Heliyon 9 (2023) e19874

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Suitable municipalities for biomass energy use in Colombia based on a multicriteria analysis from a sustainable development perspective

Maria Jisset Calvo-Saad [a,*], Juan Sebastián Solís-Chaves [a,b], Walter Murillo-Arango [c]

[a] Universidad ECCI, Cra 19 No 49-20, Bogotá, 111311, Colombia, Grupo de investigación GADES and Universidad de Manizales
[b] Universidad ECCI, Cra 19 No 49-20, Bogotá 111311, Colombia, Grupo de investigación GIATME
[c] Universidad de Manizales, centro de investigación en Medio Ambiente en Desarrollo Sostenible y Medio Ambiente CIMAD and Universidad del Tolima, Facultad de Ciencias, Colombia

ARTICLE INFO

Keywords:
Analytical hierarchy process
Biomass
Colombia
Geospatial information systems
Multi-criteria decision analysis
Sustainable development
QGIS
Renewable energy sources
Rank-sum
Weighted linear combination

ABSTRACT

Using renewable energies is a global strategy to mitigate the acceleration of global warming generated by industrial processes and is a sustainable way to diversify the energy matrix in all countries. Biomass is a renewable energy source that produces biofuels and generates electricity and heat. The primary purpose of this work is to identify the municipalities in Colombia where agricultural, livestock, and urban residual biomass could be suitable for energy generation in a sustainable and renewable way. To that end, we carried out a Geostatistical Multi-Criteria Decision Methodology using Analytical Hierarchy Processes such as Rank-Sum and Weighted Linear Combination, as well as considering a set of sustainable development indicators applied to official Colombian data. Two scenarios are considered for comparison purposes. The first one is according to expert criteria, and the second one considers The Sustainable Development Goals proposed by the United Nations. Under both proposed scenarios, 127 municipalities were found to be suitable for agricultural-urban residual biomass and 162 for livestock-urban residual biomass for energy generation. One of the main limitations for the use of urban biomass is that municipalities need to have sufficient production potential to fulfill their own energy needs. An additional comparison with previous works to evaluate the performance of the Multi-Criteria Decision Methodologies MCDM is also proposed.

1. Introduction

Fossil fuels continue to be the most used resource for energy production worldwide; however, prolonged dependence on these resources, their massive use, their non-renewable nature, and their high rate of pollutant emissions have led to the deterioration of the environment [1–4]. Therefore, it is necessary to increase the use of Renewable and Non-Conventional Energy Sources (RNCES), such as wind, solar/photovoltaic, and biomass energy. Given their environmental and economic RNCES are being increasingly integrated into the energy mix by both the public and private sectors worldwide [5]. International agreements such as the Kyoto Protocol and the Sustainable Development Goals (SDGs) established in the Paris 2015 agreement at COP21 have proposed increased efforts to improve the use of natural resources, mitigate climate change, and increase the use of RNCES. Colombia, as of the year 2020, progressed

* Corresponding author. Universidad ECCI, Cra 19 No 49-20, Bogotá, 111311, Colombia.
E-mail addresses: calvo.maria@ecci.edu.co, jisset.calvo@gmail.com (M.J. Calvo-Saad).

https://doi.org/10.1016/j.heliyon.2023.e19874
Received 10 April 2023; Received in revised form 3 September 2023; Accepted 4 September 2023
Available online 9 September 2023
2405-8440/

Nomenclature

GIS	Geographical information system
RNCES	Renewable and Non-Conventional Energy Sources
SDGs	Sustainable Development Goals
IAEA	The International Atomic Energy Agency
UN	United Nations
MCDM	Multi-Criteria Decision Methodologies
AHP	Analytic Hierarchy Process
WLC	Weighted Linear Combination
ILs	Information layers
BEP	Biomass Energy Potential
ASB	Agricultural Sector Biomass
LSB	Livestock Sector Biomass
USWB	Urban Solid Waste Biomass
NIZ	Non-Interconnected Zone
HDI	Human Development Index
mHDI	The municipal HDI
GHG	Greenhouse Gases
NNPs	National Natural Parks
MEII	Municipal Economic Importance Indicator
ENA	National Agricultural Survey
DANE	National Administrative Department of Statistics (abbreviated in Spanish)
SIN	National Interconnected System
IGAC	Instituto Geográfico Agustín Codazzi
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
IPES	Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (abbreviated in Spanish)

54.83% forward the SDG targets proposed in the 2030 agenda [6]. In order to achieve the goals proposed for the next decade, the country must increase its technical and scientific efforts. These changes aim to ensure more efficient, cleaner, and more affordable energy, as stated in SDG7; this makes biomass a particularly attractive resource for power generation.

1.1. Renewable energies and sustainable development indicators

The energy sector plays a fundamental role in developing a country, and it is a major gatekeeper of the diversification of energy sources by the integration of RNCES. Among the benefits to countries from using RNCES are independence from fossil fuels, reduction of greenhouse gases, job creation, and improved air quality [3,7,8]. Quantifying the sustainability of the energy sector requires the use of indicators that provide accurate information about the reality of the energy sector (i.e., whether the energy produced is sustainable) in a simplified manner that uses basic statistics [9]. The International Atomic Energy Agency (IAEA) and CEPAL have developed approximately 30 indicators related to sustainable development that are useful for decision-making and analysis in the energy sector [10]. Gunnarsdottir et al. have reviewed several sets of these indicators [11]. From the point of view of Sustainable Development, the United Nations (UN) has generated the 2030 Agenda for its member countries, which seeks to mitigate environmental impact, support the energy transition, and facilitate a paradigm shift to a more balanced relationship between the capitalist economic system and nature [12]. These different indicators can be integrated and prioritized using methodologies such as multi-criteria analysis for decision-making, which uses a combination of different strategies to reach the best solution to the proposed problem [13,14].

1.2. Multi-criteria decision methods to solve renewable energy scenario

Several types of research with GIS and Multi-Criteria Decision Methodologies (MCDM) have been proposed in past decades and are still currently used. Cornerstone studies such as Cardoso et al. [13] and De Lima [15] were pioneers in identifying suitable areas in Brazil employing Geographic Information Systems (GIS), MCDM, and including sustainable development energy indicators to establish suitable locations for wind turbines. Kumar et al. used similar methodologies to identify locally available RNCES that could be used to design an electrical microgrid in a specific municipality in the Himalayas [16,17]. Authors like Ghenai et al. evaluated sustainability indicators for different RNCES systems using a hybrid method combining the multi-criteria model with a Step-wise Weight Assessment Ratio Analysis/Additive Ratio Assessment (SWARA/ARAS) [18]. As can be seen, the most frequently used methods in these types of applications are the Analytic Hierarchy Process (AHP) method, developed by Saaty [19], its fuzzy logic version, also known as Fuzzy AHP [20,21], the Fuzzy Group decision-making AHP (FGAHP) [22], the Criteria Importance Through Intercriteria Correlation (CRITIC) [20], the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [23, 24)], and the VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method [23,24,25].

Table 1
Works of MCDM strategies, sustainable development concepts, and renewable energies.

Year	Renewable Energy	Purpose/target	Location	Criteria and indicators	N° Criteria	Stage	MCDM method	Reference
2018	Waves	Feasible Location	India	Wave height (Hs) Water depth (Wd) Wind speed (Ws) Wind duration (Wi) Fetch (F)	5	1	Genetic Algorithm, Polynomial neural network, Multilinear regression model, Differential evolution	[35]
]2020	Biomass	Assessment and potential-site determination	Mexico	Wheat crops Faults-fractures Transmission lines Localities Roads Aqueducts, canals and water flows Ramsar sites are restrictions for power plant installation	7	1	GIS AHP	[32]
2021	Municipal solid waste	Potential location	Turkey	Digital elevation model Administrative boundaries Population Landuse Power lines and transformers Road network MSW generation rate MSW transfer stations, landfills and their service areas Neighbourhood locations	9	1	Fuzzy AHP	[22]
2022	Solar PV	Suitability mapping	Egypt	Solar radiation Annual average cloudy days Elevation Slope Soil texture Annual average temperature Distance from urban areas Lightning strikes flash rate Distance from power transmission lines Distance from major roads	10	1	AHP	[31]
2023	Wind on shore	Suitable locations	Saudi Arabia	Average wind speed Distance to power lines Distance to roads distance to settlement areas slope Water bodies and wetlands Land use and protected areas Important birds' areas Airports and airfields	9	1	AHP	[29]
2021	Hydro Wind Solar Photovoltaic Hybrids: Diesel + PV Diesel + PV + Batteries Biomass and Biofuels Natural gas	Suitable Energy Projects for Ambient Licences	Brazil	Potential for market transformation Cost for Society Increase in subsidies Tax collection Social acceptance Electricity access Local development Previous experience Difficulty of implementation Easiness to monitor and evaluate the policy Foreseen impacts Alignment with international agreements Alignment with national policies Political risks	19	2	Fuzzy AHP and Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	[23]

(continued on next page)

Table 1 (*continued*)

