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CASE STUDY

Electrification as a development and sustainability approach in rural areas using renewable energy sources

J. Fábregas Villegas[1,2], I. Tovar Ospino[1], A. Palencia Día[2,*]

[1] *Mechanical Engineering Program, Autonomous University of the Caribbean, Colombia*

[2] *Doctorate Program in Engineering, Technological University of Bolívar, Colombia*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Within the Colombian Caribbean region, a number of rural communities utilize self-generated energy as a result of their limited access to the national electricity network. This energy generated is achieved through a combination of combustion engines and renewable sources. However, certain communities face challenges maintaining daily energy autonomy, resulting in developmental disparities. Consequently, the study seeks to create a method for evaluating the accessibility of renewable resources and performing risk assessments to facilitate the introduction of electrification projects in rural regions of the Colombian Caribbean.

METHODS: A review was made of the feasibility of financing projects with a focus on renewable energies by government financing entities in Colombia. Subsequently, risk mitigation strategies were utilized in projects of this kind, analyzing the available renewable resources in the locality such as wind and photovoltaic solar energy.

FINDINGS: The main factor impeding the success of renewable energy projects in the Colombian Caribbean is political risk. Despite the region's significant solar and wind energy potential, as demonstrated by statistical analyses based on meteorological data, these projects frequently struggle to achieve optimal operational outcomes due to political instability. Presenting potential solar radiation levels ranging from 5 kilowatt-hours per square meter per day, and wind speeds exceeding 2 and 7 meters per second in certain localities. The aforementioned statement suggests that the projects that have been signed are backed by insufficient dimensioning.

CONCLUSION: The strategies devised for effective administration of energy supply to these communities are outlined, taking into account the assessment of wind and solar energy capacities specific to each area, as well as the identification of potential political and financial risks which pose the most significant uncertainties for such initiatives. The solar radiation assessments obtained are conducive to accurately sizing photovoltaic systems, while the identified wind speeds indicate a need to reevaluate methods for harnessing these wind resources efficiently.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
42	5	3

*Corresponding Author:
Email: *argpalencia@utb.edu.co*
Phone: +5730 1372 2376
ORCID: 0000-0003-4947-5659

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INTRODUCTION

In certain areas of the Colombian Caribbean (CC), there are rural populations (RP) that are not connected to the national interconnected grid for their electricity supply, due to their remote locations or being on islands. Consequently, electricity production in these regions relies on internal combustion engines or sustainable resources such as hydro, biomass, solar, and wind (Sánchez-Gómez and Fajardo-Pinilla, 2020). Even with these self-generation methods, full coverage of the energy supply for these populations is not achieved, resulting in less than 15 hours of daily electricity service, according to reports from the national monitoring center of Colombia (NMCC) for some communities. The institute for planning and promotion of energy solutions (IPPES) in Colombia is currently formulating strategies to extend energy access to underserved communities in non-interconnected regions, aiming to uplift the living standards of these marginalized populations. Nonetheless, the ongoing social inequity encountered by these groups obstructs the efficient realization of these all-encompassing electrification schemes (Ortiz, 2019; Godínez *et al.*, 2019). In the projects carried out to electrify certain rural areas (RA) of the CC, there has been a lack of proper planning regarding the technological acquisition for energy self-generation. There are no arrangements in place to support and educate local residents in executing the installations and scheduled maintenance tasks for the systems. Consequently, there is an expedited breakdown of these factors, and there are no foreseen social prospects for these individuals (Díaz *et al.,* 2022). Addressing the issue of social inequality that still prevails in the rural areas of the Colombian territory is part of development processes that progress at a slower pace than in other cities, mostly favored by public policies and private investment. The rise in social disparities has consequently resulted in unequal access to vital public services like electricity, which in turn impacts the overall provision of other public amenities (López, 2019; Rendón and Gutiérrez, 2019). In studies focused on the social and sustainable development of RP in Colombia, there is a need and commitment among these residents to participate in projects that facilitate entrepreneurship and innovation. It is essential to tailor the tools for promoting and supporting socially oriented projects from public policies to the specific context of each rural area, rather than applying a one-size-fits-all approach (Londoño and Álvarez, 2021; Rodríguez *et al.,* 2021). The armed conflict experienced by different locations in Colombian territory is reflected in indicators of horizontal inequality, ranging from differences between strata, public services, public policies, and access to education, among others (García *et al.,* 2022; González and Valenci, 2019). Naderipour *et al.* (2021) introduced a novel metaheuristic approach, known as the Spotted Hyena Optimizer, to assess the optimal utilization of wind turbines (WT) in their investigation of wind potential. They evaluated probabilistic methods and a deterministic method, highlighting that the former was more realistic and accurate, thus providing a clearer view of the impact of the wind renewable resource. In their study on hybrid renewable energies (RE), including solar and wind, the researchers utilized a multicriteria design to evaluate various aspects such as costs, reliability, and emission costs. (Naderipour *et al.*, 2021) presented a novel framework for optimizing RE systems to minimize total net present costs, loss-of-load costs, and emission costs, while meeting reliability constraints for the probability of energy not supplied in both autonomous and grid-connected systems. Dealing with project proposals (PP) aimed at closing these gaps will contribute to the development of these vulnerable populations. The advancement of this study involves advocating for the adoption of RE to address technological disparities and enhance the quality of life, by utilizing natural resources to achieve independence in public electricity supply and thereby enhancing other essential services for the daily necessities of a rural population in the CC. Therefore, a detailed study of the potential for RE in the study locations, which are Isla Fuerte (IF), Isla Múcura (IM), Santa Cruz Del Islote (SCI), and Nazareth (Nth), all located in the CC is proposed. The investigation assesses the energy supply capacities of the aforementioned areas to analyze potential risks and create public policies with a focus on powering these locations. The study utilized records of wind and solar energy (Se) potentials, collected by the instruments implemented by the institute of hydrology, meteorology, and environmental studies (IHMES) of Colombia, to quantify these renewable resources. The objective of the study is to devise a method for appraising the availability of renewable resources and carrying out risk analysis to bolster the advancement of electrification endeavors in RA of the CC. It is crucial for vulnerable populations with restricted energy autonomy to attain improved sustainable development by means of a PP that offers them energy independence using. This aligns with the country's energy transition objectives. This study was conducted at the beginning of 2024.

