ENERGY VIABILITY STUDY OF MICROGRIDES IN NON-INTERCONNECTED AREAS OF THE DEPARTMENT OF CAUCA (COLOMBIA)

MASTER IN INGEGNERIA E GESTIONE DELL' INNOVAZIONE
FACULTY OF ENGINEERING
UNIVERSIDAD CATÓLICA DE COLOMBIA
UNIVERSITÀ DEGLI STUDI DI SALERNO

OSCAR JAVIER ACEVEDO DAGUA
Matricola: 0670400026

Relatore:
Prof. Francisco Javier Novegil González-Anleo

Direttore del Master:
Prof. Domenico Guida

ACADEMIC YEAR 2020/21

ENERGY VIABILITY STUDY OF MICROGRIDES IN NON-INTERCONNECTED AREAS OF THE DEPARTMENT OF CAUCA (COLOMBIA)

OSCAR JAVIER ACEVEDO DAGUA

MASTER IN ENGINEERING AND INNOVATION MANAGEMENT
FACULTY OF ENGINEERING
UNIVERSIDAD CATÓLICA DE COLOMBIA & UNIVERSIDAD DE SALERNO
BOGOTÁ, JUNE 2021

ACCEPTANCE NOTE

Belkis Yennifer Lara
Jury

Wilfredo Marimón Bolívar
Jury

Francisco Javier Novegil González-Anleo
Advisor

Doménico Guida, PhD
Advisor

Bogotá, June 2021

GRATITUDE

The author expresses his thanks to:

To Dr. MIRYAM LILIANA CHAVES ACERO, Mechanical Engineer, Director of the Master in Engineering and Innovation Management, for her unconditional support, guidance and accompaniment of her in my academic process from the beginning.

To Dr. FRANCISCO JAVIER NOVEGIL GONZÁLEZ-ANLEO, graduate in Physics, advisor to this degree work, who, with his knowledge, motivation and admirable human quality, was key to the successful completion of this document.

To the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE, for its acronym in Spanish) for clarifying my concerns and providing relevant information for this degree project.

To the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM, for its acronym in Spanish), for advising me with the management of the Interactive Atlas.

And finally, I thank each and every one of my colleagues with whom I studied this Master since their support, advice and recommendations were key to the development and completion of this postgraduate degree.

TABLE OF CONTENTS

Pg.

LIST OF FIGURES

Pg.

LIST OF TABLES

Pg.

LIST OF ANNEXES

Pg.

ABSTRACT

This degree project studies the island mode microgrids or isolated microgrids of the National Interconnected System (SIN, for its acronym in Spanish) as an alternative to supply the energy demand of users located in rural areas designated as Non-Interconnected Zones (ZNI), for its acronym in Spanish) of the department of Cauca in Colombia.

The motivation for the project arises from understanding a social problem and wanting to find a solution through renewable energy resources that is reliable, economically viable and efficient for the environment.

The project begins by examining the world panorama, passing through Latin America until focusing on the national panorama, more specifically in the department of Cauca (Colombia). Topics on uncertainty, modeling and decision making, simulation of hybrid energy systems (photovoltaic, wind, hydrokinetic, battery bank and diesel generators) are explored; giving importance to innovative, technical, economic, social and environmental aspects.

All the information collected, especially that concerning the 3 municipalities that are part of the Non-Interconnected Zones: López de Micay, Timbiquí and Guapí, is analyzed with a multi-objective optimization methodology. Problem solving is carried out with the help of the mathematical method Hierarchical Analytical Process (AHP) to reduce the uncertainties that arise when considering the multiple variables for the search for energization solutions, prioritizing the most viable areas for the implementation of microgrids.

The information of the selected zone is converted into input data for a simulation in a free-use software that allows optimal modeling for electric hybrid systems called Homer Pro® (Free version). At this point, the analysis focuses on the economic and technical feasibility whose output data are the results and validations on the most appropriate microgrid for a case study analyzed in the computational tool.

Finally, the results and possible paths to follow in future studies are presented.

Keywords: Isolated microgrids, Non-Interconnected Zones (ZNI, for its acronym in Spanish), renewable energy resources, multi-objective optimization, hybrid energy systems.

RESUMEN

El presente proyecto de grado estudia las microrredes modo isla o microrredes aisladas de la red del Sistema Interconectado Nacional (SIN, por sus siglas en español) como alternativa para suplir la demanda energética de los usuarios ubicados en áreas rurales designadas como Zonas No Interconectadas (ZNI, por sus siglas en español) del departamento del Cauca en Colombia.

La motivación del proyecto surge a raíz de comprender una problemática social y querer encontrar una solución a través de recursos de energía renovable que sea fiables, económicamente viables y eficientes para el medioambiente.

El proyecto comienza examinando el panorama mundial, pasando por Latinoamérica hasta focalizarse en el panorama nacional, más puntualmente en el departamento del Cauca (Colombia). Se exploran temas sobre incertidumbre, modelado y toma de decisiones, simulación de sistemas híbridos de energía (fotovoltaica, eólica, hidrocinética, banco de baterías y generadores diésel); dándole importancia a aspectos innovadores, técnicos, económicos, sociales y medioambientales.

Toda la información recopilada, especialmente la concerniente a los 3 municipios que hacen parte de las Zonas No Interconectadas: López de Micay, Timbiquí y Guapí, es analizada con una metodología de optimización multiobjetivo. Se realiza la resolución de problemas con la ayuda del método matemático Proceso Analítico Jerárquico (AHP) para reducir las incertidumbres que surgen al considerar las múltiples variables para la búsqueda de soluciones de energización, priorizando las zonas más viables para la implementación de microrredes.

La información de la zona seleccionada se convierte en datos de entrada para una simulación en un software de uso libre que permite el modelamiento óptimo para sistemas híbridos eléctricos llamado Homer Pro® Versión gratuita). En este punto, el análisis se concentra en la viabilidad económica y técnica cuyos datos de salida son los resultados y validaciones sobre la microrred más adecuada para un caso de estudio analizado en la herramienta computacional.

Finalmente, se presentan los resultados y posibles caminos a seguir en futuros estudios.

Palabras clave: Microrredes aisladas, Zonas No Interconectadas (ZNI), recursos de energía renovable, optimización multiobjetivo, sistemas híbridos de energía.

1. INTRODUCTION

"Guarantee access to affordable, reliable, sustainable and modern energy for all" [1] are the 4 dimensions of the seventh Sustainable Development Goal: Affordable and Clean Energy of the United Nations Development Program (see annex A). In total, 17 goals were adopted by all Member States in 2015 to end poverty, protect the planet, and guarantee peace and prosperity for all people by 2030 [2].

In contrast, for the year 2019, the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the United Nations (UN), the World Bank (WB) and the World Health Organization (WHO), reported that the number of people without electricity in the world for the year 2017 was 840 million, 3 billion people continue to burn biomass for cooking and predicting at the end that about 674 million people will be without access to electricity in the year 2030 [3].

The energy resource has become a vital element for the development of humanity, about 84.7% of the energy consumed on the planet comes from fossil sources and only 10.8% from renewable sources [4].

Various studies [5,6,7] have shown the close relationship between the human development index and access to electricity, showing that the most industrialized countries are those with the highest per capita and per capita energy consumption index. Consequently, a society that is able to make greater use of energy and energy resources can offer a greater degree of well-being and quality of life to its inhabitants, but the unconscious and inefficient consumption of energy will also bring negative consequences.

Greenhouse emissions each year have reached historical records such as that of 2018, which increased by 147% in Carbon Dioxide (CO_2), 259% Methane (CH_4) and 123% Nitrous Oxide (N_20) [8].

The collateral effects of the pandemic that originated in 2019, projected a 7% drop in emissions of CO_2; however, this effect will be minimal in the long term when compared to the global warming prospect that remains above 3ºC [9].

The incessant demand and energy dependence for decades on oil, coal, natural gas and nuclear fuels have reaffirmed their finite qualities, being hit by various global adversities, which has encouraged the energy transition to Non-Conventional Sources of Renewable Energy (NCRE) that contribute to the reduction of greenhouse effect emissions [10].

Currently, countries such as the United States, China, Germany and Spain are more at the forefront of technological and innovative advances for the optimization of their installed energy capacities as well as in the transition to other sources of solar, wind and geothermal origin. The United States and Germany stand out in the use of bioenergy in transportation and the United States, China and Turkey are champions in the use of thermal energy in the form of heat and geothermal energy [11].

The outlook for Latin America is challenging, important changes have been made to have a greater participation in renewable energy sources: legislative reforms, tax incentives, start-up of large NCRE projects, among others. An example of this are countries such as Brazil, Chile and Uruguay [12].

According to the World Economic Forum, Colombia is the Latin American country with the greatest progress towards the energy transition, rising from position 34 to 25, by 2020, among 115 countries [13]. Its privileged location allows it to have a great variety of natural resources and weather phenomena suitable for the generation of renewable energy (hydraulic, solar and wind sources) but it has also suffered drastic climate changes where the country has had to suffer energy shortages, increases in the prices of the energy service and the generation of electricity from fossil fuels.

For Colombia, increasing its generation capacity with clean energy by 1,500 MW, compared to the current 22.4 MW, is one of the 20 goals of the National Development Plan (2018-2022) [14]; a challenge that demands a great innovative component considering the intermittency of energy resources. Dimensioning a system of renewable sources that complement each other could become a disruptive solution that would reduce in the Non-Interconnected Zones (ZNI, for its acronym in Spanish), the energy poverty of communities that do not have access to the National Interconnected System (SIN, for its acronym in Spanish).

This in-depth modality degree work was structured by chapters as follows: Chapter 1 is the present introductory segment; Chapter 2 describes the problem posed by Non-Interconnected Zones (ZNI) and also presents the proper justifications for the project; Chapter 3 lists the objectives of the job; Chapter 4 frames the fundamental concepts and methodologies; Chapter 5 is the theoretical framework and the multi-objective methodology to start solving the problem; Chapter 6 presents the State of the Art; Chapter 7 shows the methodological application for ranking criteria; In chapter 8 the project methodology is applied with a case study through optimization simulations for electric hybrid systems, in chapter 9 results are presented; Chapter 10 shows the validation of the project presented; Chapter 11 describes the project from the innovation edge and its potential, Chapter 12 shows conclusions and future work, Chapter 13 bibliographically supports the research and Chapter 14 are annexes that support topics of special interest.

2. PROBLEM STATEMENT

A Non-Interconnected Zone (from now on interpreted as ZNI by its acronym in Spanish) is defined in Colombia by Law 143 of 1994 in article 11, as an area of the geography where there is no provision of public electricity service through the Interconnected System National (SIN) [15]. The origin of the ZNI, arises with the beginnings of the National Interconnected System (from now on interpreted as SIN for its acronym in Spanish); at the end of the 19th century, when the municipalities obtained through concessions with private and mixed companies, the services for public lighting, then industrial and commercial properties and finally the homes of wealthy families. In 1889, with the first electric company in the country: Bogotá Electric Light Co. [16], a new era of high voltage interconnections began in the most representative and central cities of the country: Bogotá in 1890, Bucaramanga in 1891 Barranquilla in 1892, Cartagena and Santa Marta in 1893 and finally Medellín in 1898 [17].

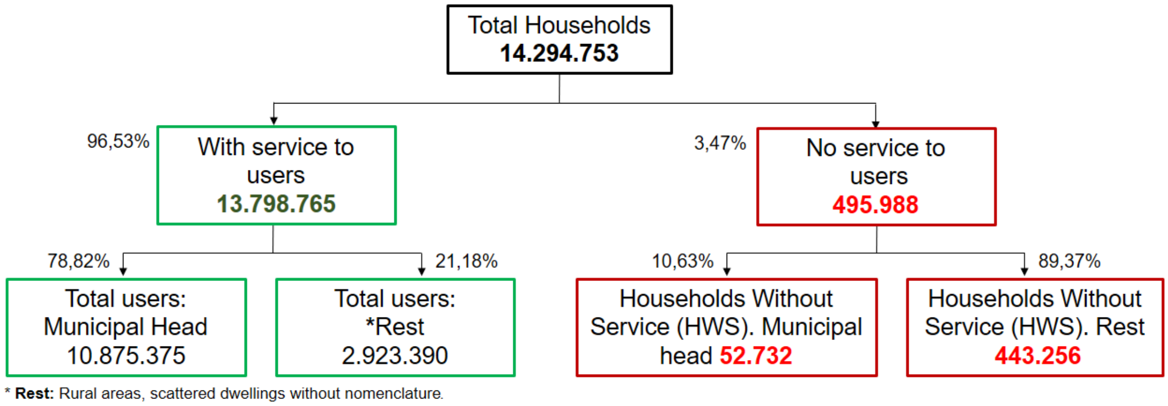
The electrical planning at that time did not contemplate many remote regions of the center of the country and to this day, some still do not have an estimated date for the provision of the electric public service through the SIN.

At present, Colombia is energetically divided into two parts, the first, by the National Interconnected System (SIN), which has the generation plants and equipment, the interconnection network, the regional and interregional transmission networks, the distribution and electrical loads of users [15]. The second part, and on which this degree work is focused, are the Non-Interconnected Zones (ZNI) that correspond to the municipalities, townships, localities and hamlets that do not have access to electricity because they are not linked to the National Interconnected System (SIN) [18].

The Mining and Energy Planning Unit (from now on interpreted as UPME, for its acronym in Spanish), calls a property with residential use housing and a user considers it as the homes classified in the residential sector that have the infrastructure available regardless of their conditions and its energy sources.

Figure 1 shows at the national level, the electricity coverage index and the energy deficit as of December 2018 [19].

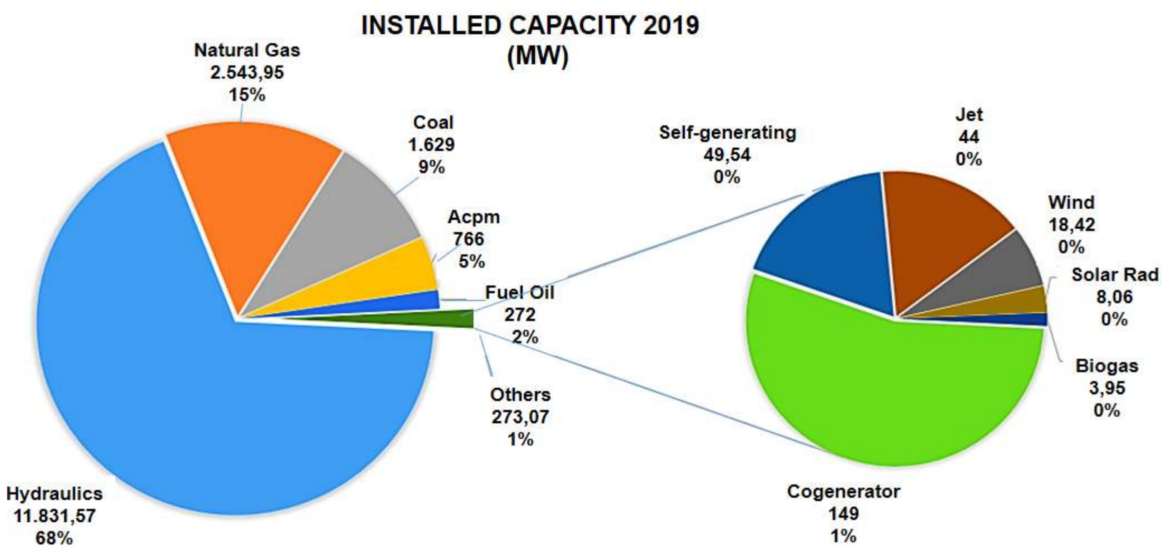
Figure 1. General scheme of energy coverage 2018.



Source: Author based on the Estimation Results of the Energy Coverage Index ICEE-2018 of the Mining and Energy Planning Unit (UPME) [19].

The Colombian energy matrix depends, to a large extent, on non-renewable energy sources and on conventional renewable sources, such as hydroelectricity. The graph in figure 3 shows the capacities installed by energy sources:

Figure 2. Effective installed capacity in Colombia 2019 (MW).



Source: Author based on Mining Energy Planning Unit – 2019 [20].

Excessive dependence, especially on the hydraulic part, makes Colombia susceptible to a great extent, to serious shortages in the face of adverse meteorological phenomena such as those that occurred with El Niño and La Niña; This is why the government, in its National Energy Plan 2020-2050, highlights the inclusion of Non-Conventional Sources of Renewable Energy (from now on interpreted as NCRE), in the country's energy matrix, either through public initiatives, private or mixed, to mitigate risks and configure a more sustainable energy matrix [20].

The National Government, through different governmental, public, private and mixed actors, headed by the Ministry of Mines and Energy (Minenergía, for its acronym in Spanish), executes different actions to promote development and the National Economy (see the figure 3).

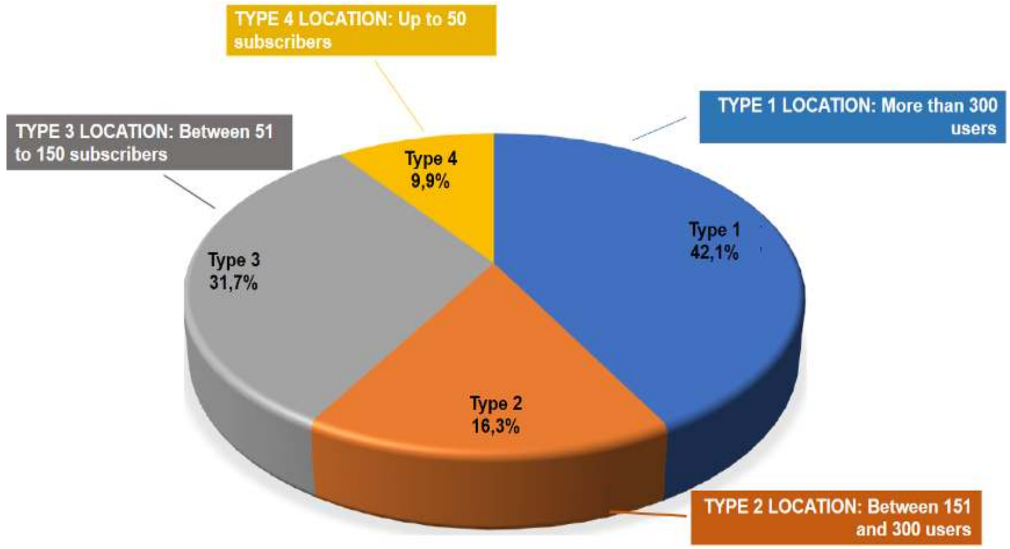
Figure 3. Structure of the Colombian electricity sector – 2021.

Source: Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones - IPSE [21].

Among the main actors mentioned, the National Government has the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE, for its acronym in Spanish), with the mission of structuring and implementing effective, durable and friendly energy solutions. the environment [21].

Article 6° of the Resolution of the Ministry of Mines and Energy 182138 of 2007, allows the IPSE to rank the ZNIs by locality as shown in figure 4.

Figure 4. Zone Non Interconect Sector Report - 2020.

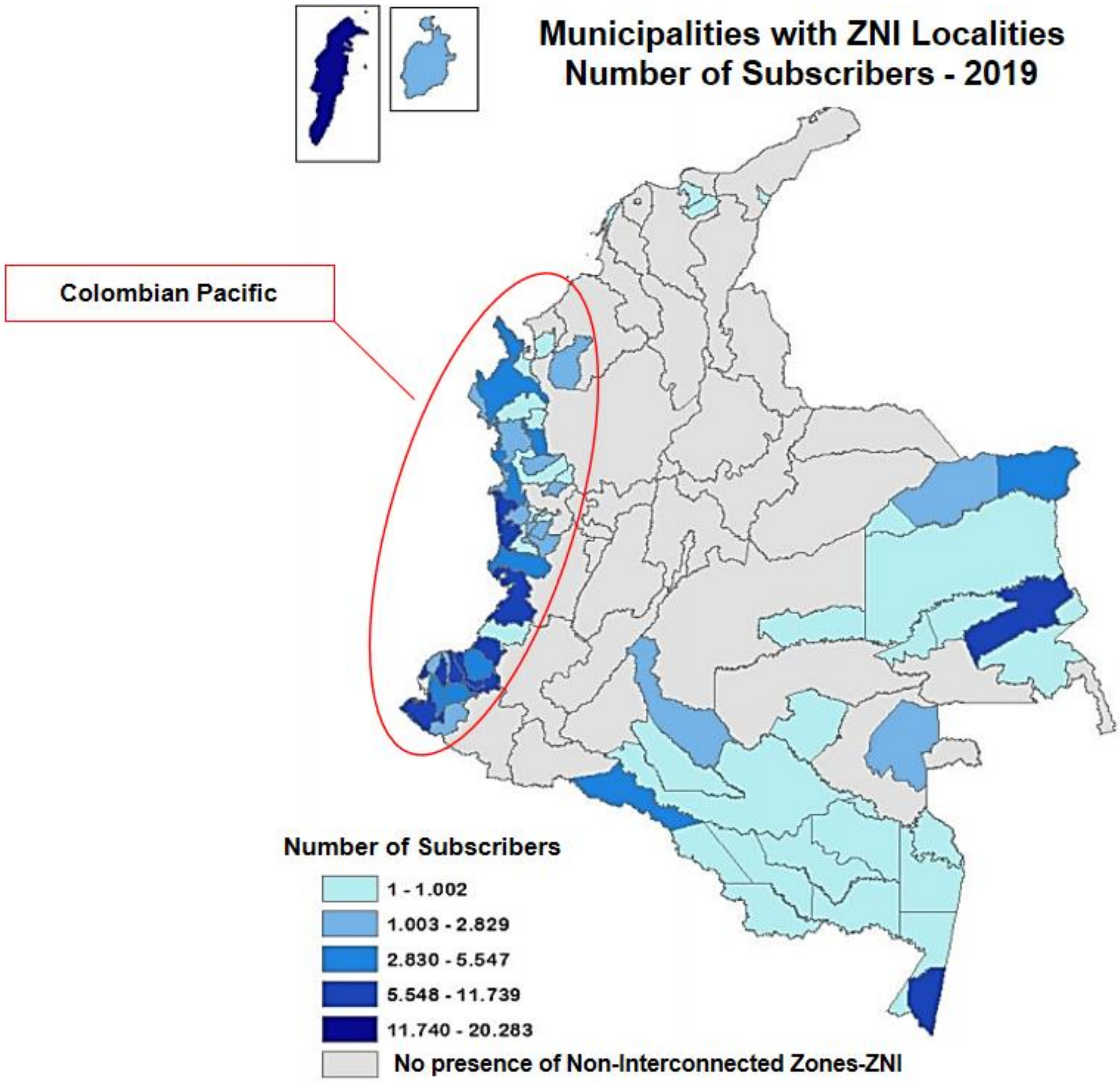


Source: Author based on The Mining and Energy Planning Unit UPME [19].

Through the National Monitoring Center (CNM, for its acronym in Spanish), the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE), obtains the energy characterization of the ZNI with monthly telemetries [22], confirming that Towns 1 and 2 have a higher concentration of users per m2 while Towns 3 and 4 present a higher dispersion of users and, consequently, a higher level of technical and economic complexity when thinking about infrastructure and network laying that are required to link them to the SIN.

The map of Colombia in Figure 5: identifies the departments linked to the National Interconnected System (SIN, for its acronym in Spanish) with gray color, identifies the departments in the Non-Interconnected Zones (ZNI, for its acronym in Spanish) in blue tones and highlighted in a red oval, the concentration of the ZNI in the Colombian Pacific.

Figure 5. Municipalities with ZNI Localities. Number of Subscribers-2019.



Source: Author based on Interconnected and non-interconnected zones 2019 [20].

By zooming in on the problem on the Colombian map, the IPSE focuses on the number of Homes Without Service (VSS, for its acronym in Spanish) as shown in table 1:

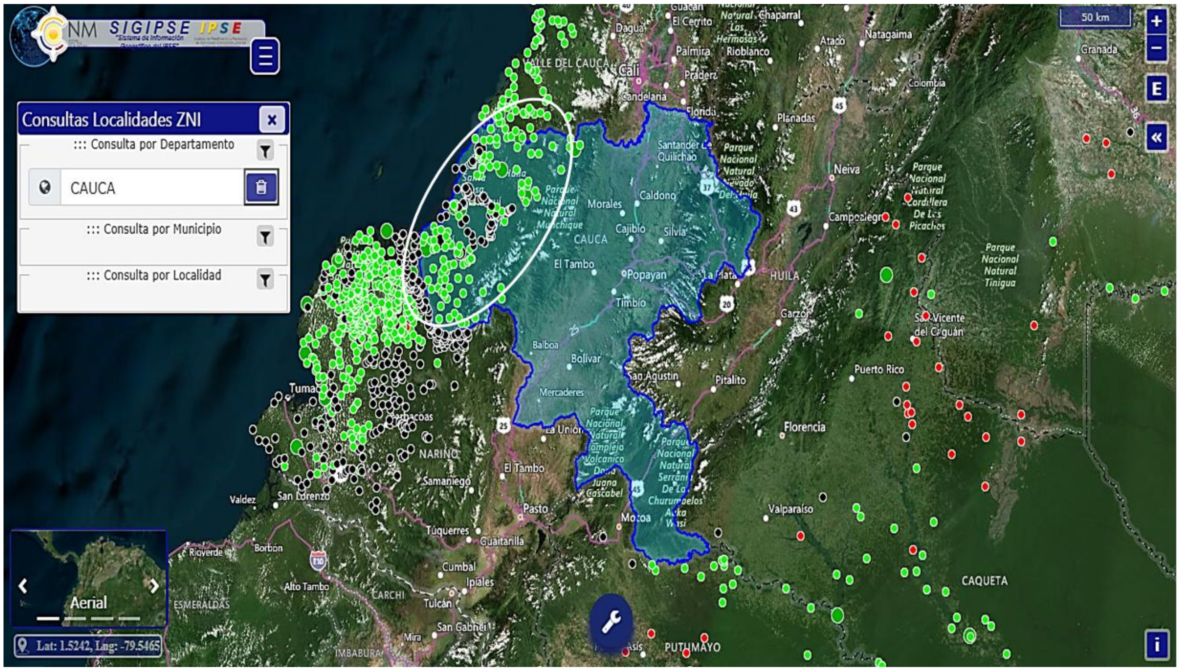
Table 1 related to the Electricity Coverage Index (ICEE, for its acronym in Spanish), shows that among the first 10 departments with the highest number of Unserved Homes (VSS), the department of Cauca is in third place, which is part of the Colombian Pacific.

Table 1. Departmental ICEE result summary - 2018.

DEPARTMENTS	TOTAL USERS	TOTAL HOUSEHOLDS	TOTAL HOUSEHOLDS WITHOUT SERVICE	TOTAL EPCI (Electric Power Coverage Index)
LA GUAJIRA	117.041	199.001	81.960	58,81%
NARIÑO	480.134	516.398	36.264	92,98%
CAUCA	**385.072**	**417.347**	**32.275**	**92,27%**
CHOCÓ	155.436	184.995	29.559	84,02%
VALLE DEL CAUCA	1.247.130	1.274.967	27.837	97,82%
BOLIVAR	466.830	491.740	24.910	94,93%
ANTIOQUIA	2.217.257	2.241.042	23.785	98,94%
META	296.543	319.920	23.377	92,69%
PUTUMAYO	72.266	94.401	22.135	76,55%
MAGDALENA	287.753	305.719	17.966	94,12%
NORTE DE SANTANDER	432.869	450.197	17.328	96,15%
CAQUETÁ	100.169	117.354	17.185	85,36%
CESAR	274.409	290.757	16.348	94,38%
CÓRDOBA	383.867	398.341	14.474	96,37%
HUILA	355.641	368.214	12.573	96,59%
TOLIMA	452.684	465.226	12.542	97,30%
SANTANDER	706.568	717.757	11.189	98,44%
BOYACÁ	484.209	494.943	10.734	97,83%
VICHADA	9.549	20.174	10.625	47,33%
CASANARE	131.683	139.906	8.223	94,12%
CUNDINAMARCA	952.176	959.376	7.200	99,25%
SUCRE	215.052	222.159	7.107	96,80%
GUAVIARE	18.619	24.776	6.157	75,15%
ARAUCA	70.384	76.418	6.034	92,10%
ATLÁNTICO	565.722	571.507	5.785	98,99%
AMAZONAS	13.814	18.025	4.211	76,64%
GUAINIA	7.540	11.266	3.726	66,93%
VAUPÉS	3.596	7.207	3.611	49,90%
CALDAS	303.121	303.466	345	99,89%
BOGOTA D.C.	2.095.535	2.095.716	181	99,99%
QUINDIO	173.900	174.061	161	99,91%
RISARALDA	300.342	300.454	112	99,96%
SAN ANDRÉS Y PROVIDENCIA	21.854	21.923	69	99,69%
NATIONAL TOTAL	**13.798.765**	**14.294.753**	**495.988**	**96,53%**

Source: Author, based on the report of the Mining and Energy Planning Unit – UPME, 2018.

Figure 6. Non-Interconnected Zones of the department of Cauca (Colombia)



Source: Author based on the Geographic Information System of the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (December 2020) [21].

Within the oval of the previous satellite photo, the geographical area where the 3 municipalities of Cauca are located with the highest number of users in Non-Interconnected Zones (ZNI) is highlighted: Timibiquí, López de Micay and Guapí.

