modeling wind resource availability. Furthermore, the application of numerical models, including the weather research and forecasting model, demonstrated effectiveness in relation to the CC, delivering comprehensive representations of atmospheric dynamics in designated regions (Gil *et al.,* 2022). On the other hand, solar energy has also been the subject of detailed analysis. Mejía *et al.* (2021) highlight how meteorological conditions such as ambient temperature and irradiance affect the performance of photovoltaic systems in the CC. From an implementation viewpoint, Diaz *et al.* (2021) recommend a holistic strategy that integrates renewable resource evaluation with green logistics and economic assessment to develop an off-grid energy generation system for the CC. These types of studies underscore the importance of conducting periodic statistical analyses at meteorological stations to identify wind and solar potential in the region. In long-term energy planning, tools like the autocorrelation function and wind rose diagrams are essential (Fabregas *et al.,* 2020; Wang and Liu, 2021; Froese *et al.,* 2022; Jooss *et al.,* 2022; Qothrunada *et al.,* 2022). In contexts like SCDI, IPSE, with the support of the Government of Colombia (GC) through its action plans, promotes access to sustainable and dignified energy autonomy for communities that have historically been excluded from the NIS. This initiative is supported by Law 1715 of 2014 (Castaño-Gómez and García-Rendón, 2020), enacted by the Colombian Congress, which aims to promote the development and use of non-conventional energy sources. By leveraging renewable energy options including solar and wind, the objective is to secure a consistent energy supply for SCDI and simultaneously encourage local development, education, and environmental conservation. Although the initial implementation costs of these technologies may be higher than those of diesel generators, their long-term operation proves to be more efficient, cleaner, and economically viable. As a preliminary measure, studying essential geographical factors such as solar irradiation, wind speed, and climate trends is critical for accurately determining renewable energy potential. This technical analysis is crucial for designing future renewable energy solutions that are tailored, sustainable, and socially impactful. This study presents an energy assessment of the solar and wind renewable resources available in the SCDI locality, based on historical meteorological data from 2020 to 2024.

MATERIALS AND METHODS

Locality of Santa Cruz Del Islote

The locality of SCDI is situated in the Bolívar Department, located at latitude 09°47’15’’N, longitude 75°51’32’’W, and at an elevation of 1 meter above sea level. It has an estimated population of over 1,000 inhabitants, resulting in a population density of approximately 125,000 people per square kilometer. This makes it one of the most densely populated islets, according to census approximations provided by the National Administrative Department of Statistics (NADS). Based on the reported population figures, it is estimated that there are more than four individuals per household, as illustrated in Fig. 1.

SCDI is a Caribbean paradise that, despite its natural beauty, faces significant infrastructure challenges. One of the most pressing issues is its limited energy autonomy approximately 11 hours of electricity per day according to the National Monitoring Center (CNM). This limitation directly impacts the quality of life of its residents. The educational center in SCDI stands as a symbol of hope and resilience for a community surrounded by the Colombian Caribbean Sea. Nonetheless, the geographic isolation and socioeconomic circumstances present a distinct illustration of the obstacles that vulnerable areas

Fig. 1:

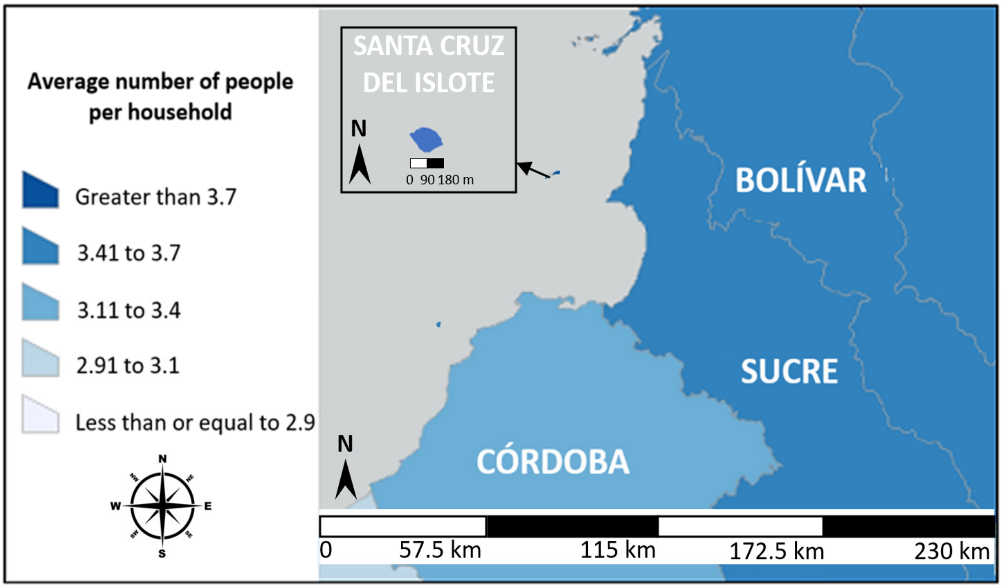


Fig. 1: Geographical location and the number of Inhabitants per Household in SCDI – Bolívar, Colombia

identified as NIIZ confront in achieving sustainable development and securing fundamental services including electricity. Education is a key tool for sustainable development, and in Santa Cruz del Islote, limited access to electricity directly affects educational quality. The unavailability of consistent power limits the application of educational technologies, curtails study hours, and endangers the refrigeration of food and essential pharmaceuticals. These issues conflict with several Sustainable Development Goals (SDGs), particularly Goal #7 (Affordable and Clean Energy), Goal #4 (Quality Education), and Goal #10 (Reduced Inequalities). Currently, the island's energy matrix relies heavily on fossil fuels, primarily through diesel generators. This source of energy is not just high-priced and polluting; it is also ineffective and inconsistent. There is an urgent need for an energy transition to improve residents' quality of life and ensure the right to a dignified education. In light of this reality, adopting renewable energy stands out as a sustainable and essential solution. Projects involving clean energy sources such as solar and wind power could not only enhance educational quality but also promote the comprehensive development of the community. SCDI currently operates a poly-generation energy system that integrates photovoltaic systems with a capacity of 67.5 kilowatt-peak (kWp) and a diesel combustion generator with a capacity of 100 kilowatt (kW), which includes 144 batteries, each with a capacity of 4,800 ampere-hours (Ah) at 2 volts (V).

