**Title: Sustainable energy solutions in Colombia based on isolated DC microgrids**

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# Sustainable energy solutions in Colombia based on isolated DC microgrids

Soluciones energéticas sostenibles en Colombia basadas en microrredes DC aisladas

UNIVERSIDAD DE ANTIOQUIA 1803

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KEYWORDS:
Energy transition, levelized cost of energy, net present cost, non-conventional renewable energy sources, non-interconnected zones, regulation.

**ABSTRACT:** Nowadays the world's energy transition is transforming the paradigm of how power systems are being developed. This is causing new alternative systems to be included into these power grids. One of these alternatives is the DC microgrids that, due to their reliability, operability, and control characteristics, are currently considered sustainable solutions within this energy transition. This paper outlines the inclusion of DC microgrids as a technological solution to the problem of Non-Interconnected Zones (NIZ) in Colombia. Specifically, this study presents a detailed comparison of a DC microgrid with respect to an AC microgrid, discusses regulatory issues for the inclusion of these elements in the National Interconnected System (NIS), and evaluates a case study in a NIZ of Colombia such as Vigía del Fuerte in Antioquia. Based on the results, it is clearly deduced that DC microgrids are a feasible and profitable solution in NIZ in Colombia and these DC small-scale grids may decrease the total Net Present Cost ($NPC$) and the Levelized Cost of Energy ($LCOE$) by 10% for both, compared to AC microgrids for different microgrid configurations. Additionally, regarding these sustainable initiatives, it is essential to standardize the procedures associated with the commissioning of the microgrids, especially with the aspects of connection, protections, and operational adjustments if required by the regional utility company.

**RESUMEN:** Actualmente la transición energética del mundo está transformando el paradigma de cómo se están desarrollando los sistemas de potencia. Esto está provocando que nuevos sistemas alternativos sean incluidos en estas redes eléctricas. Una de estas alternativas son las microrredes DC que, por sus características de fiabilidad, operatividad y control, se consideran actualmente como soluciones sostenibles dentro de esta transición energética. Este artículo describe la inclusión de microrredes DC como un desarrollo tecnológico a la problemática de las Zonas No Interconectadas (ZNI) en Colombia. Específicamente, este estudio presenta una comparación detallada de una microrred DC con respecto a una microrred AC, discute aspectos regulatorios para la inclusión de estos elementos al Sistema Interconectado Nacional (SIN) y evalúa un caso de estudio en una ZNI de Colombia como Vigía del Fuerte en Antioquia. Basado en los resultados, se deduce claramente que las microrredes DC son una solución factible y rentable en ZNI de Colombia y estas redes DC de pequeña escala pueden disminuir el Valor Presente Neto ($VPN$) total y el Costo Nivelado de Energía ($CNE$) en 10% para ambos, en comparación con las microrredes AC para diferentes configuraciones de la microrred. Adicionalmente, por lo que se refiere a estas iniciativas sustentables, es esencial estandarizar los procedimientos asociados al comisionamiento de las microrredes, especialmente con los aspectos de conexión, protecciones y ajustes operativos si son requeridos por la compañía operadora de red local.



## 1. Introduction

The progressive increase in the earth's temperature due to Carbon Dioxide ($CO_2$) emissions endangers sustainable development. These $CO_2$ emissions are largely caused by the use of fossil fuels (oil, coal, diesel, and natural gas) in activities such as transportation, industry, and electricity generation. In this sense, emerging technologies and greater environmental awareness encourage the use of Non-Conventional Renewable Energy Sources (NCRES), which have a lower environmental impact. In Colombia, the penetration of NCRES is coordinated by the Unidad de Planeación Minero Energética (UPME), and it is expected that the participation of the NCRES will increase by the end of 2030, as indicated in figure 1. With these NCRES proposals, the dynamics would change from traditional electrical sources, which do not visualize the integration of intermittent energy sources, such as wind energy and solar photovoltaic. Diversification in energy sources helps offset the impacts of the El Niño phenomenon's dry season, which can lead to electricity price hikes of as much as 4%. These increases are primarily attributed to rising market electricity costs, driven by additional expenses for thermal generation fuels and electricity imports from the regional market [1].

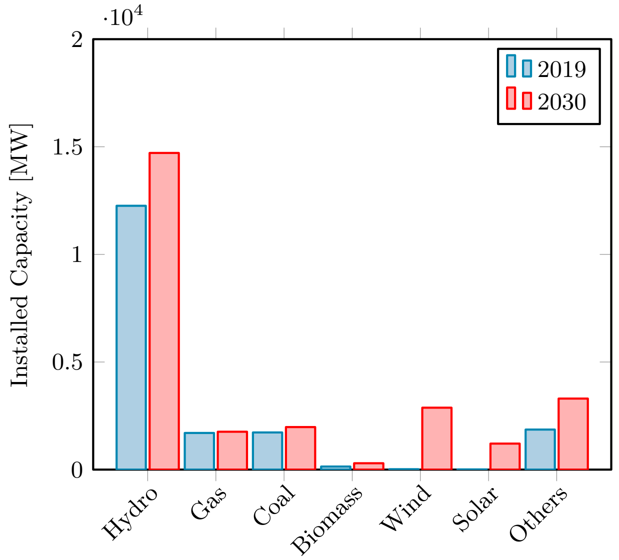


**Figure 1** Prospect of installed capacity in Colombia from 2019 to 2030 [1].

Under this transition scenario, NCRES technologies and their high penetration into modern electrical systems have modified their planning, operation, and control dynamics [2], leading the well-known microgrids [3, 4]. A microgrid is a localized grouping of electricity generation, energy storage, and loads that normally operates connected to and synchronous with the traditional large-scale power grid (macrogrid), but can also disconnect and function autonomously as physical and/or economic conditions dictate [5, 6]. These modern electric technologies have been considered important in the operation of electric power systems due to their efficiency, reliability, and controllability [6–8]. At the same time, these elements are subjected to political, regulatory, and technical challenges with the aim to be implemented, due to the variety, the location, and the control of NCRES within these energy systems [9].