Year	Renewable Energy	Purpose/target	Location	Criteria and indicators	N° Criteria	Stage	MCDM method	Reference
				Accountability and sector sustainability Foreign dependency Reliability of power supply Environmental impact				
2022	Offshore Wind	Optimal site selection	Gulf of Maine	Average wind speed (m/s) Bathymetry (m) Water Quality (oxygen concentration) Distance to substations (m) Distance to coast (m) Distance to ports (m) Capital expenditure (CAPEX) Operational expenditure (OPEX) Decommissioning expenditure (DECEX)	9	2	AHP, Fuzzy GIS	[28]
2022	Nuclear	Site suitability	Indonesia	Physiographic Land slope Groundwater Soils Rainfall Climate Land use and land cover Landsystem Distance from settlement Accessibility Central Business District Vital and dangerous infrastructures Geological structures Disaster risk	14	2	AHP, BWM (Best Worst Method)	[30].
2022	Solar PV	Geolocation	Ecuador	Digital elevation model Wind speed Annual average global radiation Substations Transmission lines Average annual temperature Road network Vegetable cover and land use Urban areas Water areas The national system of protected areas Ecuador continental limits	12	2	AHP, ARAS, OCRA,PSI, SMART, Weighted Superposition, TOPSIS, and VIKOR.	[23]
2023	Tidal	Potential marine areas Optimal site selection	China	Marine Ecological Red Line Water Depth (m) Tidal Current Power Density (W/m2) Distance from the Shore (km) Distance from the Port (DP) (km) Distance from the Power Grid (DPG) (km) Distance from the Fairway (DF) (km) Distance from Coastal Tourist Areas (DCTA) (km) Population Served (PS)	9	3	Fuzzy Group decision making AHP (FGAHP) CRiteria Importance Through Intercriteria Correlation (CRITIC)	[20]

Table 1 summarizes some representative works that combine MCDM strategies, sustainable development concepts, and renewable energies. Many of them have been efficient tools for strategic planning when integrated with geospatial analysis using geographic information systems (GIS), as is shown in Refs. [19,26]. MCDM successfully estimated the ideal locations for different generation systems based on wave [27], tidal [20], wind [28,29], nuclear [30], and solar PV [22,31] energy sources, including biomass systems used for biofuel production and electricity or heat generation [23,32]. The criteria used in each case depend on the proposed method; the number of criteria can range from 5 to 20, sometimes divided into one or two (even three) decision stages, as is shown in the works of Sanchez-Lozano et al. [28], Susiati et al. [30], Villacreces et al. [23] and Ángel-Sanint [33]. Diverse approaches and methods, such as genetic algorithms, Polynomial neural networks, Multilinear regression model [27], and Supply Chain Network Design (SCND) [34] have also been proposed to resolve questions about feasible and suitable locations for waves and biodiesel plants. Commonalities in the criteria used in these papers include the axes of sustainability that is, the economic, social, environmental, and technical issues [27,29,32] and their expansion to physical, cultural, landscape, and political frames [24,33].

1.3. Biomass use in Colombia

Colombia has a privileged geography and location for the production of large-scale crops such as sugar cane and oil palm. Furthermore, multiple harvesting seasons of different crops throughout the year generate a constant flow of biomass that could be harnessed for energy production. The energy potential of the residual biomass produced by Colombia's agricultural, agro-industrial, and forestry processes has been estimated using its physicochemical properties at around 204.8–235.3 PJ, assuming the current level of unused biomass [36]. However, the use of bioenergy in the country is still limited to producing first-generation biofuels. The future technical biomass supply potential in Colombia is high. It may reach up to 5200 PJ within the next four decades, which is 6.5 times the country's current total final energy consumption [37]. Colombia must overcome barriers to including biomass as a driver for energy production in order to take advantage of that high potential. However, there are currently no incentives for implementing new technologies, taxes, or subsidies aimed at stimulating significant private-sector participation [38].

Several technological developments are used to transform residual biomass for energy uses, such as gasification, esterification, pyrolysis, and anaerobic digestion (biodigesters) [39–41]. Furthermore, the CO_2 generated from the transformation of residual biomass into energy is biogenic and is therefore considered carbon neutral. In terms of research, Colombia has developed several studies analyzing the energy potential of different types of residual biomass, including using different technologies and diverse national and regional scenarios [42–45]. The Mining and Energy Planning Unit (abbreviated UPME in Spanish) has determined that the residual biomass generated in the country could supply 41% of the national energy demand [1]. Thus, the report: "Atlas del Potential Energético de la Biomasa en Colombia" [40] has been Colombia's first initiative to identify the types of biomass that can be used in the country. However, these data have not been analyzed to identify suitable areas for the sustainable use of biomass for energy generation in a way that accounts for the specific needs of each municipality.

1.4. Research significance

This research aims to fill the existing gap in identifying suitable locations for renewable energy sources that can contribute to the energy transition in Colombia. Two previous works have addressed a similar line of research in Colombia. The first determined the most feasible location for wind microgeneration systems [46], and the second does the same thing for SPV plants [47]. From 2012 to 2023, some interesting Colombian approaches employed MCDMs in junction with different sets of criteria according to the sustainability axes to perform computational simulations and thus obtain novel results, such as sustainable energy supply [24], renewable and sustainable energy plans [25], suitable locations for biodiesel plants [25] and potential maps for wind an SPV energy sources [33]. Some notable characteristics of these studies are summarized in Table 2. However, MCDM analysis has not yet been used to determine a suitable location for biomass-based energy generation using energy indicators. Therefore, this study was conducted to identify sustainable development indicators related to the energy sector to use as criteria under an AHP MCDM approach to generate a geospatial analysis and a geostatistical model through QGIS® software to determine the municipalities with high biomass energy potential in Colombia. Based on these analyses, we propose a suitable geolocation map under two different scenarios: the first considering expert opinions and the second considering some of the sustainable development goals proposed by the UN. We hope that this research will be the basis for applications of MCDM with more than one decision stage for renewable energy.

To do that, we first carried out a bibliographic review to determine which indicators have been established for the sustainable development of the energy sector. We then organized the information into vector format and normalized the data collected for each selected indicator. Then, we applied AHP, Rank-sum, and WLC multicriteria methods to determine which municipalities in Colombia are suitable for using biomass as an energy source for each of the two proposed scenarios. Finally, we obtained the suitable geolocation map for each of the cases. These steps are presented in Sections 2 and 3, the maps are shown in Section 4, Section 5 contains concluding remarks, and Section 6 details some recommendations for future research.

2. Multi-criteria decision methodology

The methodology used for this work consisted of three steps and seven sub-steps, as shown in Fig. 1.

2.1. Study area

Colombia is a country located in northwestern South America. It has a continental area of 1,141,748 km^2 and 988,000 km^2 of maritime territory. It comprises 32 departments and 1121 municipalities, including the Capital District of Bogotá. The estimated population in 2022 was 51,609,474 inhabitants. Colombia's variety of thermal zones allows for the development of a variety of agricultural and livestock activities. To date, three types of useable biomass have been characterized in Colombia: agricultural waste, livestock waste, and urban organic waste. The National Agricultural Survey (ENA) conducted by the National Administrative Department of Statistics (abbreviated DANE in Spanish) shows that the total agricultural production in 2019 alone was 63,247,863 tons, presenting a land use of 501 $\times$ 10^9 m^2; 77.9% of that area was used for livestock production and 9.2% for crop cultivation [48].

Regarding urban organic solid waste, approximately 7 million tons were disposed of in 2019 [49]. These data suggest that the biomass waste generated in these different sectors in Colombia may be sufficient for energy generation. For the analyses, we included all municipalities for which basic information was available on the amount of agricultural, livestock, and urban biomass and their respective energy potential. In the case of agricultural biomass, this comprised 1022 municipalities; for livestock biomass, 1095 municipalities; and for urban biomass, 17 municipalities (Fig. 2).

2.2. Criterial selection for MCDM application

We conducted a literature review to select sustainability indicators for the energy sector. We consulted the International Atomic Energy Agency et al. [10], Gunnarsdottir et al. [11]., De Lima [15], Cardoso et al. [13], and Kumar et al. [16]. Our selection of indicators considered the availability of current information for each municipality. At least one indicator was established for each sustainable development dimension (technical, social, environmental, and economic). The information related to each selected indicator was obtained from national organizations specialized in each area (IDEAM, DANE, IGAC, UPME). Each of the indicators was organized and adapted into an information layer (IL) in shapefile format (*.shp) generated using QGIS® software. The indicators were entered into spreadsheets (*.xlsx), then organized and converted into comma-separated data (*.CVS), and finally converted into (*.shp) format. The ILs were constructed using the national CMT 12 cartographic projection (datum: MAGNAS SIRGAS) using the Transverse Mercator projection, Latitude: 4.0° N, Longitude: 73.0° W.

2.3. Classification of indicators as factor criteria and/or exclusion criteria and approach to biomass utilization scenarios

Once we had determined which variables would be included in the model, it was necessary to classify each one as a factor criterion or an exclusion criterion. A factor criterion is a criterion in which the suitability of the alternative increases or decreases on a continuous scale according to the analysis; that is, it has a greater or lesser value within the proposed scenario. On the other hand, an

Table 2
Relevant research with application of MCDM in RNCES.

Year	Renewable Energy	Purpose/target	Criteria and indicators	N° Criteria	Stage	MCDM/Optimization Method	Reference
2012	Micro hydro Solar photovoltaic Biomass Hybrid: Diesel + biomass Diesel + solar PV Diesel + microhydro	Sustainable energy supply	Physical Financial Human Social Natural	5	1	Sustainable Livelihoods Approach (SLA), VIKOR, Compromise Programming (CP)	[24]
2012	Wind Solar Thermal Photovoltaic Wood Energy Biomass Co-combustion/ Biomass	Renewable sustainable energy plans	Annual Energy Investment per installed power Implementation time Useful life Non-emitted CO_2 Land use	6	1	AHP VIKOR	[25]
2017	Biodiesel	Sustainable facility location	Install. costs, economic, social, environmental, technological factors, market and customers, workforce availability	51	2	Supply Chain Network Design (SCND)	[34]
2023	Solar PV, Wind	Solar and Wind Potential Maps	Physical Biotic Economic Cultural Political	5	2	Spatial multi-criteria decision-making process	[33]

exclusion criterion is a criterion under which the proposed alternative is either suitable (1) or unsuitable (0), i.e., it has a binary response under Boolean logic. An indicator can simultaneously be a factor criterion and an exclusion criterion if the variable has stipulated limits based on normative or technical thresholds [13,50].