To make an approach in the three municipalities located in the Non-Interconnected Zones (ZNI), in table 2 a population dimensioning is made for each municipality.

Table 2. ZNI prioritization in Cauca, January 2021.

MUNICIPALITY	TOWNSHIP	CATEGORY	NUMBER OF RESIDENTIAL USERS
TIMBIQUÍ	**Puerto Saija**	**Township/Corregimiento**	457
TIMBIQUÍ	Santa María	Township/Corregimiento	402
GUAPI	**Limones**	**Township/Corregimiento**	350
LÓPEZ DE MICAY	Zaragoza	Township/Corregimiento	281
TIMBIQUÍ	Los Brazos	Municipal Headquarters/Cabecera Corregimiento Municipal	269
TIMBIQUÍ	San José Timbiquí	Township	267
TIMBIQUÍ	Coteje	Township	265
GUAPI	San Antonio de Guajui	Township	255
LÓPEZ DE MICAY	**San Antonio de Chuare**	**Township**	253
LÓPEZ DE MICAY	Betania - Río Naya	Township	224
LÓPEZ DE MICAY	Noanamito	Township	218
TIMBIQUÍ	Santa Rosa de Saija	Township	212
LÓPEZ DE MICAY	La Concha - Concepción	populated center/Centro Poblado	182
LÓPEZ DE MICAY	Dos Quebradas Río Naya	Minor Locality/Localidad Menor	180
LÓPEZ DE MICAY	Boca Grande	populated center/Centro Poblado	175
LÓPEZ DE MICAY	San Isidro	populated center/Centro Poblado	175
TIMBIQUÍ	Comunidad de Chete	Municipal Headquarters/Cabecera Corregimiento Municipal	167
TIMBIQUÍ	Chacón	Minor Locality/Localidad Menor	157
LÓPEZ DE MICAY	Isla de Gallo	Township	152
3 Municipalities	**19 townships**	**Most townships**	**3854 Users NOT connected to the SIN**

MUNICIPALITY	TOTAL NUMBER OF RESIDENTIAL USERS
TIMBIQUÍ	2196
LÓPEZ DE MICAY	1308
GUAPI	350
TOTAL	**3854**

Source: Author based on Telemetry Report, January 2021- IPSE [22].

The reasons for the ZNI to continue to prevail in the department of Cauca are its rugged geography, diversity of climates, altitudes and forests; situations that hinder the expansion of electrical networks for connection to the SIN and, consequently, are highly complex and costly to manage. In addition, these areas have significant ecological and cultural importance due to the presence of parks, nature reserves and areas of archaeological finds, as well as ethnic and Afro communities. All of the above reduces the environmental viability for the execution of energization projects [23].

The users of the electric power service in the ZNI must resort mostly to diesel generators, this leads to high costs of transportation, fuel and equipment maintenance; that is: high costs, limited hours of electricity and environmental pollution.

The department of Cauca (Colombia) by the Western Electric Company (CEO, for its acronym in Spanish), has 220 kV and 115 kV power substations, with which it would be initially thought as a solution, to extend the networks electricity for those more distant users but when the users are more isolated from the networks, the supply depends only on small hydroelectric plants, which due to their limited capacity and location, represent considerable technical losses and voltage drops in the system; furthermore, the ability to supply demand at peak hours is hampered, causing an imbalance between generation and demand and as a consequence it makes the supply arrive discontinuously [24].

A renewable energy system is flexible to the challenges that the exposed limitations may present; their technological advances, commercial diversification and their boom in the market have made them more affordable solutions in the last 10 years [25], but their efficiency in meeting energy demand is limited since their primary resource is intermittent. Hence the great interest and current innovative advances in technology to develop hybrid systems of Non-Conventional Renewable Energy Sources (NCRE); microgrids (MG) that meet the energy demand in a certain time whose energy systems (Solar, wind, hydrokinetic, diesel, etc.) can supply energy to the other when it is necessary to support it, but this would lead to new problems due to solve as the different variables to consider so that the systems work harmoniously with each other.

2.1 PROBLEM QUESTION

For the department of Cauca (Colombia), what would be the most viable microgrid with hybrid systems to meet the energy needs in rural areas that are not interconnected?

2.2 JUSTIFICATION

The present degree work is justified from the following aspects:

2.2.1 Social aspect. The energization of the ZNI for a community would be translated as the axis for the proper development of domestic activities, health, education, entrepreneurship in productive and commercial activities [26], Communities without public lighting or without means of communication are vulnerable, for example, to the presence of irregular forces that, ultimately, hinder their development and quality of life, situations that can be changed with the provision of the energy service.

2.2.2 Innovative aspect. The international standard UNE-ISO 56002: 2019 defines innovation as *“A new or modified entity that realizes or redistributes value”*. The above definition is consistent with microgrids as innovative projects for isolated rural areas since, through innovative technological advances, they provide unconventional solutions to complex problems for the optimization of electricity generation, transmission and distribution in communities that do not have the supply. electric.

2.2.3 Technical aspect. The Colombian Pacific has a wide diversity of water, wind and solar resources that, for the purposes of this project, are conducive to exploring innovative technologies that are adapted to its conditions. Proof of the above is the national government program: "Pacific Pure Energy" which, together with the Ministry of Science, Technology and Innovation and the Inter-American Development Bank (IDB), have promoted clean and renewable energy solutions for this area of the country [27].

2.2.4 Environmental aspect. Eliminate or minimize the use of fossil fuel-based generators (power plants), minimize the emission of polluting gases and establish the felling of trees for cooking food and other purposes, are some of the strongest arguments to consider the microgrids based on hybrid systems of Non-Conventional Energy Sources as sustainable solutions to produce electricity and as a clean energy development mechanism from an environmental perspective.

2.2.5 Financial aspect. The alternatives to electrically energize the ZNIs could be summarized to a large extent, in generators and photovoltaic systems, which in many cases do not tend to be viable in certain regions. Current microgrid solutions made up of hybrid systems would be a more viable alternative, with greater reliability, longer component life, lower operating and maintenance costs, and lower environmental impact to meet electricity demand.

3. OBJECTIVES

3.1 GENERAL OBJECTIVE

Propose the best microgrid alternatives for the Non-Interconnected Zones of the department of Cauca (Colombia) through the use of multiobjective and optimization tools.

3.2 SPECÍFIC OBJECTIVES

- Identify the methodologies, research and strategies that have addressed the problems of energizing with microgrids in Non-Interconnected Zones (ZNI).

- Formulate an energy planning strategy that integrates the geographic dimensioning of the region, the energy resources of the ZNI, the types of microgrids, the hybrid photovoltaic, wind, hydrokinetic and diesel systems, their electrical distribution, technical, economic and environmental aspects.

- Select the best alternatives for the implementation of microgrids in Non-Interconnected Zones through a mathematical optimization method.

- Simulate the operation of the microgrid through a case study in an optimization model for electric hybrid systems.

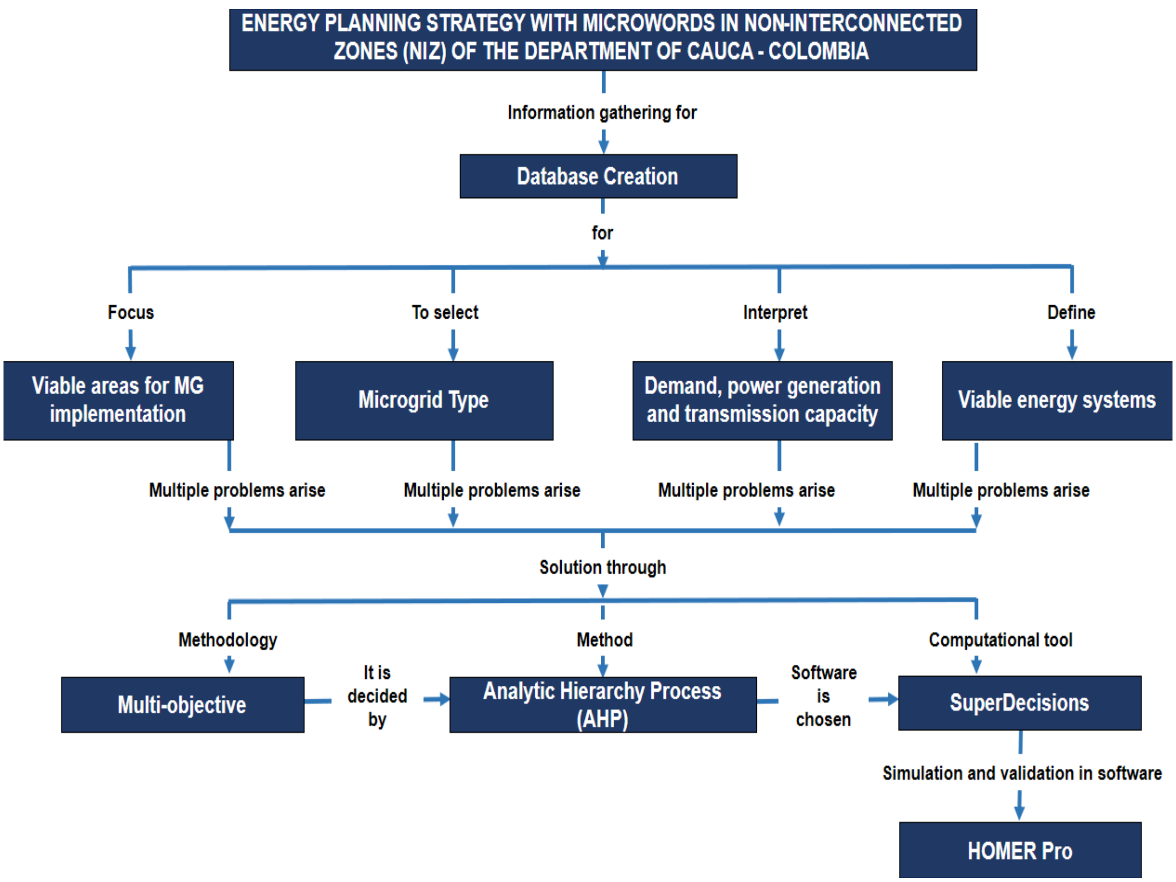
4. CONCEPTUAL FRAMEWORK

This work starts with the implementation of an energy planning strategy [28], focused on satisfying the demand of the ZNI, seeking to reduce costs, generate energy savings and efficiencies with microgrids.

The methodology is based on the proposal for independent energy planning on the effective integration of non-conventional renewable energies proposed by the Inter-American Development Bank (IDB) to the electricity systems in Latin America proposed [29].

The concept map in Figure 7 shows an overview of the methodology, the topics studied and their relationship between them.

Figure 7. Methodological concept map.



Source: Author.

4.1 METHODOLOGIES, INVESTIGATIONS AND STRATEGIES OF MICROGRIDES (MG)

Based on the first specific objective of this project, this chapter is developed starting with a brief historical context to frame the subject of microgrids.

According to the International Renewable Energy Agency - IRENA, a microgrid (from now on interpreted as MG) can be defined as a system that interconnects electrical loads and distributed generation sources and that can act both in connection with the electrical system and autonomously, also known as isolated or island modality [30].

MGs are not a new concept, if the previous definition is rigorously followed, the first MG could be historically framed in 1881 with the first electrical power generation facility by Thomas Edison in Pearl Street, Manhattan [31]; However, the concept of isolating and keeping a low voltage distribution network in operation in the event of a failure upstream of the Low Voltage / Medium Voltage (LV/MV) transformer, is a concept closer to MG originated by Nikola Tesla [32].

Only until the 1980s, after the advances in solar panels in the space industry, the costs became more affordable for people to the point of beginning to be implemented on farms in the United States through photovoltaic installations, lead acid batteries and Diesel generation (Combination of renewable source and fossil fuel), principles of a hybrid system [33].

At present, the most ambitious and innovative approach to a large-scale MG is probably the one presented in Australia [34], where four possible scenarios for the country's electricity system were contemplated for the year 2050. In one of these scenarios, Australia has a goal of abandoning the grid through an extensive transition towards user autonomy based on distributed generation and storage. 64% of the generation would be obtained from renewable sources and 31% from distributed sources.

On the investigations carried out on the subject of microgrids (MG), academics, companies and governments have concluded positive results on the benefits they provide; according to Dr. Nikos Hatziargyriuo, an MG makes it possible to control the flow of active and reactive power, allowing to guarantee energy efficiency between generation and demand [35]; Other important advantages offered by a MG are the reduction of polluting gas emissions, high reliability, low electrical losses and the possibility of operating in an interconnected or isolated mode from a conventional electrical network or another MG [36].
.

4.2 METHODOLOGY AND TYPES OF MICROGRIDES

The National Institute of Electricity and Clean Energy (INEEL, for its acronym in Spanish), through the electricity planning methodology, classifies the MGs according to the management of loads and distributed generation that need to be implemented in 3 groups that are presented below [37].

4.2.1 Alternating Current (AC) microgrids. They have a common Alternating Current (AC) bus to which loads that operate on Alternating Current / Direct Current (AC/DC), energy storage systems and renewable energy sources are connected. They can be integrated into the conventional electrical grid, although their energy efficiency may decrease, due to the DC / AC conversion of their resources, also due to difficulties in the synchronization of distributed generators and due to three-phase unbalance.

4.2.2 Direct Current (DC) microgrids. To connect to your local network with an AC / DC converter. These Direct Current (DC) MG classes are more efficient than Alternating Current (AC) MGs since energy conversion losses are reduced. With this type of microgrids, household appliances, electric vehicles, photovoltaic panels, etc., work with high-efficiency DC/DC converters.

4.2.3 Hybrid Alternating-Direct Current (AC/DC) microgrids. It is the combination of AC/DC. By having the advantage of both types of MG, integration to Distribution Networks (RD) is facilitated, reduction in energy losses and fewer energy conversion stages.

4.3 OPERATIONAL STRATEGY FOR THE USE OF MICROGRIDES

A microgrid (MG) can be connected to a conventional electrical network or it can work without it (Isolated microgrid or island mode) [30]. Due to their mode of operation or use, they are also known as MG in connected mode or disconnected mode [38]:

4.3.1 Microgrid connected to the Distribution Network (DN). This modality is the most normal. The quality of the DN is not disturbed and electricity can be imported or exported to it.

4.3.2 Isolated microgrid or island mode. This modality works and depends on its own generation capacity through its renewable or non-renewable energy sources and its generation capacity vs the consumption in kWh of the connected loads. It is also known as an autonomous microgrid.

4.4 CLASSIFICATION OF MICROGRIDES BY TYPE OF OPERATION

MGs are classified according to their use (community, commercial, industrial, campus, institutional, military, etc.). Considering that this work focuses on the ZNI without access to the National Interconnected System (SIN), the classification is made under two types:

- Isolated microgrids with dispersed loads.
- Isolated microgrids with concentrated load.

Isolated microgrids with dispersed loads tend to consider low numbers of users and very distant from each other [39], while MGs with concentrated loads are considered to have large population settlements [40].

For the purposes of this work, the isolated MGs with dispersed load are considered for the Type 3 Locality (between 51 to 150 users) and the Type 4 Locality (Up to 50 users) and the isolated MGs with concentrated load for the Type 2 Localities (between 151 and 300 users) and Type 1 Locality (more than 300 users) [41].

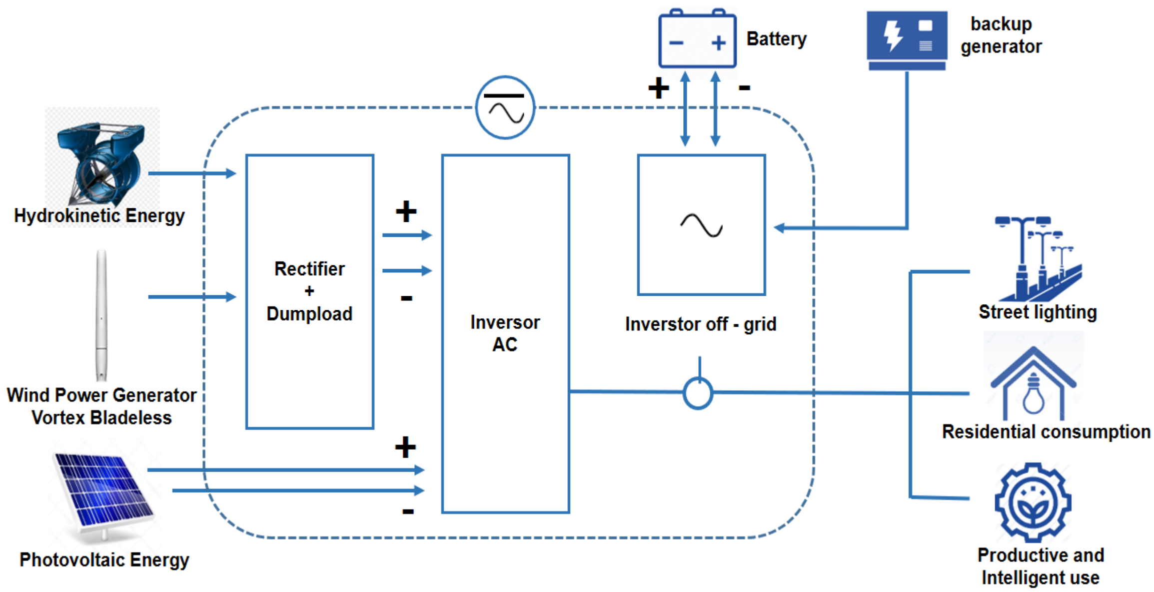
Studies on MG planning in ZNI with concentrated loads [42,43], conclude that considering this type of microgrids (with high user settlements), facilitate energy storage and establish the diesel backup system due to its proximity to the loads of higher power.

In order that this feasibility study also offers reliability and omits energy losses in distribution, the characteristics of the microgrids for this degree work will be:

- Hybrid microgrids (Combination between renewable sources and diesel generation)
- Isolated microgrid or island mode (Autonomous)
- Microgrids in rural and residential communities with productive potential
- Microgrids in ZNI with concentrated load (Type 2 locations)

Figure 8 represents the design of an Off grid microgrid based on the following components: photovoltaic energy, wind energy and hydrokinetic energy, a generator set (diesel generator) as system backup, a converter and a battery bank [44].

Figure 8. Design of an isolated microgrid with hybrid systems.



Source: Author.

4.5 HYBRID ENERGY SYSTEMS

A hybrid energy system is one that usually has two or more renewable energy sources that are used in combination to provide greater system efficiency and a better balance in the energy supply. For example, if the system does not have solar or wind energy available, most hybrid systems supply energy by means of batteries or a motor generator powered by conventional fuels such as diesel [45].

4.5.1 Solar energy. It is the energy transported by electromagnetic waves that comes from the sun. The emission of energy from the surface of the sun is called solar radiation; and the energy emitted is called radiant energy. The radiant energy that falls on the earth's surface per unit area (irradiation or insolation), is measured in kWh/m^2; and the radiant power that affects the earth's surface per unit area (irradiance), is measured in kW/m^2 [46].

Solar energy can be harnessed using different technologies such as photovoltaic solar, thermal solar and passive solar. For the purposes of this degree project, the study will focus on the photovoltaic cell system (PV).

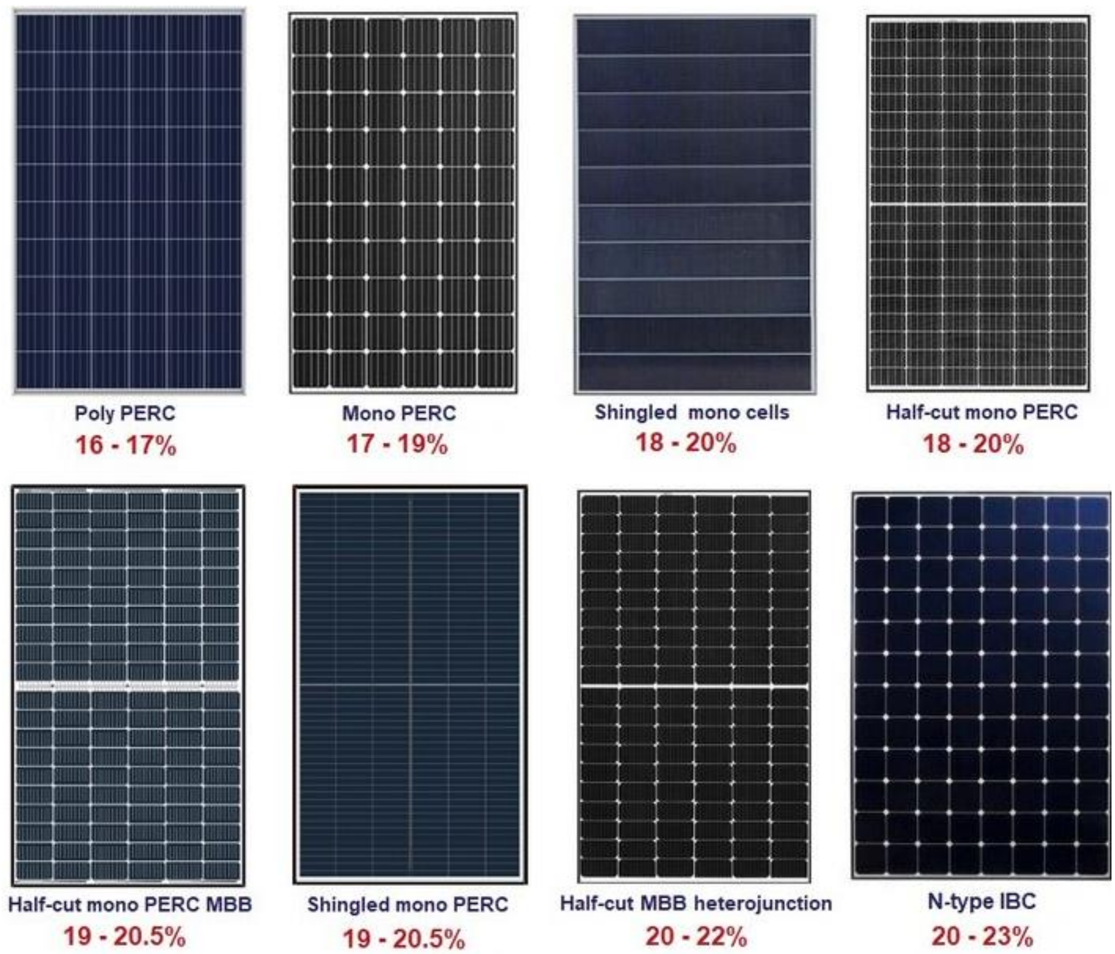
• **Photovoltaic solar energy:** It consists of the direct transformation of light energy into electrical energy. Solar panels made up of photovoltaic cells are used to capture this energy and transform the light (photons). The materials for the panels are usually Crystalline Silicon or Gallium Arsenide [47].

The way to determine the solar resource is according to the solar irradiation received at ground level, this has an average power of 1 kW for each square meter (m^2) of flat terrain, being relevant to consider the angle of inclination of the photovoltaic (PV) cell panels that capture solar radiation; However, in intertropical areas such as Colombia, solar panels are usually placed horizontally or at small angles but, due to the wide angular variation of the sun's position during the day, maximum capture is achieved with automated systems of follower panels. of the direction of incidence of sunlight, which allows more time capturing solar energy but at higher investment costs.

The amount of solar energy that affects the photovoltaic system on a daily basis, is measured in kilowatt-hours (kWh) for each square meter during a day, or $kWh/m^2/d$, thus depending on the number of hours of sunlight. Taking into account that solar irradiation is 1 kW/m^2, for the calculations the term Peak Sun Hours is defined (PSH), corresponding to the number of hours per day equivalent to the maximum potential of 1 kW/m^2 in the place. Reaching the maximum potential will be largely related to the climatic conditions and the cloudiness of the site. This is how the average daily energy ($kWh/m^2/d$) available on the spot is given by the product: PSH (h/d) x 1 kW/m^2 [48].

Figure 9 shows the types of photovoltaic panels on the market:

Figure 9. Solar Cell Type and Efficiency.



Source: Clean Energy Reviews [49].

The research carried out aims to propose monocrystalline photovoltaic (PV) panels for future simulations to be carried out in this work, considering their level of efficiency, useful life and technological level required by microgrids (MG) in the department of Cauca (Colombia).

4.5.2 Wind power. It is obtained from the movement of the air mass (kinetic energy of the wind), and its use depends directly on the speed of the wind on site. Next, the different events in which this type of energy can be used are presented [50].

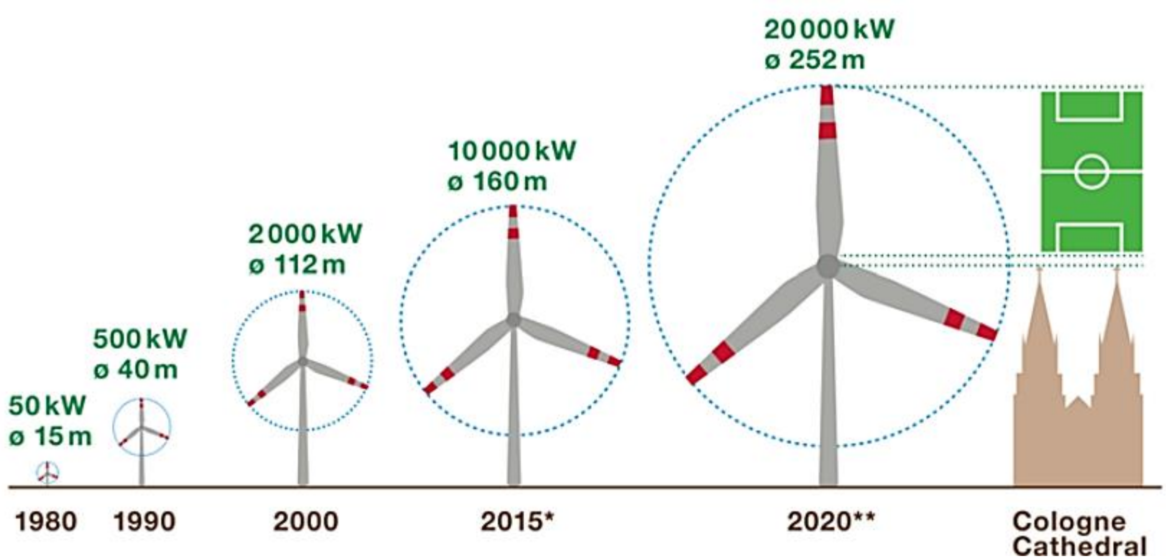
Table 3. Wind speed and its potential for electrical use.

ANNUAL AVERAGE WIND SPEED AT 10 METERS HEIGHT	POSSIBLE USE OF ELECTRICAL ENERGY
Less than 3m / s	Usually not feasible, unless there are special circumstances for a better evaluation
3 - 4 m/s	It can be a good option for pumping equipment but not very viable for electricity generation
4 - 5 m/s	The wind pumps are economically competitive with respect to diesel equipment, being a viable system.
More than 5 m/s	Viable for wind pumping and electrical generation
More than 6 m/s	Viable for off-grid microgrids or connected to a conventional electrical grid.

Source: Author based on Atlas of wind and wind energy in Colombia [50].

The data in table 3, together with figure 10, show that, today, the search for higher altitudes for greater electricity production is becoming more and more necessary:

Figure 10: Larger wind turbines for more energy.



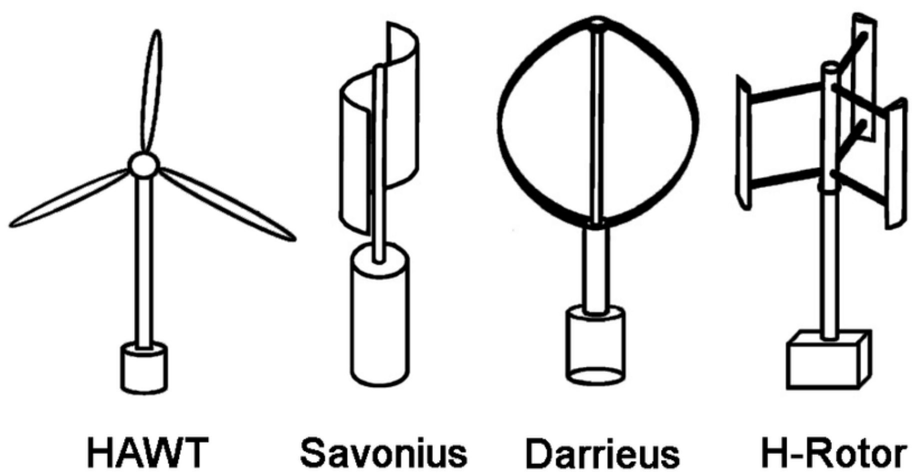
Source: Wind turbines grow into the sky [51].

The types of wind turbines are varied according to the principle used to capture the wind flow [52]:

- Vertical axis wind turbines (VAWT).
- Horizontal axis wind turbines (HAWT).
- According to its power.

Figure 11 presents the most conventional types of wind turbines in a consolidated way:

Figure 11. Types of wind turbines.