MATERIALS AND METHODS

Adequate funding is a critical component for the development of a PP that meets the management criteria. Consequently, an examination of governmental or private organizations that facilitate the implementation of initiatives centered on the specified domain is necessary (Quirama *et al.,* 2022). Information concerning institutions and projects that aid in the study and project completion is outlined in Table 1.

Table 1 demonstrates that private entities, specifically banks, could be the preferred alternative from an investment viewpoint for expeditious capital acquisition for project implementation. However, utilizing of this financing entails repayment of the debt along with the agreed-upon interest by these entities and considering the projected economic crisis due to the recent health emergency (Alexánder and España, 2014; Castañeda *et al.,* 2020). In order to obtain funding from governmental bodies, it is necessary to have previously engaged in a competitive application process and to have been deemed eligible for financial support by said entities. The advantages of this type of credit include that the majority of the project is financed by the Colombian government, along with matching funds from companies interested in the benefits derived from the execution of the proposal (Torres *et al.,* 2020). The progress of local development hinges on the involvement of multiple entities, including state investment, to ensure an even distribution of benefits and services across the region. Yet, these RA have been lagging due to scarcity and lack of state resources to enable self-generation or improve their local development. These particular areas are

Table 1: Entities that promote research projects in Colombia

Entity	Benefit	Feature
Minciencias	Official entity of the state, opens calls for the financing of projects periodically, allows to carry out doctoral studies, do research projects financed by the state. It is the leader of the national system of science, technology and innovation in Colombia.	Financial support for: Research Education, Research, Innovation, Scientific Mindset and Culture.
Colombia científica	Call designed for R&D projects regulated by ministry of science, technology and innovation (MSTI) of Colombia and supported by Colombian institute of educational credit and technical studies abroad (CIECTSA), allows the development of projects in partnership with multiple national and international higher education institutions.	It funds research and innovation programs that promote the creation and promotion of knowledge networks.
Finagro	The primary focus of the banking institution lies in the advancement, innovation, and exploration endeavors within the agricultural sector. It offers financial assistance to rural inhabitants and organizations that are committed to the sustained growth of agriculture.	Up to 100 percent (%) of the project costs can be financed, depending on the vegetative or productive cycle of the activity to be financed and the cash flow of the project.
Bancoldex	Funding entity for projects focused on large companies that require large loans for innovation development. You must have previously participated and approved in MSTI call.	Financing of R&D projects, has project credits.
Sena	Financing entity for targeted projects for micro-entrepreneurs who require credits for innovation development. You must have previously participated and approved in MSTI call.	The company must have a recognized R&D unit or research alliances.
Bancuadra	Official state entity, which encourages the generation and financing of projects.	It is a project of the secretary of economic development of the mayor's office of Medellin Colombia that grants free consumption credits.
Banking entities	Private entities that through free investment credits can be used to generate research, innovation and technological development, do not need prior approval of the project to be developed.	Differential rates depending on user profile, Payment of debt in instalments of 12 to 72 months.