Renewable energy in SCDI

Renewable energy sources like solar and wind offer sustainable solutions to reduce reliance on diesel generators. Solar energy utilizes plentiful sunlight, whereas wind power harnesses coastal winds to produce clean electricity. Together, these technologies can improve living conditions, support education, and promote environmental resilience.

Assessment of solar energy potential in SCDI

Atmospheric transmittance (AT) is a key parameter in assessing the solar potential of a region, as it determines the fraction of solar radiation that successfully passes through the Earth's atmosphere and reaches the surface. This occurrence is affected by various elements, such as the atmospheric chemical makeup, the elevation of the site, and the existence of aerosols, clouds, and contaminants. Each of these elements can attenuate, absorb, or scatter solar radiation, significantly affecting the amount of energy available for solar applications (Gutiérrez-Trashorras *et al.,* 2018). In the specific case of SCDI, a low-altitude island located in the CC, AT takes on particular importance. Its geographic location near the equator provides high solar irradiance throughout the year. Nonetheless, higher levels of relative humidity and the potential for suspended marine particles may impact the quality of radiation reaching the surface. Understanding AT in this context is not only essential for accurately estimating the photovoltaic generation potential, but also for designing efficient solar systems tailored to local environmental conditions.

Bird and Hulstrom model

The bird and Hulstrom model (BHM) enables the calculation of total irradiance by combining the values of direct and diffuse irradiance on a horizontal surface. As one of the most comprehensive models available, it provides highly reliable results, using Eq. 1 (Benharrats and Mahi, 2023):

$$I_{TH} = I_{DH} + I_{dH} \tag{1}$$

Where;

I_{TH}: Total irradiance.

I_{DH}: Direct irradiance.

I_{dH}: Diffuse irradiance.

The direct irradiance on a horizontal surface can be determined using Eq., 2 (Budiyanto and Lubis, 2020):

$$I_{DH} = 0.9662 C_r \tau_r \tau_0 \tau_g \tau_w \tau_a sinsin\, A \tag{2}$$

Where;

C_r: Daily solar constant in W/m².

τ_r: Transmittance due to Rayleigh scattering by air molecules.

τ_o: Transmittance due to ozone absorption.

τ_g: Transmittance due to absorption by uniformly mixed gases.

τ_w: Transmittance due to water vapor absorption.

τ_a: Transmittance due to aerosol absorption and scattering.

A: Solar altitude angle in degrees.

The value of C_r varies according to Eq. 3 (Gutiérrez-Trashorras *et al.,* 2018):

$$C_r = C\left(1 + 0.033 cos \frac{360n}{365}\right) \tag{3}$$

Where;

C: Normalized solar constant = 1367 W/m².

n: Julian day.

To accurately model the attenuation of solar radiation as it passes through the atmosphere, it is essential to consider several distinct transmittance components. This encompasses the transmittance resulting from Rayleigh scattering by air molecules, the transmittance due to ozone absorption, the transmittance resulting from absorption by uniformly mixed gases, the transmittance due to water vapor absorption, and the transmittance caused by both absorption and scattering due to the presence of aerosols, using Eqs. 4, 5, 6, 7, and 8 (Vanegas *et al.,* 2020; Gutiérrez-Trashorras *et al.,* 2018):

$$\tau_r = e^{-0.0903 m_a^{0.84}\left(1 + m_a - m_a^{1.01}\right)} \tag{4}$$

$$\tau_0 = 1 - \left[0.1611\left[\left(L_o m_{rel}\right)\left(1 + 139.48 L_o m_{rel}\right)^{-0.3035}\right] + \frac{0.002715 L_o m_{rel}}{1 + 0.044 L_o m_{rel} + 0.003\left(L_o m_{rel}\right)^2}\right] \tag{5}$$

$$\tau_g = e^{-0.0127 m_a^{0.26}} \tag{6}$$

$$\tau_w = 1 - \frac{2.4959\left(WW m_{rel}\right)}{\left(1 + 79.034 WW m_{rel}\right)^{0.6828} + 6.385 WW m_{rel}} \tag{7}$$

$$\tau_a = 0.12445\alpha - 0.0162 + \left(1.003 - 0.125\alpha\right) e^{-\beta m_a (1.809\alpha + 0.5123)} \tag{8}$$

Where;

m_a: Optical air mass

L_o: Ozone layer thickness

m_{rel}: Relative air mass

WW: Precipitable water content in the vertical column

α: Mean particle size

β: Atmospheric turbidity coefficient

The product of all these coefficients, which account for the attenuation of direct radiation, is referred to as the global atmospheric transmittance of direct radiation.

Diffuse irradiance is calculated, using Eq. 9 (Vanegas *et al.,* 2020):

$$I_{dH} = I_{dr} + I_{da} + I_{dm} \tag{9}$$

Where;

I_{dr}: Scattering by air molecules.

I_{da}: Presence of dust and aerosols.

I_{dm}: Multiple reflections between the ground and the atmosphere.

The diffuse irradiance due to air molecules is calculated using Eq. 10 1ne 11 (Vanegas *et al.,* 2020):

$$I_{dr} = 0.79 C_r \tau_0 \tau_g \tau_w \tau_{aa} 0.5 \frac{1-\tau_r}{1-m_a+m_a^{1.02}} sinsin\, A \tag{10}$$

$$\tau_{aa} = 1-\left(1-\omega_o\right)\left(1-m_a+m_a^{1.06}\right)\left(1-\tau_a\right) \tag{11}$$

Where;

τ_{aa}: Transmittance due to aerosol absorption.