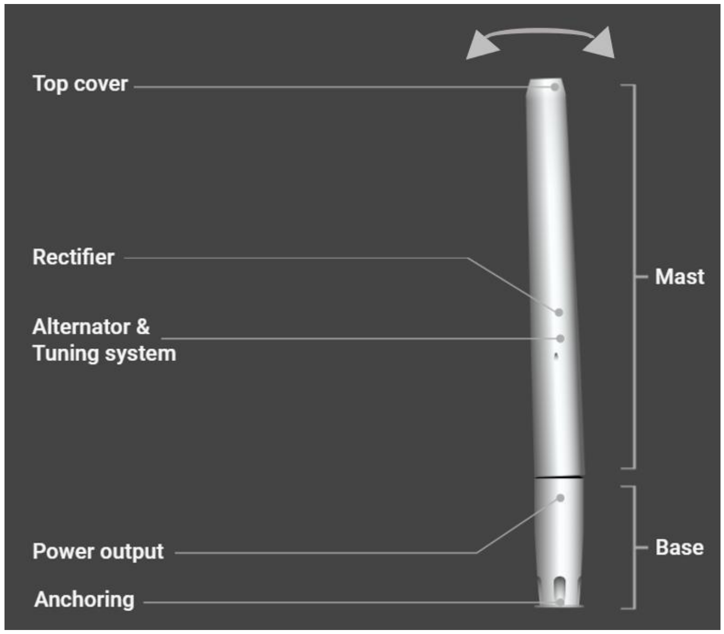


Source: Complete guide to wind energy [52].

The figures presented in the current market exist in different sizes and designs that, in terms of advantages and disadvantages for the production of electrical energy, could be determined by their height and size of the blades in exchange for their greater or lesser efficiency and conditions. to maintenance costs, useful life, noise produced, required area, among other aspects.

Within the line of innovation that seeks to present this degree work, a new type of wind power generator system called Vortex Bladeless® is presented (See figure 12), which presents greater benefits than a traditional wind turbine because it does not have blades, obtaining wind energy through oscillation without the need for gears, brakes or oil [53] and whose radical design characteristics can become part of an integral solution for a microgrid (MG) such as those required by the ZNI of the Department of Cauca .

Figure 12. Vortex Bladeless wind turbine based on aeroelastic resonance.



Source: Vortex Bladeless®: The first wind generator without blades or gears [53].

4.5.3 Hydrokinetic Energy. Hydrokinetic turbines are the evolved version of river turbines whose antecedents can be traced back to installations in Egypt and Sudan at the ends of the River Nile. The inventor of river turbines was the English engineer Peter Garman in the 1980s; After that, different versions of Garman turbines have been designed, seeking ever greater innovation in the search for greater electricity generation capacity [54].

Hydrokinetic turbines resemble wind turbines since they handle similar physical principles, the advantage of hydrokinetic turbines over wind turbines lies in the density of the fluid, since water has a higher density than air, therefore, it can be extract more energy potential. Another important characteristic is that in hydrokinetic turbines the direction of the fluid is more predictable, which can facilitate the logistics for its installation compared to wind turbines.

Hydrokinetic turbines are made up of blades that can be horizontal or vertical to the flow, these transmit the rotational movement to a shaft, which transmits the rotational movement to a power transmission that can be with pulleys, chains or gears, arriving by last to the generator that transforms mechanical energy into electrical energy. This type of turbines can generate from 0.25 kW to 10 MW according to the conditions for which it is designed, such as the height of the river and the speed of the fluid in a given area [55].

Turbines are classified mainly by two aspects: by the pressure change in the rotor and by the direction of flow with which they enter the rotor.

Due to the change in pressure in the rotor, they can be classified into action turbines, where the water does not undergo considerable pressure changes as it passes through the rotor; while in reaction turbines the water does undergo pressure changes as it passes through the rotor. Regarding the direction of the flow with which the water enters the rotor, they can be classified as: radial, axial or mixed

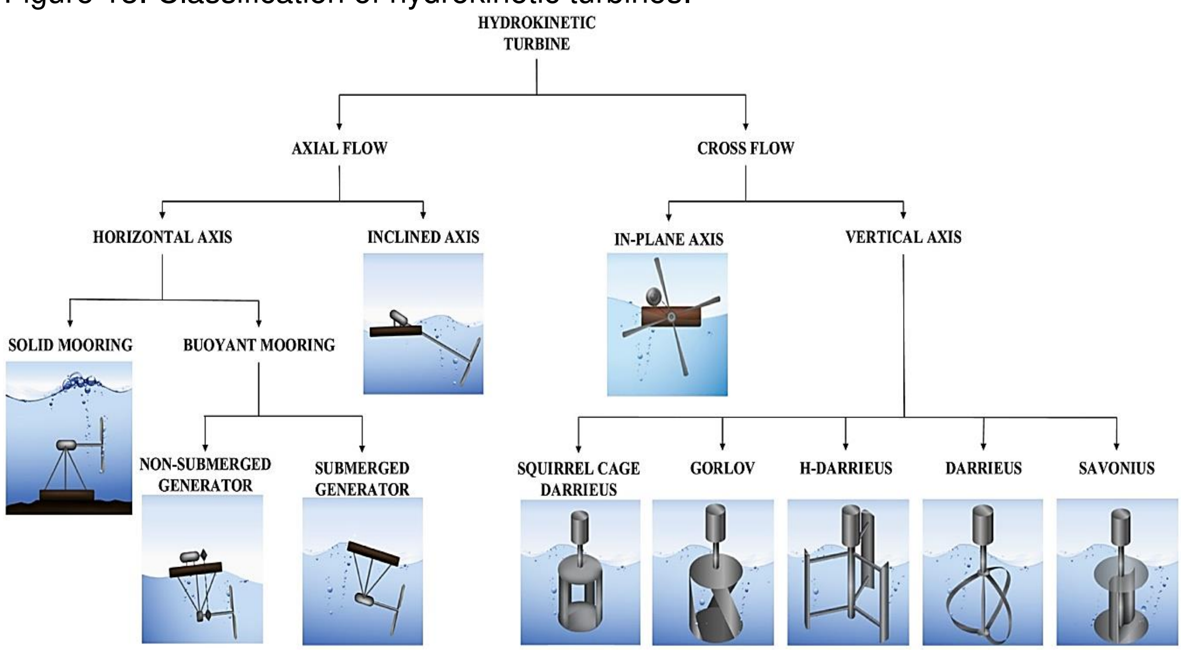
Currently, there are two types of turbines that are divided according to their operating principles [56]:

- **Impulse turbines** (They are commonly used for large waterfalls such as the Penton Turbine, the Turgo turbine and the Banki turbine).

- **Reaction turbines** (Often used in large hydroelectric plants that have huge flow rates and low head drops.

- **Hydrokinetic Turbines** (They can be classified into horizontal axis or vertical axis turbines and usually installed rivers, canals and in the sea).

Figure 13. Classification of hydrokinetic turbines.



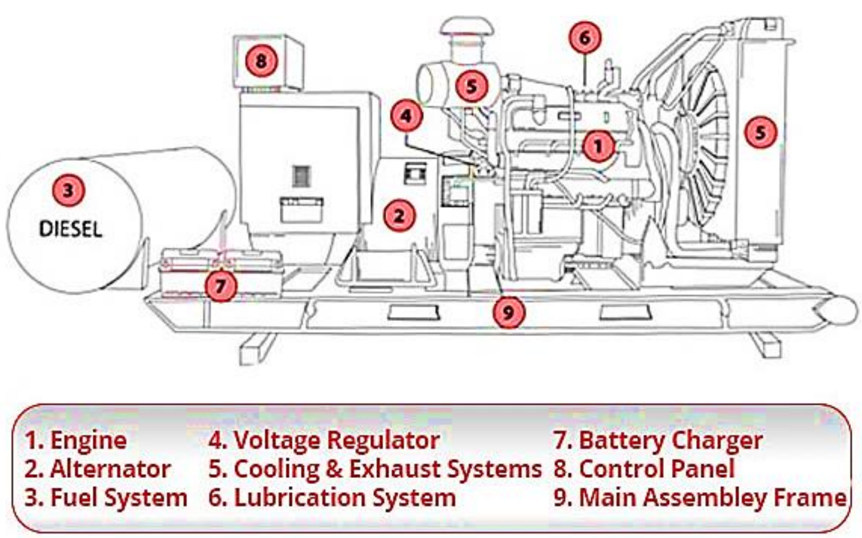
Source: Hidrokietic Turbine [55].

Hydraulic energy is the most abundant resource in Colombia, its level of pollution, like solar energy, in its productive state, is practically nil when it comes to Mini Hydro, Micro Hydro and Hydrokinetic applications. Its environmental impacts are low when compared to Large Hydro applications [57]. It is a technology with continuous advances in the academy and in the market, supported by more than one hundred years of continuous development, it is considered highly efficient, since more than 90% of hydraulic energy can be converted into electricity. The previous arguments make this work focus on hydrokinetic type turbines for the microgrid system that are sought to be made viable.

4.5.4 Generator Group. It is the backup system translated into a rotating machine that drives an electric generator using an internal combustion engine and is used in areas where there is no permanent supply of electrical energy.

Regarding their consumption, the generators are normally fed with diesel fuel since they are suitable to achieve powers that exceed 5 kW and for intensive use compared to generators such as gasoline that despite being cheaper, they are used for more sporadic activities than those of diesel and finally, the Naphtha and Gas generators that supply powers less than 2 kW, are more environmentally friendly than those of diesel and gasoline but are not suitable to supply more power. For all the above, it allows to conclude that, for the selection of the MG generator set to study in the ZNI of the department of Cauca, it must be a group that considers power and fuel consumption since they are directly related [58].

Figure 14. Diesel generator.



Source: The components of a Diesel Generator [59].

4.5.5 Battery bank. It is a set of several batteries connected to each other in order to temporarily store electrical energy and its subsequent delivery to the system to which it is connected [60].

The battery bank is a solution to supply electrical energy to store surplus energy in low demand hours and then be able to supply them in high demand hours, for example, at night.

Battery capacity is the amount of electricity that can be drawn during a complete discharge from a fully full battery. This capacity is measured in amp hours (Ah) for a given discharge time.

The useful life of a battery is the number of charge and discharge cycles that can be at a given depth of discharge. In addition, battery life is proportional to the depth of discharge (the ratio of the charge removed from a battery to its nominal capacity) typical [61].

The best known batteries on the market are:

- Monoblock batteries
- Stationary batteries
- Lithium ion batteries

Figure 15. Type of batteries

Source: Author based on various commercial sources.

For the purposes of this work, the options for lithium-ion batteries will be taken into account, they are currently the most expensive on the market, but the growing development that has led to their exploitation, their advances in production and their projection of price reduction [62], makes it the best option in the type of battery to consider in this project.

4.6 LEGAL AND REGULATORY FRAMEWORK

In the framework of renewable energies, Colombia has a robust legal and regulatory history that has been really nurtured since the last 6 years. For the purposes of this work, the main legal guidelines regarding Non-Conventional Sources of Renewable Energy (NCRE) adopted by the national government and that directly affect this project:

- Law 142 [63] and Law 143 of 1994 on Domiciliary Public Services [64]: These two laws characterized actors in the electricity sector and considered feasible programs to energize Non-Interconnected Zones (ZNI) as a priority.

- Law 697 of 2001 [65]: Law promoting the Program for the rational and efficient use of energy and other forms of non-conventional energies of the Program for the Rational and Efficient Use of Energy (PROURE, for its acronym in Spanish).

- Law 1715 of 2014 [66]: Focused on generating energy generation incentives from (NCRE) and allowing these clean sources to be an energy supply option for ZNIs.

Two more points to highlight of Law 1715 of 2014 are: First, the incentive to industries of various sectors that produce their own energy and that they can sell their surpluses at the market price, when it rises in times of drought and second, the exemption of the payment of tariffs to those who import equipment for the assembly of a solar plant or other non-conventional energy plants [66]; Reasons why today more and more companies and private and commercial properties are generating their own energy through solar panels in the country.

5. THEORETICAL FRAMEWORK

5.1 MATHEMATICAL BASES FOR THE MODELING OF THE MICROGRID

Proposing solutions for the electricity supply in the Non-Interconnected Zones (ZNI) of the department of Cauca (Colombia) implies considering climatic and geographical conditions to meet the technical needs of the systems that will integrate the microgrids (MG) and conditions of energy demand of the community.

To estimate climatological variables, a stochastic approach will be used (Set of unpredictable variables, at random, such as the climate) and to estimate electricity demand conditions, a Deterministic approach will be used since it implies social events of thought and even human actions [67].

The way to carry out the mentioned variables will be by combining both approaches through a Multiobjective Methodology that will be explained in greater detail in chapter 6. This clarification is made since, from the mathematical approach that starts this project and the technical aspects of Each energy system will result in the most optimal input data for later simulation.

5.1.1 Electric demand. It is the amount of electricity that a group of users needs to supply itself, while the operational electricity demand is consumption by each sub-area of the country [68].

The Demand Factor is calculated as follows:

$$\text{Demand Factor} = \frac{\text{Maximum demand of a system}}{\text{Total Connected Load}} \tag{5.1}$$

The demand factor is always less than 1. The lower the Demand Factor (DF), the lower the electrical power that the MG hybrid system must supply to serve the connected load.

5.1.2 Electrical distribution. One of the objective strategies of the degree project is to consider an optimal MG in the ZNI of Cauca (Colombia), for this purpose, the feeder conductors must have a sufficient amperage to transport the current to the demanded load, for this situation not calculating the installed load of the ZNI is required and the feeder circuit amperage does not always have to be equal to the total of all equipment loads.

The demand factor allows the feeder circuit amperage to be less than 100% of the sum of all circuit loads connected to the feeder [69].

The demand factor is expressed as a percentage (%) or as a number less than 1. In Colombia it is considered that a person consumes an average of 38 kWh per month; that is, that a family of 4 people, the average monthly consumption should be 152 kWh per month of energy [70].

5.1.3 Photovoltaic system. Photovoltaic (PV) systems originate from intermittent energy sources, the power generated depends largely on solar radiation (the solar rays that really affect the generation of electricity are ultraviolet and infrared rays, hence the importance of knowing the spectrum of sunlight of the ZNI), and of the temperature of the operation [71].

The objective is to achieve the highest energy efficiency of the panels and to be able to cover the demand of the users; To achieve this, the amounts of photovoltaic power required are calculated as follows [72]:

$$P_T = \frac{E}{A_G \cdot \eta_G \cdot G_d} \cdot P_M \quad (5.2)$$

Where:

P_T: Peak Photovoltaic Power.

E: Energy to be generated.

A_G: Module area in m^2.

η_G: Module efficiency.

G_d: Average value of the incident daily radiation on the module surface.

P_M: Selected module power.

5.1.4 Wind generation based on aerolastic resonance. Considering designs, advantages and disadvantages of the best-known wind turbines on the market presented in figure 11, a new innovative alternative with great potential is explored to meet the energy needs expected in the microgrid required by the ZNI of the Department of Cauca: Vortex Wind Turbines Bladeless® [73].

Table 4 shows an approximation of the possible power obtained for different wind speeds with conventional turbines versus the Vortex Bladeless system:

Table 4. Installed power of the Wind Turbines.

INSTALLED POWER OF THE WIND TURBINES			
Wind speed (m / s)	Little HAWT (W)	Little VAWT (W)	Vortex Bladeless (W)
3.5	**0**	**0**	**3**
6	72	44	35
7	104	66	60
8	135	86	80
9	160	105	93
Nominal speed	**400**	**200**	**100**

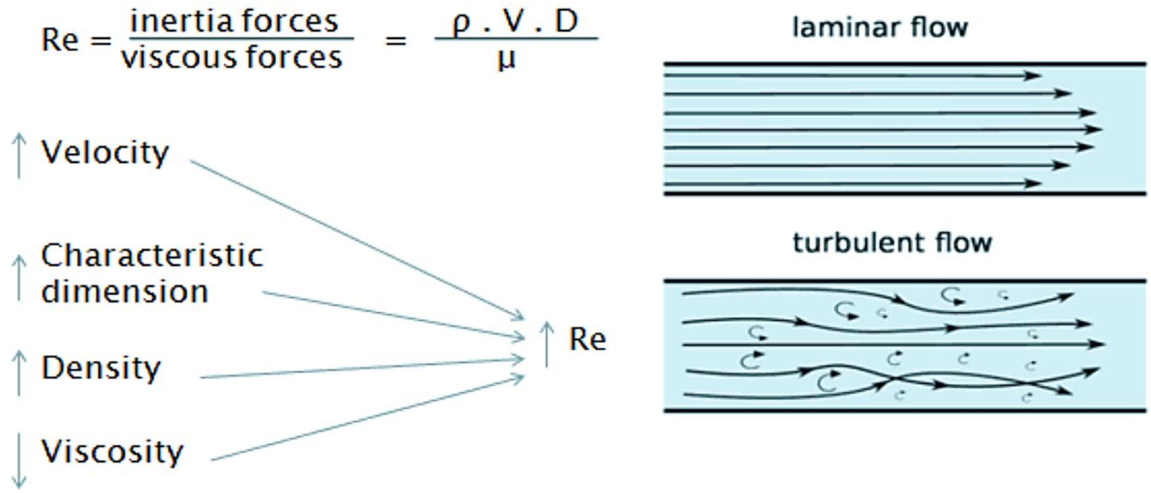
Source: Author based on Vortex Bladeless® [73].

Regarding their operation, Vortex Bladeless devices have the ability to generate electrical energy due to the resonance or tuning that takes place when the oscillation of a body is produced or reinforced by an external periodic movement. Air can induce oscillatory motion in a body if its natural frequency and the frequency of the vortex shedding waves are similar. The vibrations produced in a body by vortices are called the VIV phenomenon (Vortex Induced Vibration) [73].

For mechanical purposes of the device, if the devices are installed in the ZNI, the Reynolds numbers (relationship between inertial forces and viscous forces) should be taken into account between the measurements, which will allow predicting whether a flow condition will be laminar. or turbulent [73]. These results will clarify the way the wind will impact the surfaces of the Vortex Bladeless® and therefore the energy they will produce.

Figure 16 shows the behavior of the air flow for this case.

Figure 16. Reynolds number.



Source: Thermal Engineering [74].

Re is a dimensionless number composed of physical characteristics of the flow. A Reynolds number shows increasing flow turbulence and is defined as [74]:

$$Re_D = \frac{\rho V D}{\mu} = \frac{V D}{\nu} \quad (5.3)$$

Where:

V: Flow velocity

D: Characteristic linear dimension (linear length traveled by the fluid, hydraulic diameter, etc.)

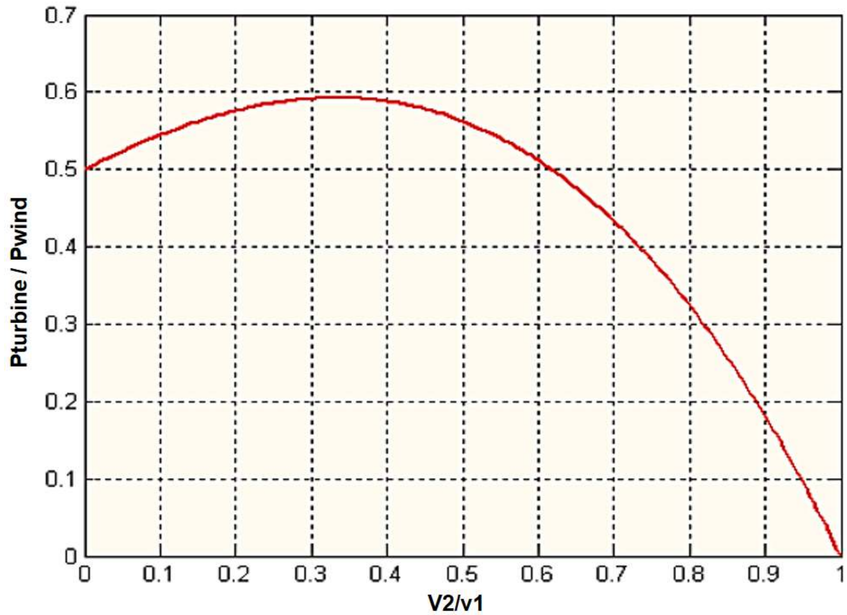
ρ: Fluid density (kg / m^3)

μ: Dynamic viscosity (Pa.s)

ν: Kinematic viscosity (m^2 / s); $\nu = \mu / \rho$

The conversion of the kinetic energy of the wind into mechanical energy will be as close as possible to the Betz limit from which no more than 59.3% of the kinetic energy of the wind can be extracted for a constant section since the flow cannot be stopped. completely, this can only be reduced. This was established by the drive disk theory, based on the laws of conservation of flow [75].

Figure 17. Graphical representation of the Betz limit.



Source: Design and analysis of small-scale vertical axis wind turbine. IEEE [76].

5.1.5 Hydrokinetic generation. Hydrokinetic technology produces electricity from the kinetic energy of a moving body of water. Since water is approximately 832 times denser than air, movements such as tides, waves, ocean currents and the free flow of rivers represent a large amount of untapped renewable energy.

Depending on the location of the rotor, turbines can be classified into two types: horizontal axis or vertical axis.

On its operation, the electricity generation starts from the water current. The type of turbine selected for this project is a horizontal axis designed to be submerged in the most viable river in the ZNI. The turbine transforms the kinetic energy of the water into electrical energy through a generator. Through the inverter, it charges batteries and at the same time feeds the users or the use they want to give. It can work without batteries as these could function as a reserve [56]

Figure 18 shows a type of hydrokinetic turbine installed in the Amazon River (Colombia).

Figure 18. Hydrokinetic power turbine.

Source: SMART Irrigation Project in Neiva, Colombia [77].

5.1.6 Generator set. The generator set is a machine capable of moving an electric generator through an internal combustion engine. The objective of this project is to consider within the hybrid components of the microgrid (MG) a generator set as a backup in case the battery bank is at the lower load limit; all of the above in order to minimize the possibility of an electrical insufficiency for the ZNI to intervene at least until a prudent stabilization stage of 1 year with very low consumption of diesel fuel; After the stabilization period, improvements to the system would be sought to reduce more and more the intervention of the generator system.

The operation of the generator set would have the following restriction of use:

- If it is out of operation, it should be for a long time.

- In case of use, the minimum generation power must be 30% and the maximum generation power must be 90% of the nominal capacity.

The restrictions presented are oriented to two main objectives: The rational and efficient use of the equipment and seeking the least possible pollution that the generator set would produce as shown in table 5 of pollution emissions [78].

Table 5. Potential for emissions at different loads.

Parameter	LOAD (kW) 10		20		30	
	Diesel	Dual-Fuel	Diesel	Dual-Fuel	Diesel	Dual-Fuel
CO (ppm)	181	635	207	640	284	734
CO_2 (%)	3,1	6,2	4,2	7,1	5,7	9,2
HC (ppm)	109	119	132	141	180	182
CH_4 (ppm)	7	18	8,4	24	10,2	21
SO_2 (ppm)	4,6	1,1	5,4	1,2	6,8	1,5
NO_X (ppm)	172	93	230	140	279	170
*PM (mg / m^3)	22	18	26	24	29	24

*Particulate matter

Source: Author based on Emission characteristics on an electricity generation system in diesel alone and dual fuel models [78].

5.1.7 Battery bank. The objective of the Battery Bank is to guarantee the balance of power, and to supply or absorb energy as appropriate Considering that the costs of a battery bank can reach 50% of the total cost of the microgrid, it is important to take care of its useful life reducing the charge and discharge cycles (SOC: State of Charge), which can be determined in the following formula [79].

Where:

$$SOC(t) = SOC(t-1) + P_{ess,ch}(t) \cdot \eta_{ess} \cdot \Delta t - P_{ess,dis}(t) \cdot \Delta t / \eta_{ess} \quad (5.4)$$

SOC (t): State of Charge in the instant t

SOC (t-1): State of Charge in a time Δt previous

η_{ess}: Charging and discharging efficiency of the battery bank.

$\eta_{ess,\,dis}$: Charging and discharging efficiency of the battery bank.

5.2 OPERATIONAL RESTRICTIONS

One of the most important characteristics of a microgrid (MG) is to improve the reliability of the users supply. User reliability is evaluated with the average and duration of interruptions; hence the importance that the MG, due to its type of Off-grid system, has a control and automation system that allows remote monitoring for corrections and improvement points that may be given [80].

In order to have a quality energy supply, it is important to bear in mind that the entire system is susceptible to technical energy losses; namely; energy losses that are normally considered as: heat dissipation, noise, material efficiency, etc.

.

The microgrid (MG) that is decided to be implemented in a ZNI must have restrictions on the limits of power losses and energy losses to protect the installed equipment and guarantee its proper functioning; that is to say: guarantee the Balance of Instantaneous Power (BIP) [81]. If the restrictions are not taken into account, problems such as:

- Voltage regulation
- Stability of the electrical system
- Increases in generated power

The following power formula shows the balance of the microgrid system:

$$\mathrm{Pgen(t) + Pdown{,}dis(t) = Pcharge(t) + Pdeliv(t) + Pchar{,}bat(t) + Ploss(t)} \quad (5.5)$$

Where:

$\mathrm{Pgen(t)}$: Power generated by distributed energy sources

$\mathrm{Pdown{,}dis(t)}$: Battery bank discharge power

$\mathrm{Pcharge(t)}$: Power demand

$\mathrm{Pdeliv(t)}$: Power delivered to the microgrid generator

$\mathrm{Pchar{,}bat(t)}$: Battery bank charging power

$\mathrm{Ploss(t)}$: Power losses of energy

Another operational restriction to take into account is the LPSP (Loss of Power Supply Probability) [82], which is equivalent to a moment when the demand is greater than the energy that the hybrid system generates and the energy stored in the battery bank in an instant of time. For this situation, what should be sought with the controllers is to define this situation as many times as possible so as not to resort to a generator set and ultimately, to avoid that even the generator set is also insufficient for the electricity supply.

5.3 FINANCIAL EVALUATION

5.3.1 Cost of acquisition, operation and maintenance. To plan the acquisition cost, it will initially be considered one of the primary sources for the resources that the microgrid (MG) would need; For this purpose, the National Government of Colombia has the Financial Support Fund for the Energization of Non-Interconnected Zones (FAZNI, for its acronym in Spanish).

The objective of the FAZNI is to facilitate the financing of investment plans, programs and projects in energy infrastructure in non-interconnected areas (ZNI). In turn, one of the economic restrictions of this source of resources is that all pre-feasibility and feasibility studies do not exceed 15% of the total project resource [83].

After considering the economic source to assume the acquisition costs, the sum of the hybrid systems must be considered. The acquisition costs of the hybrid components of the MG, interest or discount rates, inflation rate, annual stock-out rate and useful life of the system. These considerations will be taken into account in the results of the investigation.

The acquisition cost includes:

- Value of wind, photovoltaic (PV), hydrokinetic equipment, battery bank and generator set.

- Expenses associated with transporting equipment to the ZNI for implementation.

- Labor for its installation, start-up and training to the community.

5.3.2 Cost of the distribution system. The most complete MG considered for this degree project includes the three types of renewable energies (Solar Photovoltaic-PV, hydrokinetic and wind), the generator set and the battery bank for a Type 2 locality of the ZNI of the department of Cauca (See figure 4). The sizing of a user settlement with these characteristics would imply considering distribution equipment according to the loads and distances of the network and, consequently, Low Voltage (LV) transformers, Medium Voltage (MV) transformers, wiring according to each node and the proper undergroundization of the wiring to have a visual and environmentally appropriate design.

5.3.3 Cost for environmental impact. The cost for the environmental impact is only associated with the power generated by the microgrid (MG) generator set and its consumption of diesel fuel.

Taking into account that the Colombian government provides tax incentives for the development and use of Non-Conventional Renewable Energy (NCRE), the cost of the environmental impact can be evaluated considering the cost in favor of each kWh / year produced with energy sources. cleanings of the MG plus the subsidy that the government grants for the system minus the cost in dollars (USD) of the Tons (The unit of measure can be adjusted according to the consumption of the generator set in the first year of use) of polluting gases produced by the generator set in the year as shown in the following table [84]:

Table 6. Environmental value of pollutants in power industry

Pollutant	**SO_2**	**NO_X**	**CO_2**	**CO**
Environmental value ($ / ton)	**923,1**	**1230,8**	**15**	**153,8**

Fuente: Author based on Conference of Optimal Planning of Microgrid applied in Remote Rural Area [84].

5.4 SOLUTION METHODS

5.4.1 Multiobjective Optimization. The design of the MG to meet the energy needs of the Non-Interconnected Zones (ZNI) of the department of Cauca (Colombia), contemplates:

- Elements: Photovoltaic (PV), wind, hydrokinetic systems, a generator set, battery bank and the distribution system to users.