In non-interconnected areas, such as rural areas, remote islands, or alpine regions, electric microgrids can provide a reliable and sustainable solution for electricity generation and distribution [7, 10, 11]. For example, Nasir et al. in [10] evaluates multiple factors that could influence the operational effectiveness of centralized microgrids for rural electrification. In addition, in [11] the authors presented a review of microgrids in latin america and discussed several microgrids as sustainable energy solutions to provide electricity to small communities off the main grid. One of the key benefits of electric microgrids in non-interconnected areas is their ability to improve energy security and reduce dependence on fossil fuels. Microgrids can also promote economic development by providing access to electricity for businesses and households.

Despite the incorporation of these microgrids into the distribution systems, there is a geographic population in Colombia that is not served by the public electricity service through the NIS. These populations are known as NIZ. According to [12], there are 1718 localities representing the NIZ in Colombia, which constitute 52% of Colombia's territory.

Numerous microgrid-based energy solutions have been devised for Colombia's NIZ. In [9], the authors conducted a comprehensive examination of off-grid energy solutions. In localities like Bolivar, Chocó, Guainía, and Magdalena, they observed the adoption of AC microgrids powered by diesel generators alongside photovoltaic systems, providing sustainable energy solutions for these communities. Conversely, in places like Caquetá, Chocó, and Vaupés, AC microgrids integrated with small hydropower plants have been employed. Notably, Nazareth in La Guajira saw the implementation of an AC microgrid powered by a combination of diesel, solar, and wind turbine sources.

In a separate study [13], a proposal was made for designing and implementing an isolated microgrid in northern Colombia, specifically for Wayúu communities lacking access to energy services. This microgrid relies on a wind turbine, photovoltaic system, and energy storage system. Additionally, in their research outlined in [14], the authors introduced a methodology for designing AC microgrids in isolated areas like Málaga and Buenaventura. This approach entails evaluating components such as photovoltaic systems, energy storage systems, wind turbines, and diesel generators. Moreover, Garzon and Saavedra in [15] proposed an approach for designing microgrids in Remote, Unconnected Areas of Colombia. However, the proposed methodology is focused to AC microgrids. Furthermore, [16] introduced an AC microgrid project situated in the Nuquí region of Chocó, equipped with solar panels, hydroelectric centrals, batteries, and multiple diesel units. Lastly, [17] presented an AC microgrid incorporating photovoltaic systems, energy storage systems, and wind turbines, integrated into the distribution grid of the University of Nariño in Colombia.

Hence, the impact of diesel-based AC microgrids on

NIZ is readily apparent. Furthermore, data from [12] and [9] indicate that approximately 96% of the electricity generated in these communities is derived from diesel, with the remaining 4% sourced from alternative energy outlets. Incorporating NCRES into NIZ presents a significant challenge, primarily in ensuring that microgrid solutions are resilient in the face of variable weather conditions, promoting uninterrupted electricity supply for these communities. Nevertheless, there has been limited discussion on the adoption of DC microgrids as sustainable solutions within these regions [18]. As a result, this paper aims to delineate the significance and constituents of DC microgrids. It also initiates a discussion concerning the regulatory considerations associated with integrating these technological components into the existing power infrastructure within the NIZ. Moreover, the choice of Vigía del Fuerte as the focal point is justified, along with the provision of an electrical load estimate. Following that, the DC microgrid proposition is put into action using Homer Pro, a tool designed to simplify the planning, simulation, and assessment of microgrid systems with diverse components. Furthermore, it enables the economic appraisal of microgrid initiatives, considering metrics like $NPC$ and $LCOE$. This evaluation ultimately results in a comprehensive comparison between DC and AC microgrids, offering a thorough exploration of their individual advantages.

Here, this paper presents an optimal economic framework for sizing hybrid micro-grids, aimed at conducting a profitability analysis within renewable-energy-based micro-grids located in Colombian NIZ. In this economic analysis, it is considered a consistent power demand that varies over time. By incorporating this temporal fluctuation, the optimization model determines the most practical approach to meet the changing demand. Additionally, the paper evaluates the performance of the optimal economic framework over two microgrids for Vigía del Fuerte as NIZ. The main contributions of this paper include the following:

- An economic framework is proposed for optimal sizing hybrid DC micro-grid for NIZ in Colombia.
- This paper proposed and discussed a specific procedure for implementing isolated and grid-connected microgrids.
- It also proposed a discussion concerning the regulatory considerations associated with integrating DC microgrids into the existing power infrastructure within the NIZ.
- The use of DC microgrids is validated by a comparison with their energy efficiency, economic operation and financial return with a similar AC configuration.

# 2. DC Microgrid Components

Considering the increasing prevalence of DC loads and NCRES, DC microgrids offer the potential for greater advantages over AC microgrids. This advantage stems from their ability to bypass the need for generator synchronization, reduce converter usage, simplify the integration of diverse NCRES and loads into the microgrid common bus with straightforward interfaces, and mitigate losses associated with AC-DC energy conversion [19, 20]. Additionally, equipment used for energy storage interfaces more efficiently with a DC microgrid compared to an AC microgrid. Many commonly used household devices, such as computers, cell phone chargers, and televisions, operate on DC voltage. Currently, these devices require AC-DC converters to obtain the necessary DC voltage. In contrast, AC microgrids necessitate two separate controller units for voltage and frequency control [19, 21]. As a result, the composition of a microgrid can vary based on specific requirements. Nonetheless, a standard microgrid allows for the connection of NCRES, energy storage components, and loads, all of which can be modeled considering technical and economic factors. Subsequent sections will provide a detailed description of these elements [22]. An example of a DC microgrid is shown in figure 2 and an example of an AC microgrid is illustrated in figure 3.