ω_o: Single scattering albedo.

Diffuse radiation due to aerosols is calculated using Eqs. 12, 13 and 14 (Silvera *et al.,* 2021):

$$I_{da} = 0.79 C_r \tau_0 \tau_g \tau_w \tau_{aa} F_c \frac{1-\tau_{as}}{1-m_a+m_a^{1.02}} sinsin\, A \tag{12}$$

$$F_c = 0.93 - 0.21 lnln\, m_a \tag{13}$$

$$\tau_{as} = \frac{\tau_a}{\tau_{aa}} \tag{14}$$

Where;

F_c: Fraction of energy at the Earth's surface due to aerosol scattering.

τ_{as}: Transmission coefficient due solely to aerosol scattering.

For the calculation of diffuse irradiance from multiple reflections, the reflection coefficients of all relevant surfaces must be considered, using Eq. 15 (Silvera *et al.,* 2021):

$$I_{dm} = \left(I_{DH} sinsin\, A + I_{dr} + I_{da}\right) \frac{\rho_g \rho'_a}{1-\rho_g \rho'_a} \tag{15}$$

To compute multiple reflections between the ground and the sky, using Eq. 16 (Silvera *et al.,* 2021):

$$\rho'_a = 0.0685 + \left(1+F_c\right)\left(1-\tau_{as}\right) \tag{16}$$

Using the aforementioned models, it is possible to perform an accurate assessment of the available solar potential for the locality of SCDI. The initial step in this process involves collecting historical meteorological data, which includes variables such as wind temperature (WT), relative humidity (RH), sunshine duration (SD), peak sun hours (PSHs), cloud cover factor (CCF), among others.

Peak sun hours

PSHs are a standardized measure that represents the amount of solar energy received by a surface in one day, expressed as the number of hours during which solar irradiance would be at 1000 W/m² the standard test condition for solar panels. This unit enables simple and consistent evaluation of solar resources across different regions and times of the year. PSHs are calculated from the total daily solar irradiation (TI_{TH}) in Wh/m², using Eq. 17 (Pérez *et al.,* 2017):

$$PSHs = \frac{TI_{TH}}{1000\, w/m^2} \tag{17}$$

Assessment of the wind energy potential in SCDI

The evaluation of wind energy potential in the locality of SCDI region requires an in-depth analysis of several meteorological and statistical parameters. Key components of this assessment include the study of wind rose diagrams to understand prevailing wind directions, the analysis of historical WS data, and the projection of wind behavior at different altitudes using vertical extrapolation models. Furthermore, the implementation of probability distribution laws, including the Weibull distributions, facilitates a more accurate illustration of WS variability over time. Furthermore, the analysis of wind frequency yields important information regarding the consistency and reliability of wind resources, which are vital for evaluating the feasibility and efficiency of wind energy systems within the region.

Probability density function of the distribution

The probability density function of the distribution (PDFD) provides the likelihood of different WSs occurring. This is vital for wind energy assessments, as the output power of a wind turbine is significantly affected by WS, generally proportional to the cube of the speed (Kassem *et a.,* 2018). By integrating the PDFD with the power curve of a wind turbine, one can estimate the expected energy output, capacity factor, and overall feasibility of wind power generation at a specific site such as SCDI.

Accurate representation of WS behavior is vital for determining the potential of wind energy. To achieve this, several probability distributions are commonly used in wind resource assessment. The following sections describe the Weibull, Gamma, and Logistic distributions, each offering unique characteristics that make them suitable for different types of WS data and analysis objectives. The Probability Density Function of the Weibull Distribution (PDFWD) is commonly used in wind energy studies due to its ability to model WS variability effectively. Its shape is determined by the scale and shape parameters. The Probability Density Function of the Gamma Distribution (PDFGD) is effective for representing data that is both asymmetric and strictly positive. Although it is less specific to WS analysis than the Weibull distribution, it can still provide valuable insights in certain contexts. The Probability Density Function of the Logistic Distribution (PDFLD) exhibits symmetry and possesses heavier tails, rendering it possibly beneficial in contexts where a more uniform distribution of WSs is expected. The mathematical expressions for each of the following probability distribution models *f(v);* Weibull, Gamma, and Logistic are presented as Weibull Distribution, using Eq. 18 (Kassem *et a.,* 2018):

$$f(v)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}e^{-\left(\frac{v}{c}\right)^{k}} \tag{18}$$

Where;
v: Wind Speed
k: Shape parameter
c: Scale parameter

Gamma distribution was applied, using Eq., 19 (Nymphas and Teliat, 2024):

$$f(v)=\frac{v^{\xi-1}}{\beta^{\xi}\Gamma(\xi)}e\left(-\frac{v}{\beta}\right) \tag{19}$$

Where;
β: Shape parameter
ξ: Scale parameter in m/s.

Logistic Distribution was applied, using Eq., 20 (Kassem *et a.,* 2018):

$$f(v)=\frac{e^{\left(\frac{v-\mu}{\sigma}\right)}}{\sigma\left\{1+e^{\left(\frac{v-\mu}{\sigma}\right)}\right\}^{2}} \tag{20}$$

Where;
μ: location parameter.
σ: Scale parameter.

Hellman's law for WS extrapolation

WS is affected by obstacles, including surface irregularities and buildings, which interfere with the natural airflow. Wind measurements are typically taken in open areas at a standard height of 10 meters, and mathematical models are then applied to estimate how WS varies with height. This underscores the necessity of evaluating surface resistance factors, including the roughness of the terrain, any obstructions, and the height of the target for WS projection (Gunda *et al.,* 2021). The following sections present the Hellman power law and logarithmic wind profile equations, both of which are commonly used to estimate WS at different elevations, using Eq. 21 (Narasimalu *et al.,* 2018).

$$\frac{v}{v_0}=\left(\frac{H}{H_0}\right)^{\alpha} \tag{21}$$

Where;
v_0: Wind speed at 10 meters.
H_0: Reference height at 10 meters.
H: Desired height for wind speed estimation.
α: Wind shear coefficient for obstacles.