famous for their rich cultural traditions and thriving agricultural sector, which are vital components of Colombia's national identity (Bocanegra and Carvajal, 2019; Serrano *et al.,* 2019; Uribe and Ramírez, 2019). The use of multilateral banking presents another possibility for a combination of financing RE projects in Colombian territory (González and Cruz, 2019; López *et al.,* 2019).

Risk management in projects

These distinct areas are well-known for their diverse cultural heritage and prosperous agricultural field, serving as essential elements in defining Colombia's national character. That is to say, estimating OR is based on minimizing financial losses for an entity. The increasing importance of operations research (OR) has impacted the design of control mechanisms and the oversight of international financial markets (Humberto *et al.,* 2018; Macías Villalba *et al.,* 2018; Faiier *et al.,* 2019). Measuring OR is inherent to all processes and operations of an entity regardless of its size and function. Despite being unpreventable, it can be controlled, lessened, or transferred, although it also presents the potential for suffering losses due to inadequate procedures, human errors, technological breakdowns, or external incidents. OR is implicit when considering credit and market risk. This is justified by the fact that the more complex the financial business, the higher the chances of human errors or system failures (Gragera and Pérez, 2018). The challenge in implementing a cutting-edge measurement system lies in the utilization of historical data to assess the frequency and severity of losses stemming from OR. As a peculiarity of OR, the component that requires the most effort in system construction is undoubtedly the identification, description, data collection, and risk mapping The absence of a well-structured risk prevention mechanism may culminate in financial setbacks caused by insufficient protocols, human fallibility, technological breakdowns, or external incidents. This applies to all sectors and industries in the market. Additionally, to effectively manage OR, it is essential to have an efficient monitoring process that, carried out periodically, can facilitate the swift detection and correction of deficiencies in policies, processes, and procedures. This greatly reduces the frequency and severity of losses. The focus of the PP is on studying electrification management in vulnerable areas, providing a foundation for the use of unconventional energy technologies in populations with limited or no access to public electricity services in the nation. Nevertheless, it may be at risk of POR due to particular interests, financial risks, transportation risks for accessing these areas, and natural risks stemming from climatic conditions in these zones.

Risk landscape for rural electrification

The classification of potential risks that could manifest within a company or project provides a framework for implementing a risk management strategy that prioritizes the prevention or mitigation of these risks (Yu *et al.,* 2020). Furthermore, it is beneficial to identify whether there exists a higher level of risk that suggests a requirement for restructuring the operational processes and management of the organization or initiative (Boronat *et al.,* 2019). The risk profiles for the development of an electrification proposal in vulnerable RA are delineated in Table 2. These perspectives were garnered through the examination of existing electrification endeavors in these regions, where insufficient planning leads to a lack of full energy independence. Additionally, inquiries with residents and public development policies reveal that departmental resources are predominantly utilized by major cities.

The risk planning processes can be applied to the development, execution, and finalization of a proposal for electrifying vulnerable rural areas, as they allow for a clear and concise evaluation of the level of correspondence that each risk has, thereby facilitating the implementation of control measures to eliminate or prevent each type of risk (Castro *et al.,* 2020; Lahr and Kooistra, 2010; Pulido *et al.,* 2020).

Public services in rural communities

The study goal elucidated the inequity present in particular residential precincts in the community, which is a result of the access to fundamental public services like electricity that are essential for the operation of other communal facilities. This access plays a vital role in advancing social development and enhancing the quality of life for the residents in those localities (Acuña, 2021). Table 3 illustrates the status of a particular RP in the CC with limited access to public electricity supply.