## 2.1 Solar photovoltaic

The most common elements into the sustainable energy solutions in non-interconnected areas are solar photovoltaic systems [9, 11], which convert the solar radiation into DC electricity, and for modeling purposes, the integration of this energy source can be represented as an electrical energy source that relies directly on the incident solar radiation on the surface of the solar panels and their rated power capacity in kilowatts. Therefore, according to [22] the solar panel energy output ($P_{PV}$) is shown in equation (1),

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_p \left( T_c - T_{c,STC} \right) \right], \tag{1}$$

where $Y_{PV}$ is the rated capacity of the solar panel array [kW], $f_{PV}$ represents the derating factor, $G_T$ is the solar incident radiation on the solar panel array [kW/m$^2$], $G_{T,STC}$ is the standard test condition (STC) incident radiation [kW/m$^2$], $\alpha_p$ represents the temperature coefficient, $T_c$ is the solar panel

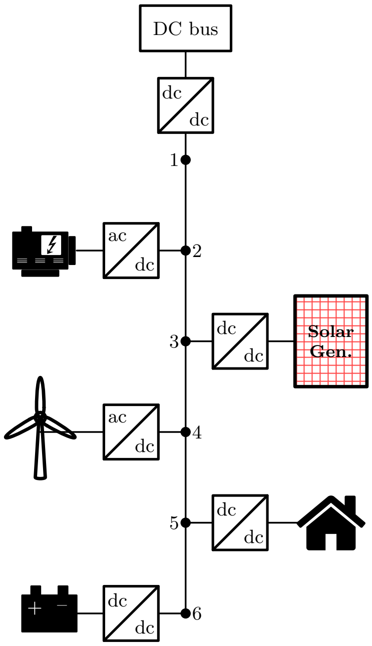


Figure 2 Proposed DC microgrid.

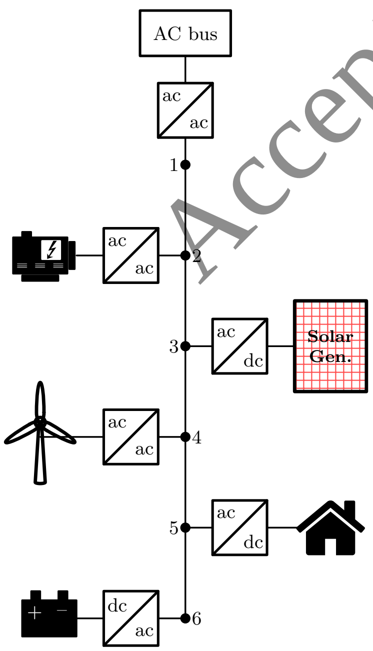


Figure 3 Proposed AC microgrid.

cell temperature [°C], and $T_{c,STC}$ is the solar panel cell temperature under STC [°C]. The investment of photovoltaic solar panels covers the initial capital cost, the operating and maintenance cost, and the replacement cost. This latter depends on the microgrid lifetime which is usually a time period of 25 years. According to [23] the investment of solar generator in terms of the fixed cost of energy is calculated as shown in equation (2),

$$c_{pv} = \frac{c_{pvi} + \sum_{i=1}^{n} c_{pvom}(1+dr)^{-i}}{\sum_{i=1}^{n} E_{pvan}(1+df)^{i-1}(1+dr)^{-i}}, \qquad (2)$$

where $c_{pvi}$ is the photovoltaic solar system investment cost, $c_{pvom}$ is the photovoltaic solar system operation and maintenance cost, $E_{pvan}$ is the annual energy produced by photovoltaic solar system, $dr$ is the discount rate, $df$ is the degradation factor, $n$ represents lifetime in years.

## 2.2 Wind turbine

On the other hand, the wind turbine transforms the kinetic energy contained in the wind flow into AC or DC electricity. The wind turbine generation is extracted from the curve relating wind speed and the power output. Thus, according to [22] wind turbine output power after air density correction is computed as shown in equation (3),

$$PWT_{actual} = PWT_{standard}\left(\frac{\rho}{\rho_0}\right), \qquad (3)$$

where $PWT_{standard}$ is the wind turbine output power under standard temperature and pressure [kW], $\rho$ is the air density [kg/m$^2$], and $\rho_0$ represents the standard air density [kg/m$^2$]. According to [22] the wind turbine hub height wind speed ($V_{hub}$) is calculated as indicated in equation (4),

$$V_{hub} = V_{anem}\left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha}, \qquad (4)$$

where $V_{anem}$ is the wind speed [m/s], $Z_{hub}$ is the wind turbine hub height [m], $Z_{anem}$ is the anemometer height [m], and $\alpha$ is the wind shear exponent. The investment of wind turbines have a similar characteristic that the investment of solar photovoltaic panels. According to [23] the investment of wind generator in terms of the fixed cost of energy is calculated as shown in equation (5),

$$c_{w} = \frac{c_{wi} + \sum_{i=1}^{n} c_{wom}(1+dr)^{-i}}{\sum_{i=1}^{n} E_{wan}(1+df)^{i-1}(1+dr)^{-i}} \qquad (5)$$

where $c_{wi}$ is the wind turbines investment cost, $c_{wom}$ is the wind turbines operation and maintenance cost,

$E_{wan}$is the annual energy produced by wind turbines system, $dr$ is the discount rate, $df$ is the degradation factor and $n$ is the lifetime in years.

## 2.3 Diesel generator

According to [22] the diesel generator fuel consumption ($F$) is modeled as a straight line, using the equation (6),

$$F = F_0 Y_{gen} + F_1 P_{gen}, \tag{6}$$

where $F_0$ is the fuel curve's y-intercept [L/h*kW], $F_1$ is the curve's slope [L/h*kW], $Y_{gen}$ is the rated capacity [kW], and $P_{gen}$ is the power output [kW]. According to [22] the investment of diesel generator in terms of the fixed cost of energy is calculated as shown in equation (7)

$$c_{gen,fixed} = c_{o\&m} + \frac{C_{rep}}{R_{gen}} + F_o Y_{gen} c_{eff}, \tag{7}$$

where $c_{o\&m}$ is the operation and maintenance cost [$/h], $C_{rep}$ is the replacement cost [$], $R_{gen}$ is the generator's lifetime [h], $F_o$ is the fuel curve y-intercept [L/h*kW], $Y_{gen}$ is the generator capacity [kW] and $c_{eff}$ is the effective price [$/L]. The marginal cost of energy for the generator is calculated as given in equation (8),

$$c_{gen,mar} = F_1 c_{eff}, \tag{8}$$

where $F_1$ is the slope of the fuel curve [L/h kW].