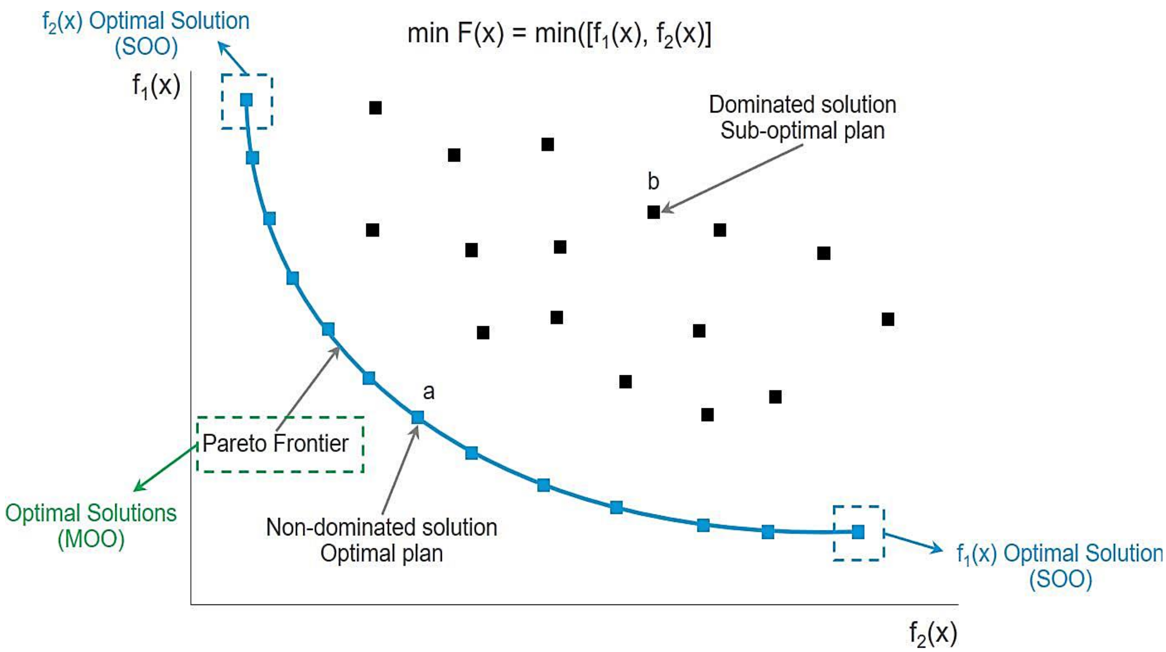
- Design Variables: Energy demand, number of monocrystalline solar panels, number of vortex bladeless® systems, number of hydrokinetic turbines, number of batteries according to the type of each system and potential required to deliver the generator set to users (Diesel Generator).

- Climatic variables: wind speed, solar irradiation, river water speed, ambient temperature.

All of the above are variables that lead to several problems that require a solution among their combinations to find the most viable MG without losing technical and economic objectives and, as a result, offer an optimal alternative that meets the needs not only of a technical nature but also social of a community.

The Multiobjective Optimization Problem (MOPs) seeks for the Pareto Front [85], to make assignments that improve the microgrid scenario without making the other variables worse.

Figure 19. Dominated, non-dominated and Pareto-front solution set.



Source: The Foundations of the Science of Man: Vilfredo Pareto [85].

This work will establish two main objectives to have clear goals to be achieved: the microgrids (MG) to be conceived viable in the Non-Interconnected Zones (ZNI), they must comply with a realistic budget that can be argued and awarded by the National Government and can be inverted if required. support of public or private capital and, secondly, the MGs must be conceived viable in the ZNI with the technical compliance in the coverage of the demand and supply of energy to the users.

The foregoing summarizes that the viability of the project must have a technical objective but mainly subject to financial resources so that it is achievable in the event that, in the future, it passes to the execution stage.

5.4.2 AHP decision-making method. Although it is established that the economic objective prevails over the technical one to make the project as realistic as possible, this does not solve the problem of selecting the best MG since if you think of a microgrid (MG) with random hybrid components for a ZNI, there is no certainty that it is viable since in the department of Cauca a series of criteria are governed that will directly affect the operation of the MG. For example, temperature and wind speed are just two of the criteria that would make the decision to include the wind system and choose it, you would have to think about the amount of equipment to install, its height and which ZNI of the 19 municipalities with electrical insufficiencies in Cauca should be planned for their installation.

Based on concepts such as those of Giuseppe Munda (Expert of multi-criteria evaluations), Nijkamp (Economist and expert in social dynamics) and the expert in decision theory, Rietveld [86], it is necessary to use models that represent in an understandable and operational way The real world. They clarify that the use of multicriteria evaluation models allow the interaction between quantitative and qualitative judgments, describe a collection of concepts, methods and techniques to help individuals or groups make decisions when different conflicting points of view and multiple stakeholders are involved.

5.4.3 Method for assigning weights of relative importance. The assignment of weights directly influences the optimization to be achieved in this ZNI energization project since for each criterion there may be the same importance as the importance may be different from one another between criteria.

Initially, methods for assigning weights were studied, such as those proposed by Von Winterfeldt and Edwards [87], which are based on the numerical assessment of weight on a certain scale of measurement, but due to the stochastic and deterministic approach of this degree project (see Chapter 5: Theoretical Framework), it is considered more appropriate to choose an indirect allocation method where the importance weights can be inferred by means of paired comparisons between the criteria.

The method for assigning weights of relative importance will be the mathematical method Analytic Hierarchy Process developed by Thomas L. Saaty that requires subjective evaluations and specifying the preference regarding the relative importance of each criterion and sub-criterion [88].

The process of the method will include the development of matrices of paired comparisons with the Saaty Scale that is handled from 1 to 9. At the end of the process it is expected to obtain the most optimal ranking.

6. STATE OF THE ART

The first step of the methodology developed for this work was the gathering of information for the creation of a Database (See figure 7); For this purpose, the bibliographic databases with the highest academic recognition were consulted, highlighting at the end the following word filter:

- Microgrids, Micro Grid, Micro-grid systems, Microgrid Operations, Islanded Microgrids, Grid-connected Modes, Smart Grid, Decentralized Control, Hybrid Energy System, Energy Policy, Rural Areas

- Renewable Energy Resources, Energy Management, Distributed Energy Source, Sustainable Development, Electrical Power Transmission Networks, Distributed Power Generation, Energy Efficiency, Power Sharing.

- Renewable Energy, Solar Energy, Photovoltaic Systems, Photovoltaic Cells, Wind Power, Wind Turbines, Small hydro energy, Hidrokinetic power generation, Electric Power System Control, Secondary Batteries, Battery Energy Storage Systems, Battery Storage, Diesel Engines.

- Decision Making, Hierarchical Control, Multiobjective Optimization, Uncertainty, Optimization Problems, Sensitivity Analysis.

The searches were carried out in Spanish and English since the case study focuses on the department of Cauca (Colombia), which made it necessary not only to know the development of the subject within the country but also in other countries.

The temporary search range was made between the last 10 and a half years (2010-May 2021). The search focused on existing innovative technologies whose combination could meet the energy needs of a rural community within parameters of viability and realism in the face of the characteristics of the Non-Interconnected Zones as well as the reality of the country.

The database with the articles obtained was organized with the topics of interest of the project and focused on:

- International policies regarding Renewable Energies

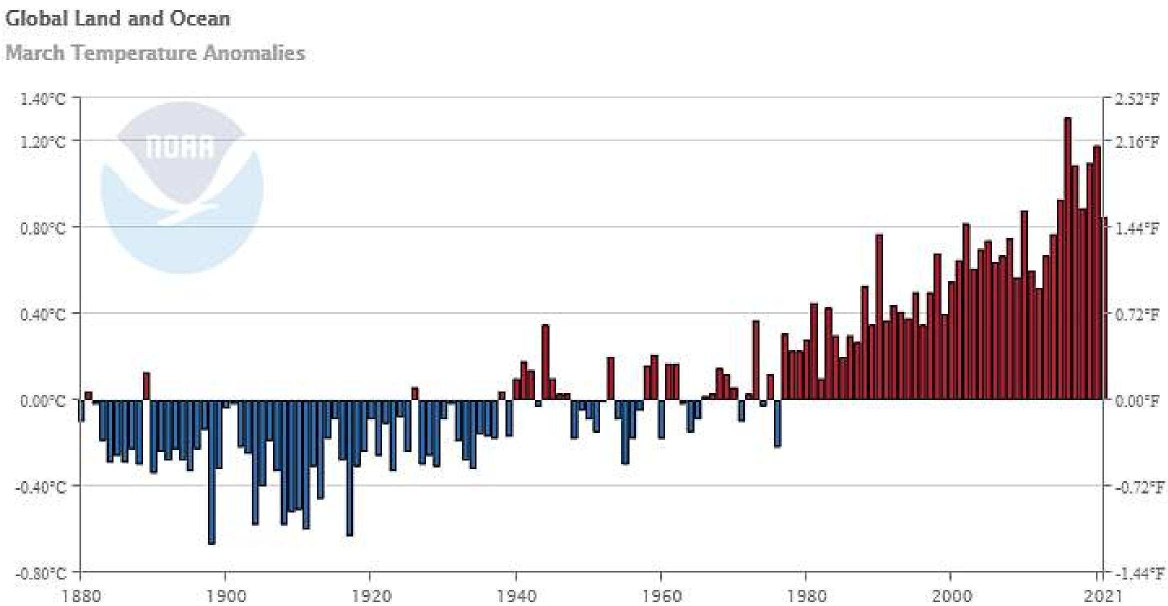
- Progress in Latin American and Caribbean countries

- Regulations, plans and progress of projects of the Colombian Government

- Technologies related to hybrid components for microgrids.

The information collected shows, among the major problems worldwide, 2021 as the year with the greatest global warming [89]. Statement in accordance with that disclosed by NASA's Goddard Institute for Space Studies [90].

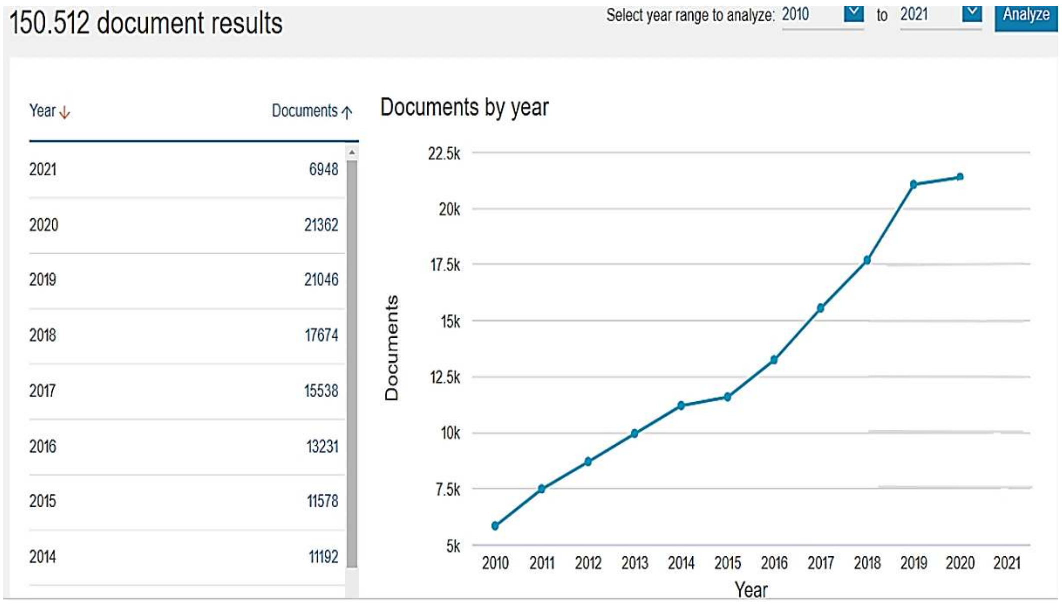
Figure 20. Global Land and Ocean: March Temperature Anomalies.



Source: National Center for Enviromental Information [89].

An example of the increase in interest in finding solutions through renewable energies are the 150,512 studies that can be found initially looking for the topic of renewable energies between 2010 and 2020, focusing 21,362 of these investigations for the year 2020 reported on the basis of SCOPUS data as shown in figure 21.

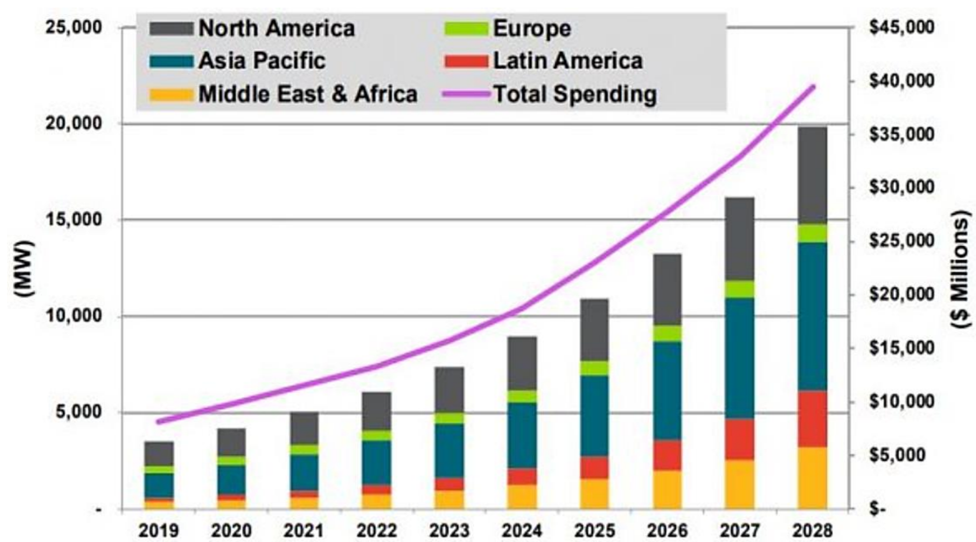
Figure 21. Studies carried out between 2010-2020 on renewable energies.



Source: Author, Scopus.

Since the 1990s, different countries have developed advances to energize non-interconnected areas [91,92,93]. And parallel to this, the implementation of microgrids connected to conventional networks and in an isolated way has increased, projecting their growth in the coming years as shown in figure 22 [93].

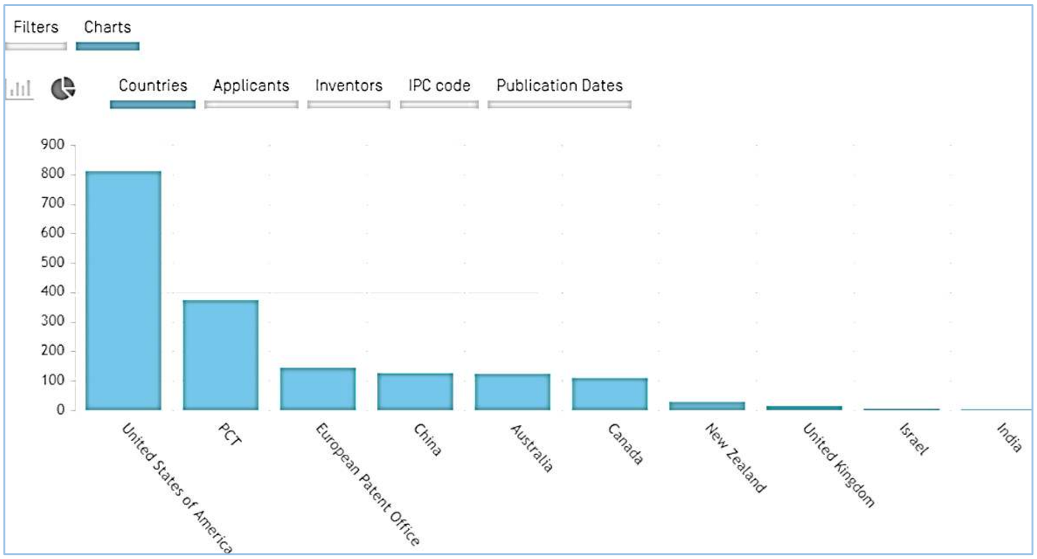
Figure 22. Annual total Microgrid Power Capacity and implementation Spending by Region World Markets: 2019-2028.



Source: Microgrid Knowledge [94]

Through the World Intellectual Property Organization (WOPI), when searching for the topic: Isolated microgrid, 1748 patent results were found for the period 2010-2020 as shown in figure 23.

Figure 23. Number of patents of hybrid power system.



Source: Author, WIPO-Patentscope.

Among the countries with notable projects in hybrid systems are: China [95], United States [96], Germany [97], Italy [98], Spain [99], Japan [100] and India [101] as shown in Table 7.

Table 7. Outstanding projects of hybrid systems in the world.

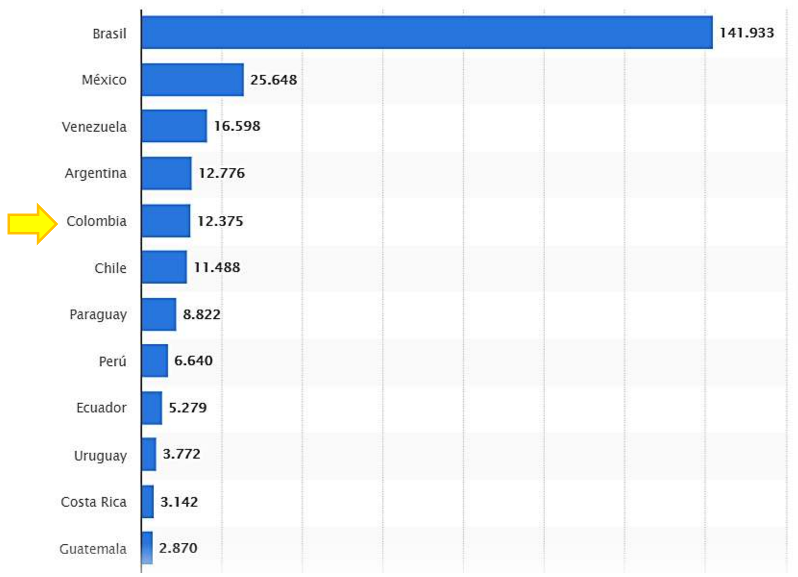
REFERENCE	COUNTRY	PROJECTS NAME	DESCRIPTION
[95]	CHINA	Luneng Haixi project	First of its kind in China to integrate wind, solar, concentrated photovoltaic (CPV) and an energy storage system into a unified grid-connected system
[96]	UNITED STATES	Azure Sky	350 MW wind facility combined with 137 MW of battery storage, will be Enel's third hybrid renewable energy + utility-scale storage project in the United States and the company's first large-scale wind energy + storage project worldwide
[97]	GERMANY	Bay Wa	Solar project connected to the network of a wind farm with a power of 24 MW.
[98]	ITALY	Apulia Solar Park	It is the largest photovoltaic park ever built in Italy connected to the grid and with 150,000,000 kWh of green energy per year
[99]	SPAIN	4 Wind energy projects + Solar Photovoltaic	The Villacastín (Segovia) wind farm, with 14.52 MW, will be expanded with 13.2 MWp solar. 13.8 MWp photovoltaic will be added to the Cruz de Hierro (Ávila) park, with the same power as the previous one. The Lomillas (Cuenca) facility, with 49.5 MW of wind power, will be expanded with 40.9 MWp of panels. And the Castillo Garcimuñoz plant (Cuenca) will add 23.63 solar MWP to its 25.5 MW of wind power.
[100]	JAPAN	Hydrogen Plant	Alkaline water electrolysis system with 10 MW (megawatts) of power. It is powered solely by renewable energy from a solar panel installation.
[101]	INDIA	Pavagada Solar Park	Solar park spread over a total area of 53 km2 in Pavagada Taluk, Tumkur district, Karnataka. Completed in 2019, the park has a capacity of 2,050 MW

Source: Author

The project examples shown show strategies aimed at the sizing and programming of combined systems including High Voltage levels to increase the efficiency of operations and thus achieve a modern energy transition in each country.

In Latin America and the Caribbean, and especially, highlighting Colombia, the potential in megawatts to advance in microgrid technologies is considerable as shown in figure 24 [102].

Figure 24. Countries with the highest renewable energy production capacity in Latin America and the Caribbean in 2019 (In megawatts)



Source: Statista [102].

The department of Cauca (Colombia) has suitable energy sources for its feasibility study in the implementation of isolated microgrids considering that, in terms of water, it has the Cauca River and its 21 tributaries; in solar irradiation it is among the regions of Colombia with solar radiation higher than 4.5. kWh/m2 per day and its average annual speed has reached 9 km/h [103]. Renewable sources that individually can supply specific energy needs but combined, would have the possibility of covering a greater spectrum of multiple solutions for a community located in the Non-Interconnected Zones of the department.

Access to energy service is still very poor in the southeastern region of the country, which leads to social protests, vandalization by illegal groups, poverty and lack of social progress in most of the Colombian Pacific. This recognized the need to expand the exploitation of non-conventional renewable sources in non-interconnected areas, giving rise to the creation of economic and social development centers.

7. METHODOLOGY FOR SELECTING THE BEST ENERGY SYSTEMS FOR THE ISOLATED MICROGRID

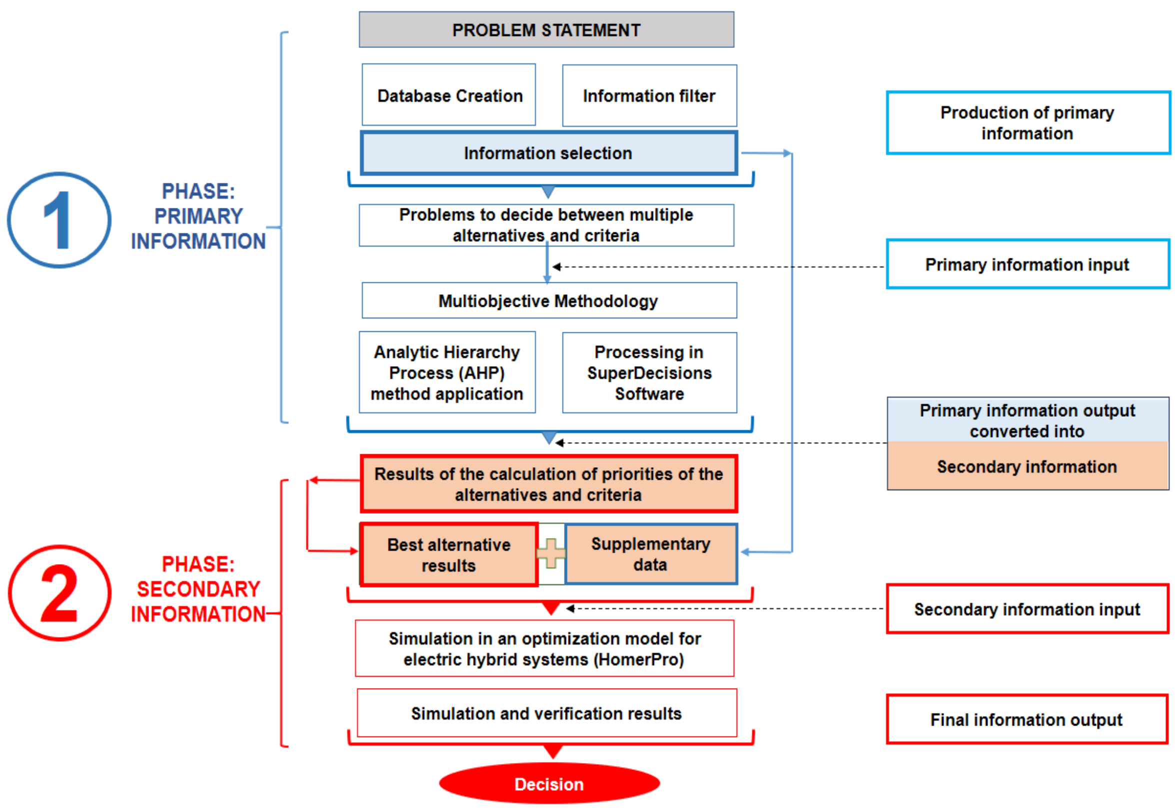
7.1 METHODOLOGICAL APPROACH

The methodology of this project (See figure 7), is based on an independent energy planning proposed by the Inter-American Development Bank (IDB) for electrical systems in Latin America [29].

The project has a stochastic approach due to the set of unpredictable variables to be treated and a deterministic approach due to the implication of social events that affect the solution that this project seeks [67].

To achieve the second specific objective of this project with specific data from the Non-Interconnected Zones (ZNI), the work is methodologically focused on two phases: A first phase to prioritize data that gives clarity to the decisions to be made (Primary information) and of these results (secondary information), move to a second phase of simulation and verification that, technically and economically confirms or distorts the decisions made. These two phases can be clearly seen in figure 25.

Figure 25. Methodological approach in two phases.



Source: Author.

7.2 CRITERIA FOR ISOLATED MICROGRID PLANNING

To achieve the objective of this degree project, the information collected must be organized and selected not only so that the primary result (See figure 24) technically meets an energy demand, but also so that it leads to compliance with economic viability standards, implementation and maintenance, environmental care and social sustainability [104].

Implementing an isolated microgrid can solve social problems from day to day in several communities: For example, the way to supply energy today is by illegally buying gallons of fuel for their diesel engines, transporting fuel in an unsafe way along the Pacific Coast, days of waiting for this supply and high costs for its acquisition. These are issues to be addressed not only from the statistics and the economy but also from the social and environmental aspects.

These particularities confirm that the planning of an isolated microgrid requires stochastic and deterministic approaches, but it also confirms that there will always be points of subjectivity to prioritize the criteria for a project of this nature.

In order to minimize subjectivity, three criteria previously studied and approved by multidisciplinary experts in the field of renewable energies are considered. The first criterion is of a world order, the second and third are of a national order:

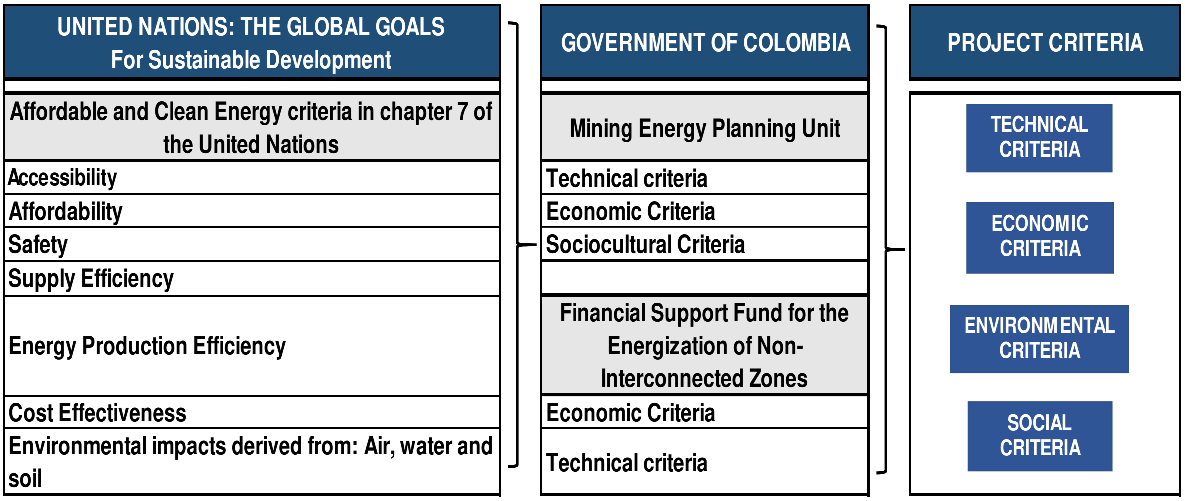
- The Affordable and Clean Energy criteria in chapter 7 of the United Nations [1,9].

- Criteria proposed by the Mining and Energy Planning Unit (UPME, for its acronym in Spanish) for a microgrid in isolated mode or interconnected to a main network [105].

- General criteria that are taken into account to identify the viability, eligibility and prioritization of projects by the Financial Support Fund for the Energization of Non-Interconnected Zones (FAZNI, for its acronym in Spanish) [106]

Figure 26 synthesizes the previously cited guidelines in four (4) key criteria that this document will follow: Technical, Economic, Environmental and Social Criteria.

Figure 26. Project background and criteria.



Source: Author

7.3 SUBCRITERIA APPROACH WITH THE AHP METHOD

Starting to respond to the third strategic objective of this document, the sub-criteria presented in table 8 are presented, which are based on the Sustainable Rural Energization Plan (PERS, for its acronym in Spanish) [107] and on technical documentation of projects developed in Colombia [108].

Table 8. Project sub-criteria.

CRITERIA	SUBCRITERIA
TECHNICAL	Generation source capacity
	Estimation of load profiles
	Sizing of the hybrid components of the microgrid
	Distribution network topology
ECONOMIC	Operation and maintenance costs
	Investment cost
	Cost of electrification Payback
ENVIRONMENTAL	SO_2 emission reduction (USD/Ton)
	NO_X emission reduction (USD/Ton)
	CO_2 emission reduction (USD/Ton)
	CO emission reduction (USD/Ton)
	Land use
	Air usage
	Water use
SOCIAL	Microgrid accessibility
	Affordability of electricity supply
	Safety of the population due to the existence of the microgrid
	ZNI Safety by Public Lighting
	Social acceptance of home energy
	Source of productivity and employment

Source: Author.

Giving a rating to the criteria depends on the quality of the data that contains the 20 sub-criteria and the objectivity to give them greater or lesser importance; However, since the data for each of the sub-criteria are based on a nature of uncertainty (Example: the climate or social acceptance of isolated microgrids) the problem has a degree of subjectivity that must be addressed through a process rational and coherent that leads to the best decision [109]

Therefore, the multiple problems that arise require two types of analysis: A quantitative analysis and a qualitative analysis to continue with a rational and coherent process that leads to reducing uncertainty and risks and thus obtaining the best decision.

7.4 TECHNICAL CRITERIA ASSESSMENT

7.4.1 Evaluation of energy supply. The technical sub-criteria are based on an evaluation of the energy supply [110, 111, 112] as shown in table 9 (see Annexes C, D, E).