RESULTS AND DISCUSSION

This study presents the results derived from the analysis of the behavior and potential of renewable energy sources available in the locality of SCDI, as a strategy to enhance the community's energy autonomy. The purpose of the initiative is to cut down on reliance on external energy sources, especially diesel-powered generators, while also contributing to the enhancement of residents' quality of life, the advancement of sustainable development, and the fortification of educational processes within the community. The findings illustrated highlight the significant influence of these endeavors on the availability of clean energy through solar and wind renewable sources. The initial acquisition of historical meteorological data was carried out through nearby weather stations operated by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) of Colombia, with additional support from the Prediction of Worldwide Energy Resources

(POWER) database, developed by the National Aeronautics and Space Administration (NASA).

Analysis of solar energy potential in SCDI

This section details the procedure for interpreting and examining meteorological data obtained from SCDI, intended to evaluate the behavior and potential of the solar energy resource in the area. The analysis initiates with crucial variables like air temperature, relative humidity, sunshine duration, and air density, all of which directly influence the efficiency and availability of solar energy. Understanding these data helps in pinpointing local climate patterns and allows for a more accurate appraisal of the practicality of adopting solar technologies within a sustainable energy transition framework for the community. Figs. 2 to 3 illustrate the monthly behavior of air temperature, relative humidity, and sunshine duration, based on measurements taken from 2020 to 2024.

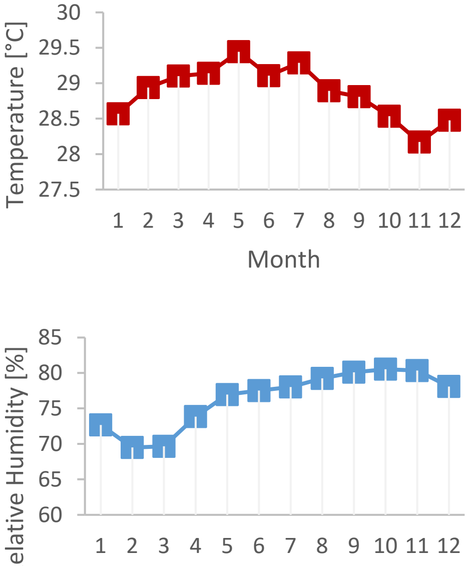


Fig. 2: Behavior of Ambient Temperature and Relative Humidity in the SCDI

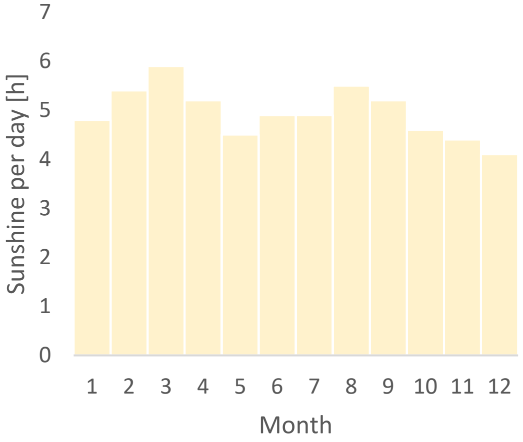


Fig. 3: Daily sunshine patterns throughout the 12 months of the year in SCDI

Table 1: Atmospheric transmittance behavior in SCDI

	Atmospheric transmittance factors				
	τ_r	τ_o	τ_g	τ_w	τ_a
JAN	0.9026	0.9842	0.9869	0.8609	0.6818
FEB	0.9079	0.9848	0.9871	0.8636	0.6989
MAR	0.9121	0.9850	0.9873	0.8649	0.7121
APR	0.9137	0.9849	0.9874	0.8639	0.7172
MAY	0.9128	0.9845	0.9873	0.8618	0.7143
JUN	0.9117	0.9843	0.9873	0.8617	0.7109
JUL	0.9122	0.9841	0.9873	0.8615	0.7126
AUG	0.9135	0.9843	0.9874	0.8622	0.7167
SEP	0.9130	0.9843	0.9873	0.8618	0.7150
OCT	0.9094	0.9842	0.9872	0.8606	0.7035
NOV	0.9039	0.9840	0.9869	0.8591	0.6860
DIC	0.9006	0.9838	0.9868	0.8582	0.6757

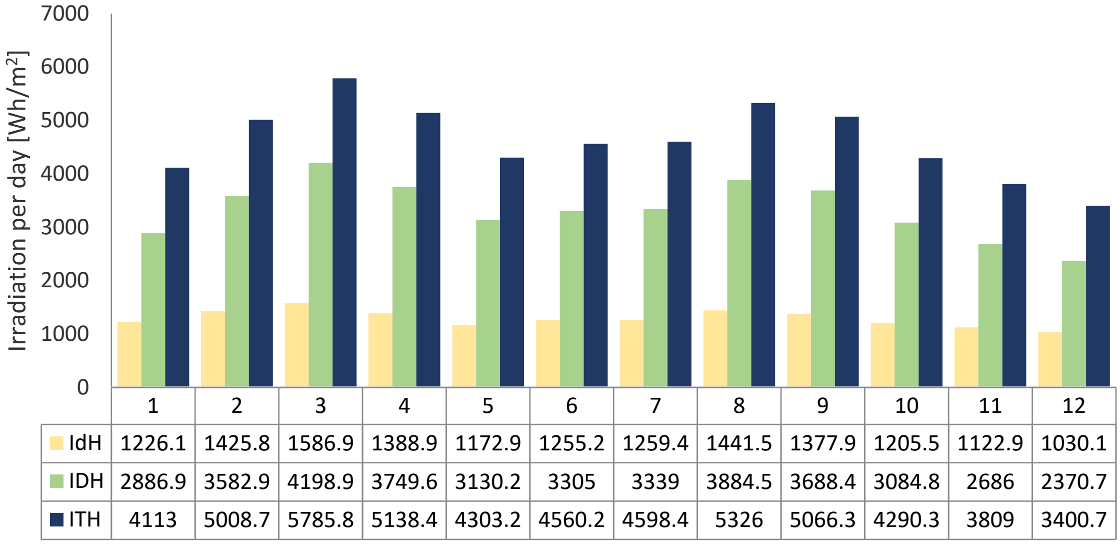
As shown in Fig. 2, the temperature behavior in SCDI reaches a minimum value of 28.17 degrees Celsius (°C) in November and a maximum of 29.44°C in May, with an average annual temperature of 28.9°C. Fig. 2 illustrates the relative humidity trends in the area, indicating minimum values of approximately 69.6 percent (%) RH during February and March, and maximum values around 80.5% RH in October and November. The annual average RH is 76.4%. Similarly, Fig. 3 presents the monthly sunshine duration in SCDI, highlighting March as the month with the highest solar exposure at 5.9 hours per day, and December as the lowest with 4.1 hours per day. On average, the annual sunshine lasts for roughly 5 hours daily.