## 2.4 Battery

Energy storage systems play a pivotal role in the growth of renewable energy. They enable the efficient capture and release of energy generated by sources like solar and wind, ensuring a consistent and reliable power supply. This contribution accelerates the transition towards a more sustainable energy grid. Specifically, batteries, as energy storage elements, can be viewed as components that store DC electricity and deliver energy to deferred loads over their operational lifespan. This process is constrained by the battery's charging and discharging rates, as per the kinetic battery model [22]. Energy storage systems with lithium-ion batteries are a viable alternative in DC microgrids due to their high power and energy density, good cycle life, and increased efficiency. Currently, lithium-ion batteries are the most mature and commercially adopted technologies in energy storage systems. However, the integration of a lithium-ion battery into a DC microgrid system requires modeling its degradation for effective and efficient operation [23]. The battery degradation cost $c_{bd}$ is calculated using the equation (9), proposal in [23]

$$c_{bd} = \frac{(c_{bi} + \sum_{i=1}^{n} c_{bom}(1-dr)^{-i})(1+dr)^n - rv}{2(1+dr)^n X_T^{ra_{ref}} X_T^{cy_{ref}} X_D^{cy_{ref}} ra_{ref} cy_{ref}}, \tag{9}$$

where $c_{bi}$ is the battery investment cost, $c_{bom}$ is the battery operation and maintenance cost, $dr$ is the discount rate, $rv$ is the residual value, $n$ is the lifetime in years, $X_T^{ra_{ref}}$ is the temperature dependent battery capacity factor, $X_T^{cy_{ref}}$ is the temperature dependent battery cyclelife factor, $X_D^{cy_{ref}}$ is the depth of discharge dependent battery cyclelife factor, $ra_{ref}$ is the rated energy capacity of Li-ion battery and $cy_{ref}$ is the reference cyclelife of Li-ion battery.

## 2.5 Converter

In accordance with the energy consumption and quality requirements of the area, grid-forming (GFM) converters would be used to transform the DC variables into AC currents and voltages, carry out control of the charge and discharge of the storage systems, and their synchronization with the system. The converter can do both processes, inversion, and rectification; it also can allow reactive power compensation, and harmonic filtering, among other benefits that provide benefits to the electrical network, facilitating its integration in the medium and long term with the NIS. The converter capacity is established as a decision variable and the modeling regards different converter sizes between 0 kW and 30 kW, which can be rotary or solid-state devices. According to [24, 25], the bridgeless power factor correction (PFC) boost converter is a viable alternative in DC microgrids. Power converter switches operate within the cutoff and saturation regions, resulting in the bridgeless PFC boost converter displaying dynamic behavior that is both nonlinear and subject to variations over time. Figure 4 illustrates the configuration of the bridgeless PFC boost converter. This setup consists of a pair of power switches, namely $Q_1$ and $Q_2$, two fast-switching diodes identified as $D_1$ and $D_2$, two standard rectifier diodes known as $D_3$ and $D_4$, two inductors with identical values represented as $L_1$ and $L_2$, a capacitor designated as $C$, and a load denoted as $R_L$. The behavior of the bridgeless PFC boost converter is described by equations (10) to (14). These equations can be consulted in detail in [24].

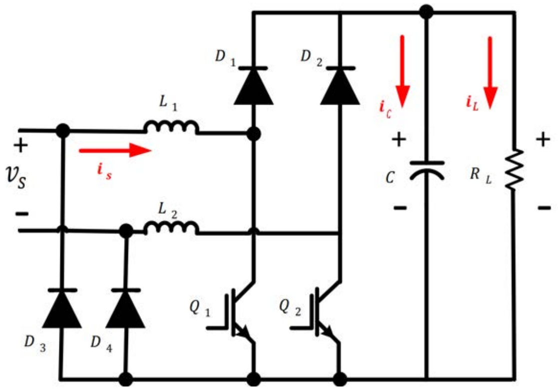


**Figure 4** Bridgless PFC boost converter topology.

$$\frac{di_s}{dt} = \frac{v_s}{L} \tag{10}$$

$$\frac{dv_c}{dt} = \frac{-v_c}{R_L C} \tag{11}$$

$$\frac{di_s}{dt} = \frac{v_s - v_c}{L} \tag{12}$$

$$i_s = i_c + i_L \tag{13}$$

$$\frac{dv_c}{dt} = \frac{i_s}{C} - \frac{v_c}{R_L C} \tag{14}$$

where $v_s$: input voltage, $i_s$: input current, $v_c$: output voltage, $i_c$: capacitor current, $i_L$: load current.

## 2.6 Load

The load modeling process begins with load estimation, detailed in section 6. Two types of loads are defined: primary and deferrable Loads. The first load type, it accounts for scheduled electric demand, including typical household loads like lights and appliances. The system must have sufficient capacity to meet the hourly load and allow for operational reserve. The second load type represents electric demand that can be met within a specified time frame, with battery-charging stations being a common example. It proves valuable when dealing with intermittent NCRES.

## 2.7 DC Microgrid Architectures

In the design of a DC microgrid, the choice of architecture configurations is influenced by practical needs, focusing on durability, adaptability, and dependability [26]. Typically, the most resilient setup involves directly connecting storage devices to the primary bus, which is why the single-bus topology is commonly employed [23, 26]. This configuration features a single shared bus where all components, such as power sources, loads, and energy storage devices, are linked through various converters [26]. It's worth noting that while the single-bus topology is straightforward, there are other alternatives in the classification of DC microgrid architectures, including multiple-bus topology and reconfigurable topology.

## 2.8 DC Microgrid Faults and Protection Schemes

DC microgrids face several challenges in the realm of protection, with the primary concern centering around faults. The architectures of DC microgrids are still in a state of ongoing development, which presents another obstacle when it comes to formulating an effective protective strategy in a broader context. These protection challenges manifest in various ways, stemming from factors such as fluctuations in load, variations in input power, the intricacies of maximum power point tracking (MPPT) control with distributed energy resources (DERs), the occurrence of temporary faults, communication delays, and more. Unlike AC microgrids, DC microgrids lack natural zero-crossings, making the extinguishing of arcs critical in cases involving open contacts. Protection devices employed in DC microgrids fall into categories such as fuses, DC circuit breakers (DCCBs), protective relays, solid-state circuit breakers (SSCBs), hybrid circuit breakers (CBs), and arc fault interrupters (AFIs). Generally, fuses are the most used equipment in microgrids due to their low cost and ease of installation. They can be a viable alternative in simple applications [26].