Table 9. Energy supply and municipalities in NIZ

QUANTITATIVE AND QUALITATIVE ASSESSMENT										
			ENERGY POTENTIAL					MUNICIPALITIES OF THE ZNI		
Ref	System	Evaluation criteria	Very low (1)	Low (3)	Medium (5)	High (7)	Very high (9)	López de Micay	Timbiquí	Guapí
[110]	Solar Photovoltaic (PV)	Solar radiation (kW/m^2)	0-3,0	3,0-4,0	4,0-4,5	4,5-5,0	>5.0	4,0-4,5 kWh/m^2 (5)	3,5-4,0 kWh/m^2 (3)	3,5-4,0 kWh/m^2 (3)
		Exhibithion time hours/year	1-1000	1001-1400	1401-1800	1801-2200	>2201	1836 *PST/Year (7)	1548 *PST/Year (5)	1188 *PST/Year (3)
[111]	Wind System	Wind speed (m/s)	0-3,0	3,0-4,0	4,0-5,0	5,0-6,0	>6	6,5 (9)	5,8 (7)	8,85 (9)
[112]	Hydrokinetic Turbine System	River speed (m/s)	1	1,0-1,5	1,5-2,0	2,5,3,0	>3	** 2,5 (7)	***1,9 (5)	****2,8 (7)

***PST:** Peak Solar Time
****Rivers of López de Micay**: San Juan de Micay, Rio Naya, Rio Joli, Rio Sigüi, y Rio Chuare
*****Rivers of Timbiquí**: Timbiquí, Saija y Bubuey.
******Rivers of Guapí:** Guapi, Napi, San Francisco y Guajui

Source: Author based on referenced literature

7.4.2 Characterization of the demand. In chapter 5 (Theoretical framework) it had been pointed out that residential consumption studies in Colombia have stipulated that a family of 4 people have an average monthly consumption of 152 kWh per month of energy [70].

To bring the results closer to the reality of the ZNI, two important variables are taken into account [113]:

• Results of the 2018 National Population and Housing Census.

• Migration flow of other inhabitants of neighboring regions towards Cauca.

Statistics show that, although since 2005 the population increase in rural areas of the Pacific region of Cauca has decreased population growth by almost 1 point with respect to the entire department of Cauca, there has also been a slight migration of inhabitants from neighboring municipalities, including from neighboring departments such as Cauca and Chocó to these areas.

The above means that, first: family nuclei of 4 people per dwelling are calculated and second, maintain a consumption per person of 38 kWh/month.

They are then considered:

- Consumption per person of 38 kWh/month
- 4 people per home
- Average consumption per home of 152 kWh/month
- Total homes: 200 homes (Type 2 Location)
- Total local consumption: 46480 kWh/month (Including an additional 20% protection factor)

7.4.3 Hybrid system component sizing. For the balanced dimensioning of the number of solar panels, wind systems and hydrokinetic turbines, first priority will be given to the system with the highest energy potential according to the data in the last table 9. (The generator set will be considered at the end of the exercise according to the energy and missing hours that are required).

Table 10. Sizing isolated microgrid components by energy potential.

MUNICIPALITY	SYSTEM	QUALIFICATION	SYSTEM	QUALIFICATION	SYSTEM	QUALIFICATION	TOTAL
López de Micay	Wind	9	Hydrokinetic	7	Photovoltaic	6,5	**22,5**
GUAPÍ	Wind	9	Hydrokinetic	7	Photovoltaic	3	**19**
Timbiquí	Wind	7	Hydrokinetic	5	Photovoltaic	4	**16**

Source: Author.

To calculate the number of solar panels it is required to use the power method:

$$No.\ of\ photovoltaic\ panels = \frac{E * 1,2}{PST * WP} \quad (7.1)$$

Where:

E: Daily consumption of each home

PST: Peak Solar Time

WP: Panel power (340 W)

1,2: Safety factor (Oversizing over 20%)

With the information considered for the ZNI, table 11 shows the estimated total of photovoltaic panels that would be required for each municipality of 200 homes:

Table 11. Number of photovoltaic panels by municipality.

Number of photovoltaic panels for NIZ in each municipality		
López de Micay	**Timbiquí**	**Guapí**
1200	1400	1800

Source: Author

To size the battery bank, it is necessary to find the current with the following formula:

$$I = \frac{E}{V} \quad (7.2)$$

Where:

I: Intensity

E: Daily consumption of each home

Vt: Working voltage (48V)

Considering 2 days of autonomy of the batteries, a discharge depth of 80% and batteries of 500Ah, with connections distributed in parallel and connections in series, there would be an approximate of 200 batteries for the 200 families.

For the wind system called Vortex Bladeless® based on aerolastic resonance, these components from 10 m to 12 m high are considered, generating 1 kW. These data, together with the wind speed of the municipalities located in the Non-Interconnected Zones (ZNI, for its acronym in Spanish), show in table 12 the following amounts of wind elements needed.

Table 12. Number of wind elements per

Number of photovoltaic panels for NIZ in each municipality		
López de Micay	**Timbiquí**	**Guapí**
64	76	99

Source: Author

The sizing of the hydrokinetic turbines starts from a conservative speed of 1.7 m/s which could generate 1.1 kW or 36 m^3 to pump water in a community and for each hydrokinetic turbine a project could be supplied for almost 8 hours a day productive such as irrigation of a plantation, a medical center or public lighting of the streets of the community.

For the aforementioned reasons and considering the high potential of rivers that each ZNI has, 1 hydrokinetic turbine is initially planned with a 5kW underwater generator that provides three-phase alternating current.

In the case of the generator set, the telemetries reported by the IPSE [22] show between 1 and 2 diesel generators with capacities ranging from 76 kVA to 300 kVA each for locations between 200 and 250 homes for an average supply time of 5 to 6 hours/day.

For efectos de este proyecto, if you consider a single electromagnetic equipment of 500 KVA and a respective transformador for the adecuada distribución eléctrica en cada (ZNI).

7.5 ECONOMIC CRITERIA

The general dimensioning of each system is presented separately; that is, the investment that would be needed individually and totally if each one supplied 100% of the Type 2 Localities of the project's ZNIs. The total estimated value will be known when there is the most viable municipality for the solution, at that time the total equipment as a whole and a total value can be measured.

It should be noted that the microgrid being sought must have an Internal Rate of Return (IRR) of less than 25 years, which is the useful life of a microgrid of this size.

- Photovoltaic System: USD $ 1'275.000 (Approximately)

- Vortex Bladeless® Wind System: USD $ 1'550.000 (Approximately)

- Hydrokinetic Turbines (2 units): USD $ 950.000 (Approximately)

It is important to note that these ranges may vary depending on the technology provider since some on the market offer hybrid systems for microgrids; for example, some sell the photovoltaic and wind solutions in a single package or the photovoltaic and hydrokinetic systems at the same time and this would reduce investment costs.

7.6 ENVIRONMENTAL CRITERIA

The environmental evaluation can be analyzed from the economic benefit of reducing harmful gases by consuming less fuel:

To make the calculations it is important to take into account that:

- 1 gallon = 3,7851 liters

- A generator set used in ZNIs can consume approximately 4 liters/hour

- The use of these generators is 6 to 8 hours on average

Based on the information described and on the data in USD / Gallon from table 6 (See Chapter 5: Theoretical Framework) and on a 500 kW generator set for the MG, a reduction of 1 ½ Ton of gases can be considered over the duration of the project that would be equivalent to a reduction of approximately USD $ 3600 and a saving in subsidies for diesel fuel of approximately USD $ 1000.

Las consideraciones del suelo, aire y agua para los tres sistemas son diferentes.

While the installation of solar panels can occupy an area of approximately 2300 m^2 at floor level. The area of Vortex Bladeless® wind systems can occupy 5 times less space than a traditional wind turbine, with less visual impact, no noise generation or oil consumption and in the case of hydrokinetic turbines, they occupy an area of approximately 5m^2 without generating pollution to the river whether it is submerged or not.

7.7 SOCIAL CRITERIA

The municipality of López de Micay has 3241 Km^2, located in the northwest of the Department of Cauca, on the Pacific Coast, with a maximum height of 2500 meters above sea level at the stone peak [114].

The municipality of Timbiquí has an area of 1813 km^2 and a height of 5 meters above sea level, it is located west of the department of Cauca, on the Pacific Coast, at a distance of 230 km from the capital, Popayán. Its topography is broken by 70% with the presence of some mountainous branches and plains [115].

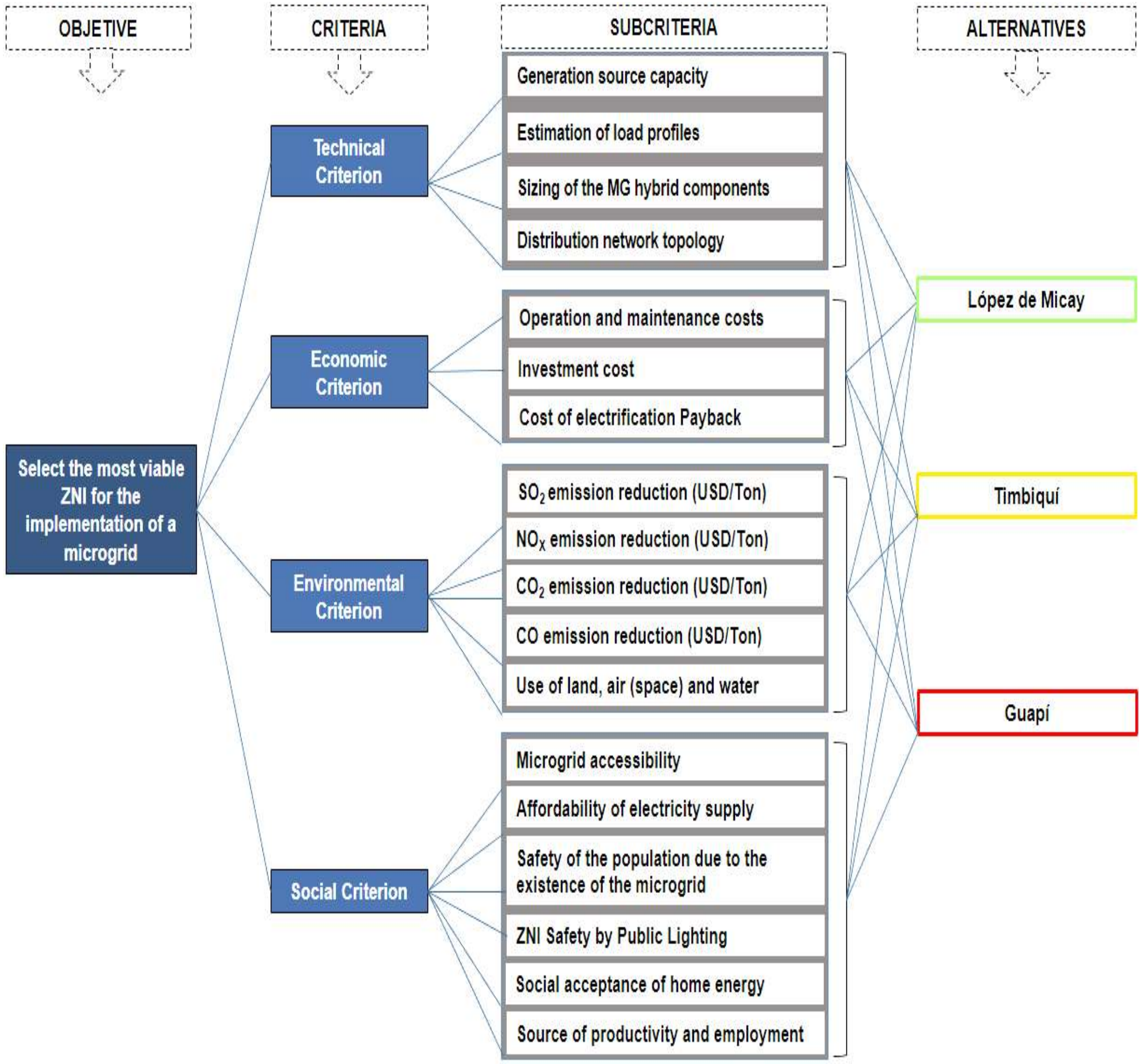
The municipality of Guapí is located to the south west of Cauca, it is bordering the slope of the Colombian Pacific on the banks of the Guapí River, it has an area of 2,688 km^2, it has a 90% flat surface and is characterized by its abundant vegetation, on a height 5 meters above sea level and an average temperature of 29ºC. [116].

The accesses and distance of each municipality to the administrative center of the department (Popayán) are key issues for the entry of technical teams, although the 3 municipalities have the same conditions for access through the Pacific Ocean.

7.8 HIERARCHICAL DECISION TREE

The main characteristic of the AHP mathematical method is the hierarchy of the problem; As shown in figure 27, in the first level of the tree is the objective problem to be solved, in the intermediate level are the criteria and sub-criteria with which the decision will be made and in the last level are the alternatives to evaluate [117].

Figure. 27. Hierarchical Decision Tree.



Source: Author.

7.9 WEIGHT ALLOCATION AND PRIORITY VECTOR RESULTS

The mathematical method Analytic Hierarchy Process (AHP) uses a scale of values called the Saaty Comparative Scale in order to determine the relative importance with reference to the selected criteria, expressing the degrees of preference of a decision element X over another Y [117]. The decision maker compares the criteria at the same level according to the scale presented in figure 28.

Figure 28. Saaty Comparative Scale.

values of scale	meaning
1	equally important
3	a little important
5	obviously important
7	very important
9	extremely important
2,4,6,8	The compromise between the two scale
Multiplicative inverse	$a_{ji} = 1/a_{ij}$

Source: Models, methods, concepts & applications of the analytic hierarchy process [117].

A series of analyzes is carried out through a square matrix that contains paired comparisons of criteria or alternatives. As shown in Equation 7.3, A is a matrix nxn, aij the element (i; j) of A, for i=1,2, ... n y, j=1,2, ...n. We say that A is a matrix of paired comparisons of n alternatives, if aij is the measure of the preference of the alternative in the row i when compared to the alternative column j. When i=j, the value of aij will be equal to 1, because the alternative is being compared with itself [118].

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix}_{nxn} \quad (7.3)$$

And if it is true that aij _ aji = 1; a matrix with some inverted data (fractions) would be given as the equation 7.4.

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}_{nxn} \quad (7.4)$$

Once the weights have been assigned, the matrices are normalized and the priority vectors for each criterion and alternative are calculated as shown in the following tables.

Table 13. Pair comparison: Criteria.

PAIR COMPARISON: CRITERIA					RESULTING VECTOR
	TECHNICAL	ECONOMIC	MEDIAMBIENTAL	ENVIRONMENTAL	
TECHNICAL	0,60810811	0,45000000	0,68789809	0,32142857	**0,517**
ECONOMIC	0,12162162	0,09000000	0,05732484	0,32142857	**0,148**
MEDIAMBIENTAL	0,20270270	0,45000000	0,22929936	0,32142857	**0,301**
SOCIAL	0,06756757	0,01000000	0,02547771	0,03571429	**0,035**

Source: Author.

In the same way, the mathematical analysis is done for the alternatives.

Table 14. Technical criterion.

ECONOMIC CRITERION				RESULTING VECTOR
	LÓPEZ DE MICAY	TIMBIQUÍ	GUAPÍ	
LÓPEZ DE MICAY	0,29	0,40	0,18	**0,28917749**
TIMBIQUÍ	0,14	0,20	0,27	**0,20519481**
GUAPÍ	0,57	0,40	0,55	**0,50562771**

Source: Author.

Table 15. Economic criterion.

ENVIRONMENTAL CRITERION				RESULTING VECTOR
	LÓPEZ DE MICAY	TIMBIQUÍ	GUAPÍ	
LÓPEZ DE MICAY	0,55	0,60	0,50	**0,54848485**
TIMBIQUÍ	0,18	0,20	0,25	**0,21060606**
GUAPÍ	0,27	0,20	0,25	**0,24090909**

Source. Author

.

Table 16. Environmental criterion.

ENVIRONMENTAL CRITERION				RESULTING VECTOR
	LÓPEZ DE MICAY	TIMBIQUÍ	GUAPÍ	
LÓPEZ DE MICAY	0,55	0,60	0,50	**0,54848485**
TIMBIQUÍ	0,18	0,20	0,25	**0,21060606**
GUAPÍ	0,27	0,20	0,25	**0,24090909**

Source: Author.

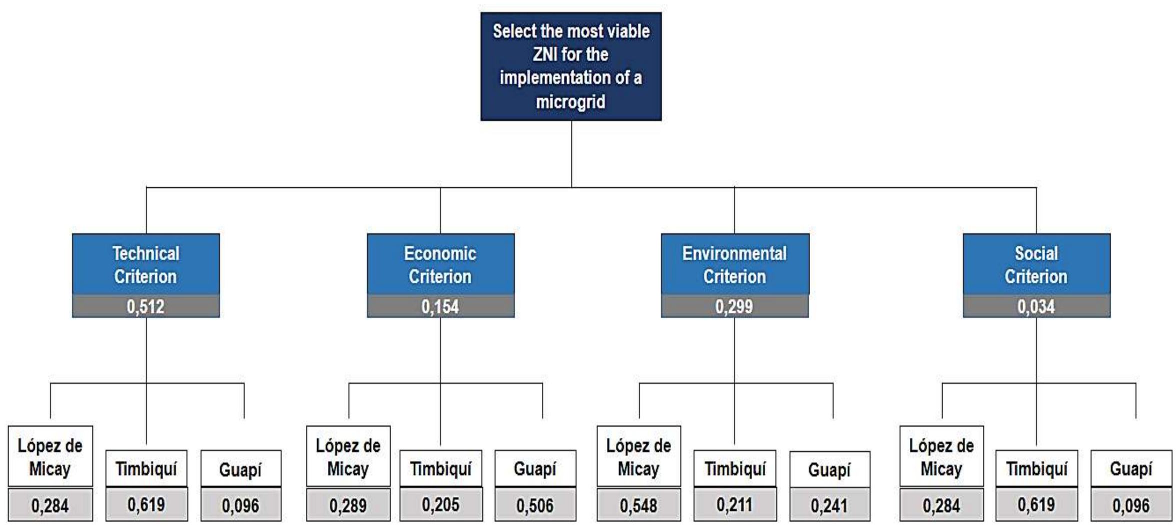
Table 17. Social criterion.

SOCIAL CRITERION				RESULTING VECTOR
	LÓPEZ DE MICAY	TIMBIQUÍ	GUAPÍ	
LÓPEZ DE MICAY	0,235294118	0,217391303	0,4	**0,284**
TIMBIQUÍ	0,70588235	0,652173914	0,5	**0,619**
GUAPÍ	0,05882353	0,13043478	0,1	**0,096**

Source. Author.

In figure 29 the solution of the AHP tree is presented.

Figure 29. AHP tree solution.



Source: Author

The resulting global vector leaves the López de Micay municipality in order of priority, followed by the Timbiquí municipality and finally the Guapí municipality as shown in table 18.

Table 18. Global resultant vector.

MOST VIABLE AREA FOR MG IMPLEMENTATION		
PRIORITY	MUNICIPALITY	GLOBAL VECTOR
1	LÓPEZ DE MICAY	↑ 0,40
2	TIMBIQUÍ	↑ 0,35
3	GUAPÍ	↓ 0,24

Source: Author.

The AHP method allows us to reach two important preliminary conclusions (before simulating) The first conclusion is that, despite considering the economic criterion for decision-making as a fundamental part, the technical and environmental criteria were predominant because they had greater weight and second, it can be seen that, although the municipality with the highest rating is López de Micay, the municipality of Timbiquí has a score very close to the first place.

7.10 SELECTION OF THE DECISION SUPPORT SYSTEM

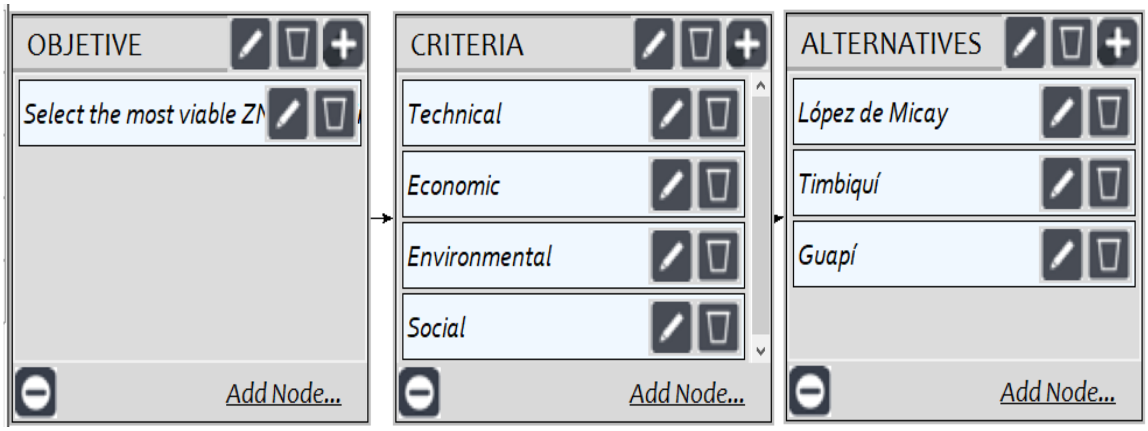
Currently, there are several computational tools that allow the AHP model to be developed and add value by showing levels of inconsistency, performing sensitivity analysis, among other options.

To give greater support to the ranking exercise carried out, 3 software for the application of the AHP method were consulted: Expertchoice [119], AHP Online System - AHP-OS [120] and SuperDecisions® [121].

The selection favored SuperDecisions® as it is an academic tool with a well-known academic and business reputation, user-friendly, practical and freely accessible.

7.10.1 Checking ranking results. The ranking exercise is checked with the SuperDecicions® Software, setting out the objective, the selected criteria and the alternatives as shown in figure 30.

Figure 30. Objective, criteria and alternatives in SuperDecisions® software.



Source: Author, SuperDecisions®.

The matrices are made in the software, the normalizations are executed and at the end a report of the calculated priorities is presented:

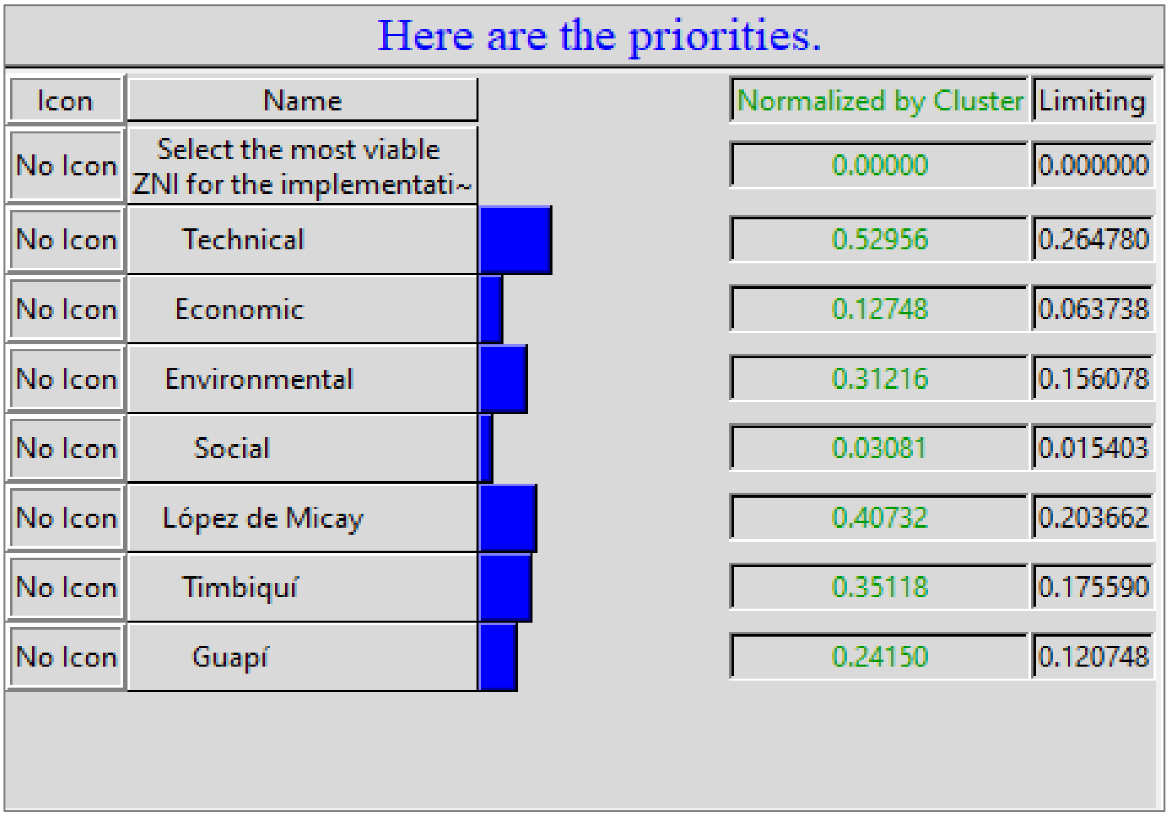
Figure 31. Synthesized priorities for the alternatives.

Name	Graphic	Ideals	Normals	Raw
Guapí		0.592884	0.241496	0.120748
López de Micay		1.000000	0.407324	0.203662
Timbiquí		0.862163	0.351180	0.175590

Source: Author, SuperDecisions®.

Figure 32 shows the final report confirming the conclusions initially obtained before the support in the software on the technical and environmental criteria as predominant and on the order of priority in viability of the municipalities.

Figure 32. Priorities of criteria and alternatives.



Here are the priorities.

Icon	Name	Normalized by Cluster	Limiting
No Icon	Select the most viable ZNI for the implementati~	0.00000	0.000000
No Icon	Technical	0.52956	0.264780
No Icon	Economic	0.12748	0.063738
No Icon	Environmental	0.31216	0.156078
No Icon	Social	0.03081	0.015403
No Icon	López de Micay	0.40732	0.203662
No Icon	Timbiquí	0.35118	0.175590
No Icon	Guapí	0.24150	0.120748

Source: Author, SuperDecisions®.

7.11 SELECTING A SIMULATION TOOL

Continuing the methodology established in the document and seeking to meet the last specific objective, a computational tool is sought that is capable of modeling and comparing various design options for energy systems to obtain results.

Initially, an exploration of systems that met these requirements was made, such as:

- RETScreen
.
- Solar Advisor Model
- PVWatts
- ViPOR
- Homer Pro® (The free version is used for cost issues)

After reviewing the advantages and disadvantages of each one such as: Ease of access, usability, scope of the software; you choose to use the free version of the Software Homer Pro®.

Homer Pro® was developed by NREL (National Renewable Energies Laboratory) and in collaboration with NASA (National Aeronautics and Space Administration) takes satellite data to optimally model isolated microgrids (Off grid or island mode) or interconnected to the network. Homer Pro® Through technical and economic data, it finds the combination of components with the lowest cost associated with renewable and non-renewable energy sources to satisfy the load demanded [122].

It is important to clarify that most of the technical and environmental data that specialized literature and control entities can offer have been taken, but the regions furthest from the Municipality of Cauca in Colombia, as well as other regions of the country, do not have daily measurements and equipment. of precision that take data continuously, which implies a point of uncertainty to be covered through averages such as those offered by the Homer Pro® Software.

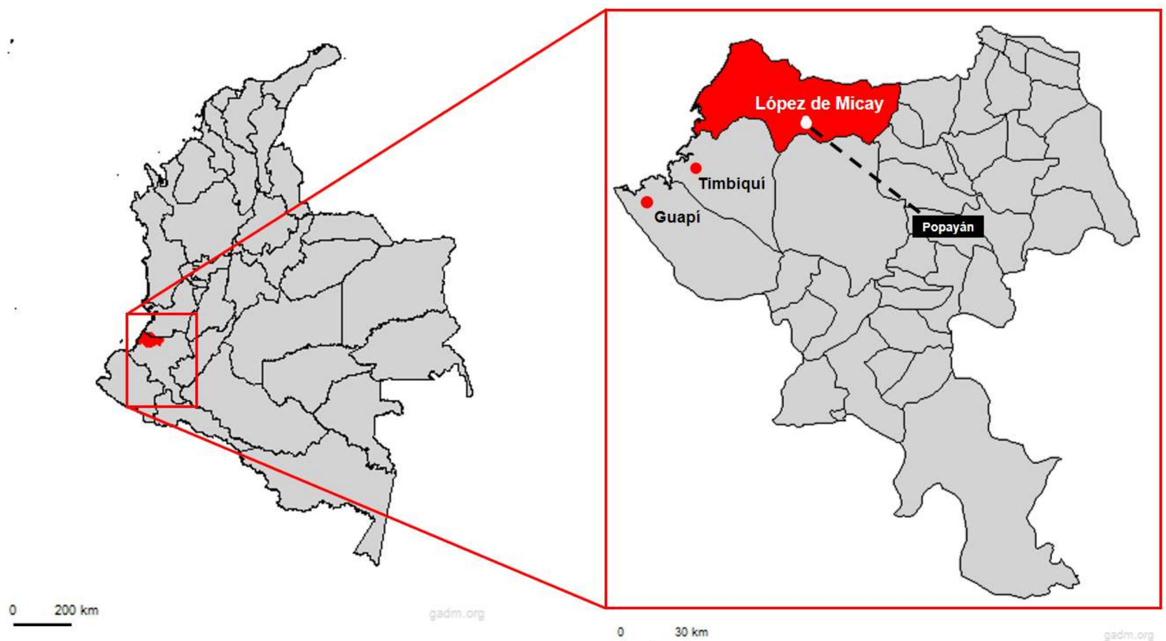
8. APPLICATION OF THE METHODOLOGY

8.1 LÓPEZ DE MICAY MUNICIPALITY CASE STUDY

In order to apply the proposed feasibility study strategy, the López de Micay municipality of the department of Cauca is selected (See figure 33) that the Analytical Hierarchy Process (AHP) method ranked as the most suitable for the implementation of a microgrid isolated.