Solar potential based on AT in SCDI

Using the BHM, equations 1 through 18 are applied to determine the available solar energy potential for the locality of SCDI, beginning with the calculation of atmospheric transmittance variables. Presented in Table 1 is the behavior of these atmospheric transmittance variables in SCDI for the period from 2020 to 2024, derived from the meteorological data previously examined.

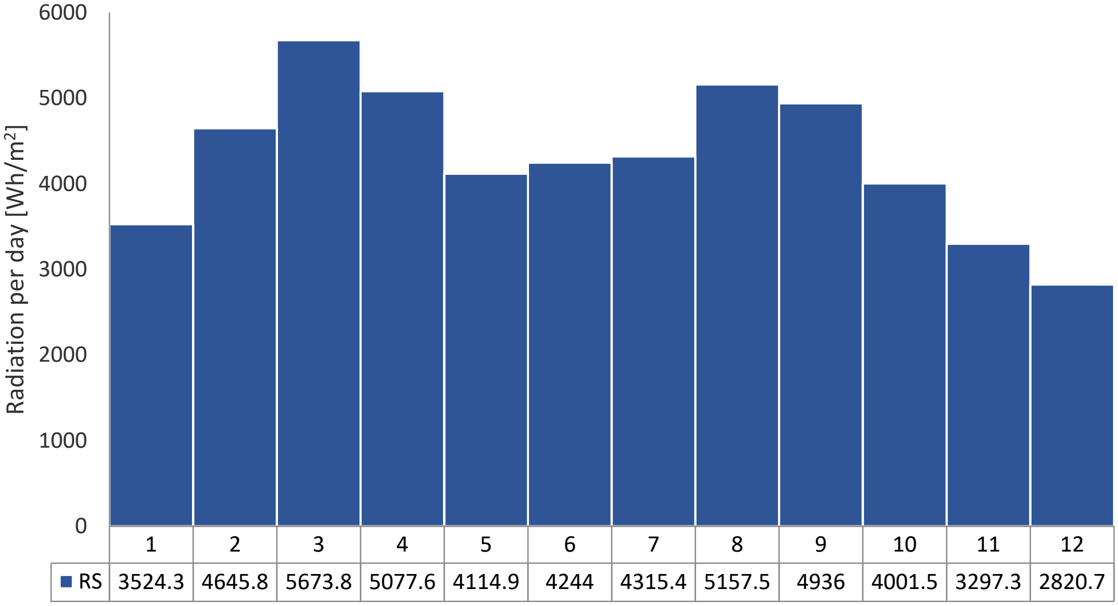
Consequently, the appropriate values for direct, diffuse, and total solar irradiation are obtained based on the estimated AT and the influence of variables such as T, RH, SD, geographic latitude, elevation above sea level, moist air density, and other essential elements mentioned in the BHM.

Fig. 4 highlights that, for the month of December, the minimum daily solar irradiation potential for SCDI is observed, with a value of 3400 Wh/m². The maximum value of 5785.8 Wh/m² occurs in March, while the average is approximately 4290 Wh/m². According to Gutiérrez-Trashorras *et al.* (2018), and Benharrats and Mahi (2023), the solar radiation values provided through the BHM are representative for the effective utilization of the available solar resource. As a component of the preliminary study for expanding a photovoltaic generation system in SCDI, an assessment of the available solar radiation potential in the area was performed (Fig. 5). The aim was to identify the renewable energy resource and lay a strong technical groundwork for later phases of the project, including system sizing and cost assessment. This initial evaluation determined an average of 4.6 PSHs per day, indicating a moderately high and relatively stable solar availability throughout the year. This facilitates the detection of seasonal changes in solar capture, which will be vital for the upcoming design of energy storage systems. The results suggest that the solar potential is sufficient to meet the community's energy demand through a photovoltaic plant, ensuring 24 h energy autonomy. However, this analysis is limited to resource characterization. The



	1	2	3	4	5	6	7	8	9	10	11	12
■ IdH	1226.1	1425.8	1586.9	1388.9	1172.9	1255.2	1259.4	1441.5	1377.9	1205.5	1122.9	1030.1
■ IDH	2886.9	3582.9	4198.9	3749.6	3130.2	3305	3339	3884.5	3688.4	3084.8	2686	2370.7
■ ITH	4113	5008.7	5785.8	5138.4	4303.2	4560.2	4598.4	5326	5066.3	4290.3	3809	3400.7

Fig. 4: Daily Solar irradiation patterns throughout the 12 months of the year in SCDI



	1	2	3	4	5	6	7	8	9	10	11	12
■ RS	3524.3	4645.8	5673.8	5077.6	4114.9	4244	4315.4	5157.5	4936	4001.5	3297.3	2820.7

Fig. 5: Available solar radiation in the SCDI Location

precise sizing of the system and the assessment of its technical and economic viability will be covered in a later study that relies on the results presented in this document.