We proposed two scenarios under which to determine the suitability of use of biomass in Colombian municipalities:

1. **Scenario I:** Professional/expert perception: This scenario is based on the Analytic Hierarchy Process (AHP) methodology, whose application will be explained in section 2.4.2.
2. **Scenario II:** Climate action and sustainable development: The approach to this scenario was based on current development needs, in which climate change is defined as the main environmental problem to be mitigated through proper resource management and clean energy production. The SDGs involved in this scenario are SDG 7: affordable and non-polluting energy, followed by SDG1: ending poverty, SDG8: decent work and economic growth, and SDG11: sustainable cities and communities.

For each of these scenarios, we developed three separate geostatistical models one for each type of biomass (agricultural, livestock and, organic urban solid waste).

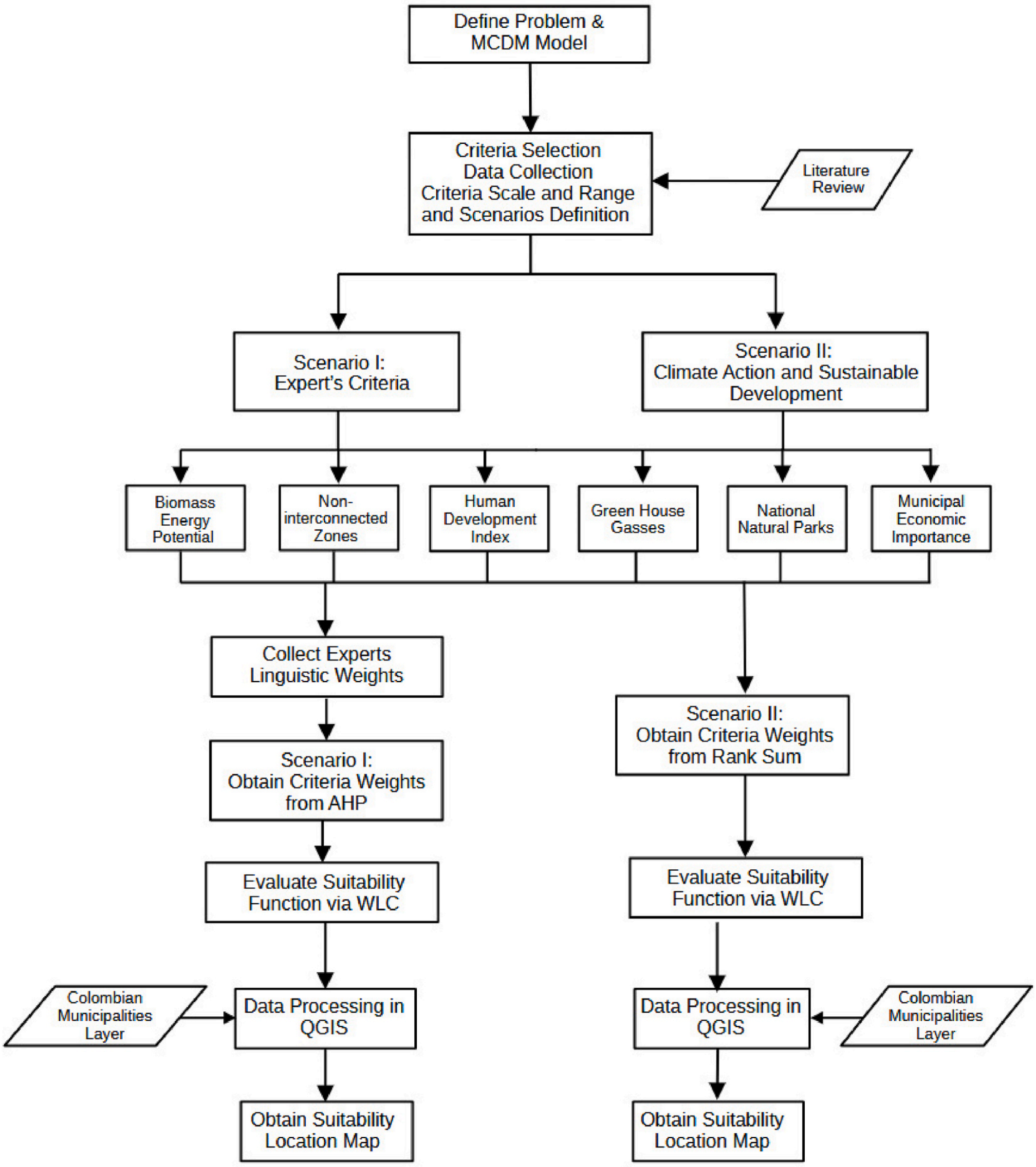


Fig. 1. Flowchart illustrating the MCDM used to identify municipalities in Colombia with potential for the use of biomass as an energy supply.

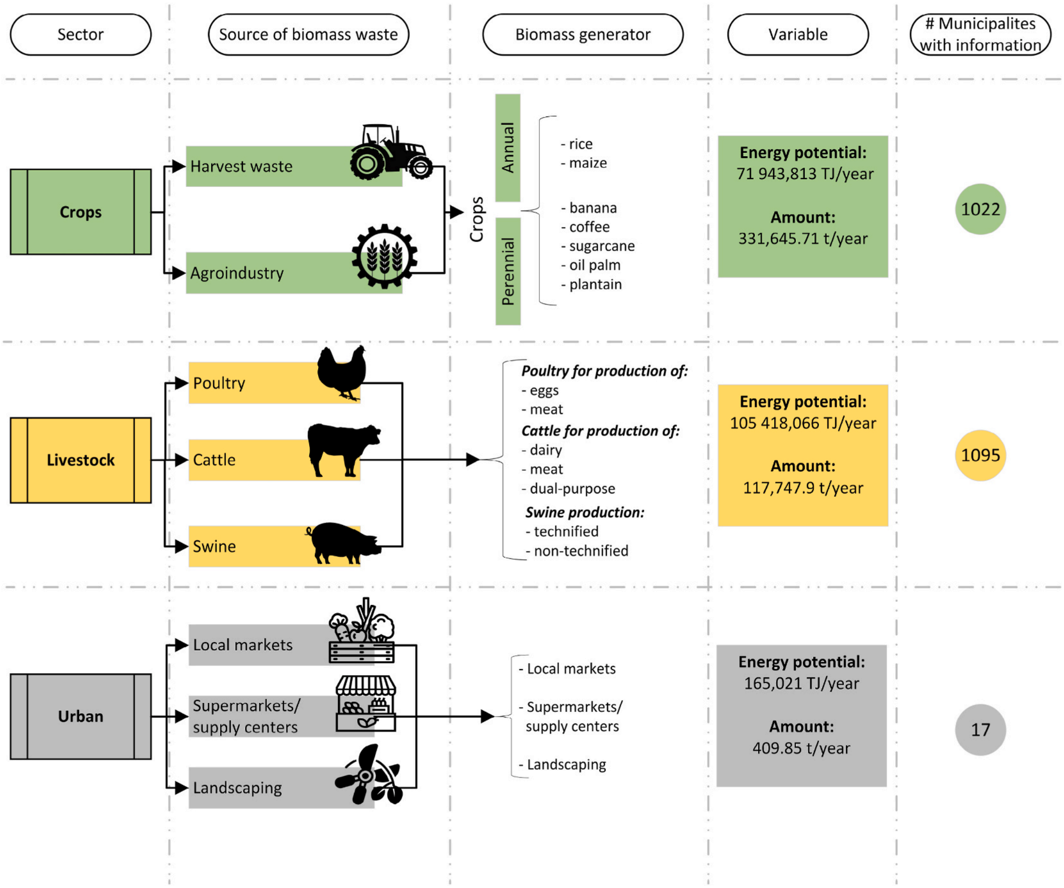


Fig. 2. Schematic summary of information on agricultural, livestock and municipal solid organic waste biomass. Source: generated by the authors, based on data from the "Atlas del Potencial Energético de la Biomasa en Colombia" [40].