López de Micay is a municipality that has 3,241 m^2 of surface and is located 84 km from the departmental capital, Popayán [123], it has 9 townships classified within ZNI that add 1308 residential users (Homes) as shown at the beginning of the document, in table 2.

Figure 33. Physical map of Cauca department.



Source: Author based on Physical map of the López de Micay municipality [123].

Different townships fulfill the characteristic of Type 2 Locality (between 151 and 300 users -homes) but, due to strategic aspects such as: better location of the hybrid systems according to natural resources, distance from the ZNI to the secondary airport of the López de Micay municipality and from the city of Popayán for access by teams and professionals, geographical accidents in the area, road and river accesses, among others; have made the township of San Isidro be specifically considered as shown in figure 34.

Figure 34. Political physical map of Cauca.

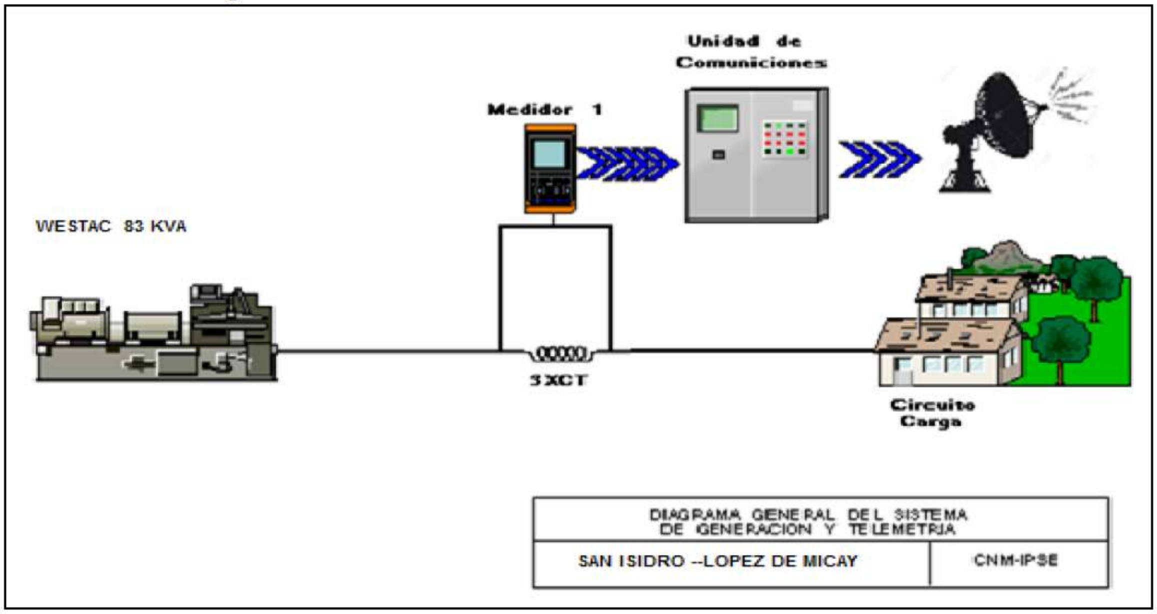
Source: Author based on Physical map of the López de Micay municipality [123].

The township of San Isidro is located at Latitude: 2.98333 and Longitude: -77.4; It has 175 users, its distance from the center of the town of López de Micay is 23.97 km, but the distance on the road is 287 km, which would translate into 7 hours and 45 minutes of travel by vehicle [124].

The township has one (1) Westac Power brand generator set with a capacity of 83 kVA [125].

Next, the one-line diagram of the locality is presented in figure 35:

Figure 35. Single line diagram of the San Isidro – township.



Source: Author based on February telemetry (San Isidro-Cauca) IPES [125].

The township of San Isidro has the provision of electric power service with a daily average of 6 Hours 8 Minutes [125].

The viability of an isolated microgrid (MG) in this town lies not only in contributing to the residential energy demand of the area with clean energy, but also in providing safety and quality of life to the community and in giving it the opportunity to be self-sustaining. With these three characteristics, an electric power system has been conceived with 3 supply purposes: Electric power for homes for residential use, public lighting, and promoting a productive project to replace an irrigation pump that is currently powered by 110 kW diesel generators.

Table 19 shows in detail the technical aspects to consider prior to a simulation of the isolated microgrid.

Table 19. Description of the technical aspects of the township San Isidro (Cauca).

DESCRIPTION OF TECHNICAL ASPECTS OF THE SAN ISIDRO TOWNSHIP (LÓPEZ DE MICAY-CAUCA)	
Township	**San Isidro of the López de Micay municipality (Cauca)**
Current inhabitants (year 2021):	175 users (homes)
Total projection of inhabitants (dwellings):	200 users (homes)
Monthly consumption per person:	38 kWh / month
Average monthly consumption per user (home):	152 kWh / month
Daily consumption of the town:	1013 kWh / day
More than 20% protection factor	1216 kWh / day
Daily hours of residential electric power service	9 horas diarias
Total monthly consumption of the town:	36480 kWh/mes (Including 20% by protection factor)
Public lighting	
Number of luminaires with 110W power	10 Luminaires
Daily lighting consumption:	13.2 kWh / day
Más el 20% de factor de protección	More than 20% protection factor
Public lighting daily service hours	12 hours (6pm to 6am) daily
Total monthly consumption of the town:	475.2 kWh / month
Productive Project	
Daily hours of 1 productive project	17.6 kWh / day (Ex. Consumption of 1 irrigation pump for agriculture)
More than 20% protection factor	21.12 kWh / day
Monthly consumption (20 productive days) total:	422,4 kWh / month

Source: Author.

9. RESULTS

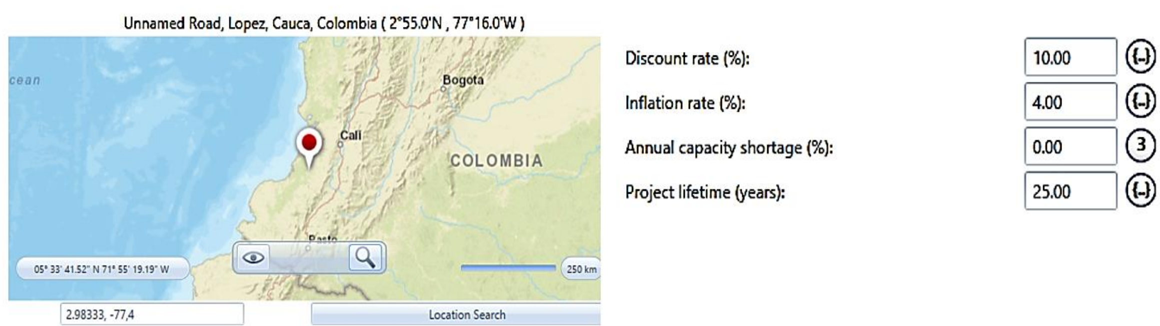
9.2 OBTAINING RESULTS THROUGH SIMULATIONS IN THE HOMER PRO® SOFTWARE

The methodological strategy used for this document, which started from a search, consolidation, organization and prioritization of information, led to a series of problems that were solved through a multi-objective methodology that ultimately ranked the López de Micay municipality as the most viable for the implementation of a microgrid (See table 18).

The preliminary conclusions that were obtained thanks to all this primary information (See phase one of figure 24) are the input data for the second phase (See phase two of figure 24) in which it is required to validate the conclusion to that point, close the gap of least subjectivity had until that moment and thus, approach technical and economic data more limited to reality.

The first step was to design the isolated microgrid proposed in this degree work, taking the input data required by the simulation software such as: geographic data, natural resources of the area (solar irradiation, wind speed, temperature) and economic considerations such as the interest or discount rate, inflation rate, annual shortage rate and useful life of the system (Theoretical concepts mentioned in Chapter 5) as shown in figure 36.

Figure 36. Microgrid design in simulation software.

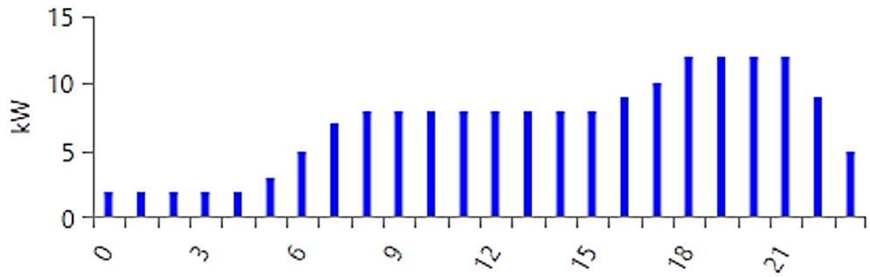


Source: Author, Homer Pro®.

Then the load profile was defined, considering the community type zone as the residential part has a greater participation than the part related to public lighting and the productive project. The daily consumption of the town is 1216 kWh/day.

Figure 37 shows the daily energy behavior that the community would have, starting with a slight increase after 6am, having a stable consumption of 9am 3pm, an increase until 9pm and then a fall for the rest of the night until it repeats. the cycle at 6am the next day.

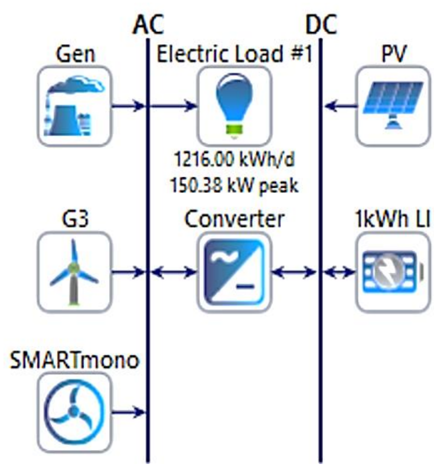
Figure 37. Daily profile for the San Isidro township.



Source: Author, Homer Pro®

The next step was to include the hybrid components for the simulation, which in this case are: Information on the electrical load demand, the photovoltaic system, the wind system, the hydrokinetic system, the diesel combustion generator set as a backup system, the system DC/AC converter and battery bank. Figure 38 shows the proposed design.

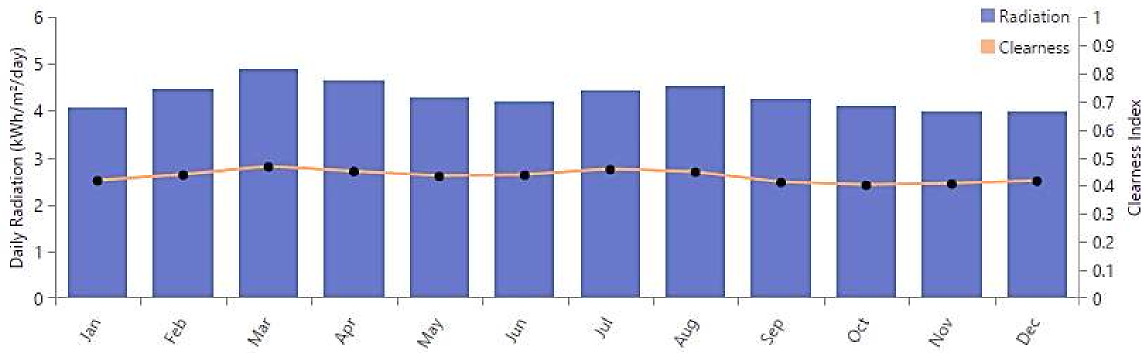
Figure 38. Microgrid topology.



Source: Author, Homer Pro®

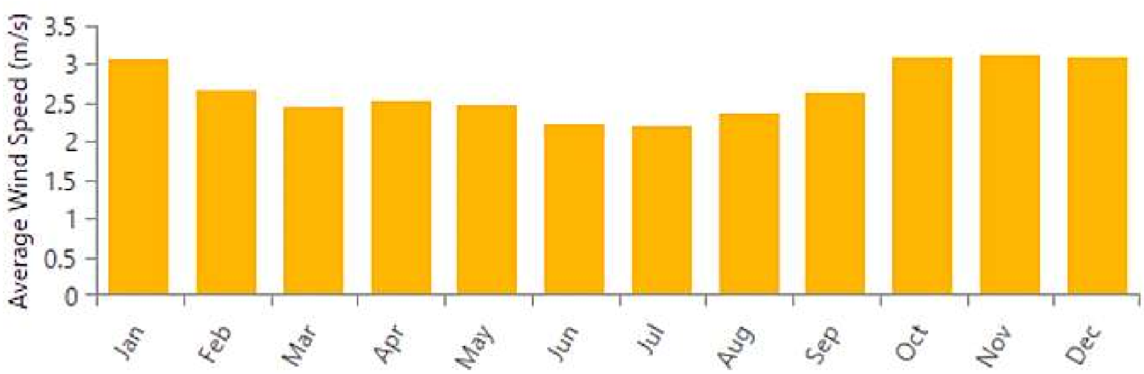
Regarding the availability of natural energy resources, for this simulation conservative scenarios were taken in order to make the visualization of an implementation in data of solar irradiation (see figure 39), wind (see figure 40) and wind speed more real. San Juan de Micay river (see figure 41) and maintaining the standard temperature data for the region.

Figure 39. Global Solar Radiation (GHI).



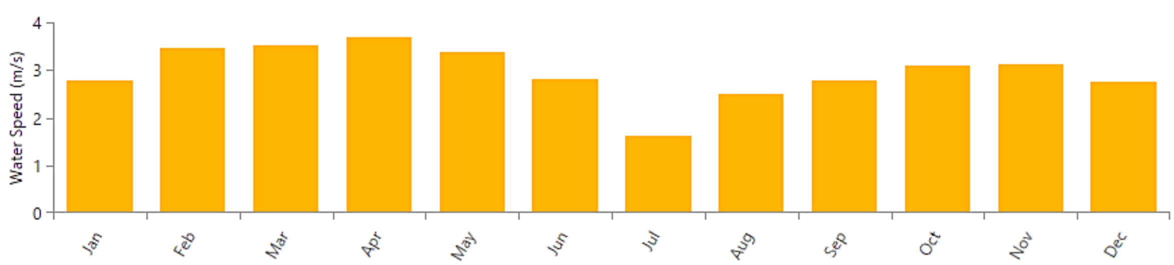
Source: Author, Homer Pro®.

Figure 40. Wind Resource



Source: Author, Homer Pro®.

Figure 41. Hydrokinetic resource.



Source: Author, Homer Pro®.

Regarding the consumption of diesel fuel for the generator set, the value of USD $ 0,591 [125] per liter was taken into account, the change from dollar to Colombian pesos for the next results analysis will be based on COP $ 3851 [126] and maintains a generator set similar to the existing one (83 KVA) since the idea is not to increase the consumption of diesel fuel.

The electrical combinations proposed by the software are technically correct, that is to say, they combine coherently since if not, the simulations would present an error message on the left side of each proposal.

9.2.1 Scenarios for simulation modeling. In table 20, four (4) simulation scenarios were proposed, which are:

- **0% Optimistic scenario:** The microgrid would operate without interruption.
- **10% Moderately optimistic:** The microgrid would not work 10% of each year.
- **20% Moderately pessimistic:** The microgrid would not work 20% of each year.
- **30% Pessimistic:** The microgrid would not work 30% of each year.

Table 20. Four (4) scenarios for economic simulation of microgrids.

Sensivity Cases of Microgrid Design									
Stage	**Simulations (1 cheapest to 4 most expensive)**	**NPC (USD $)**	**LCOE (USD $)**	**Photovoltaic energy**	**Wind power**	**Generator set**	**Battery bank**	**Hydrokinetic energy**	**Converter**
Optimistic (O%-MG working without interruptions)	1	1'228.580	0,2119	● (green)			● (green)	● (green)	● (green)
	2	1'228.712	0,2118	● (green)		● (green)	● (green)	● (green)	● (green)
	3	1'293.976	0,2231	● (green)	● (green)	● (green)	● (green)	● (green)	● (green)
	4	1'315.042	0,2268	● (green)	● (green)		● (green)	● (green)	● (green)
Moderately optimistic (MG working with 10%	1	696.243	0,129	● (yellow)			● (yellow)	● (yellow)	● (yellow)
	2	759.886	0,141	● (yellow)	● (yellow)		● (yellow)	● (yellow)	● (yellow)
	3	1'228.711	0,2118	● (yellow)		● (yellow)	● (yellow)	● (yellow)	● (yellow)
	4	1'293.976	0,2231	● (yellow)	● (yellow)	● (yellow)	● (yellow)	● (yellow)	● (yellow)
Moderately pessimistic (MG working with 20%	1	558.004	0,111	● (orange)			● (orange)	● (orange)	● (orange)
	2	629.559	0,126	● (orange)	● (orange)		● (orange)	● (orange)	● (orange)
	3	1'228.712	0,2118	● (orange)		● (orange)	● (orange)	● (orange)	● (orange)
	4	1'293.976	0,2231	● (orange)	● (orange)	● (orange)	● (orange)	● (orange)	● (orange)
Pessimistic (MG working with 30% interruptions)	1	480.006	0,103	● (red)			● (red)	● (red)	● (red)
	2	543.021	0,116	● (red)	● (red)		● (red)	● (red)	● (red)
	3	1'228.712	0,2118	● (red)		● (red)	● (red)	● (red)	● (red)
	4	1'293.976	0,2231	● (red)	● (red)	● (red)	● (red)	● (red)	● (red)

● (green) Microgrid that would operate all year round without interruption
● (yellow) Microgrid that would have 10% per year without operation
● (orange) Microgrid that would have 20% per year without operation
● (red) Microgrid that would have 30% per year without operation

Source: Author

Table 20 presented a complete consolidation of the 4 scenarios and their first 4 most economically viable options according to their configurations, including the NCP (Net Present Cost) and the Levelized Cost of Energy (LCOE).

Finally, in the lower part of figure 42, the result of the first best combinations of a series of multiple simulations carried out for each scenario is shown, reviewing in each one of them the budgets that it presented and if technically, the hybrid components could or not relating in harmony.

The field called architecture, shows in its first columns the hybrid systems that would intervene (if there was a coexistence error between the systems, an alert would appear on the left side). At the front is the PV (kW) column that indicates the energy that the entire photovoltaic system must produce, the capacity in kW required by the batteries, the number of Smart type turbines (1 turbine), the kW that must be converted from AC/DC the converter system, the total project value (Net Present Cost) and the kilowatt-hour value (Levelized Cost Of Energy-LCOE).

Figure 42. Economic results of the simulation.

Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Sensitivity	Architecture								
Capacity Shortage (%)	PV (kW)	G3	Gen (kW)	1kWh LI	SMARTmono	Converter (kW)	Dispatch	NPC ($)	COE ($)
0	947			2,439	1	164	CC	$1.23M	$0.212
10.0	620			1,143	1	122	CC	$696,243	$0.129
20.0	473			950	1	103	CC	$558,004	$0.111
30.0	406			823	1	80.6	CC	$480,006	$0.103

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

PV (kW)	G3	Gen (kW)	1kWh LI	SMARTmono	Converter (kW)	Dispatch	NPC ($)	COE ($)
947			2,439	1	164	CC	$1.23M	$0.212
975		170	2,060	1	161	LF	$1.23M	$0.212
974	1	170	2,113	1	157	LF	$1.29M	$0.223
844	1		2,761	1	152	CC	$1.32M	$0.227
		170	569	1	152	CC	$7.71M	$1.33
	1	170	571	1	144	CC	$7.77M	$1.34

Source: Author, Homer Pro®.

The optimized results of each scenario conclude that the wind system is the most disposable initially and is included in the other combinations, but for this, higher costs must be assumed.

The best ideal scenario, with no pollution from diesel combustion, would be great for the environment; that is, exclude the generator system, but considering the geographical conditions of the area, the lack of support from the National Interconnected System (SIN) or the absence of other microgrids in the area that would supply the load intelligently; make it a necessary component to supply the community's energy supply.

As a result, the study favors the second optimized result of the optimistic scenario, which excludes the wind system, but instead considers the rest of the hybrid systems of the microgrid (Photovoltaic, generator set, battery bank, hydrokinetic energy and converter).

Table 21 shows the net present value of the microgrid.

Table 21. Net present cost of the microgrid.

Component	Capital (USD $)	Replacement (USD $)	Operation and maintenance (USD $)	Fuel (USD $)	Salvage (USD $)	Total (USD $)
Autosize Genset	$340.00	$0.00	$79,979.44	$4,348.73	-$78.64	$84,589.53
Generic 1kWh Li-Ion	$339,900.00	$190,948.17	$40,381.77	$0.00	-$36,324.59	$534,905.35
Generic flat plate PV	$487,736.77	$0.00	$38,244.03	$0.00	$0.00	$525,980.80
SMART Monofloat 5kW	$7,000.00	$0.00	$980.14	$0.00	$0.00	$7,980.14
System Converter	$40,203.85	$17,333.15	$21,016.22	$0.00	-$3,297.33	$75,255.89
Total System	**$875,180.62**	**$208,281.32**	**$180,601.60**	**$4,348.73**	**-$39,700.56**	**$1,228,711.71**

Source: Author, Homer Pro®.

Other relevant costs for sizing the total investment in this microgrid are the values that pollutant gases would generate each year from diesel combustion through the generator set as shown in table 22, which are monetized as energy production inefficiencies in the system.

Table 22. Emission of polluting gases from the generator set.

AMOUNT OF EMISSION OF POLLUTANT GASES	
Carbon Dioxide (kg/yr)	1474
Carbon Monoxide (kg/yr)	929
Unburned Hydrocarbons (kg/yr)	0,41
Particulate Matter (kg/yr)	0,06
Sulfur Dioxide (kg/yr)	3,610
Nitrogen Oxides (kg/yr)	8,73
TOTAL (kg/yr)	**2416**

Source: Author, Homer Pro.

Finally, costs for energy distribution (wiring, poles, lights, residential connections), technical energy losses and other items must be considered, which would total a single total cost of the microgrid as shown in table 23.

Table 23. Total costs of the microgrid.

TOTAL COSTS OF THE PROJECTED MICROGRID FOR A USEFUL LIFE OF 25 YEARS	
COMPONENT	**VALUE (USD $)**
System cost	1'228.711
toxic gas emissions	37.402
Electrical Distribution	16.150
Loss of energy	2.015
Other expenses	16842
TOTAL	**$1`301.120**

Source: Author.

The analysis concludes by distorting the budgets initially conceived prior to the simulation (Average budget of USD $ 1’258.000) since, when simulating the microgrid, more and higher costs standout such as operation and maintenance of the energy systems, high value for the generator set and costs associated with electrical distribution.

In matters of added value, the results also conclude with an Internal Rate of Return (IRR) of 172% and an ROI of 166%, which implies a recovery after year 25 (Return for year 37 if you have a policy of charging per kW after the first 5 years of use). The reason for these values focuses on 4 fundamental characteristics of the project:

The project is not focused on giving dividends to a short-term private investment in exchange for any specific good or service.

• The implementation of the isolated microgrid points to its financial leverage through national government plans, resources from the National Royalties Fund and the Cauca Government's own resources that would be destined to the municipalities in Non-Interconnected Zones.

• For the selected Non-Interconnected Zone (ZNI), it is not easy to size an IRR and a TIO that reflect positive effects such as: the reduction of violence in an area that begins to have public lighting, the possibility of being self-sustaining with a project productive, the benefits of a community that begins to have the home electricity public service and that contributes to the health and education of the community thanks to the implementation of the microgrid.

10. VALIDATION OF RESULTS

It is worth remembering at this point of validation that the microgrid architecture is considered optimal when the lowest Net Present Cost (NPC) and the lowest Normalized Energy Cost (LCOE) are obtained.

To verify the results obtained, a comparison is made between the current state of the San Isidro district with the generator set that partially supplies them with electricity during the day and the comparison with a second scenario with the microgrid to supply the electricity service in the area.

Table 24 shows the current scenario vs the isolated microgrid.

Table 24. Comparison between the current and proposed energy system.

	COMPARISON BETWEEN THE CURRENT SYSTEM AND THE MICROGRID	
Economic concepts	System only with generator set	Proposed Microgrid System
TOTAL NPC:	$3'412.367	$1'228.712
Leveliced Cost	$ 0,59	$ 0,2118
Operation Cost:	$ 254,61	$ 27.052,08

Source: Author

Another important validation to take into account is the environmental impact that would be generated if only the generator system were used for energy supply, several generator sets of approx 500 kVA would have to be considered, which would generate approximately a 180% increase in emissions as shown in table 25:

Table 25. Comparison of emissions between the generator system and the MG.

AMOUNT OF EMISSION OF POLLUTANT GASES		
Description	Diesel generator	Microgrid
Carbon Dioxide (kg/yr)	426328	1474
Carbon Monoxide (kg/yr)	2687	929
Unburned Hydrocarbons (kg/yr)	117	0,41
Particulate Matter (kg/yr)	16,3	0,06
Sulfur Dioxide (kg/yr)	1044	3,610
Nitrogen Oxides (kg/yr)	2524	8,73
TOTAL (kg/yr)	432716	2416

Source: Author, Homer Pro®

11. DESCRIPTION OF THE PROJECT

11.1 INNOVATIVE CHARACTER OF THE PROJECT

The use of technology reducing costs, optimizing materials and resources and being environmentally sustainable are a priority today. For these reasons despite knowing for years the benefits of renewable energy systems, efforts in academic and business scientific research and developments in innovation continue to be promoted to make these energy systems more economical, efficient and ultimately within reach. of more people.

This isolated microgrids project starts from a well-known base that is renewable energies, but it differs by considering several novel components such as: an innovative wind system without blades, hydrokinetic turbines of which until a few years ago are taking more welcome in projects of rivers in Colombia, photovoltaic energy with higher efficiencies today and lithium batteries at a lower cost and greater storage capacity. Elements that, combined technically, economically and environmentally in the correct way, generate a differential social project for the Non-Interconnected Zones of the country.

It has a very novel component when looking for a practical method to initially solve the multiple problems that this type of project generates and then, the search for its validation with a simulation tool that is at the forefront in hybrid energy systems.

Culturally it is a project that promotes a paradigm shift by seeking the social inclusion of isolated regions in the definition of energy generation and distribution systems through 3 pillars: residential electricity supply, public lighting and a productive project. The three in search of making the project sustainable through the empowerment of the community towards the isolated microgrid or island mode microgrid.

Finally, innovation also resides in its potential for future years, an energy solution of this type would encourage employment in the region, the academic and institutional alliance and, ultimately, the increase in the quality of life of people in the Zones. Not Interconnected.

11.2 POTENTIAL APPLICATIONS ON THE RESULTS

The methodology offered in this project and the course with which each of the investigated topics is carried out are conducive to delving further into the way of investigating not only problems related to renewable energies, but also social, economic and environmental issues. even cultural.

The multiobjective optimization and the multicriteria method are only one way to evaluate multiple problems. Mathematics offers other avenues with different technological tools to explore the possibility of new and better ways of approaching these types of projects.

The results obtained are applicable to investigations on system dynamics that occur in these types of scenarios in which technology and people converge.

This project shows the deep interest of other research groups in different universities in Colombia and in other countries. The search for other applications of microgrids not only for communities, but also in commercial aspects such as the transmission of renewable energies to the traditional electricity grid, industrial self-generation projects, government environmental projects, the exploration of microgrids with combinations of other hybrid systems such as the Hydrogen, biomass, geothermal energy, among others.

Finally, this project, through the various bibliographic references and expert sources consulted, shows that Colombia has the potential to design its own solutions, manufacture and apply them without resorting entirely to the foreign market.

12. CONCLUSIONS AND FUTURE WORK

12.1 CONCLUSIONS

Based on the solar, water, wind and temperature resources of the department of Cauca (Colombia), it is feasible to find, through a microgrid, the appropriate combinations of its hybrid components to satisfy its energy demand in the Non-Interconnected Zones (ZNI).

Answering the original problematic question of this degree project, the most viable microgrid with hybrid systems to satisfy the energy needs in Non-Interconnected Zones (ZNI) is mainly composed of: a photovoltaic system, a hydrokinetic system, a generator set, a bank of batteries and a converter.

For the proposed microgrid, the wind system is excluded unless a minimum additional investment of USD $ 60000 is made, plus additional operation and maintenance costs without ensuring the expected efficiency, since there are no detailed current studies of the speed of the winds in the selected ZNI.

The cost distribution of the microgrid (43.53% in the battery bank, 42.80% in the photovoltaic system, 6.88% in the generator system, 0.64% in the hydrokinetic turbine and 6.12% in the AC/DC conversion system) show that investment in batteries becomes almost as high as photovoltaic technology.

Isolated microgrid projects have been approached from different methodologies by different countries according to their resources and needs. In this project, the multi-criteria methodology and the mathematical method Analytic Hierarchy Process (AHP) are selected as the most appropriate to rank the most viable solutions for the ZNI of the department of Cauca.