The illustration in Fig. 1 depicts the distribution of electrical energy generation systems within

Table 2: Types of risks identified in the proposal

Type of risk	Observation	Assessment
Production risks (PR)	This type of risk is not applicable to the development of the proposals.	No risk
Sales risks (SR)	This type of risk is not applicable to the development of the proposals.	No risk
Management risks (MR)	Due to the unfamiliarity with the implementation of environmentally friendly technologies for energy conversion, there may be resistance to costs compared to benefits for both residents and financial institutions.	Moderate risks
Financial risks (FR)	Assessment of the level of indebtedness and short and long-term credit demand from rural area residents for technology acquisition if a project with the government for the benefit of this vulnerable population is not approved.	Severe risks
Environmental risks (ER)	Due to the location of rural homes, there are high levels of climate change, flooding, extensive droughts, and landslides.	Severe risks
Personal risks (PER)	For the personnel hired to implement the technology, there is a possibility of illness or accidents.	Severe risks
Material damage risks (MDR)	Risks from natural phenomena such as floods, earthquakes, and windstorms. Additionally, there is a possibility of damage from guerrilla attacks, and other types of material damage such as oxidation from aggressive environments, structural damage from poor installation.	Severe risks
Legal claims risks (LCR)	Legal claims may arise due to product warranties, life insurance once the technological elements are installed, guided by research, negligence, and occupational accidents, as well as transportation of technology to these rural areas.	Severe risks
Political risks (POR)	Due to the political interests within the current state or transition with a subsequent government, projects may end up affected from their planning, economic indicators, and duration of delivery.	Catastrophic risks

Table 3: Availability of electrical service by locality (IPSE, 2022)

Location	Measurement date	Average daily service	Energy type
IF (Cartagena - Bolívar)	NOV/15/2022	6 hours 30 minutes	Solar and combustion
IM (Cartagena - Bolívar)	NOV/26/2022	12 hours 23 minutes	Solar and combustion
SCI (Cartagena - Bolívar)	NOV/02/2022	12 hours 38 minutes	Solar and combustion
Nth (Uribia - La Guajira)	AGO/16/2022	12 hours 40 minutes	Solar and combustion

the examined RP, emphasizing the prevalence of photovoltaic systems (PS), their corresponding battery banks, and internal combustion plants. Notably, wind energy systems are absent, and this distribution suggests a reliance on solar power and traditional combustion methods, reflecting the specific environmental and economic considerations of these areas, the choice of photovoltaic systems likely stems from the abundant solar resources, while the internal combustion plants provide reliable backup power. Inadequate wind resources or increased costs related to wind technology may account for the absence of wind energy systems in these specific regions.

RESULTS AND DISCUSSION

The RP in the CC with less than 15 hours of electric service autonomy is presented in Table 3. It is evident from the table that energy capture and transformation methods like PS and combustion engines (CE) are inadequate to ensure a continuous 24-hour electric service. It is also mentioned that the CE are implemented as backups to recharge the batteries, supporting the PS once the solar hours have ended. This indicates that the CE is utilized to extend the longevity of the battery banks by preventing discharge levels that could potentially harm their integrity. One of the main disadvantages of PS is that their operational time depends on the number of daylight hours during which they can harness the available solar resource, and on how long the battery systems can operate before discharging to a level that would affect their durability. Table 3 shows that for the specified populations, a higher level of electric service autonomy can be achieved by increasing the quantity of PS and batteries in proportion to the current availability of hours. This implies a significant additional investment beyond what has already been implemented. Fig. 2 below shows the levels of