# 3. Regulatory Framework for Microgrids

As mentioned, this paper proposes a specific procedure for implementing isolated and grid-connected microgrids, complementing well-defined technical guidance for planning and design [27, 28], but acknowledges the need for addressing regulatory aspects. To execute the aforementioned, figure 5 shows the flowchart with the most important aspects associated with the proposed regulatory management to be followed from the pre-feasibility, feasibility, designs, commissioning, and the start-up of a microgrid, within the Colombian context. In addition, the most relevant aspects of figure 5 are described in detail, in conjunction with the summary of public politics, economic regulation, technical regulation, and standards in the table 1.

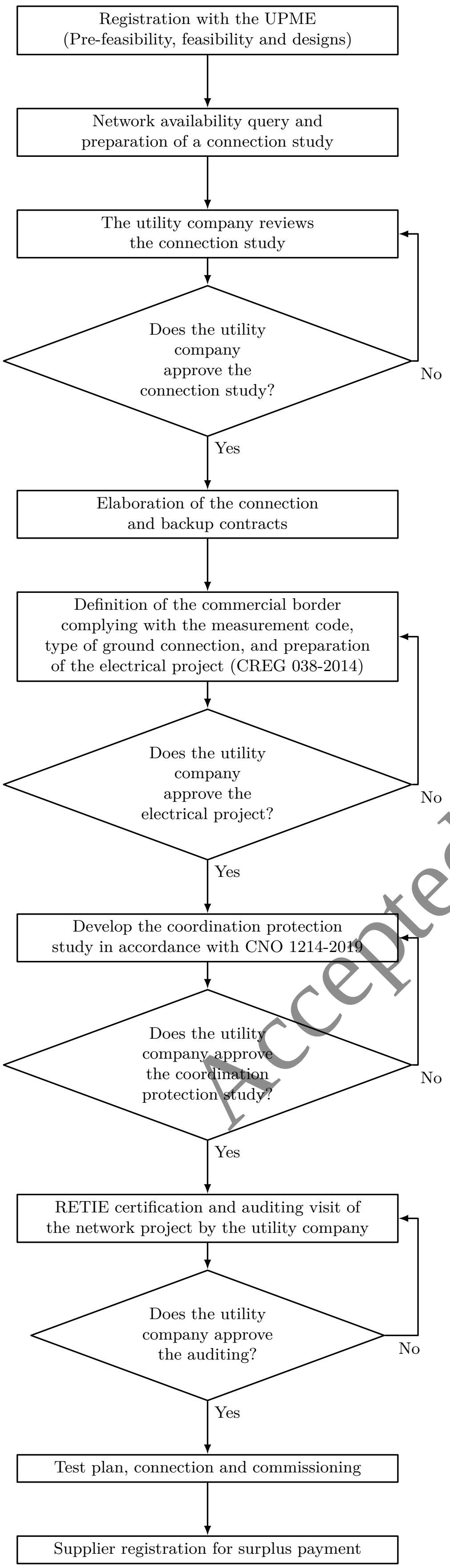


**Figure 5** Proposed procedure for microgrid projects.

## 3.1 Registration with the UPME

The registration of microgrids is voluntary and serves as an informative mechanism for UPME. However, it becomes a requirement for specific procedures related to utility companies and for accessing tax benefits as outlined in Law 1715 of 2014. Isolated and grid-connected microgrid projects must adhere to the registration process with UPME in compliance with UPME resolutions 520 of 2007, 638 of 2007, and 143 of 2016.

## 3.2 Connection study

The level of detail for the connection study and its requirements may vary according to the installed capacity of the microgrid, as well as the concept of entities that make feasible that study. Microgrids may not need a standard connection contract as per Resolution 174 of 2021; instead, a contract for backup capacity might suffice. In the case of islanded microgrids, no connection study is necessary, as they don't require a connection point to the NIS for energy supply.



## 3.3 Definition of commercial border (CREG 038-2014)

The definition of the commercial border must be done in accordance with the provisions of the measuring code Comisión de Regulación de Energía y Gas (CREG) 038 of 2014. An islanded microgrid doesn't need network project approval or a commercial border. However, when installing a metering system, it's advisable to adhere to the metering code and standards of the regional utility company.

## 3.4 Protection coordination study (CNO 1214-2019)

In accordance with the installed capacity of the project, this study considers the parameters indicated in the Consejo Nacional de Operación (CNO) 646 agreement, its respective CNO 1214 of 2019 update, and the 1322 of 2020 agreement. The protection coordination study is reviewed and approved by the regional utility company and the Centro Nacional de Despacho (CND).

The islanded microgrids do not require the presentation of this study, however, the adequate coordination of protections within the microgrid must be carried out in accordance with the requirements of the Reglamento Técnico de Instalaciones Eléctricas

**Table 1** Summary of politics, regulations, and standards for microgrids.

| Public politics | Economic regulation | Technical regulation | Standards of reference |
|---|---|---|---|
| Colombian law 1715-2014 Government decree Ministerio de Minas y Energía 2469-2014 Comprehensive Climate Change Management Plan Ministerio de Minas y Energía (PIGCCme, 2018) | Resolution CREG 038-2014 Resolution CREG 166-2020 Resolution CREG 174-2021 Resolution CREG 002-2021 Circular UPME 018-2019 | Resolution 025-1995 Resolution UPME 520-2007 Resolution UPME 638-2007 Technical agreement CNO 646-2013 Resolution UPME 281-2015 Resolution UPME 143-2016 Resolution UPME 463-2018 Technical agreement 1214-2019 RETIE standard | EPM RA8001-2017 IEEE 1547-2018 NTC 2050-2020 |

(RETIE).