2.4. Multi-criteria analysis

We applied the Multicriteria Analysis and integrated the selected indicators in the proposed scenarios by first normalizing the information layers using the linear increasing (equation (1)) or decreasing (equation (2)) function or by the Boolean method, depending on the classification of the variable as a factor and/or exclusion criterion. For scenario I, we used the subjective weighting method of the Analytic Hierarchy Process (AHP) [51]. For scenario II, we used the Rank-Sum method. Finally, we use the Weighted Linear Combination (WLC), which allows us to compensate for the indicators used for each of the scenarios and define the appropriate municipalities whose weighting is > 0.75 [15]. The method consisted of the following steps:

2.4.1. Standardization of information layers (ILs)

The information layers containing the indicators were standardized to convert all indicators to the same scale, which allows for direct comparison and cross-checking of the data. To do this, we used an increasing linear function (Equation (1), where the highest values are prioritized by assigning the value 1, i.e., suitable) and a decreasing linear function (Equation (2), in which the lowest values are prioritized by normalizing to 0, i.e., not suitable) [13,16,17]. This normalization was performed for each IL in QGIS® software, using the field calculator module and inserting the corresponding equation, thus obtaining a new column in the attribute table.

$$\mu_C = \left(\frac{x - x_a}{x_b - x_a}\right) \tag{1}$$

$$\mu_D = \left(\frac{x_b - x}{x_b - x_a}\right) \tag{2}$$

Where:
μ_C: Normalization of increasing criterion
μ_D: Normalization of decreasing criterion
x: Value to normalize

x_a: Minimum point of the criterion
x_b: Maximum point of the criteria

2.4.2. Scenario I: obtain criteria weights from the analytical hierarchy process (AHP)

Following the methodology of Saaty [19,26], Cardoso et al. [13], and De Lima [15] for the application of the AHP method, the indicators were weighted according to the scale of importance presented in Table 3. The participants who responded to the questionnaire were those professionals and experts in the area who's academic, research, and work activities were related to renewable energy, biomass, and public policies on energy efficiency. The score given by the respondents was organized into the consolidated criteria weighting matrix (square matrix), expressing the importance of the indicator (row *i*) for each criterion (column *j*) as shown in Table 3. The main diagonal of this matrix had a value of one (1), since the indicator is compared to itself. The values below the diagonal were calculated as the multiplicative inverse of the values above the diagonal, which are the values given by the respondents.

Once the surveys had been tabulated, we calculated the eigenvector to indicate the weighting of the comparison criteria. This method selects the hierarchical criteria that tend to conflict with each other. Subsequently, we calculated the consistency index, which indicates the coherence between the responses obtained and the consistency rate, which should be less than 10% [19,26]. This is achieved by following the steps below:

Step 1) Reciprocity analysis: We constructed the global consolidated criteria weighting matrix using the geometric mean method of the rows, using Equation (3), which determined the reciprocity value.

$$r = exp\left[\frac{1}{N}\sum_{j=1}^{N} Ln\left(a_{ij}\right)\right] = \left(\prod_{i=1}^{N} a^{ij}\right)^{\frac{1}{N}} \tag{3}$$

where:

r: Consolidated value of reciprocity
N: Total number of surveys applied.
a_{ij}: Decision-making element

Step 2) Homogeneity Analysis: This was performed by normalizing the global consolidated criteria weighting matrix, constructed from r, using Equation (4). Note that the sum of the columns of the global consolidated matrix must be equal to 1.

$$p = \frac{r}{\sum_{i}^{N} r_j} \tag{4}$$

where:

p: Normalized value
r: Consolidated value of reciprocity
N: Total number of surveys applied

Step 3) The eigenvector was calculated by applying Equation (5), which is used to determine the contribution of each indicator to the proposed scenario.

$$w = \frac{\sum p_j}{n} \tag{5}$$

where:

w: eigenvector of the normalized matrix
p_j: Normalized value
n: Total number of decision criteria

Step 4) We calculated the consistency rate, which quantifies the coherence of the information. For a matrix containing >5 criteria, the consistency rate should have a maximum value of 10% [19]. The consistency rate was determined by calculating the eigenvector of the matrix expressed as λmax (Equation (6)), which was then used to calculate the consistency index (Equation (7)), which was finally input into Equation (8) to calculate the consistency rate.

$$\lambda_{máx} = \sum\left(w_i * \sum r_j\right) \tag{6}$$

Table 3
Relative importance scale for determining indicator weights in Scenario I.

Less important				1	More important			
1/9	1/7	1/5	1/3		3	5	7	9
Extremely less important	Much less important	Moderately less important	Somewhat less important	Same importance	Somewhat more Important	Moderately more important	Much more important	Extremely more important

where
λ_{max}: eigen vector of the normalized matrix
w_i: eigen vector of the normalized matrix
r: Consolidated value of reciprocity

$$C_I = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

where:
C_I: consistency index
λ_{max}: eigen vector of the normalized matrix
n: Total number of decision criteria

$$C_R = \frac{C_I}{R_I} \tag{8}$$

where:
C_R: Consistency rate
C_I: consistency index
R_I: random consistency index (for matrix of size 5 = 1.25)

2.4.3. Scenario II: obtain criteria weights from Rank-Sum

The Rank-sum method is based on ordering the indicators in a ranking established by the decision-maker or formulator of the scenario being evaluated. In the ranking, a value equal to 1 is assigned to the most important criterion, 2 to the second most important criterion, and so forth, until a ranking is given to each of the established indicators [13,14]. After assigning ranks, the hierarchy was established by applying Equation (9).

$$W_j = \frac{n - r_j + 1}{\sum_k (n - r_j + 1)} \tag{9}$$

where:
w_j: normalized weight of attribute j.
r_j: consolidated reciprocity value
n: number of indicators

2.4.3. Evaluate the suitability function via the Weighted Linear Combination method (WLC)

We used the WLC method to balance the variables to calculate the overall suitability (S) of the result using Equation (10). The municipalities with an S value greater than 0.75 were considered suitable for using residual biomass for energy generation.

$$S = \sum_{i=1}^{n} w_i * x_i * \prod_{j=1}^{k} c_j \tag{10}$$

where:
S: Suitability
w_i: Weight of factor i (with $i = 1, \ldots, k$)
n: number of factors
x_i: score of factor criterion i
c_j: score of constraint criterion j (with $j = 1, \ldots, k$)
k: number of exclusion criteria

3. MCDM application

This section shows the application of the MCDM and its numerical results up to the suitability function.

3.1. Variable selection: geostatistical model indicators and information layers (ILs)

Table 4 summarizes the categories, several indicators, and the principal authors referenced in the literature review. The indicators generally reflected the interaction between the energy sector, social needs, environmental conditions, and economic growth. The references presented in Tables 1 and 2 complement this information. Interested parties can consult them as an important input to be applied in their research, starting from this work as a baseline.

To measure its progress toward SDG 7, Colombia has adopted three targets (and their respective indicators) related to increasing access to electricity, use of RNCES, and energy efficiency. Colombia's SDG progress report shows that by 2020, overall compliance with

Table 4
Summary of sustainable development indicators proposed for the energy sector, organized by author. When the original title is not in English, a translation is provided in parentheses.

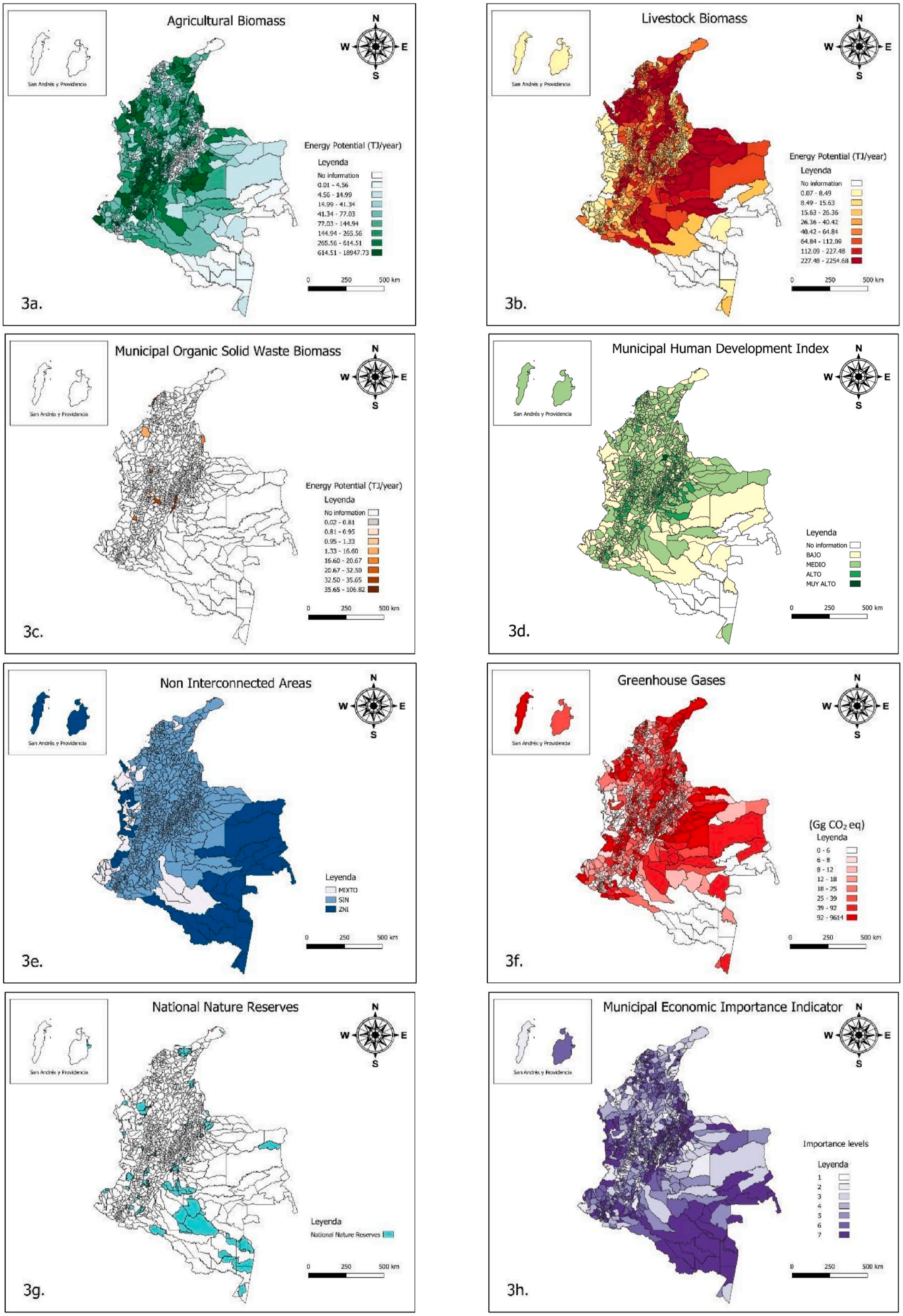
Author	Year	Study title	Indicator categories (# of indicators)	Reference
CEPAL et al.	2003	Energía y desarrollo sustentable en América Latina y el Caribe: Guía para la formulación de políticas energéticas. (*Energy and sustainable development in Latin America and the Caribbean. Guide for the formulation of energy policies)*	1. Economy (3) 2. Equity (2) 3. Natural resources (3)	[9]
International Atomic Energy Agency (IAEA)	2005	Energy Indicators for Sustainable Development: Guidelines and methodologies	1. Social dimension (4) 2. Economic dimension (16) 3. Environmental dimension (10)	[10]
Cardoso et al.	2015	Location of distributed generation by the perspective of sustainable development	1. Social dimension (9) 2. Economic dimensión (7) 3. Environmental dimension (3)	[13]
De Lima, C.	2017	Análise multicritério e aplicação sig para localização do potencial eólico, visando o desenvolvimento sustentável (*Application of multicriteria analysis and GIS for locating potential for sustainable wind energy development*)	1. Social dimension (7) 2. Economic dimension (5) 3. Environmental dimension (7)	[15]
Kumar et al.	2016	A Multi Criteria Decision-based rural electrification system	1. Technical criteria (7) 2. Social criteria (4) 3. Economic criteria (4) 4. Environmental criteria (3)	[51]
Gunnarsdottir et al.	2020	Review of indicators for sustainable energy development	A total of 57 indicator sets were found, grouped into the following four categories: 1. Sustainable energy development 2. Energy Security 3. Energy indicators in general Sustainable Development indicator sets 4. Other	[11]