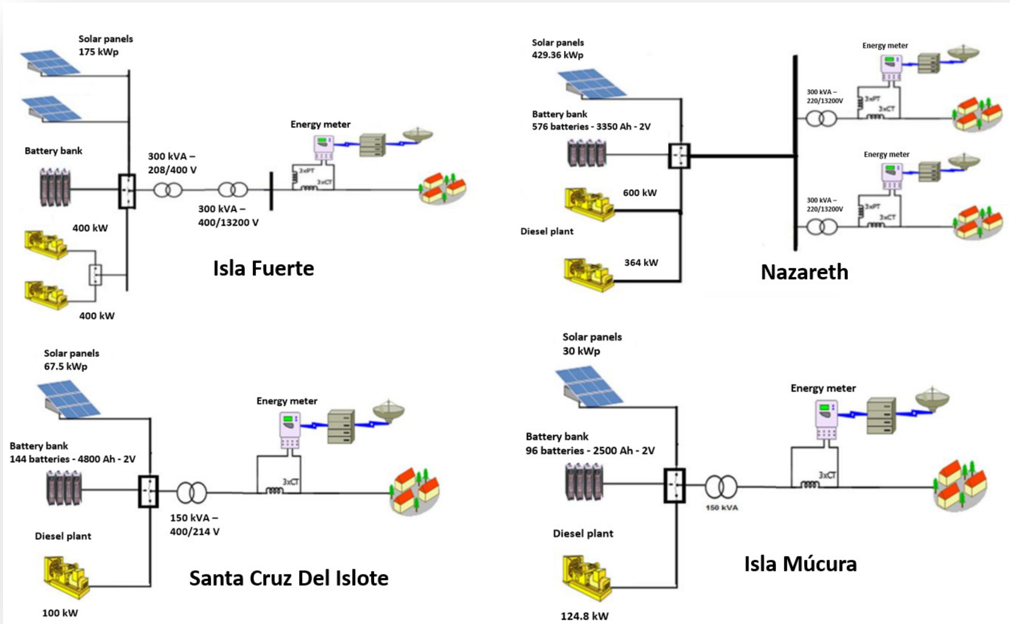

Fig. 1: Energy distribution of the studied locations (IPSE, 2022)

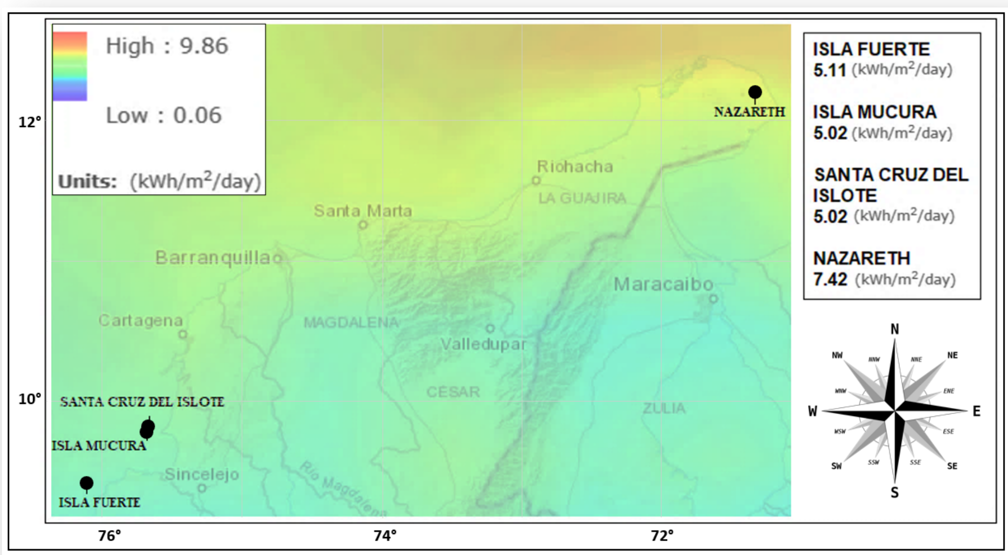

Fig. 2: Availability of solar radiation resource in the Colombian Caribbean

available solar radiation for each location indicated in the study.

Based on engineering criteria, the availability of solar resources shown in Fig. 2 is suitable for the implementation of Solar Farms (SF) to provide electrical energy services to the RP under study (Diaz *et al.*, 2021; Mejía *et al.*, 2021; Kabir *et al.*, 2023; Kassem *et al.*, 2018). Nevertheless, it has been noted before that there is a necessity to broaden the current SF to accomplish daily electrical service independence. In locations where systems rely exclusively on daily solar hours to generate energy, it is important to consider other available energy sources when the current systems are not functioning. This is where wind power in these locations can come into play. Currently, in the northern region of La Guajira in the CC, a project is underway for electrification through Wind Systems (WS) called "Guajira Wind Farm I", given that the wind speeds (WSs) available in this location are suitable for these systems. In Fig. 3 illustrates the WS availability for these locations from 2019 to 2022.