Wind energy potential analysis in SCDI

This section outlines the process of decoding and analyzing meteorological data collected in SCDI to evaluate the behavior and potential of wind energy resources in the region. The study emphasizes important variables, including WS and wind direction, that are crucial for evaluating the effectiveness and feasibility of wind energy systems. By interpreting these data, it is possible to identify local wind patterns and assess the feasibility of implementing wind energy technologies as part of a sustainable energy transition strategy for the community. Figs. 6 and 7 illustrate the monthly variations in WS and direction, based on measurements recorded between 2020 and 2024.

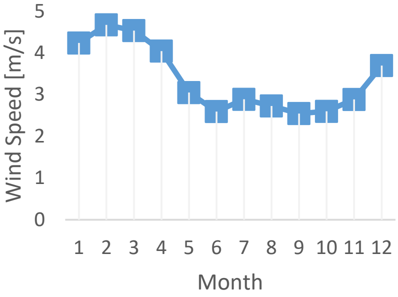


Fig. 6: Wind speed behavior throughout the 12 months of the year in SCDI

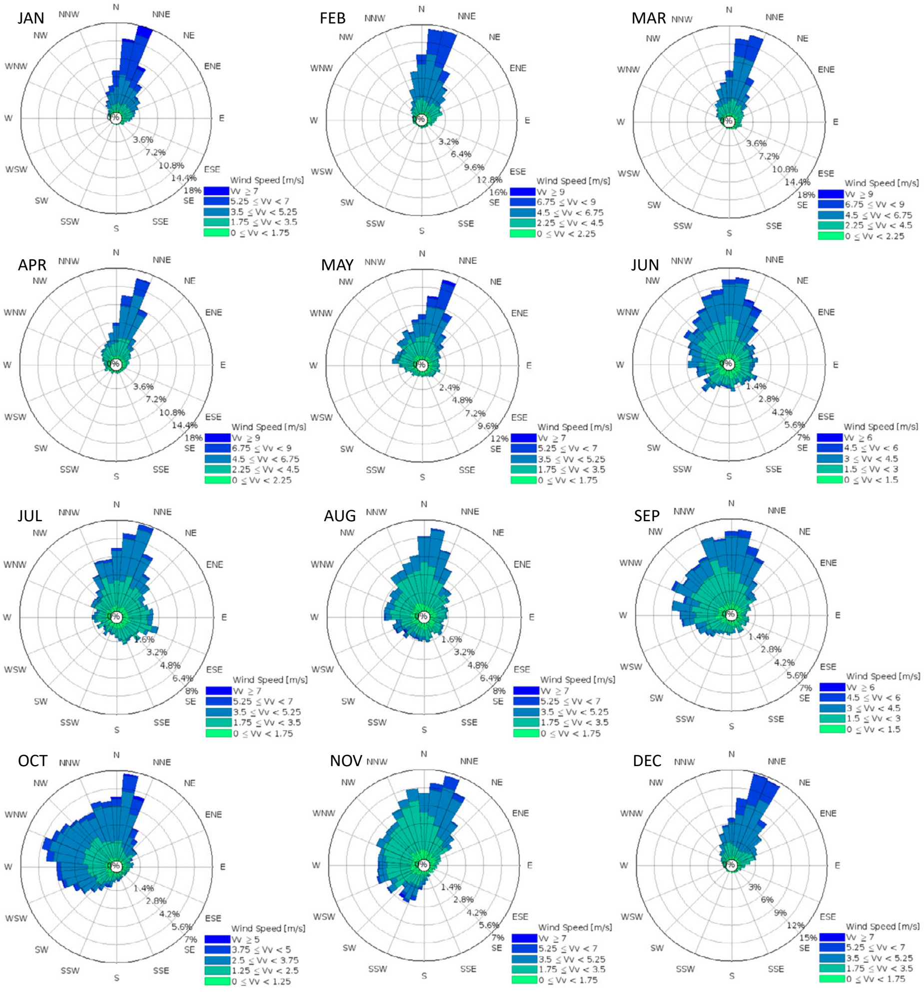


Fig. 7: Monthly wind rose diagrams in SCDI

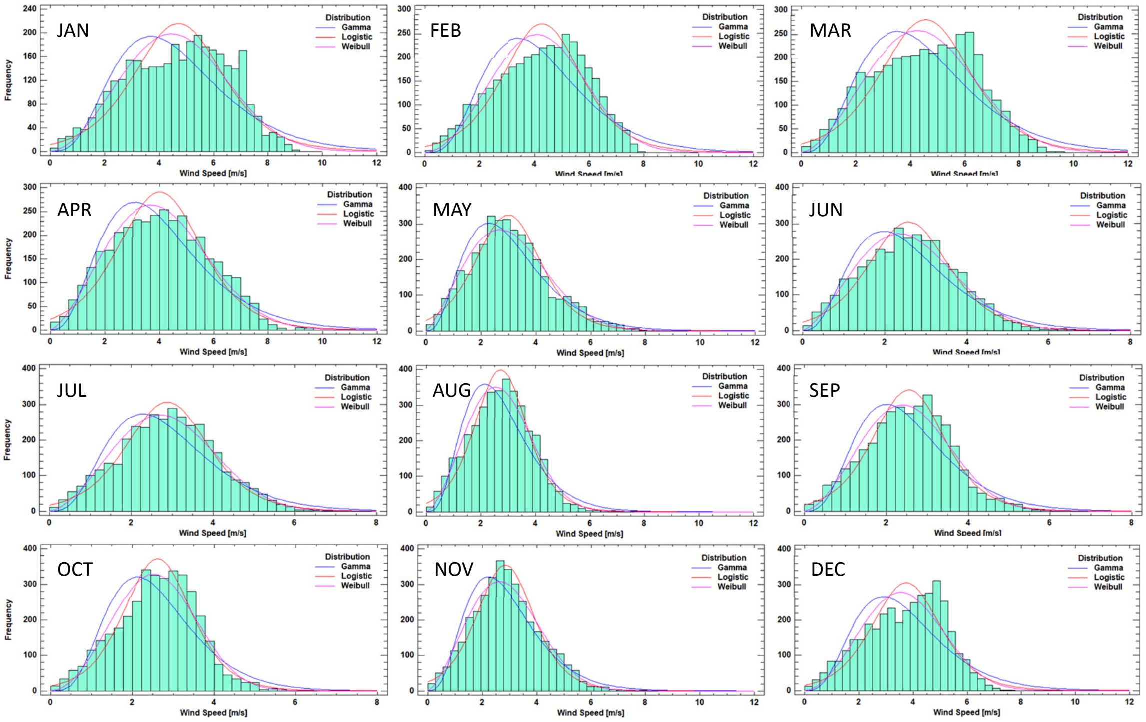


Fig. 8: Frequency histograms and PDFD of WS throughout the 12 months of the year in SCDI

Based on the obtained WS values, minimum and maximum speeds of 2.6 meters per second (m/s) and 4.7 m/s were observed, respectively, with an average value of 3.4 m/s (Fig. 6). It is essential to emphasize that these outcomes pertain to measurements taken at a reference height of 10 m above ground level. However, despite having minimum, maximum, and average WS values, these figures should not be directly used for sizing wind energy systems. Instead, statistical foundations such as WS frequency distribution studies and probability density functions should be applied for accurate energy potential assessments. Fig. 7 illustrates the wind direction behavior represented as wind roses, showing monthly patterns for the years 2020 through 2024. This illustration emphasizes the primary wind directions along with their occurrence frequency. The data reveals a greater frequency of winds from the north and north-northeast, with maximum wind speeds surpassing 9 m/s in particular months. The data show that the highest wind frequency is directed toward the north and north-northeast, with wind speeds most commonly falling within the range of 2.25 m/s to 4.5 m/s. The results imply that a horizontal axis wind turbine model (HAWT) can be installed with minimal necessity for directional adjustment mechanisms.