this goal had advanced by 30.66%, most notably due to an increase in solar and wind energy generation capacity [52]. Apart from these indicators, Colombia can implement other indicators related to the energy sector that show progress in a sustainable energy sector. For example, for the sustainable development dimension related to the technological axis, Capacity Factor indicators show the time during which a system would not be available or would generate less energy due to specific situations, such as the lack of availability of the generating source [18]. Another indicator is system efficiency. For the social dimension, the percentage of households with access to commercial electricity distributed by the National Interconnected System of Colombia (SIN) can be included. The se data are equivalent to the data consolidated by DANE on access to public services, together with the reports of the

Table 5
Indicators selected for the multicriteria geostatistical model. English translations of titles in Spanish are provided in parentheses.

Sustainable development dimension	Indicator	Information source	Format
Technical	Biomass energy potential (BEP)	UPME, IDEAM, COLCIENCIAS y Universidad Industrial de Santander, (2015). Atlas del Potencial Energético de la Biomasa Residual en Colombia. (*Atlas of Waste Biomass Energy potential in Colombia*) [7]	Geodatabase (GDB)
Social	Non-interconnected zones (Households without access to commercial electricity) (NIZ)	UPME, https://ipse.gov.co/	Shapefile (*.shp)
	Human development index (HDI)	Duque, H y Garizado, P. (2020). Colombia: medición del Índice de Desarrollo Humano Municipal. *Revista de Economía & Administración*. Vol. 17 No. 2. (*Colombia: Measurement of the Municipal Human Development Index)*	Excel (*.xls) database
Environmental	Green House Gasses (GHG)	Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)	Excel (*.xls) database, one file per department (32)
	National Natural Parks (NNP)	IGAC. 2020. Colombia en mapas- áreas protegidas de Colombia. (*Colombia in maps- protected areas of Colombia)* https://www.colombiaenmapas.gov.co/#	Shapefile (*.shp)
Economic	Municipal economic I mportance indicator (MEII)	DANE. 2016. https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-departamentales/indicador-de-importancia-economica-municipal	Excel (*.xls) database

Note: the base layer of departments and municipalities is from https://www.dane.gov.co/files/geoportal-provisional/index.html.



(caption on next page)

Fig. 3. Information layers of selected indicators. Panels 3a, 3b and 3c indicate energy potential of the three biomass sources: 1 Giga gram of CO_2 eq is equal to 1000 T CO_2 eq. Panel 3d – 3h. Panels 3d – 3h show the selected indicators described in Table 5 for the dimensions of sustainable development. **Source:** Prepared by the authors.

non-interconnected zones given by the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones – IPSE [53–56]. Thus, Colombia does gather and make available information that can be used to calculate other valuable indicators to measure the progress of the energy sector in terms of sustainability.

The indicators that we selected to construct the geostatistical model are listed in Table 5, along with the description of the source of information and the format in which it was obtained.

3.1.1. Biomass energy potential (BEP)

Biomass from the agricultural sector (ASB), biomass from the livestock sector (LSB), and biomass from organic urban solid waste (USWB) are characterized in the report "Atlas del Potential Energético de la Biomasa Residual en Colombia" by UPME et al. [40]. Fig. 2 summarizes the sources of residual biomass generation in Colombia, the amount generated per year (t/year), the energy potential (TJ/year), and the number of municipalities that have information on biomass produced. The ILs of the total energy potential by biomass type are shown in Fig. 3a, b, and 3c. ASB had a higher energy potential (71,943,813 TJ/year) than the other two biomasses (Fig. 2). At the same time, a smaller quantity of ASB is required to generate energy because the plant material contains long chains of carbon and hydrogen that are involved in exothermic reactions that generate energy. In comparison, the energy potential of LSB is lower on a per-weight basis because it has a high percentage of relative humidity [40].

Information on ASB and LSB was available for 91.2% and 97.7% of Colombian municipalities, respectively. Meanwhile, quantification of USWB was available only for major cities and population centers, accounting for only 1.5% of the country's municipalities. This lack of information can be attributed to the informal management of urban solid waste in all but the most densely populated municipalities.

3.1.2. Non-interconnected zone (NIZ)

Non-Interconnected Zones (NIZ) refer to geographic areas that are not connected to the National Interconnected System (SIN) electrical grid. Although they do not have access to electricity through an interconnected system, they may have local power generation solutions such as liquid fuels. It has been estimated that the NIZ represents 52% of the national territory, with approximately 1,900,000 inhabitants. The NIZ currently includes 17 departments, mainly San Andrés and Providencia, Amazonas, Chocó, Vaupés, Vichada, Guainía, and Nariño, for a total of 97 municipalities and an estimated total of 1728 localities (including villages, population centers, and townships). The NIZ is characterized mainly by being areas with low population density, low average consumption of public services, as well as a low payment capacity by users; the presentation of the energy service is intermittent and with high costs [57]. Currently, in Colombia, the NIZ and their localities are classified into two types, NIZ with telemetry (8.6%) and NIZ without telemetry (91.4%). Geographic conditions are the main limitation for the implementation of a monitoring and measurement system in all NIZ [53,54]. Fig. 3e shows the distribution of the NIZ in the country.

3.1.3. Human development index (HDI)

According to the United Nations Development Program (UNDP), the HDI seeks to measure three essential components in a person's development life expectancy, educational level, and income and the HDI is the geometric mean of each of the related indicators [58]. The municipal HDI (mHDI) used for this work was developed by Duque and Garizado [59] for the year 2015 and was adapted into an IL (Fig. 3e) from the database in Excel format (*.xlsx). This index reflects the need for social and economic investment in the national territory to improve the inhabitants' quality of life. The mHDI shows a low level of human development in the municipalities in the country's peripheries. This evidences the need for more decentralization of administrative and economic resources, which is important for developing investment projects that improve the affordability of energy sector services.

3.1.4. Greenhouse gases (GHG)

One of the main characteristics of GHGs is their global warming potential, which corresponds to their capacity to absorb solar radiation. This characteristic, together with atmospheric concentrations of GHGs, generates what is known as the greenhouse effect [60]. The quantification of GHGs for the country was carried out by IDEAM, which updated the inventory of emission sources for 2018. The Unidad de Planeación Minero Energética (UPME) mainly generates information for the energy sector. Among the reports is the Useful Energy Balance, which contains information on fuel production, supply, and national consumption [38]. The total data for GHGs, specifically for the energy sector, was 92,940 Gigagrams (Gg) of CO_2 eq. Fuel combustion was the most significant contributor, with 90.02% of emissions. Among the departments and municipalities that generate the highest concentration of GHG are Cundinamarca (which includes the capital, Bogotá), Santander, and Antioquia, with values of 18,374, 8660.04, and 8048.32 Gg of CO_2 eq, respectively. To construct the IL by municipality (Fig. 3f), a relative weight was determined by dividing the total GHG generated in the department by the relative weight of the aggregate of the municipal economic importance indicator, which reflects the GHG contribution of each municipality to the departmental economy.

3.1.5. National natural parks (NNPs)

According to the governmental organization National Parks of Colombia, NNPs are areas within the national territory whose

Table 6
Classification of indicators as factor and/or exclusion criteria under each scenario.