The wind behavior values shown in Fig. 3 for these locations indicate that there is available and exploitable potential for the proper sizing of wind systems, with greater availability for the population of Nth, which presents wind speeds exceeding 7 m/s. Compared to other studies, other populations have similar available potential (Fabregas *et al.,* 2017, 2020). It is noteworthy that wind energy is reliably accessible, in contrast to solar power which is dependent on the length of daylight. However, in order to take advantage of the wind potentials in regions like IF, IM, and SCI, where wind speeds are around 2 m/s, it is crucial to ensure proper sizing. The exponential projection of wind speed relative to height for these locations, using Eq. 1 (Gómez *et al.,* 2020) of Hellman's law to obtain in Fig. 4.

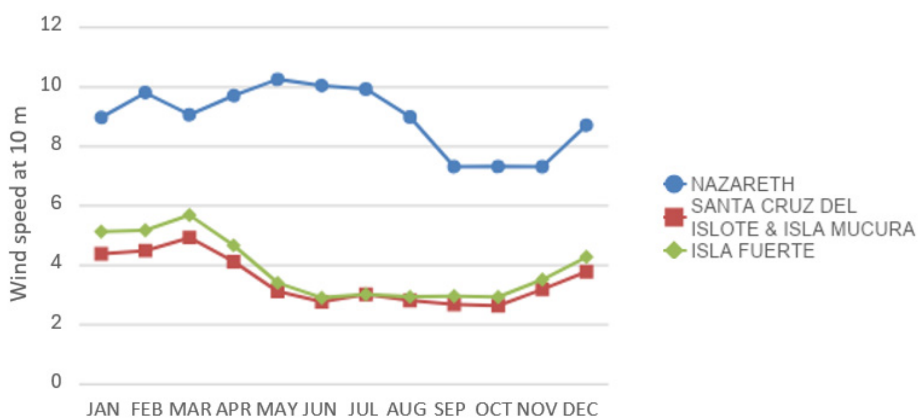

Fig. 3: Wind resource in RP of the CC

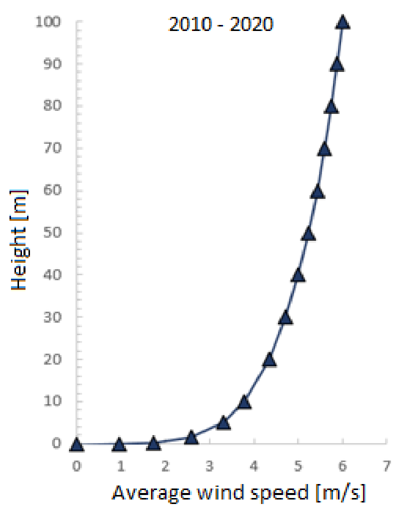

Fig. 4: Average wind speed relative to height IF, IM, SCI

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\alpha} \quad (1)$$

Where; v and H are the projected wind speed and height, v_0 is the wind speed measured at a base height H_0 of 10 meters, and α is the terrain obstruction factor, which is 0.2 for a small town with some trees and shrubs.

Evaluating strategies to develop hybrid solar and wind projects is an excellent option to provide these vulnerable populations with the right to access public electric service 24 hours a day, thereby enabling improvements in other services. This will greatly contribute to decreasing the current disparity among these communities and improve their social progress. Regarding the study of wind potential, research such as that by Baranitharan *et al.* (2024) provided an excellent analysis of wind potential as a renewable energy source, promoting the transition to cleaner means of generation. Various techniques, including the Weibull distribution, are utilized to assess the potential wind energy output accurately.

Proposal for electrification of vulnerable populations

As a result of the analyses based on the use of RE generation sources to benefit RP lacking daily electrical service autonomy, Fig. 5 is proposed as a flowchart outlining the process components necessary to energize these populations and contribute to minimizing social inequality.