The results obtained by the AHP method prioritize the municipality of López de Micay (global vector 0,40) as the most viable geographic area for the implementation of the microgrid, followed by the municipality of Timbiquí (global vector 0,35) and finally the municipality Guapí (global vector 0,24).

The simulation in Homer Pro® confirmed the bibliography on solar radiation in the Lopez de Micay municipality between 4 and 4.5 kWh/m^2 and with a Peak Solar Hour of 1548 PST/year, which makes energy production viable in San Isidro. with the photovoltaic system.

The wind system is not part of the best options of the 4 simulated scenarios; It is located between the third and fourth options of microgrids, which leaves the possibility of not completely ruling out this type of energy solution.

The researched bibliography and the simulation in Homer Pro® confirm that the hydrokinetic system could supply the dimensioned production project through the San Juan de Micay river.

If only diesel generators continue to be used in the ZNI, the simulation estimates a production of 432716 kg / year of polluting gases while the proposed microgrid (including the diesel generator as backup) would be 1496 kg / year. Reduction of more than 99% of toxic gases for the community and the environment.

By analyzing the variables with the AHP method, it was possible to calculate a microgrid of approximately USD $ 1’200.000. The simulation in the Homer Pro® software plus the additional cost considerations such as Operation and Maintenance reflected a value of USD $ 1’301.120; concluding that the Multiobjective Optimization gave a clear approach to the estimated budget and the Software confirmed its validity by reporting a more accurate value to reality.

Regarding the legislative part, it can be concluded that the National Government of Colombia, in its National Development Plan, grants investors, small and medium-sized companies and individuals; benefits in terms of deductions and elimination of taxes. through recent changes to Law 1715 of 2014 that promote investment, research and development of clean technologies in the country.

12.2 FUTURE WORK

Continuing to explore innovative systems that reinvent the way of acquiring clean, safe, sustainable and environmentally friendly electrical energy is one of the greatest invitations offered by this degree project.

The research carried out provides the opportunity not only to improve the current proposal of an isolated microgrid thinking about other combinations of hybrid systems based on renewable energies but also to explore smart microgrids for rural areas and in other areas of Colombia with apparent low generation potential electricity through its natural resources to confirm its viability and even offer disruptive solutions to major social problems that have prevailed for years.

This project shows the great importance of exploring and applying analytical techniques with empirical contrasts to solve complex problems not only in the electricity sector, but also in the economy and transport, production, commercialization, public sector, in the evaluation of new technologies, in applications environmental, among other sectors.

As part of future work that requires validating results through computational simulation tools, it is valid that more Artificial Intelligence methods are incorporated into robust tools that complement each other to obtain better results.

Thinking about solving the most defined aspects such as those of a technical and economic nature in Non-Interconnected Zones is only one part of the process, the consequences of this type of projects related to thinking, the assimilation and future actions of each user, families, communities, institutions and the government towards this type of alternative solutions, is where the viability of this type of projects for other areas of the world can be determined as real as possible. country and even in other regions of the planet.

13. REFERENCES

[1] United Nations - UN. (2020), Affordable and Clean Energy. 17(7). Available in: https://sdgs.un.org/goals/goal7

[2] Programa de las Naciones Unidas para el Desarrollo. (2021). Fecha límite 2030. La década de Acción para los Objetivos de Desarrollo Sostenible. Available in: https://www.undp.org/content/undp/es/home/stories/decade-of-action.html

[3] Energy Sector Management Assistance Program - ESMAP. (2019). The Energy Progress Report, (1-7). Available in: https://trackingsdg7.esmap.org/data/files/downloaddocuments/tracking_sdg7_2019_highlights.pdf

[4] Statistical Review of World Energy. (2019). Available in: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[5] Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Patterson, C. (2009). Managing the health effects of climate change. Lancet and University College London Institute for Global Health Commission. The Lancet, 373(9676), 1693-1733. doi: 10.1016/S0140-6736(09)60935-1

[6] Caballero, F., Sauma, E., & Yanine, F. (2013). Business optimal design of a grid-connected hybrid PV (photovoltaic)-wind energy system without energy storage for an easter island's block. Energy, 61, pp. 248-261. doi: 10.1016/j.energy.2013.08.030

[7] Raman, P., Murali, J., Sakthivadivel, D., & Vigneswaran, V. S. (2012). Opportunities and challenges in setting up solar photo voltaic based micro grids for electrification in rural areas of India. Renewable and Sustainable Energy Reviews, 16(5), pp. 3320-3325. doi: 10.1016/j.rser.2012.02.065

[8] Organización de las Naciones Unidas - ONU: Se alcanzan niveles récord de concentración de gases de efecto invernadero en la atmósfera. (2019). Available in: https://news.un.org/es/story/2019/11/1465851

[9] United Nations: Peace, dignity and equality on a healthy planet, Climate Change. (2019). Available in: https://www.un.org/en/global-issues/climate-change

[10] International Renewable Energy Agency - IRENA Renewables Policies Database. (2008). Law 20.257. Available in: https://www.iea.org/policies/4853-non-conventional-renewable-energy-law-law-20257

[11] International Renewable Energy Agency - IRENA. Renewable Capacity Statistics 2020. www. Irena.org/Publications, pp. 1-66. ISBN: 978-92-9260-239-0. Available in: https://www.irena.org/Statistics/Download-Data.

[12] Altomonte H. (2017). Las Energías Renovables: panorama mundial, latinoamericano y síntesis de tres estudios de caso. Santiago de Chile: CEPAL, Comisión Económica para América Latina y el Caribe, pp.1-156. Available in: https://www.cepal.org/es/publicaciones/40975-energias-renovables-convencionales-la-matriz-generacion-electrica-tres-estudios

[13] World Economic Forum - WEF. (2020). Fostering Effective Energy Transition, pp.13-52. Available in: http://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2020_Edition.pdf

[14] Departamento Nacional de Planeación - DNP. (2019). Las 20 metas del Pacto por Colombia, pacto por la equidad. Available in: https://www.dnp.gov.co/DNPN/Paginas/Metas-del-Plan-Nacional-de-Desarrollo-2018-2022.aspx

[15] Comisión Reguladora de Energía y Gas - CREG. (1994). Artículo 11 de la Ley 143 de 1994. Available in: http://apolo.creg.gov.co/Publicac.nsf/Indice01/Leyes-1994-Ley143-1994

[16] Empresa de Energía de Bogotá, Universidad Externado de Colombia (1999). Historia de la Empresa de Energía de Bogotá. Bogotá: D`VINNI, 1(66), pp. 1-433. ISBN: 958-616-437-3.

[17] Villamil Guzmán, C. (2014). Antecedentes de energía y electricidad en Colombia y Boyacá en el siglo XIX y XX. Cultura Científica, (12), pp. 30-37. Available in: https://www.jdc.edu.co/revistas/index.php/Cult_cient/article/view/150

[18] Congreso de Colombia. (2003). Ley 855 de 2003. Artículo 1°. Available in: http://www.secretariasenado.gov.co/senado/basedoc/ley_0855_2003.html

[19] Sistema de Información Eléctrico Colombiano - SIEL (2021). Unidad de Planeación Minero Energética, Metodología y resultados de la estimación del Índice de Cobertura de Energía Eléctrica ICEE - 2018. Available in: http://www.siel.gov.co/Inicio/CoberturadelSistemaIntercontecadoNacional/ConsultasEstadisticas/tabid/81/Default.aspx

[20] Unidad de Planeación Minero Energética (2020). Plan Energético Nacional, la transformación energética que habilita el desarrollo sostenible. Available in: https://www1.upme.gov.co/Paginas/Plan-Energetico-Nacional-2050.aspx

[21] Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas - IPSE. (2021). Direccionamiento Estratégico, Misión y Visión. Available in: https://ipse.gov.co/mapa-del-sito/ipse/direccionamiento-estrategico/mision-y-vision/

[22] Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas - IPSE. (2021). Caracterización Energética de las ZNI. Available in: https://ipse.gov.co/cnm/caracterizacion-de-las-zni/https://ipse.gov.co/cnm/caracterizacion-de-las-zni/

[23] Bustos J.F., Sepúlveda A.L., Triviño K. (2014). Zonas NO Interconectadas Eléctricamente en Colombia: Problemas y Perspectivas. Universidad Nacional de Colombia, Econografos, Bogotá.

[24] Compañía Energética de Occidente. (2019). Informe Anual de Gestión. KPMG LTDA. Cauca, Colombia, pp. 1-176. Available in: https://www.ceoesp.com.co/archivos_usuarios/file-3891-InformeGestion2019_CEO_VF.pdf

[25] International Renewable Energy Agency. (2020). Renewable Power Generation Costs in 2019. IRENA, International Renewable Energy Agency, Abu Dhabi, pp. 1-144. ISBN: 978-92 9260-244-4n:

[26] Sidhu, A. S., Pollitt, M. G., & Anaya, K. L. (2018). A social cost benefit analysis of grid-scale electrical energy storage projects: A case study. Applied Energy, (212) pp. 881-894. doi: 10.1016/j.apenergy.2017.12.085

[27] Ministerio de Ciencia, Tecnología e Innovación - Minciencias (2021). Pacífico Pura Energía, La Energía Renovable: Una alternativa de transformación. Available in: https://ideasparaelcambio.minciencias.gov.co/proyecto/pac%C3%ADfico-pura-energ%C3%Ada

[28] Latin American Energy Organization - OLADE. (2017). Energy Planning Manual 2017, (2) pp. 1-335. ISBN.9978-70-120

[29] Paredes J.R. (2017). La Red del Futuro: Desarrollo de una red eléctrica limpia y sostenible para América Latina. Banco Interamericano de Desarrollo - BID. Zetta Comunicadores, (16) pp. 1-58. IDB-MG-565. Available in: https://publications.iadb.org/es/publicacion/14076/la-red-del-futuro-desarrollo-de-una-red-electrica-limpia-y-sostenible-para

[30] Shafiee, Q., Guerrero, J. M., & Vasquez, J. C. (2014). Distributed secondary control for islanded microgrids-a novel approach. IEEE Transactions on Power Electronics, 29 (2), pp. 1018-1031. doi: 10.1109/TPEL.2013.2259506

[31] Josephson M. (2018). Edison - A Biography. Ed. Plunkett Lake Press, United States, pp. (25) 511. ISBN: 978-0965569934

[32] Stevanovic, V. D., Ilic, M., Djurovic, Z., Wala, T., Muszynski, S., & Gajic, I. (2018). Primary control reserve of electric power by feedwater flow rate change through an additional economizer – A case study of the thermal power plant “Nikola tesla B”. Energy, 147, 782-798. doi: 10.1016/j.energy.2018.01.102

[33] Spanggaard, H., & Krebs, F. C. (2004). A brief history of the development of organic and polymeric photovoltaics. Solar Energy Materials and Solar Cells, 83 (2-3), pp. 125-146. doi: 10.1016/j.solmat.2004.02.021

[34] Paterson M. Future Grid Forum. CSIRO Energy Flagship. Available in: https://scsearch.csiro.au/CSIROau?q=australia%202050&site=All&start=0&sort=score%20desc

[35] Hatziargyriou, N. (2013). Microgrids: Architectures and control. Microgrids: Architectures and control, pp. 1-317 doi:10.1002/9781118720677

[36] Liu, M., Wang, C., Guo, L., Zhao, B., Zhang, X., & Liu, Y. (2012). An optimal design method of multi-objective based island microgrid. Dianli Xitong Zidonghua/Automation of Electric Power Systems, 36 (17), 34-39. doi: 10.3969/j.issn.1000-1026.2012.17.007

[37] Ruíz J.M., Montero J.C., Enriquez H.G. (2018). Transición Energética: Ciencia al descubierto. Available in: http://transicionenergetica.ineel.mx/Revista.mvc/CD3n1v1#:~:text=Tipos%20de%20microrredes-,Tipos%20de%20microrredes,y%20corriente%20directa%20(CD).

[38] Centro Nacional de Energías Renovables - CENER. (2021). Introducción a las Microrredes. Available in: http://www.cener.com/introduccion-a-las-microrredes/

[39] Song, M., Shi, J., Liu, Y., & otros. (2015). 100 kJ/50 kWHTS SMES for micro-grid. IEEE Transactions on Applied Superconductivity, 25(3). doi:10.1109/TASC.2014.2386345

[40] Ross, M., Hidalgo R., Abbey C., Joós G. (2010). Analysis of Energy Storage sizing and technologies. Publisher: IEEE Electrical Power & Energy Conference. DOI: 10.1109/EPEC.2010.5697212

[41] Ministerio de Minas y Energía - Minenergía (2007). Artículo 6° de la Resolución del Ministerio de Minas y Energía 182138 de 2007, Ley 142 de 1984, Decreto 381 de 2012. Available in: https://www.minenergia.gov.co/documents/10192/24091568/Resolucio%CC%81n+Subsidios+Fotovolta%CC%81icos+-+Final.pdf/90507218-3614-47da-8b66-3a7d6b1cd9f7

[42] Logenthiran, T., Srinivasan, D., Khambadkone, A. M., & Raj, T. S. (2010). Optimal sizing of an islanded microgrid using evolutionary strategy. Paper presented at the 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2010, pp.12-17. doi:10.1109/PMAPS.2010.5528840

[43] Wang Z., Chen B., Wang J., Kim J., Begovic M. (2014) Robust Optimization Based Optimal DG Placement in Microgrids, Smart Grid IEEE Transactions on, vol. 5, no. 5, pp. 2173-2182. DOI: 10.1109/TSG.2014.2321748

[44] Loh, P. C., Li, D., Chai, Y. K., Blaabjerg, F. (2013). Autonomous operation of hybrid microgrid with ac and dc subgrids. IEEE Transactions on Power Electronics, 28(5), pp. 2214-2223. doi:10.1109/TPEL.2012.2214792

[45] Ibrahim, H., Younès, R., Ilinca, A., Dimitrova, M., & Perron, J. (2010). Study and design of a hybrid wind-diesel-compressed air energy storage system for remote areas. Applied Energy, 87(5), pp. 1749-1762. doi: 10.1016/j.apenergy.2009.10.017

[46] Instituto de Hidrología, Meteorología y Estudios Ambientales (2021). Generalidades del sol: Características de la Radiación Solar. Available in: http://www.ideam.gov.co/web/tiempo-y-clima/generalidades-del-sol

[47] Departamento de Eficiencia Energética y Energías Renovables (2015). Conocimiento de Energía: Principios Esenciales y Conceptos Fundamentales para la Educación de la Energía, Washington: pp. 7-20. Available in: https://www.energy.gov/sites/default/files/2015/04/f21/ConocimientoEnergia_low_res.pdf

[48] Von Appen, J., Braun, M., Stetz, T., Diwold, K., & Geibel, D. (2013). Time in the sun: The challenge of high PV penetration in the german electric grid. IEEE Power and Energy Magazine, 11 (2), pp. 55-64. doi:10.1109/MPE.2012.2234407

[49] Clean Energy Reviews (2021). Most Efficient Solar Panels 2021: Solar Cell Type and Efficiency. Available in: https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

[50] Unidad de Planeación Minero Energética (2006). Atlas del Viento y Energía Eólica en Colombia. Bogotá, (1) 16. Available in: http://www.upme.gov.co/Docs/MapaViento/CAPITULO1.pdf

[51] News of the wind sector in Spain an in the word - REVE (2014). Wind turbines grow into the sky. Available in: https://www.evwind.es/2014/11/05/wind-turbines-grow-into-the-sky/48513

[52] Gallardo T., Fernández J. M. (2011). Guía Completa de la Energía Eólica. Aerogeneradores: Tipos de Aerogeneradores. Madrid: AMV Editores, (8) 246. ISBN 978-8-494-89199-1

[53] Vortex Bladeless (2021). Bladeless Wind Energy: Reinventing wind turbines. The first wind generator without blades or gears Available in: https://vortexbladeless.com/

[54] Laws, N. D., Epps, B. P. (2016). Hydrokinetic energy conversion: Technology, research, and outlook. Renewable and Sustainable Energy Reviews, 57, pp. 1245-1259. doi: 10.1016/j.rser.2015.12.189

[55] Laín, S., Contreras, L. T., & López, O. (2019). A review on computational fluid dynamics modeling and simulation of horizontal axis hydrokinetic turbines. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41(9) doi:10.1007/s40430-019-1877-6

[56] Hidrored. (2002). Red Latinoamericana de Micro Hidroenergía. (2) 16, ISSN 0935 - 0578.

[57] Paish, O. (2002). Small hydro power: Technology and current status. Renewable and Sustainable Energy Reviews, 6(6), pp. 537-556. doi:10.1016/S1364-0321(02)00006-0

[58] Katiraei F., Abbey C. (2007). Diesel plant sizing and performance analysis of a remote wind-diesel microgrid. IEEE Power Eng. Soc. Gen. Meet. PES, pp. 1–8, 2007.

[59] Diesel Generator Direct (2020). The Components of a Diesel Generator. Available in: https://dieselgeneratordirect.uk/how-does-a-diesel-generator-work.html

[60] Comisión Reguladora de Energía y Gas - CREG. (2019). Resolución 098 del 30 de agosto de 2019. Mecanismo para Incorporar Sistema de Almacenamiento de Baterías en el SIN. Available in: http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/28669c6087eb69be0525846c006e9690?OpenDocument

[61] Expóstio A., Sudirà A. (2017). El Almacenamiento de Energía en la Distribución Eléctrica del Futuro. Endesa. Madrid: Grafilia, S.L., pp. 16-180. ISBN 978-84-95662-56-9

[62] Inter-American Development Bank. (2021). Lithium: White Gold fof a Region`s Development. Available in: https://www.iadb.org/en/improvinglives/lithium-white-gold-regions-development

[63] Congreso de Colombia. (1994). Ley 142 de 1994. Artículos 1, 2 y 4. Available in: http://www.secretariasenado.gov.co/senado/basedoc/ley_0142_1994.html

[64] Congreso de Colombia (1994). Ley 143 de 1994. Available in: https://www.minenergia.gov.co/documents/10180/667537/Ley_143_1994.pdf

[65] Congreso de Colombia (2001). Ley 697 de 2001. Available in: http://www.secretariasenado.gov.co/senado/basedoc/ley_0697_2001.html

[66] Congreso de Colombia (2014). Ley 1715 de 2014. Available in: http://www.secretariasenado.gov.co/senado/basedoc/ley_1715_2014.html

[67] Ríos S., Mateos A., Caballeron., Bielza Ma C., Jiménez A. (2004). Investigación operativa: modelos determinísticos y estocásticos. Universitaria Ramón Areces, ISBN 848004666X, 9788480046664.

[68] XM Filial de la empresa Interconexión Eléctrica S.A. E.S.P. - ISA (2021). Consumo: Histórico de Demanda. Available in: https://www.xm.com.co/Paginas/Consumo/historico-de-demanda.aspx

[69] Gussow M. (1997) Fundamentos de Electricidad. México D.F.: McGraw-Hill, pp. 275-453. ISBN 0-07-025240-8

[70] Empresas Públicas de Medellín (2021). Tips para el uso inteligente. Available in: https://www.epm.com.co/site/clientes_usuarios/clientes-y usuarios/empresas/energ%C3%ADa/grandes-empresas/tips-para-el-uso-inteligente

[71] Khanum K., Rao A., Balaji N., Mani M., Ramamurthy P. (2016). Performance evaluation for PV systems to synergistic influences of dust, wind and panel temperatures: Spectral insight. IEEE 43rd Photovoltaic Specialists Conference (PVSC), IEEE: pp. 1-4. DOI 10.1109/PVSC.2016.7749917

[72] Sobczynski D. (2018). Impact of Light Source Spectrum in Laboratory Test of Commercially Available Photovoltaic Panels. IEEE, pp. 1-69, DOI 10.1109/PAEE.2018.8441062

[73] El-Shahat, A., Hasan, M. -., & Wu, Y. (2019). Vortex bladeless wind generator for nano-grids. Paper presented at the GHTC 2018 - IEEE Global Humanitarian Technology Conference, Proceedings, doi:10.1109/GHTC.2018.8601572

[74] Thermal Engineering. (2020). ¿Qué es el número de Reynolds? Available in: https://www.thermal-engineering.org/es/que-es-el-numero-de-reynolds-definicion/

[75] Yanez D. (2018). VIV Resonant Wind Generators. Vortex Bladeless. Available in: https://vortexbladeless.com/download-green-paper/

[76] Howell, R., Qin, N., Edwards, J., & Durrani, N. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. Renewable Energy, 35(2), pp. 412-422. doi: 10.1016/j.renene.2009.07.025

[77] Smart Hidro Power (2021). SMART Irrigation Project in Neiva, Colombia. Available in: https://www.smart-hydro.de/decentralized-rural-electrification-projects-worldwide/colombia-irrigation-project/?noredirect=en_US

[78] Uma, R., Kandpal, T. C., & Kishore, V. V. N. (2004). Emission characteristics of an electricity generation system in diesel alone and dual fuel modes. Biomass and Bioenergy, 27(2), pp. 195-203. doi: 10.1016/j.biombioe.2004.01.003

[79] ENERSIS (2009). Especificación Técnica: Banco de Baterías y Cargador (E-SE- 013). Available in: https://www.eneldistribuicao.com.br/rj/documentos/E-SE-013_R-00.pdf

[80] Guerrero, J. M., Vasquez, J. C., Matas, J., De Vicuña, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids - A general approach toward standardization. IEEE Transactions on Industrial Electronics, 58(1), pp. 158-172. doi:10.1109/TIE.2010.2066534

[81] Zúñiga F.A., Caicedo F.E., López D. (2016). Gestión óptima de la potencia eléctrica en una microrred conectada, basada en el algoritmo genético para optimización multiobjetivo MOGA. UIS Ingenierías, vol. 15, no. 2, pp. 17-33. Available in: https://revistas.uis.edu.co/index.php/revistauisingenierias/article/view/17-33/7414

[82] Abouzahr I., Ramakumar R. (1991). Loss of power supply probability of stand-alone photovoltaic systems: a closed form solution approach. IEEE Transactions on Energy Conversion (6), pp. 1 - 11. DOI 10.1109/60.73783

[83] Fondo de Apoyo Financiero para la Energización de las Zonas no Interconectadas-FAZNI. (2000). Artículo 82 de la Ley 633 de 2000. Available in: https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=6285

[84] Liang, H., Liu, H., & Fan, M. (2012). Optimal planning of microgrid applied in remote rural area. Paper presented at the 44th International Conference on Large High Voltage Electric Systems 2012

[85] Pornoy L. (2001). Los Fundamentos de la Ciencia del Hombre: Vilfredo Pareto. Centro Editor de América Latina, pp. 114. ISBN950-25-2060-2

[86] Munda, G., Nijkamp, P., & Rietveld, P. (1994). Qualitative multicriteria evaluation for environmental management. Ecological Economics, 10(2), pp. 97-112. doi:10.1016/0921-8009(94)90002-7

[87] Winterfeldt V., Fasolo, B. (2009). Structuring decision problems: A case study and reflections for practitioners. European Journal of Operational Research, 199 (3), pp. 857-866. doi: 10.1016/j.ejor.2009.01.063

[88] Saaty T.L. (1980). Multicriteria, Decision Making: The Analytic Hierarchy Process. New York: Mc. Graw-Hill. (2), pp. 36-287. ISBN-10 0070543712

[89] Bateman J. (2021). March 2021 and year to date were among Earth's top-10 warmest: Arctic sea ice coverage was 9th smallest on record for the month. National Oceanic and Atmospheric Administration-NOAA. Available in: https://www.noaa.gov/news/march-2021-and-year-to-date-were-among-earth-s-top-10-warmest

[90] Greene T., Jacobs P. (2021). 2020 Tied for Warmest Year on Record, NASA Analysis Shows. National Aeronautics and Space Administration-NASA. Available in: https://www.nasa.gov/press-release/2020-tied-for-warmest-year-on-record-nasa-analysis-shows

[91] Thom, C. (2000). Use of grid electricity by rural households in South Africa. Energy for Sustainable Development, (4), pp. 36-43. doi: 10.1016/S0973-0826(08)60262-8

[92] Murni, S., Whale, J., Urmee, T., Davis, J., & Harries, D. (2012). The role of micro hydro power systems in remote rural electrification: A case study in the Bawan Valley, Borneo. Paper presented at the Procedia Engineering, (49), pp. 189-196. doi: 10.1016/j.proeng.2012.10.127

[93] Syahputra, R., & Soesanti, I. (2021). Renewable energy systems based on micro-hydro and solar photovoltaic for rural areas: A case study in Yogyakarta, Indonesia. Energy Reports,7, pp. 472-490. doi: 10.1016/j.egyr.2021.01.015

[94] Asmus P. (2019). Microgrids Ramp Up in Latin America but Asia Pacific Remains the Global Leader. Microgrid Knowledge. Available in: https://microgridknowledge.com/microgrids-navigant/

[95] Qu, C., Sun, W., Sun, Y., Qi, W., He, G., & Gan, J. (2019). Study on reactive voltage regulation and optimal control strategy of PV power station considering energy storage system. Paper presented at the IET Conference Publications, 2019(CP764) doi:10.1049/cp.2019.0497

[96] Marcus, A. A. (2015). Innovations in sustainability: Fuel and food. Innovations in sustainability: Fuel and food, pp. 1-363. doi:10.1017/CBO9781139680820

[97] World Energy Trade (2020). BayWa construye un sistema híbrido de energía solar-eólica en Alemania. Available in: https://www.worldenergytrade.com/energias-alternativas/energia-solar/baywa-construye-un-sistema-hibrido-de-energia-solar-eolica-en-alemania

[98] Semeraro, T., Pomes, A., Del Giudice, C., Negro, D., & Aretano, R. (2018). Planning ground based utility scale solar energy as green infrastructure to enhance ecosystem services. Energy Policy, 117, pp. 218-227. doi: 10.1016/j.enpol.2018.01.050

[99] Sanz, F., Montalvo, G., López, A. L., Piñeiro, C., Bigeriego, M., & Sanz, M. J. (2012). Ammonia and methane emissions from a dairy farm in Segovia (Spain). doi:10.3920/978-90-8686-741-7_5

[100] Komiyama, R., Otsuki, T., & Fujii, Y. (2015). Energy modeling and analysis for optimal grid integration of large-scale variable renewables using hydrogen storage in japan. Energy, 81, pp. 537-555. doi: 10.1016/j.energy.2014.12.069

[101] Padmavathi, K., & Daniel, S. A. (2013). Performance analysis of a 3MWp grid connected solar photovoltaic power plant in India. Energy for Sustainable Development, 17(6), pp. 615-625. doi: 10.1016/j.esd.2013.09.002

[102] Statista (2020). Países con mayor capacidad de producción de energías renovables en América Latina y el Caribe en 2019. Available in: https://es.statista.com/estadisticas/1076835/energia-renovable-capacidad-america-latina-por-pais/

[103] Instituto de Meteorología y Estudios Ambientales - IDEAM (2021). Available in: http://www.ideam.gov.co/

[104] Xu Z.R., Yang P., Chen Z., Yang C.M., Zheng Q., Zheng C.L. (2015). Energy management strategy for medium-voltage Isolated microgrid. Yokohama: IECON 2015, pp 80-85. doi: 10.1109/IECON.2015.7392079

[105] Unidad de Planeación Minero Energética-UPME. (2019). Plan Indicativo de Expansión de Cobertura de Energía Eléctrica (PIEC 2019-2023). UPME, pp 19-58. Available in: http://www.upme.gov.co/Siel/Siel/Portals/0/Piec/Informacion_Base_PIEC_Dic302019.pdf

[106] Ministerio de Minas y Energía - Minenergía (2014). Manual guía para la formulación, presentación y registro de proyectos para acceder a los recursos del Fondo de Apoyo Financiero para la Energización de las Zonas No Interconectadas - FAZNI. Available in: https://www.minenergia.gov.co/documents/10180/468021/Manual_FAZNI.pdf

[107] Unidad de Planeación Minero Energética-UPME (2015). Guía para la elaboración de un Plan de Energización Rural Sostenible (PERS). Bogotá: Escripo S.A.S., pp. 11-38. ISBN 978-958-8363-27-1. Available in: http://www.siel.gov.co/portals/0/fondos/Guia_de_un_PERS.pdf

[108] Garzón H., Saavedra A.J. (2017). Una metodología de diseño de micro redes para zonas no interconectadas de Colombia. TecnoLógicas. 20. 39-53. doi: 10.22430/22565337.687.