Once the WS behavior has been determined, PDFD laws such as Weibull, Gamma, and Logistic are applied. The aim is to pinpoint, each month, the areas exhibiting the greatest frequency density of WS occurs, based on statistical analyses of frequency, shape factors, and scale parameters.

Fig. 8 shows that WS behavior varies significantly throughout the year, highlighting the need for a detailed analysis to properly size a functional wind farm. In the last month and the early part of the year, there is a tendency for data density to gather around a WS of 4 m/s. In contrast, from May to November, the trend shifts to wind speeds between 2.5 m/s and 3 m/s. This pattern is reflected in the PDFWD, which provides a more accurate representation for wind energy studies, as noted by Kassem *et al.* (2018). Through the examining of WS's monthly behavior via PDFD, a yearly summary is created, as depicted in Fig.

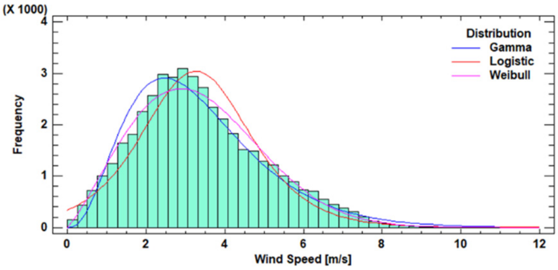
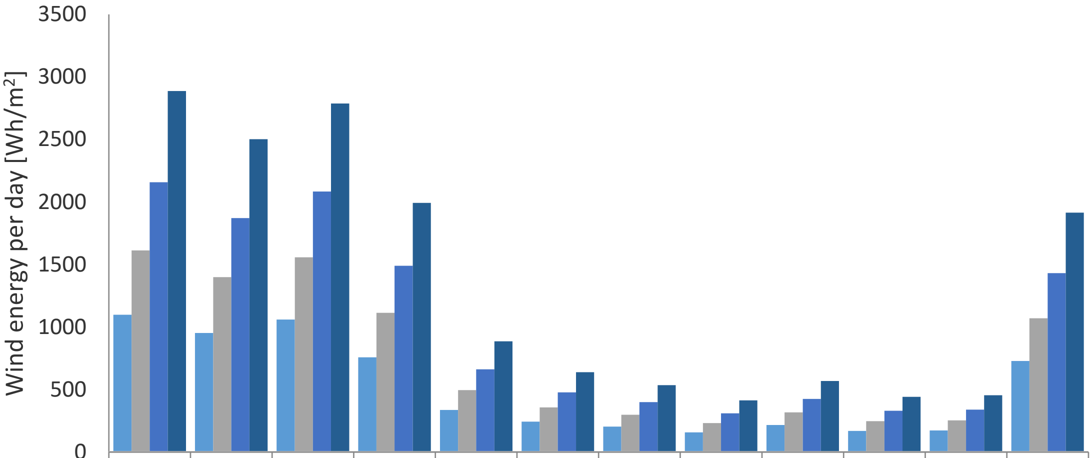


Fig. 9: Annual frequency histograms and PDFD of WS



	1	2	3	4	5	6	7	8	9	10	11	12
■ 10m	1097.2	951.11	1059.4	757.23	336.57	242.55	202.94	157.19	215.63	167.9	172.32	727.73
■ 25m	1612.2	1397.5	1556.6	1112.7	494.55	356.4	298.2	230.97	316.84	246.72	253.21	1069.3
■ 50m	2157	1869.8	2082.6	1488.7	661.67	476.83	398.97	309.03	423.9	330.09	338.77	1430.7
■ 100m	2885.9	2501.7	2786.4	1991.7	885.26	637.97	533.8	413.45	567.15	441.63	453.26	1914.1

Fig. 10: Wind energy potential at different heights throughout the 12 months of the year in SCDI

9. According to the PDFWD law and at the intersection point of the PDFGD and PDFLD a WS value of 3.1 m/s is identified. This value serves as the benchmark for energy design in wind turbine systems. The shape and scale factors used for replicating the PDFWD were *k* = 2.2 and *c* = 3.8 m/s, respectively.