Sustainable development dimension	Indicator	Variable to normalize	Criterion type under Scenario I	Criterion type under Scenario II	Type of normalization	Normalization scale	Description of normalization	Considerations for classification
Technical	BEP	Energy potential in TJ/año	Factor and Exclusion	Factor and Exclusion	Boolean method	0 1	<10% >10%	When normalizing the data, we considered that the energy potential available must meet the energy demand of at least 10% of the homes in the municipality. We considered that each home had an average energy consumption of 157 kWh/month[1] in 2015 [64]. We assigned a value of 0 (not suitable) to municipalities whose energy potential fulfilled the demand of <10% of homes and 1 (suitable) to those with a value > 10%.
Social	NIZ	Non-interconnected zone, NIS, or mixed	Exclusion	-	Boolean method	0 1	Non-NIZ (NIS or mixed) NIZ	The normalization was done by assigning a value of 0 (unsuitable) to municipalities connected to the NIS or mixed and 1 (suitable) to NIZ
	HDI	Development level	Factor	Factor	Increasing	0 1	<0.69 >0.7	For the normalization of the municipal HDI we considered the quantitative scale applying the increasing linear function (Equation (1)).
Environmental	GHG	GHG concentration in Gg CO_2 eq	Factor and Exclusion	Factor and Exclusion	Increasing	0 1	>10 <100	For normalization, we established that major cities, important population centers, industrial municipalities, and mining and petroleum-producing municipalities would be assigned a value of 1 (suitable) due to their socioeconomic conditions. The remaining municipalities received a value based on the increasing linear function (Equation (1)).
	NNP	NNP	Factor and Exclusion	-	Boolean method	0 1	With NNP No NNP	The data were normalized by assigning a value of 0 (unsuitable) for municipalities with NNP and 1 (suitable) to those without NNP.

(continued on next page)

Table 6 (*continued*)

Sustainable development dimension	Indicator	Variable to normalize	Criterion type under Scenario I	Criterion type under Scenario II	Type of normalization	Normalization scale	Description of normalization	Considerations for classification
Economic	MEII	Degree if importance	Factor	Factor	Increasing	0 1	7 1	For the normalization we considered the degree of importance values by municipality, which are associated with the gross domestic product value.

Note: [1]Average of four people per household. Number of inhabitants is from DANE 2020.
Source: Prepared by the authors

ecosystems have not presented significant anthropic alteration and have an ecological self-regulation, in which there is a healthy biotic, abiotic, cultural, and scientific interaction. Special management rules exist for their protection and conservation [61]. Within the study area, there are a total of 39 NNPs. Fig. 3g show the distribution of NNPs in Colombia.

3.1.6. Municipal economic importance indicator (MEII)

Law 1551 of 2012 defines economic importance as " … the relative weight represented by the Gross Domestic Product (GDP) of each municipality within its department" [62]. Considering this definition and the scale of this work, the MEII is taken as the indicator that indirectly expresses the municipality's wealth and directly, the municipal economy. For the elaboration of the ILs (Fig. 3g), we established a scale of importance ranging from 1 to 7 based on the value added to the GDP and the value added from different productive activities [63]. Fig. 3h shows the information collected for each of the ILs in their standard units of measurement.

3.2. Definition of indicators as factor and/or exclusion criteria and normalization of information layers (ILs)

Table 6 shows the classification of each indicator as a factor and exclusion criterion, considering the nature of the data and the proposed scenarios. It also explains how the normalization of the ILs was determined in Fig. 4, as follows: Normalization of energy potential for three types of biomass is shown in Fig. 4a to c. It can be seen in Fig. 4d that the non-interlinked areas are mainly placed in the savannah, Pacific, and Amazon regions. Fig. 4e to h shows the environmental, social, and economic IPs that include all sustainability dimensions.

For the normalization of the data, each of the selected indicators was analyzed to establish a scale of 0 and 1. We classified these indicators as factor and/or exclusion criterion. Table 6 describes how the data were normalized for each variable. For the BEP, we established that for conditions to be considered suitable for each type of biomass, the energy potential must be sufficient to meet the energy demand of at least 10% of the households in the municipality. We restricted this condition to the biomass generated within the municipality, classifying zero (0) as not suitable and one (1) as suitable. However, this restriction showed that there are municipalities that generate more residual biomass than they could use and municipalities that do not generate a sufficient amount for use.

After performing the normalization of the energy potential by biomass type and applying the criteria described above, where one is suitable and zero is not suitable for the use of biomass for energy production, we found that of the 1021 municipalities with available information, 77 were classified as suitable for ASB use. For LSB, out of 1095 municipalities with information, 47 were classified as suitable to be included in the model. In the case of the USWB, the 17 municipalities from which information could be obtained were all classified as ineligible according to the restriction established in this study. This is because these municipalities are the country's main cities and have a high number of inhabitants, which ruled out the use of the biomass generated b ecause it could not supplying at least 10% of the households in the municipality.

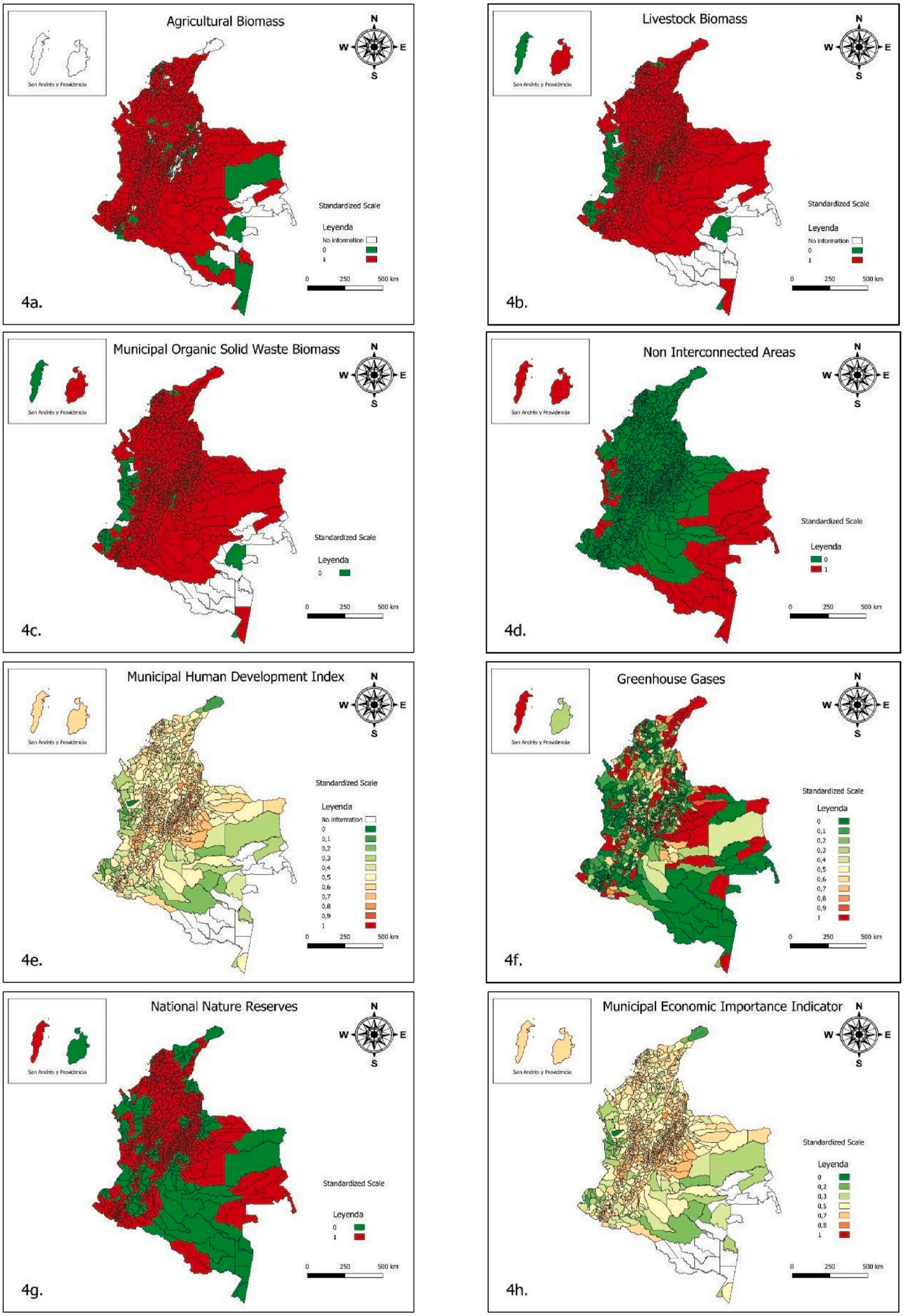
Regarding the normalization of the GHG indicator, the current information is structured on a department scale. To interpolate these data to a municipal scale, we assigned a relative weight to each municipality based on its score on the municipal economic importance indicator, which represents the relative weight of the GDP of each municipality. Given that this indicator was related to various commercial and industrial activities, it provides indirect information on the GHG produced by each municipality [37]. However, this value may be overestimated for some municipalities whose economic activities generate low GHG emissions.

In the case of the indicators NIZ, HDI, GHG, and MEII, the normalization was carried out considering the scale used by each of the entities that generate the information, since they used a specific scale that agreed with the classification as a factor or exclusion criterion established in this study.