[109] Osorio J.C., Orejuela J.P. (2008). El Proceso de Análisis Jerárquico (AHP) y la Toma de Decisiones Multicriterio: Ejemplo de Aplicación. Scientia Et Technica, vol. 14, (39), pp. 247-252. ISSN 0122-1701

[110] Instituto de Hidrología, Meteorología y Estudios Ambientales (2017). Promedios Mensuales de Brillo Solar. Available in: http://atlas.ideam.gov.co/basefiles/6.Anexo_Promedios-mensuales-de-brillo-solar.pdf

[111] Instituto de Hidrología, Meteorología y Estudios Ambientales (2017). Atlas de Viento de Colombia. Bogotá: Imprenta Nacional de Colombia, pp. 44-158. ISSN 978 958 8067 96 4. Available in: http://www.andi.com.co/Uploads/VIENTO.compressed.pdf

[112] Corporación Autónoma Regional del Valle del Cauca-CVC. (2017). Evaluación Regional del Agua. Available in: https://www.cvc.gov.co/sites/default/files/2018-10/EVALUACION_REGIONAL_AGUA_Ajustes2018_2.pdf

[113] Departamento Administrativo Nacional de Estadística-DANE (2018). Resultados Censo Nacional de Población y Vivienda 2018. Available in: https://www.dane.gov.co/files/censo2018/informacion-tecnica/presentaciones-territorio/190814-CNPV-presentacion-Resultados-generales-Cauca.pdf

[114] Alcaldía López de Micay (2020). Available in: https://www.lopezdemicay-cauca.gov.co/

[115] Alcaldía Municipal de Timbiquí - Cauca (2021). Available in: http://www.timbiqui-cauca.gov.co/

[116] Alcaldía Municipal de Guapí - Cauca. (2021). Guapí somos todos. Available in: http://www.guapi-cauca.gov.co/

[117] Zangeneh, A., Jadid, S., & Rahimi-Kian, A. (2009). A hierarchical decision making model for the prioritization of distributed generation technologies: A case study for Iran. Energy Policy, 37 (12), 5752-5763. doi: 10.1016/j.enpol.2009.08.045

[119] Expertchoice (2021). Available in: https://www.expertchoice.com/2021

[120] AHP Online System - AHP-OS (2021). Available in: https://bpmsg.com/ahp/

[121] SuperDecisions (2021). Available in: http://www.superdecisions.com/

[122] Bahramara, S., Moghaddam, M. P., & Haghifam, M. R. (2016). Optimal planning of hybrid renewable energy systems using HOMER: A review. Renewable and Sustainable Energy Reviews, 62, 609-620. doi: 10.1016/j.rser.2016.05.039

[123] Fundación delMacizo, Casa del Cauca (2021). Información Básica Territorial del Cauca. Available in: http://fundaciondelmacizo.org/2013/08/informacion-basica-territorial-del-cauca/

[124] Las distancias.net. (2021). Distancia de San Isidro a López de Micay. Available in: http://co.lasdistancias.net/calcular?from=zaragoza%2C+cauca&to=lopez+de+micay%2C+cauca

[125] Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas - IPSE. (2021). Informe Mensual de Telemetría: marzo 1-31 de 2021, pp. 167-506. Available in: https://ipse.gov.co/documentos_cmn/documentos/informes_mensuales_de_telemetria/2021/marzo/informe%20mensual%20de%20telemetria%20marzo%202021.pdf

[126] Ministerio de Minas y Energía (Minenergía). 2021. Precios de Combustibles Año 2021: Precios Año 2021 vigentes a partir del 14 de abril. Available in: https://www.minenergia.gov.co/precios-ano-2021

[127] Superintendencia Financiera de Colombia (SFC). 2021. Tasa de Cambio Representativa del Mercado- TRM. [consulted 5 May 2021]. Available in: https://www.superfinanciera.gov.co/inicio/informes-y-cifras/cifras/establecimientos-de-credito/informacion-periodica/diaria/tasa-de-cambio-representativa-del-mercado-trm-60819

14. ANNEXES

Annex A. United Nations: Sustainable Development Goals

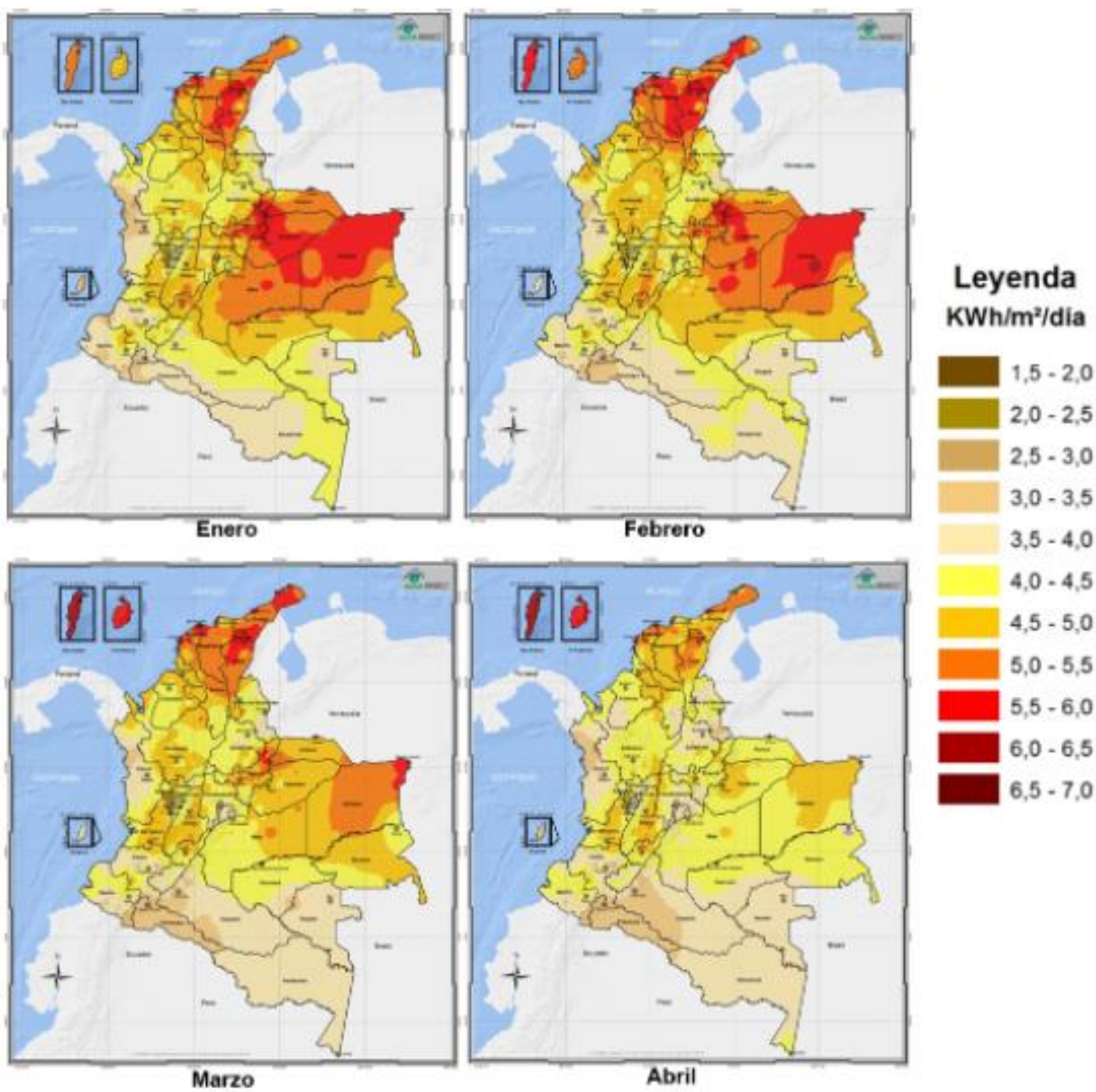
Annex B. Electricity Coverage Index in Cauca – ICEE 2018.

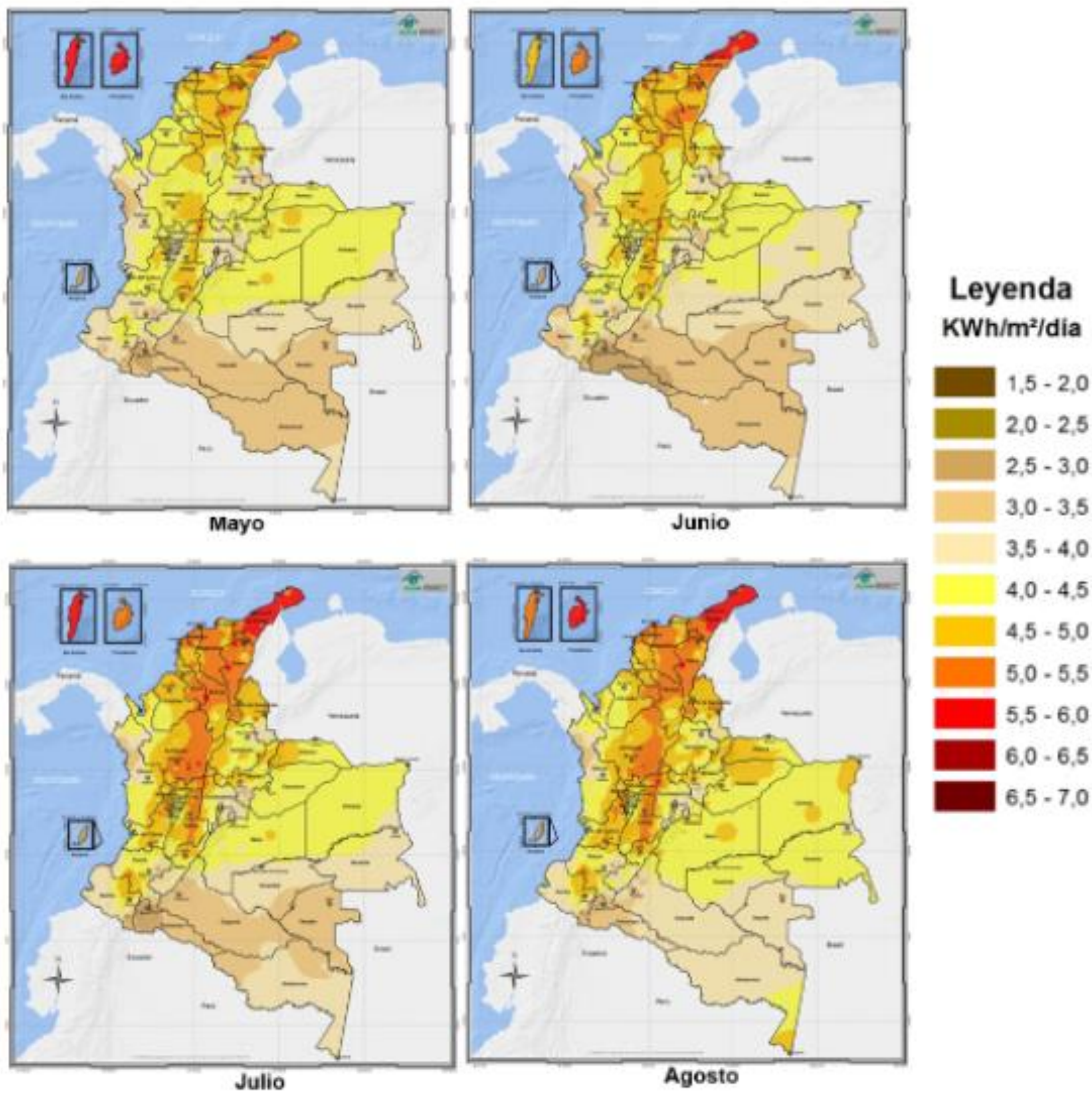
				USUARIOS REPORTADOS A LA UPME									
Depto		**Cod-DANE**	**Municipio**	Usuarios Cabecera Municipal SIN	Usuarios Resto SIN	**Usuarios Total SIN**	Usuario Barrios Subnormales	Usuarios Zonas de Dificil Gestion	Usuario Areas Rurales de menor desarrollo	Usuarios Cabecera municipal ZNI	Usuario Resto ZNI	**Usuarios total ZNI**	OR quien reporta información de Usuarios
Cauca	19	19001	Popayán	83.928	12.612	96.540	-	-	-	-	-	-	CEO - 2018
Cauca	19	19022	Almaguer	585	4.538	5.123	-	-	-	-	-	-	CEO - 2018
Cauca	19	19050	Argelia	780	6.704	7.484	38	-	-	-	-	-	CEO - 2018
Cauca	19	19075	Balboa	1.625	4.272	5.897	-	-	-	-	-	-	CEO - 2018
Cauca	19	19100	Bolívar	1.697	9.743	11.440	-	-	-	-	-	-	CEO - 2018
Cauca	19	19110	Buenos Aires	972	6.108	7.080	-	-	-	-	-	-	CEO - 2018
Cauca	19	19130	Cajibío	680	9.532	10.212	-	-	-	-	-	-	CEO - 2018
Cauca	19	19137	Caldono	627	8.299	8.926	-	-	-	-	-	-	CEO - 2018
Cauca	19	19142	Caloto(1)(3)	1.748	5.966	7.714	-	-	-	-	-	-	CEO - 2018
Cauca	19	19212	Corinto	4.105	4.768	8.873	-	-	-	-	-	-	CEO - 2018
Cauca	19	19256	El Tambo	1.043	12.830	13.873	-	-	-	-	-	-	CEO - 2018
Cauca	19	19290	Florencia	383	1.010	1.393	-	-	-	-	-	-	CEO - 2018
Cauca	19	19300	Guachené (1)	1.810	3.706	5.516	-	-	-	-	-	-	CEO - 2018
Cauca	19	19318	Guapi	-	-	-	-	-	-	2.198	1.297	3.495	IPSE - 2018
Cauca	19	19355	Inzá	457	6.926	7.383	-	-	-	-	-	-	CEO - 2018
Cauca	19	19364	Jambaló	300	2.764	3.064	-	-	-	-	-	-	CEO - 2018
Cauca	19	19392	La Sierra	520	2.958	3.478	-	-	-	-	-	-	CEO - 2018
Cauca	19	19397	La Vega	443	6.312	6.755	-	-	-	-	-	-	CEO - 2018
Cauca	19	19418	López	-	-	-	-	-	-	3.163	2.489	5.652	IPSE - 2018
Cauca	19	19450	Mercaderes	1.863	2.975	4.838	-	-	-	-	-	-	CEO - 2018
Cauca	19	19455	Miranda	6.229	3.279	9.508	-	-	-	-	-	-	CEO - 2018
Cauca	19	19473	Morales	769	6.611	7.380	-	-	-	-	-	-	CEO - 2018
Cauca	19	19513	Padilla	1.291	1.336	2.627	-	-	-	-	-	-	CEO - 2018
Cauca	19	19517	Paez	1.052	5.791	6.843	-	-	-	-	-	-	CEO - 2018
Cauca	19	19532	Patía	3.959	5.512	9.471	-	-	-	-	-	-	CEO - 2018
Cauca	19	19533	Piamonte	938	494	1.432	-	-	-	-	-	-	EEPUTUMAYO - 2018
Cauca	19	19548	Piendamó	4.608	7.110	11.718	-	-	-	-	-	-	CEO - 2018
Cauca	19	19573	Puerto Tejada	6.150	1.734	7.884	-	2.557	-	-	-	-	EMCALI - 2018; CEO - 2018
Cauca	19	19585	Puracé	264	2.820	3.084	-	-	-	-	-	-	CEO - 2018
Cauca	19	19622	Rosas	392	2.783	3.175	-	-	-	-	-	-	CEO - 2018
Cauca	19	19693	San Sebastián	215	3.011	3.226	-	-	-	-	-	-	CEO - 2018
Cauca	19	19698	Santander de Quilichao	19.846	13.438	33.284	-	-	-	-	-	-	CEO - 2018
Cauca	19	19701	Santa Rosa	329	1.518	1.847	-	-	-	-	-	-	CEO - 2018; EEPUTUMAYO - 20
Cauca	19	19743	Silvia	1.935	6.324	8.259	-	-	-	-	-	-	CEO - 2018
Cauca	19	19760	Sotara	213	3.295	3.508	-	-	-	-	-	-	CEO - 2018
Cauca	19	19780	Suárez	1.447	4.194	5.641	-	-	-	-	-	-	CEO - 2018
Cauca	19	19785	Sucre	477	1.738	2.215	-	-	-	-	-	-	CEO - 2018
Cauca	19	19807	Timbío	4.068	6.287	10.355	-	-	-	-	-	-	CEO - 2018
Cauca	19	19809	Timbiquí	-	-	-	-	-	-	3.031	3.726	6.757	IPSE - 2018
Cauca	19	19821	Toribio	693	8.332	9.025	-	-	-	-	-	-	CEO - 2018
Cauca	19	19824	Totoró	247	4.455	4.702	-	-	-	-	-	-	CEO - 2018
Cauca	19	19845	Villa Rica	3.978	1.822	5.800	-	-	-	-	-	-	CEO - 2018
CAUCA	19			162.666	203.907	366.573	38	2.557	-	8.392	7.512	15.904	

1) Contiene los usuarios de ZNI reportados por el IPSE
2) Respecto a la información de viviendas:
* Viv. PP CNPV/18: Corresponde al reporte de viviendas con personas presentes del censo nacional de poblacion y vivienda 2018.
** Viv. PP, PA y UT CNPV/18: Corresponde al reporte de viviendas con personas presentes, con personas ausentes o categorizadas como de uso temporal del censo nacional de poblacion y vivienda 2018.

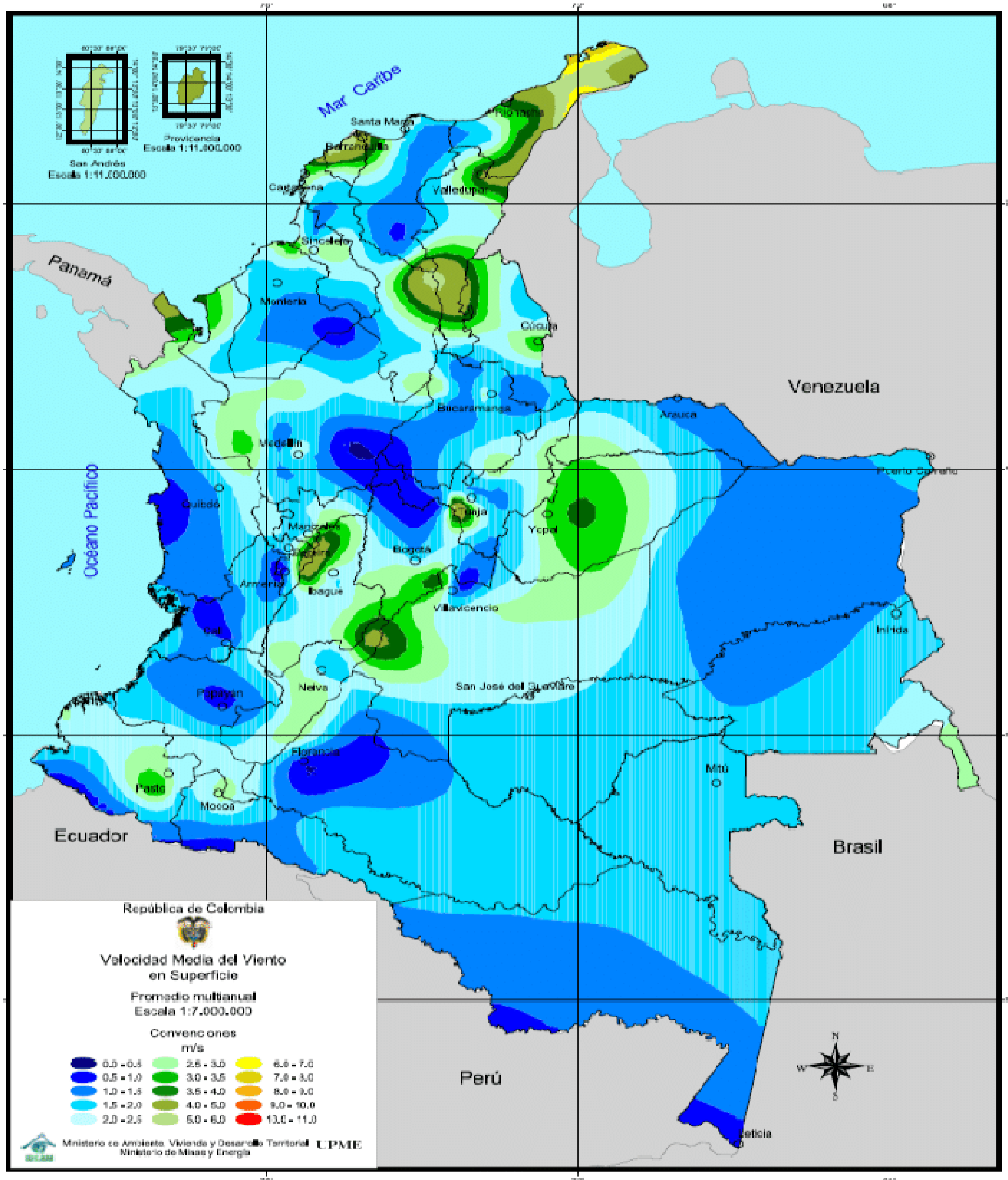
USUARIOS PARA LA ESTIMACIÓN DEL ICEE (1)				VIVIENDAS AJUSTADAS PARA LA ESTIMACIÓN DEL ICEE (2)				VIVIENDAS SIN SERVICIO - VSS				INDICE DE COBERTURA DE ENERGIA ELÉCTRICA - ICEE		
Total Usuarios Cabecera Municipal	Total Usuarios Resto	**Total Usuarios**	**Fuente de información**	Viviendas Cabecera municipal	Viviendas Resto	**Total Viviendas**	**Fuente de información**	VSS Cabecera Municipal	VSS Resto	**VSS Totales**	**Fuente de información**	ICEE cabecera municipal	ICEE resto	**ICEE Total**
83.928	12.612	96.540	*OR*	83.928	12.900	96.828	*OR*	-	288	288	*OR*	100,00%	97,77%	99,70%
585	4.538	5.123	*OR*	599	5.419	6.018	*Viv. PP CNPV/ 18**	14	881	895	*CNPV/ 18*	97,66%	83,74%	85,13%
818	6.704	7.522	*OR*	835	7.369	8.204	*Viv. PP CNPV/ 18**	17	665	682	*CNPV/ 18*	97,96%	90,98%	91,69%
1.625	4.272	5.897	*OR*	1.636	4.557	6.193	*OR*	11	285	296	*CNPV/ 18*	99,33%	93,75%	95,22%
1.697	9.743	11.440	*OR*	1.710	10.652	12.362	*Viv. PP CNPV/ 18**	13	909	922	*CNPV/ 18*	99,24%	91,47%	92,54%
972	6.108	7.080	*OR*	983	6.969	7.952	*Viv. PP CNPV/ 18**	11	861	872	*CNPV/ 18*	98,88%	87,65%	89,03%
680	9.532	10.212	*OR*	693	10.509	11.202	*Viv. PP CNPV/ 18**	13	977	990	*CNPV/ 18*	98,12%	90,70%	91,16%
627	8.299	8.926	*OR*	638	8.975	9.613	*Viv. PP CNPV/ 18**	11	676	687	*CNPV/ 18*	98,28%	92,47%	92,85%
1.748	5.966	7.714	*OR*	1.762	6.483	8.245	*Viv. PP CNPV/ 18**	14	517	531	*CNPV/ 18*	99,21%	92,03%	93,56%
4.105	4.768	8.873	*OR*	4.140	5.211	9.351	*Viv. PP CNPV/ 18**	35	443	478	*CNPV/ 18; OR*	99,15%	91,50%	94,89%
1.043	12.830	13.873	*OR*	1.062	14.524	15.586	*Viv. PP CNPV/ 18**	19	1.694	1.713	*CNPV/ 18*	98,21%	88,34%	89,01%
383	1.010	1.393	*OR*	391	1.045	1.436	*Viv. PP CNPV/ 18**	8	35	43	*CNPV/ 18*	97,95%	96,65%	97,01%
1.810	3.706	5.516	*OR*	1.824	3.824	5.648	*OR*	14	118	132	*CNPV/ 18*	99,23%	96,91%	97,66%
2.198	1.297	3.495	*OR*	2.574	3.870	6.444	*OR*	376	2.573	2.949	*CNPV/ 18*	85,39%	33,51%	54,24%
457	6.926	7.383	*OR*	460	7.562	8.022	*Viv. PP CNPV/ 18**	3	636	639	*CNPV/ 18*	99,35%	91,59%	92,03%
300	2.764	3.064	*OR*	300	3.565	3.865	*OR*	-	801	801	*OR; PROYECTOS*	100,00%	77,53%	79,28%
520	2.958	3.478	*OR*	520	3.427	3.947	*OR; Viv. PP, PA y UT CNPV/ 18***	-	469	469	*OR*	100,00%	86,31%	88,12%
443	6.312	6.755	*OR*	447	6.537	6.984	*Viv. PP CNPV/ 18**	4	225	229	*CNPV/ 18*	99,11%	96,56%	96,72%
3.163	2.489	5.652	*OR*	3.180	5.003	8.183	*OR*	17	2.514	2.531	*CNPV/ 18*	99,47%	49,75%	69,07%
1.863	2.975	4.838	*OR*	1.887	3.191	5.078	*Viv. PP CNPV/ 18**	24	216	240	*CNPV/ 18*	98,73%	93,23%	95,27%
6.229	3.279	9.508	*OR*	6.251	3.488	9.739	*Viv. PP CNPV/ 18**	22	209	231	*CNPV/ 18*	99,65%	94,01%	97,63%
769	6.611	7.380	*OR*	793	8.311	9.104	*Viv. PP CNPV/ 18**	24	1.700	1.724	*CNPV/ 18*	96,97%	79,55%	81,06%
1.291	1.336	2.627	*OR*	1.318	1.362	2.680	*Viv. PP CNPV/ 18**	27	26	53	*CNPV/ 18*	97,95%	98,09%	98,02%
1.052	5.791	6.843	*OR*	1.072	7.669	8.741	*Viv. PP CNPV/ 18**	20	1.878	1.898	*CNPV/ 18*	98,13%	75,51%	78,29%
3.959	5.512	9.471	*OR*	3.996	6.272	10.268	*Viv. PP CNPV/ 18**	37	760	797	*CNPV/ 18*	99,07%	87,88%	92,24%
938	494	1.432	*OR*	989	1.358	2.347	*OR*	51	864	915	*CNPV/ 18*	94,84%	36,38%	61,01%
4.608	7.110	11.718	*OR*	4.659	7.518	12.177	*Viv. PP CNPV/ 18**	51	408	459	*CNPV/ 18*	98,91%	94,57%	96,23%
8.707	1.734	10.441	*OR*	10.300	1.742	12.042	*Viv. PP CNPV/ 18**	1.593	8	1.601	*CNPV/ 18*	84,53%	99,54%	86,70%
264	2.820	3.084	*OR*	275	3.322	3.597	*OR*	11	502	513	*CNPV/ 18*	96,00%	84,89%	85,74%
392	2.783	3.175	*OR*	395	2.889	3.284	*Viv. PP CNPV/ 18**	3	106	109	*CNPV/ 18*	99,24%	96,33%	96,68%
215	3.011	3.226	*OR*	225	3.225	3.450	*Viv. PP CNPV/ 18**	10	214	224	*CNPV/ 18*	95,56%	93,36%	93,51%
19.846	13.438	33.284	*OR*	19.914	13.858	33.772	*Viv. PP CNPV/ 18**	68	420	488	*CNPV/ 18*	99,66%	96,97%	98,56%
329	1.518	1.847	*OR*	331	1.783	2.114	*Viv. PP CNPV/ 18**	2	265	267	*CNPV/ 18*	99,40%	85,14%	87,37%
1.935	6.324	8.259	*OR*	1.952	7.059	9.011	*Viv. PP CNPV/ 18**	17	735	752	*CNPV/ 18*	99,13%	89,59%	91,65%
213	3.295	3.508	*OR*	213	3.598	3.811	*Viv. PP CNPV/ 18**	-	303	303	*CNPV/ 18*	100,00%	91,58%	92,05%
1.447	4.194	5.641	*OR*	1.464	4.652	6.116	*OR*	17	458	475	*CNPV/ 18*	98,84%	90,15%	92,23%
477	1.738	2.215	*OR*	491	1.903	2.394	*Viv. PP CNPV/ 18**	14	165	179	*CNPV/ 18*	97,15%	91,33%	92,52%
4.068	6.287	10.355	*OR*	4.086	6.567	10.653	*Viv. PP CNPV/ 18**	18	280	298	*CNPV/ 18*	99,56%	95,74%	97,20%
3.031	3.726	6.757	*OR*	3.123	6.736	9.859	*OR*	92	3.010	3.102	*CNPV/ 18*	97,05%	55,31%	68,54%
693	8.332	9.025	*OR*	695	8.647	9.342	*Viv. PP CNPV/ 18**	2	315	317	*CNPV/ 18*	99,71%	96,36%	96,61%
247	4.455	4.702	*OR*	256	5.571	5.827	*OR*	9	1.116	1.125	*CNPV/ 18*	96,48%	79,97%	80,69%
3.978	1.822	5.800	*OR*	4.007	1.851	5.858	*OR; Viv. PP, PA y UT CNPV/ 18***	29	29	58	*CNPV/ 18*	99,28%	98,43%	99,01%
173.653	211.419	385.072		176.374	240.973	417.347		2.721	29.554	32.275		98,46%	87,74%	92,27%

Annex C. Global Horizontal Irradiation in Colombia




Mayo
Junio
Julio
Agosto
Leyenda
KWh/m²/día
1,5 - 2,0
2,0 - 2,5
2,5 - 3,0
3,0 - 3,5
3,5 - 4,0
4,0 - 4,5
4,5 - 5,0
5,0 - 5,5
5,5 - 6,0
6,0 - 6,5
6,5 - 7,0

Annex D. Annual wind map of Colombia.



Annex E. Hydrological Map of the Pacific Region in Colombia