It is crucial to engage the local population in the planning and execution of electrification projects in non-interconnected areas of Colombia to enhance social development and ensure the sustainability of the infrastructure. This is because this technological

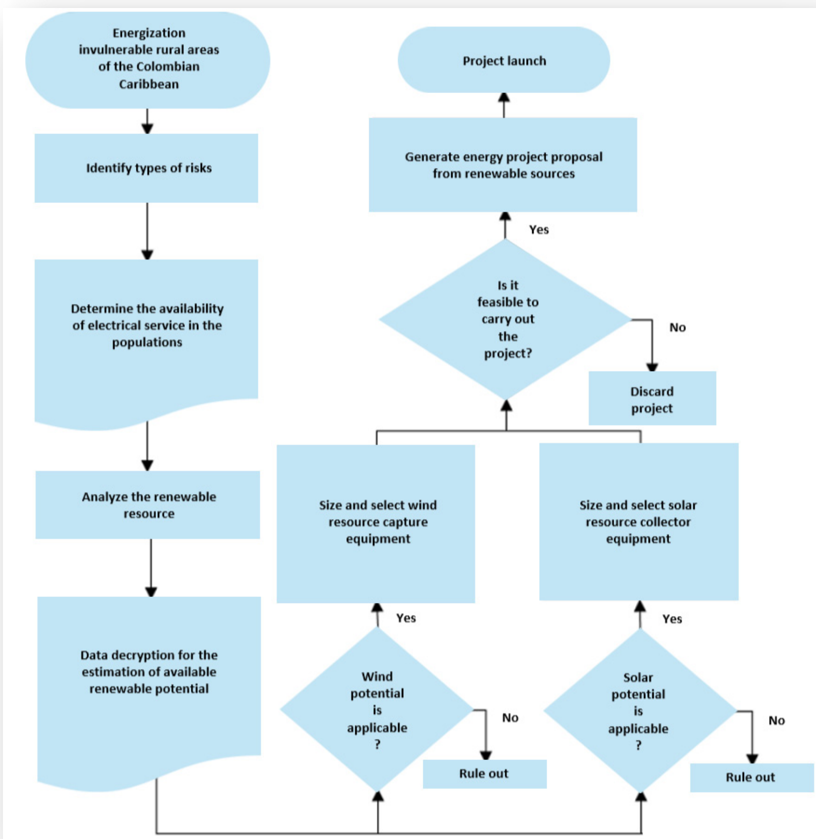

Fig. 5: Flowchart proposal for electrification project

equipment must be constantly monitored, supervised, and maintained to project greater durability. Full energy autonomy in these vulnerable areas, facilitated by electrification initiatives overseen by either the government or private entities, has the potential to drive social development within these communities. Currently, accessing high-quality education requires technological tools and thus electric service; hospitals, parks, and cultural enrichment spaces also need reliable electricity. The purpose of this proposal is to increase awareness and address the inequality present in the Colombian Caribbean region.

limitation of the energization study

The objective of the study was to raise awareness of the energy challenges faced by certain populations in the CC area, with a focus on the potential for harnessing both solar and wind energy. However, it underscores the need for proper sizing and management of renewable energy capture equipment, as well as effective project management aimed at bridging social gaps in these studied localities. The lack of homogeneous conditions compared to other citizens has led to developmental delays in these areas. This study does not present a breakdown of the equipment needed to power these populations. Instead, it highlights the current state of implemented systems, which do not meet the requirement for 24-hour energy self-sufficiency in these communities. It is suggested to carry on with the exploration of the genuine solar and wind capabilities that can be harnessed in these specific areas, while also planning for the sizing of equipment and associated costs needed to carry out a comprehensive electrification project for these vulnerable populations.