### 3.5 RETIE certification

Regardless of the type or installed capacity of the microgrid, it must comply with the RETIE. This The activity must be carried out according to two events, The first is related to the delivery of plans, documents, reports, catalogs, products certificates, and other requirements by section 10.1.1 of the RETIE submitted to the certification company, and the second is associated with an on-site visit of a inspector who verifies compliance with the RETIE standard to certify the installation, after finished the audit.

## 4. Methodology

The proposed methodology for the microgrid evaluation covers three important steps: selection of microgrid location, load estimation and microgrid simulation. For the selection of microgrid location, a microgrid planning task takes into consideration the nature of the energy sources and additionally the meteorological conditions of the site where the microgrid is installed, given the particular conditions for solar radiation and wind speed [29]. The software Homer Pro obtains this online information from the Renewable Resource Data Center. The load estimation stage is made using the Building Energy Optimization Tool (BEopt), which is software for simulating residential buildings' performance. This process is completed by running a detailed hour-by-hour simulation for annual performance [30]. Finally, the simulation is done by using the software Homer Pro, which performs an hourly time-series simulation, verifying at each step if the microgrid generation and storage systems are able to serve the load. After that, Homer Pro executes the optimization process, where different microgrid configurations are tested, looking for the one that satisfies technical restrictions at the lowest life-cycle cost, which is the total cost of installing and operating the microgrid project over its entire lifetime. In economic terms, the life-cycle cost is represented by the $NPC$ and the $LCOE$. The $NPC$ is the present value of all the costs the microgrid incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. The $NPC$ is calculated as shown in equation (15),

$$NPC = \sum_{t=0}^{N} \frac{AA_{TC}}{(1+i_r)^n} + I_{cc}, \tag{15}$$

where $AA_{TC}$ are adjusted annual total costs [\$], $i_r$ is the interest rate, $n$ is the year number and $I_{cc}$ is the initial capital cost [\$]. On the other hand, the $LCOE$ is the average cost per kWh of useful electrical energy produced by the system. The $LCOE$ is calculated as shown in equation (16),

$$LCOE = \frac{C_{ann,tot}}{E_{served}}, \tag{16}$$

where $C_{ann,tot}$ is the total annualized cost of the system [\$/yr] and $E_{served}$ is the total electrical load served [kWh/yr].

## 5. Results Analysis

The implementation of the proposed methodology is described below.

### 5.1 Selection of microgrid location

The areas encompassing the NIZ in Colombia are spread across 18 different departments. These regions are currently supplied with electricity for an average of 12 hours and 35 minutes per day. Refer to table 2 for a breakdown of locations with the lowest daily average electricity service. Based on this data, we have chosen to focus our study on Vegaez. Situated within the municipality of Vigía del Fuerte in the department of Antioquia, the precise location of Vegaez can be observed in Figure 6.

Vigía del Fuerte stands out as the sole municipality in Antioquia that remains unconnected to the NIS. Here, electricity provision for remote communities

Table 2 Locations with the lowest daily average electricity service [12].

| Location | Maximum monthly power [kW] | Monthly energy [kWh] | Average daily energy [kWh] | Daily average service provision |
|---|---|---|---|---|
| Vegaez (Vigía del Fuerte - Antioquia) | 47.07 | 1236 | 41 | 1 hour 24 minutes |
| Napipi (Bojayá (Bellavista) - Choco) | 64.00 | 2648 | 88 | 1 hour 45 minutes |
| Santa Fe del Caguan (Cartagena del Chaira - Caquetá) | 39.96 | 3081 | 103 | 3 hours 24 minutes |
| Bocas de Prieta (Olaya Herrera - Nariño) | 20.59 | 1602 | 53 | 4 hours 18 minutes |
| Togoroma Playa (El Litoral del San Juan - Choco) | 7.95 | 770 | 26 | 4 hours 27 minutes |

Figure 6 Location of Vigía del Fuerte (Antioquia) [31].

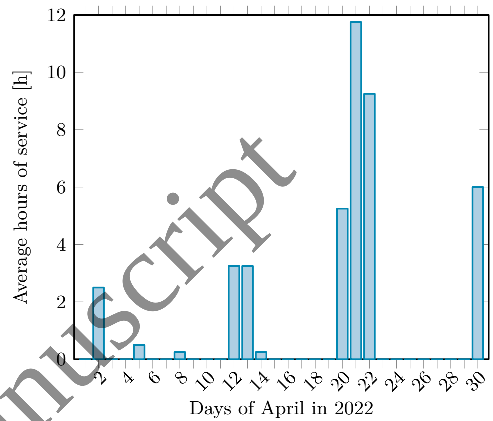


Figure 7 Daily average electricity service for Vegaez.



heavily relies on diesel generators, leading to significant drawbacks such as exorbitant costs, elevated emissions, and logistical complexities in fuel supply. The current electrical service in Vigía del Fuerte is facilitated through a 185 kW diesel generator, compounding the region's reliance on fuel availability, which results in two primary predicaments. Firstly, the intermittency of power supply leads to frequent periods, as depicted in Figure 7, where communities endure several days each month without electricity. Secondly, this setup subjects the region to the volatility of diesel fuel prices, necessitating frequent budget adjustments to accommodate escalating costs.

As a starting point, it is proposed to carry out a review of the databases referring to the natural resources in the region.

### 5.1.1 Solar radiation

For the solar radiation, the figure 8 shows the monthly average solar radiation data for Vigía del Fuerte, depicting two prominent peaks in March and July, followed by a gradual decrease in solar radiation during the latter months of the year.

### 5.1.2 Wind speed

On the other hand, figure 9 illustrates the average wind speed in Vigía del Fuerte. This graph reveals that the wind speed maintains a relatively consistent level throughout the year, hovering around 2 m/s. There is a slight uptick in wind speed from July to October, where it reaches its peak at 2.5 m/s. It's worth noting that the turbines are assumed to have a lifespan of 20 years, as mentioned by [32].

## 5.2 Load estimation

In the case of load estimation, BEopt calculates household electrical and thermal load based on typical dwelling architecture, size, occupancy, and location. This takes into consideration the actual conditions of the community of Vegaez in Vigía del Fuerte as illustrated in figure 10. In the context of DC microgrids, it is essential to note that AC loads require the inclusion of a DC/AC converter.