3.3. Multicriteria analysis

3.3.1. Analytical hierarchical process (AHP) for scenario I

Table 7 shows the results of the surveys and the application of the AHP model (Table S1 shows the results of surveys completed by the panel of professionals and experts). Initially, the global consolidated matrix is shown, which contains the data obtained from the



(caption on next page)

Fig. 4. Standardized information layers considering the criteria described in Table 5, where 1 (red color) indicates suitable conditions and 0 (green color) indicates unsuitable conditions. The intermediate colors in 4e, 4f and 4g show municipalities with intermediate suitability. **Source:** Prepared by the authors.

surveys consolidated by the geometric mean method and the calculation of the lower diagonal from the multiplicative reciprocal of the upper diagonal. This was followed by the normalized global consolidated matrix data whose column sum was 1. The eigenvector established the hierarchy of the variables according to the importance given by the experts. As a result, the most important indicator was the PEB, corresponding to the biomass energy potential, followed by the GHG indicator. The consistency rate (CR) was 8.4%, below the maximum threshold of 10% [26], which confirms that the experts who participated in the survey were consistent in their assessments of the established indicators. Thus, it was possible to continue the multicriteria analysis using the WLC method.

3.3.2. Rank-Sum process for scenario II

In the hierarchical Rank-sum method, the most important indicator for the application of the model was the BEP, followed by GHG (Table 8). This was the same order as in the AHP method. Currently, the climate crisis requires the integration of various sectors to

Table 7
Results of the application of the AHP method under scenario I.

Global matrix — Stage 1: Reciprocity analysis

r	BEP	NIZ	HDI	GHG	NNP	MEII
BEP	1,00	3,81	1,93	2,54	2,24	0,83
NIZ	0,26	1,00	2,36	0,60	1,40	1,03
HDI	0,52	0,4	1,00	1,47	1,38	0,93
GHG	0,39	1,7	0,7	1,00	2,12	1,17
NNP	0,45	0,7	0,7	0,5	1,00	1,23
MEII	1,20	1,0	1,1	0,9	0,8	1,00
Sum	**3,82**	**8,60**	**7,76**	**6,93**	**8,94**	**6,20**

Normalized Matrix — Stage 2: Homogeneity Analysis

p	BEP	NIZ	HDI	GHG	NNP	MEII	Sum of rows
BEP	0,26	0,44	0,25	0,37	0,25	0,13	1,70
NIZ	0,07	0,12	0,30	0,09	0,16	0,17	0,90
HDI	0,14	0,05	0,13	0,21	0,15	0,15	0,83
GHG	0,10	0,19	0,09	0,14	0,24	0,19	0,96
NNP	0,12	0,08	0,09	0,07	0,11	0,20	0,67
MEII	0,31	0,11	0,14	0,12	0,09	0,16	0,94
Sum	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	

Eigen vector

Average	W
BEP	0,28
NIZ	0,15
HDI	0,14
GHG	0,16
NNP	0,11
MEII	0,16
Sum	**1,00**

Calculation of the consistency index and rate — **Stage 3: Consistency Analysis**

Main value of the Eigen vector	Λmax	Consistency index	CI	Consistency rate	CR	%
			0,105		0,084	**8.4**
BEP	1,086					
NIZ	1,286					
HDI	1,075					
GHG	1,104					
NNP	1,002					
MEII	0,972					
Sum	**6,52**					

Table 8
Results of Rank-sum methodology application under scenario II.

Scenario II	Category	W
BEP	1	0,333
HDI	3	0,200
GHG	2	0,267
NNP	5	0,067
MEII	4	0,133
Sum		1

Table 9
Results of the WLC method.

Agricultural residual biomass				Livestock residual biomass			
Municipality	**WLC Scenario I**	**Municipality**	**WLC Scenario II**	**Municipality**	**WLC Scenario I**	**Municipality**	**WLC Scenario II**
Barrancabermeja	0.813	Barrancabermeja	0.960	Cota	0.816	Barrancabermeja	0.960
Tenjo	0.801	Tenjo	0.927	Barrancabermeja	0.813	Cota	0.947
Sabaneta	0.786	Sabaneta	0.907	Tenjo	0.801	Tenjo	0.927
Caloto	0.786	Caloto	0.907	Sabaneta	0.786	Sabaneta	0.907
Funza	0.786	Funza	0.907	Sogamoso	0.786	Sogamoso	0.907
Yumbo	0.786	Yumbo	0.907	Duitama	0.786	Duitama	0.907
Sopó	0.772	Girardota	0.887	Caloto	0.786	Caloto	0.907
San Gil	0.772	Manizales	0.887	Cajicá	0.786	Cajicá	0.907
Girardota	0.771	Popayán	0.887	Funza	0.786	Funza	0.907
Manizales	0.771	La Jagua De Ibirico	0.887	Tocancipá	0.786	Tocancipá	0.907

achieve the global objective of reducing greenhouse gas emissions. The latest IPCC report on climate change (2022) highlights the increase and diversity of actors interested in actions to mitigate and reduce greenhouse gases [65]. Like the conclusions of the IPCC report, the results of the Rank-Sum method showed a strong priority of proposing sustainable changes and solutions within the energy production system.

3.3.4. *Weighted Linear Combination average (WLC)*

Our application of the WLC method allowed us to identify the municipalities with suitable characteristics for developing projects to utilize agricultural and livestock residual biomass. This provides information for private, public, and international investors' decision-making and local scale studies. Table 9 shows the municipalities that were determined as suitable for biomass utilization according to the criteria of the WLC method.

4. Results and discussion

The application of the MCDM (Section 3) yielded exciting results that demonstrate the suitability of biomass as an alternative for energy generation in Colombia according to the characteristics associated with its energy potential, the amount generated, and the place of origin of the biomass. RNCES use has increased worldwide, and renewable energy sources accounted for 17.7% of energy production in 2019. Countries such as Germany have strengthened their energy matrix by increasing RNCES from 9% to 27% in a decade, with wind energy being the most widely used in this country [66]. Germany has also managed to increase the service access rate from 83% to 91%, benefitting 467 million people [67]. Several studies in Colombia have shown that the energy sector depends mainly on fossil fuels, accounting for 93% of energy production, followed by hydroelectric with 4%, and only 3% of energy is currently produced using different types of biomasses. At the same time, it has been determined that biomass has the potential to meet 41% of Colombia's national energy demand [1]. Studies that characterize biomass quantity and energy potential in the country are critical to decision-makers as a technical tool to evaluate the feasibility of using renewable energy resources. It is, therefore, necessary to update the Atlas of biomass energy potential in Colombia, considering the objectives proposed based on the National Development Plan (2022–2026), which seeks to improve agricultural production and quality [63]. Increased agricultural production would also result in a more significant amount of residual biomass, which, if incorporated into the production chain as an energy source, would strengthen the country's circular economy.

The results of the Geolocation of suitable areas for biomass utilization under scenario I for residual agricultural biomass (Fig. 5a) identified 36 municipalities with suitable conditions for energy production, distributed in 17 of the 32 departments of the country (Appendix A Table 10). Barrancabermeja and Tenjo were the most suitable municipalities for this type of biomass. For livestock biomass (Fig. 5b), scenario I identified 63 municipalities as suitable for the use of this type of biomass ((Appendix Table 11). The municipalities of Cota, Barrancabermeja, and Tenjo obtained the highest scores. Under scenario I, the total number of suitable municipalities was 166. Of these, 13 scored higher than 0.90 in the WLC analysis; the top 3 municipalities were Barrancabermeja, Cota, and Tenjo.

Under scenario II (Fig. 6), of the 1121 municipalities that make up Colombia, 125 were considered suitable for using agricultural or livestock biomass (Appendix A Table 11), again, with the municipality of Barrancabermeja in first place. The indicators showed that Barrancabermeja has high energy potential, possible sources of financing and investment, and high GHG emissions that must be mitigated using clean technologies. This analysis shows that projects should be formulated not just from an economic perspective, but also from a sustainable development perspective, which requires studies and strategies to use biomass using appropriate indicators, such as those used in this work.

When reviewing the municipalities for each of the proposed scenarios (I and II) and the two types of biomass (ASB and LSB), the