CONCLUSION

The energy appraisal conducted for the surveyed locations unveils unsatisfactory results of the present energy generation systems. These systems were initially designed for solar thermal polygeneration accompanied by wind energy (WE) for the locality of Nth, and solar thermal polygeneration for IF, SCI, and IM. Nevertheless, these systems are not enough to fulfill the energy requirements of the residents, as shown by the limited hours of electric service autonomy, leading to energy vulnerability in comparison to their fellow citizens. It is important to note that the wind systems installed in Nth have not been operational since their installation in 2011 due to poor energy design in the selection of wind turbines (WT). The absence of a solid scientific basis for choosing and implementing energy systems is apparent in the case of the WT in Nth, where inadequate scientific analysis led to the selection of inappropriate equipment. Moreover, the current operational systems are limited to providing less than 15 hours of autonomy per day, which does not meet the comfort standards of the LP. Specifically, in IF, the installed capacity offers around 6 hours of service daily, failing to meet the comfort requirements of its inhabitants. Identified within the types of risk based on the ISO-31000 standard, the main risks associated with the planning of sustainable energy projects in Colombia include deciphering historical data on renewable potentials, political interests, commercial financing, lack of scientific basis, and logistical challenges in acquiring energy capture equipment, transportation, maintenance, and proper installation. The methodology that has been put into practice allows for a predictive assessment of the sustainable potential in different locations by utilizing historical data on solar and wind patterns. This predictive approach aligns with the goals proposed by the United Nations in the sustainable development goals (SDG), specifically goal 7, which advocates for affordable and clean energy, vital for these studied localities that are not connected to the national energy grid. Moreover, it is in line with the objectives of energy conservation and efficiency as outlined in government policies and supported by the ISO 50001 standard. This standard advocates for a continuous improvement process in the development of energy projects for vulnerable localities. It is highlighted that all localities have highly exploitable potential for Se, with particularly intense solar potential (SP) in Nth. With the exception of Nth, the localities have a WE potential with low wind speeds (WS). This indicates the need for studies on devices capable of capturing and transforming WE from WS of 2 m/s. Conversely, Nth boasts favorable wind conditions. Selecting the correct WT that can operate efficiently with WSs starting at 6 m/s is of utmost importance. This implies a detailed analysis and careful selection of turbine models that match the specific wind profiles of the area. Properly designed and selected WT can significantly increase the energy generation capacity in Nth, making it a model for effectively integrating solar and WE systems. Communities with limited wind resources require innovative wind energy solutions. Developing wind turbines that can operate efficiently at lower wind speeds, such as around 2 m/s, would be highly beneficial. These turbines could serve as a supplementary energy source to enhance the overall energy resilience of these areas in conjunction with solar energy systems.

ACKNOWLEDGEMENT

This study was developed around the energy sustainability of vulnerable populations in the CC, specifically in localities in non-interconnected areas. Additionally, this work is part of the requirements for the doctoral degree in Engineering at the Technological University of Bolivar, Colombia.

CONFLICT OF INTEREST

The authors declare 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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ABBREVIATIONS

%	Percent
CC	Colombian Caribbean
CE	Combustion engines
CIECTSA	Colombian institute of educational credit and technical studies abroad
ER	Environmental risks
FR	Financial risks
h	Hour
IF	Isla Fuerte
IHMES	Institute of hydrology, meteorology, and environmental studies
IM	Isla múcura
IPPES	Institute for planning and promotion of energy solutions
LCR	Legal claims risks
LP	Local population
MDR	Material damage risks
MR	Management risks
MSTI	Ministry of science, technology and innovation
NMCC	National monitoring center of Colombia
Nth	Nazareth
OR	Operational risk
PER	Personal risks
POR	Political risks
PP	Project proposals
PR	Production risks
PS	Photovoltaic systems
RA	Rural areas
RE	Renewable energies
RP	Rural populations
Se	Solar energy
SCI	Santa cruz del islote
SDG	Sustainable development goals
SF	Solar farms
Sp	Solar potential
SR	Sales risks
WE	Wind energy
WS	Wind systems

WSs	Wind speeds
WT	Wind turbines

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AUTHOR (S) BIOSKETCHES

Fábregas Villegas, J., Ph.D. Candidate, Researcher, Mechanical Engineering Program, Autonomous University of the Caribbean, Colombia. And Ph.D. candidate, Engineering, Technological University of Bolívar, Colombia.
- Email: *jonathan.fabregas@uac.edu.co, jfabregas@utb.edu.co*
- ORCID: 0000-0003-1924-8666
- Web of Science ResearcherID: GVS-8825-2022
- Scopus Author ID: 57353034200
- Homepage: https://investigaciones.uac.edu.co/grupos-de-investigacion-giima

Tovar Ospino, I., Ph.D., Professor, Mechanical Engineering Program, Autonomous University of the Caribbean, Colombia.
- Email: *ivan.tovar@uac.edu.co*
- ORCID: 0009-0000-9999-2414
- Web of Science ResearcherID: NA
- Scopus Author ID: 57195715767
- Homepage: https://investigaciones.uac.edu.co/grupos-de-investigacion-giima

Palencia Díaz, A., Ph.D., Professor, Doctorate Program in Engineering, Technological University of Bolívar, Colombia.
- Email: *argpalencia@utb.edu.co*
- ORCID: 0000-0003-4947-5659
- Web of Science ResearcherID: NA
- Scopus Author ID: 57353034200
- Homepage: https://www.utb.edu.co/profesores/argemiro-palencia-diaz

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