The results of BEopt simulation show the site electricity use in terms of illumination, home appliances, and ventilation fan as illustrated in figure 11, which are the input data for the microgrid simulation and optimization. Additionally, it presents

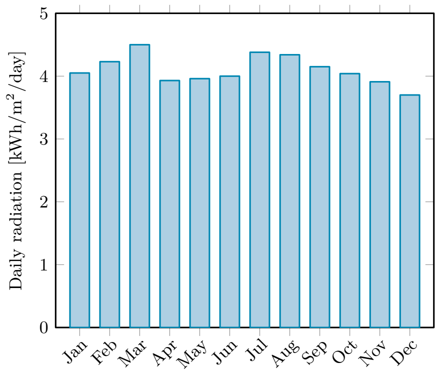


**Figure 8** Monthly averages for solar horizontal radiation in Vigía del Fuerte.

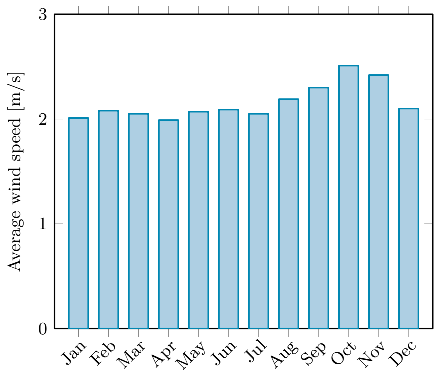


**Figure 9** Monthly average wind speed data in Vigía del Fuerte.

the $CO_2$ emissions, regarding also the natural gas consumption as illustrated in figure 11.

## 5.3 Microgrid simulation

This subsection presents the simulation of proposed microgrids that consist of the components depicted in Figure 2 for the DC scenario, and an identical configuration in the AC scenario, as shown in Figure 3. These components include a Diesel Generator (DG), Solar Photovoltaic (SP), Wind Turbine (WT), and Battery System (BS). The results for both cases DC and AC are indicated in table 3, where it is evidenced the 10% reduction in the $NPC$ and $LCOE$, comparing the DC with the AC counterpart. These results correspond to the selection of the configuration which satisfies the user-specified constraints at the lowest $NPC$.

Table 3 presents results arranged in ascending order of the lowest $NPC$, leading to the selection of six distinct microgrid configurations. These configurations remain consistent for both DC and AC microgrids. The first configuration is the most cost-effective and only uses

**Figure 10** Modelling in BEopt.

PV and BS with a Cycle Charging (CC) strategy, which means that whenever a generator needs to serve the primary load, it operates at full output power. The second configuration employs SP, BS, and DG with a Load Following (LF) strategy, which means that whenever a generator is needed, it produces only enough power to meet the demand. The third configuration utilizes SP, WT, BS with a CC strategy, and the fourth configuration is the only one that uses the complete components. The fifth and sixth are the more expensive configurations and have the characteristic of not using SP.

The first and third configurations are based only on NCRES without the complementary DG, so these options could represent a complete contribution to the energy transition toward clean energy sources, and they additionally imply the removal of the dependency on fuel diesel supply and prices. In contrast, the fifth configuration uses DG without the participation of NCRES, which has in addition 4,2 times greater $NPC$ as compared with the PV solution, and 2,8 times $NPC$ as compared with the combined PV and WT solution.

The results in table 3 can be divided into three different categories based on the similarities in the $NPC$ outcomes. For the DC microgrid case, the first and second configurations have an average $NPC$ of US$ 42,286 (first category, solutions 1 and 2), the third and fourth configurations have an average $NPC$ of US$ 62,736 (second category, solutions 3 and 4), and the fifth and sixth configurations have an average $NPC$ of US$ 187,376 (third category, solutions 5 and 6). The first category uses SP, the second category uses PV and WT, with a $48,4\%$ percentage increase, and the third category does not use SP, with a $343,1\%$ percentage increase. Therefore, only the first and second configurations could be considered feasible and cost-effective solutions.

From the regulatory point of view, the first and the third configurations can access the benefits of Law 1715 of 2014 to reduce the initial investment

Table 3 Six energetic solutions are proposed using a DC and an AC microgrid.

| Solution | PV | WT | DG | BS | Dispatch | DC Microgrid | | AC Microgrid | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $NPC$ (US$) | $LCOE$ (US$) | $NPC$ (US$) | $LCOE$ (US$) |
| 1 | ✓ | | | ✓ | CC | 42,028 | 0.792 | 47,421 | 0.893 |
| 2 | ✓ | | ✓ | ✓ | LF | 42,543 | 0.801 | 48,493 | 0.913 |
| 3 | ✓ | ✓ | | ✓ | CC | 62,139 | 1.17 | 67,669 | 1.27 |
| 4 | ✓ | ✓ | ✓ | ✓ | LF | 63,332 | 1.19 | 68,734 | 1.29 |
| 5 | | | ✓ | ✓ | LF | 177,542 | 3.34 | 417,984 | 7.87 |
| 6 | | ✓ | ✓ | ✓ | LF | 197,210 | 3.71 | 436,014 | 8.21 |

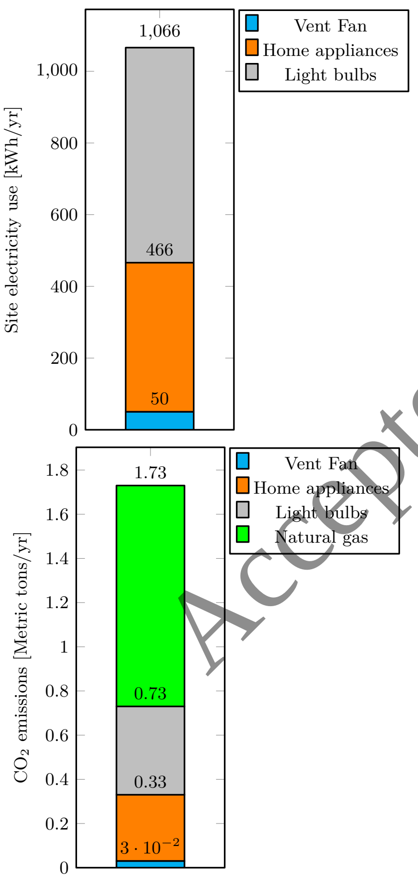


Figure 11 (a) Site electricity use [kWh/yr]. (b) $CO_2$ emissions [Metric tons/yr].

for electromechanical equipment, avoid paying some tariff procedures apply accelerated depreciation of this equipment, and increase the value of the investment for shareholders. If the project is carried out off-grid, some regulatory procedures are simplified or eliminated like non-accredited approval of the connection study (Connection code CREG 025 of 1995), electrical project (EPM RA8-001 of 2017), or protection coordination study (Technical agreement CNO 1214 of 2019) by the regional utility company, speeding up the start-up times of the project. In addition, the installation must comply with RETIE and the measurement code (CREG 038 of 2014) and it is recommended that the commercial boundaries must be telemetered for monitoring and planning by the Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas (IPSE), which is the responsible entity of the NIZ.