The annual wind energy potential available for the SCDI locality is determined using wind behavior data and the PDFWD. In light of the results, Fig. 10 demonstrates how this potential behaves at various elevations, utilizing the equation from Hellman's law, which is presented in Equation 22. A significant increase in available wind power potential can be observed with height. However, from May to November, the daily wind resource potential remains low. The practicality of creating a wind energy generation site in proximity to the SCDI locality relies on the wind potential patterns depicted in Fig. 10. Nevertheless, as a naturally available resource, it can still be harnessed to benefit this vulnerable population. In a forthcoming study project, the authors aim to examine approaches for leveraging this existing wind potential. Additionally, it is important to highlight that providing energy access to a vulnerable population in an NIIZ, such as SCDI, aligns with the strategic objectives of the GC and the IPSE. Their strategic plans focus on expanding sustainable energy solutions to marginalized communities, especially by implementing clean energy technologies. This initiative not only promotes social equity and energy inclusion but also contributes to national efforts toward energy decarbonization and environmental sustainability.

CONCLUSION

This study highlights the urgent need to transform the energy matrix of island communities such as SCDI, where limited electricity autonomy and continued dependence on fossil fuels pose not only economic and environmental challenges but also restrict access to fundamental rights such as education. Another thorough analysis of meteorological and energy data indicates that suitable conditions are present for the deployment of renewable energy technologies—specifically solar and wind energy customized to the island's specific geographic and atmospheric traits. The high annual solar irradiance and the presence of exploitable, albeit variable, wind patterns provide a solid foundation for the design of hybrid systems capable of delivering continuous, efficient, and sustainable energy supply. The potential for daily solar irradiance averaging 4,290 Wh/m^2 indicates a considerable resource that can be leveraged to assist this vulnerable population classified as NIIZ. The average daily wind energy potential of 745.4 Wh/m^2, projected at a height of 25 meters, while lower in magnitude compared to solar potential, indicates the presence of a viable natural resource for energy generation. This facilitates the creation of initiatives that encourage the utilization of clean energy sources. This shift towards sustainable energy will not just decrease pollutant emissions and operational expenses; it will also directly strengthen educational infrastructure, increase access to digital resources, and advance equity in learning opportunities. In this context, energy becomes a cross-cutting pillar for sustainable development, aligned with the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 4 (Quality Education), and SDG 10 (Reduced Inequalities). The implementation of clean energy solutions in the Southern Caribbean Islands is not only technically feasible but also socially imperative and ethically unavoidable. This investigation sets the stage for upcoming studies that seek to improve the application of solar and wind resources in order to create holistic strategies that enhance the resilience of island communities when confronted with energy, educational, and environmental obstacles.

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This study addresses the challenge of sustainable electrification in an island region with limited energy autonomy. It focuses on developing viable solutions to improve energy access and resilience in non-interconnected areas. The study is being carried out as part of the Ph.D. candidacy in the Doctoral Program in Engineering at the Technological University of Bolívar, Colombia.

CONFLICT OF INTEREST

The authors declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
AT	Atmospheric transmittance
BHM	Bird and Hulstrom model
CC	Colombian Caribbean
CCF	Cloud cover factor
COVID-19	Coronovirus desease 2019
HAWT	Horizontal axis wind turbine model
IDEAM	Institute of hydrology, meteorology and environmental studies
NADS	National administrative department of statistics
NASA	National aeronautics and space administration
NIS	National interconnected system
NIIZ	Non-interconnected insular zones
NIZ	Non-interconnected zones
CNM	National Monitoring Center
PDFD	probability density function of the distribution
GC	Government of Colombia
PDFGD	Probability Density Function of the Gamma Distribution
PDFLD	Probability Density Function of the Logistic Distribution
PDFWD	Probability Density Function of the Weibull Distribution
POWER	Prediction of worldwide energy resources
IPSE	Institute for planning and promotion of energy solutions for non-interconnected zones
PSHs	peak sun hours
RH	Relative humidity
SCDI	Santa Cruz del Islote
SD	Sunshine duration
SDGs	Sustainable development goals
WS	Wind speed
WT	Wind temperature
I_{TH}	Total irradiance
I_{DH}	Direct irradiance
I_{dH}	Diffuse irradiance
I_{dr}	Scattering by air molecules
I_{da}	Presence of dust and aerosols
I_{dm}	Multiple reflections between the ground and the atmosphere
TI_{TH}	Total daily solar irradiation
τ_r	Transmittance due to Rayleigh scattering by air molecules
τ_o	Transmittance due to ozone absorption
τ_g	Transmittance due to absorption by uniformly mixed gases
τ_w	Transmittance due to water vapor absorption
τ_a	Transmittance due to aerosol absorption and scattering
τ_{aa}	Transmittance due to aerosol absorption
τ_{as}	Transmission coefficient due solely to aerosol scattering
A	Solar altitude angle in degrees
C	Normalized solar constant
C_r	Daily solar constant
h	Hours
n	Julian day
m_a	Optical air mass

L_o	Ozone layer thickness
m_{rel}	Relative air mass
m/s	Meters per second
Wh/m^2	Watt-hours per square meter
m	Meter
km	kilometer
kW	kilowatt
kWp	kilowatt-peak
Ah	Ampere-hours
V	Volts
WW	Precipitable water content in the vertical column
α	Mean particle size
β	Atmospheric turbidity coefficient
ω_o	Single scattering albedo
F_c	Fraction of energy at the Earth's surface due to aerosol scattering
$f(v)$	probability distribution models
v	Wind Speed
k	Shape parameter
c	Scale parameter
β	Shape parameter
ξ	Scale parameter
μ	location parameter
σ	Scale parameter
v_0	Wind speed at 10 meters
H_0	Reference height at 10 meters
H	Desired height for wind speed estimation
α	Wind shear coefficient for obstacles

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