## 6. Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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## 8. Author contributions

- Joseph Camilo Sosapanta Salas: simulation and analysis of microgrid results.
- Carlos David Zuluaga Ríos: conceptualization, formal analysis, writing, and original draft

preparation.

- Sergio Danilo Saldarriaga Zuluaga: conceptualization, data curation, funding acquisition, and writing—review, and editing.

- Juan David Velásquez Gómez: regulation framework, microgrid modeling and technical standards analysis.

## 9. Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

## 10. Conclusions

This article compellingly illustrates the potential of DC microgrids as a viable, feasible, and profitable solution to enhance the well-being of Colombia's ZNI, with a specific focus on Vigía del Fuerte. Through simulations, it has been shown that DC small-scale grids can significantly reduce the $NPC$ and the $LCOE$ by 10% when compared to AC microgrids. This study delves into six potential energy solutions based on wind generation, with only three of them incorporating wind turbines. This observation underscores the limited relevance of wind power in Vigía del Fuerte, given its low wind speed regime. Furthermore, the article explores energy solutions combining wind and solar generation, ultimately highlighting solar photovoltaic solutions as the most pertinent option. It is crucial to acknowledge that these potential energy solutions must be approached with special consideration, given their intermittent, seasonal, and non-dispatchable characteristics. Nonetheless, the low operational costs associated with NCRES take precedence over the lower initial capital costs of conventional energy sources. Lastly, the study provides a clear and actionable methodology for the implementation of both AC and DC microgrids throughout Colombia.

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## 11. Glossary

| | |
|---|---|
| $Y_{PV}$ | rated capacity of the solar panel array [kW] |
| $f_{PV}$ | derating factor |
| $G_T$ | solar incident radiation on the solar panel array [kW/m$^2$] |
| $G_{T,STC}$ | standard test condition (STC) incident radiation [kW/m$^2$] |
| $\alpha_p$ | temperature coefficient |
| $T_c$ | solar panel cell temperature [°C] |
| $T_{c,STC}$ | solar panel cell temperature under STC [°C] |
| $c_{pvi}$ | photovoltaic solar system investment cost |
| $c_{pvom}$ | photovoltaic solar system operation and maintenance cost |
| $E_{pvan}$ | annual energy produced by photovoltaic solar system |
| $dr$ | discount rate |
| $df$ | degradation factor |
| $n$ | lifetime in years |
| $PWT_{standard}$ | wind turbine output power output under standard temperature and pressure [kW] |
| $\rho$ | actual air density [kg/m$^2$] |
| $\rho_0$ | standard air density [kg/m$^2$] |
| $V_{anem}$ | anemometer wind speed [m/s] |
| $Z_{hub}$ | wind turbine hub height [m] |
| $Z_{anem}$ | anemometer height [m] |
| $\alpha$ | wind shear exponent |
| $c_{wi}$ | wind turbines investment cost |
| $c_{wom}$ | wind turbines operation and maintenance cost |
| $E_{wan}$ | annual energy produced by wind turbines system |
| $dr$ | discount rate |
| $df$ | degradation factor |
| $F_0$ | fuel curve's y-intercept [L/h*kW] |
| $F_1$ | curve's slope [L/h*kW] |
| $P_{gen}$ | power output [kW] |
| $c_{o\&m}$ | operation & maintenance cost [$/h] |
| $C_{rep}$ | replacement cost [$] |
| $R_{gen}$ | generator's lifetime [h] |
| $Y_{gen}$ | generator capacity [kW] |
| $c_{eff}$ | effective price [$/L] |
| $c_{bi}$ | battery investment cost |
| $c_{bom}$ | battery operation and maintenance cost |
| $rv$ | residual value |
| $X_T^{ra_{ref}}$ | temperature dependent battery capacity factor |
| $X_T^{cy_{ref}}$ | temperature dependent battery cycle life factor |
| $X_D^{cy_{ref}}$ | depth of discharge dependent battery cycle life factor |
| $ra_{ref}$ | rated energy capacity of Li-ion battery |
| $cy_{ref}$ | reference cycle life of Li-ion battery |
| $v_s$ | input voltage |
| $i_s$ | input current |
| $v_c$ | output voltage |
| $i_c$ | capacitor current |
| $i_L$ | load current |
| $AA_{TC}$ | adjusted annual total costs [$] |
| $i_r$ | interest rate |
| $n$ | year number |
| $I_{cc}$ | initial capital cost [$] |
| $C_{ann,tot}$ | total annualized cost of the system [$/yr] |
| $E_{served}$ | total electrical load served [kWh/yr] |

| | |
|---|---|
| BEopt | Building Energy Optimization Tool |
| BS | Battery System |
| CND | Centro Nacional de Despacho |
| CNO | Consejo Nacional de Operación |
| CREG | Comisión de Regulación de Energía y Gas |
| DG | Diesel Generator |
| IPSE | Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas |
| NCRES | Non-Conventional Renewable Energy Sources |
| NIS | National Interconnected System |
| NIZ | Non-Interconnected Zones |
| RETIE | Reglamento Técnico de Instalaciones Eléctricas |
| UPME | Unidad de Planeación Minero Energética |
| SP | Solar Photovoltaic |
| WT | Wind Turbine |
| $LCOE$ | Levelized Cost of Energy |
| $NPC$ | Net Present Cost |