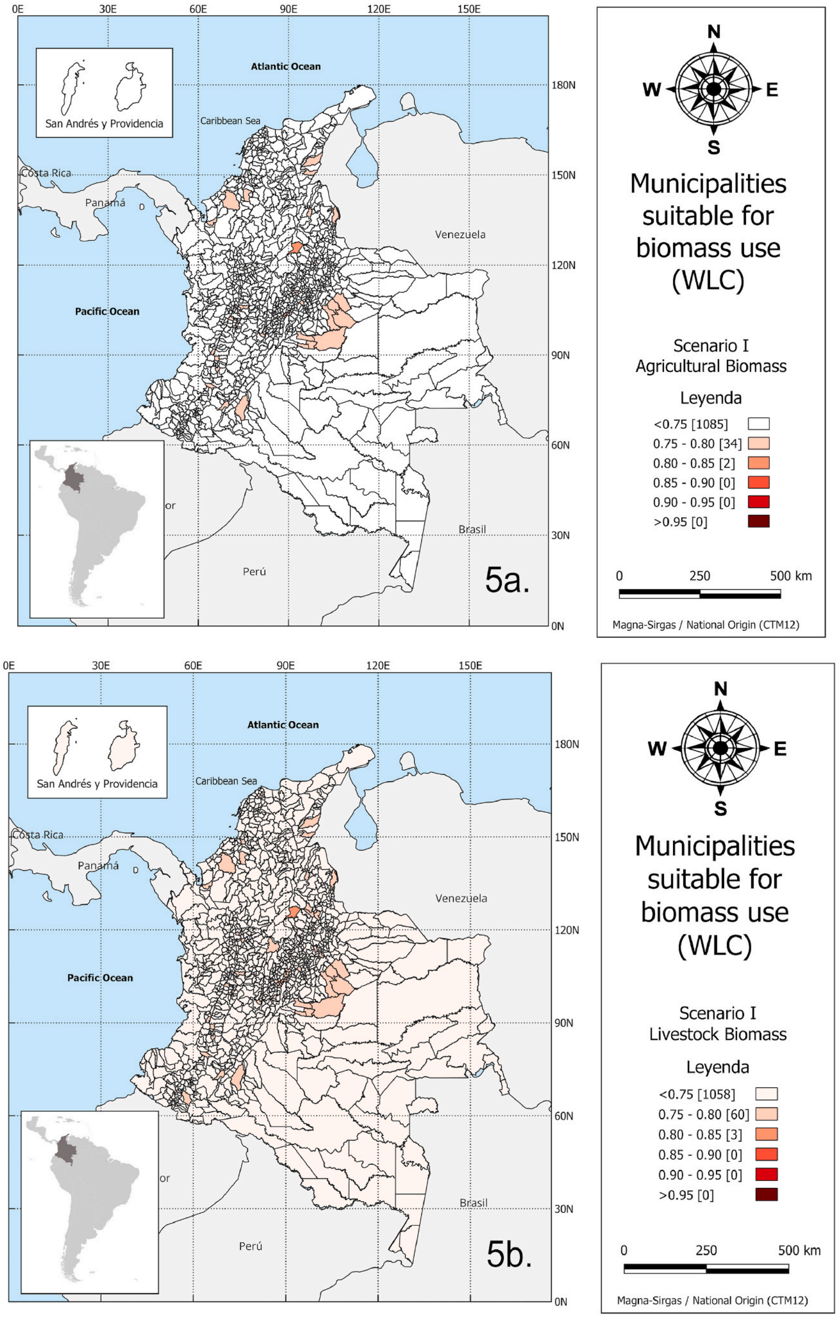


Fig. 5. Maps showing the Colombian municipalities identified as suitable for the use of agricultural biomass for energy production under the WLC method Scenario I.

municipalities of Barrancabermeja, Tenjo, and Sabaneta all had similar results using the WLC method, which makes them suitable under both scenarios and both types of biomass (Table 9). Barrancabermeja is located in the Magdalena Medio region of central Colombia, near the Magdalena River. It is one of the major oil-producing cities of Colombia, the location of the largest oil refinery in the country, and the most important industrial municipality in the department of Santander [46]. Barrancabermeja had a high score in the model for biomass utilization because it has high energy potential, sufficient to supply local energy needs at the residential level, and high production of GHG due to its oil and industrial activities. GHG emissions were prioritized within the scenarios, since they provide the opportunity to mitigate emissions by using biogenic energy.

Our results show that residual biomass has the capacity to supply local energy generation needs in more than 160 municipalities in the country. The need for an updated estimate of useable residual biomass and the reincorporation of urban waste into the production

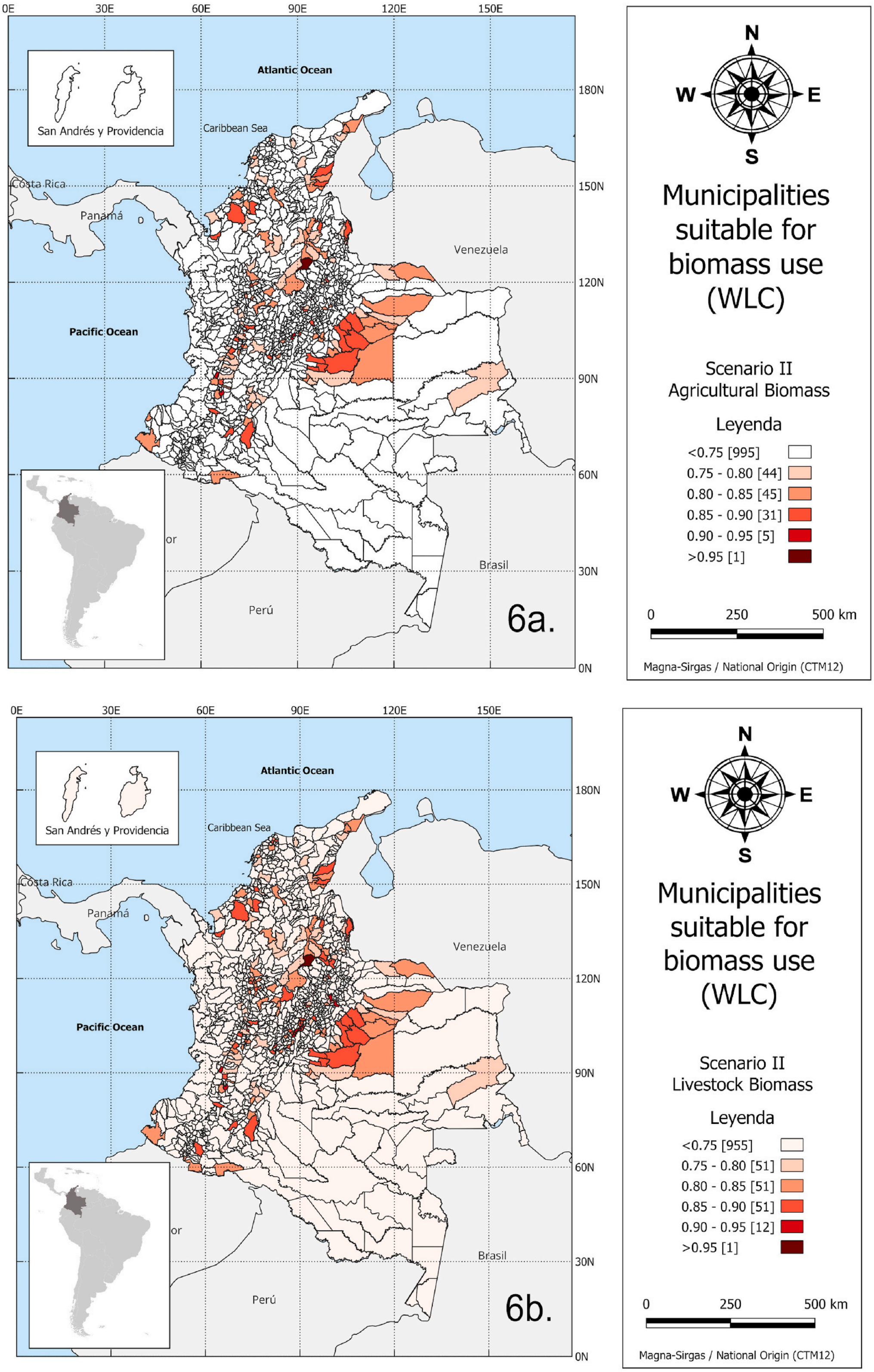


Fig. 6. Maps showing the Colombian municipalities identified as suitable for the use of livestock biomass for energy production under the WLC method Scenario II.

chain was highlighted by the Action Plan for the Sustainable Management of Residual Biomass of the Ministry of Environment and Sustainable Development, given the annual production of an estimated 9.76 million tons of waste. In response, the National Working Group for the Use of Residual Biomass was formed in June 2021 [47], based on the needs proposed within the National Circular Economy Policy. The activities formulated by the working group include the proposal of technical environmental guidelines for the design and operation of biomass utilization systems, technical documents that cover the biomass life cycle and utilization, and pilot projects for biomass utilization. Our work is a technical input to advance biomass utilization actions in Colombia, providing a methodology applicable at a local scale.

Although our analysis showed that no single municipality was suitable for USWB energy production, it is possible that projects that combine USWB from neighboring municipalities could amass sufficient energy potential to justify collective projects that supply energy to adjacent municipalities. For example, the municipality of Bogotá D.C. generates a total of 52,697 t/year of USWB, which has an estimated energy potential of 106.82 TJ/year, which would supply the energy needs of 15,750 homes. That amount of energy would be sufficient to supply energy to 77 of the 116 municipalities in the department of Cundinamarca, where Bogotá is located. Given the large, and ever-increasing, amount of USWB generated each year, there is a high potential for its use. The CONPES 3874 of 2016 estimates that by 2030, 18.74 million tons of solid waste will be generated per year in Colombia, compared to 13.8 million tons per year in 2014, representing a 13.4% increase in solid waste production per capita [24].

The integration of indicators under the multicriteria methodology for decision making allows the prioritization of suitable areas for the use of biomass, considering the sustainable development of the region. It should also be noted that one of the most accepted forms of biomass utilization today is the generation of electricity or heat, as in the case of biogas; however, biomass also has other uses such as transformation into organic fertilizers, which allows any type and quantity of biomass to be integrated into a productive cycle.

The Colombian National Energy Plan (2020–2050) uses only two indicators. The first one refers to energy intensity the relationship between energy demand or consumption and GDP in order to measure energy use efficiency. With the commitments acquired with the SDGs, Colombia needs to reduce energy intensity. By 2018, this indicator had a value of 3,3 TJ/billion (COP) and is expected to achieve 12% reduction by 2030. This is expected to be achieved by implementing policies and programs for rational energy use [45].

The second indicator corresponds to CO_2 emissions intensity, which is calculated by dividing CO_2 emissions by the GDP. This indicator also has a reduction target of 34% by 2030 [45]. Although these indicators show an overview of the energy sector in the country, other indicators can be incorporated to highlight the political efforts in the adoption of RNCES and their impact on the population.

Other studies conducted in Colombia related to the use of MCDM have focused on other renewable energy sources, such as photovoltaic [46] and wind [47], which have different characteristics than biomass. Although those studies used other indicators, a common purpose is evident among the works, considering sustainable development as an essential variable when formulating projects related to using renewable energies that favor the population in vulnerable areas. On the other hand, the suitable municipalities were smaller for photovoltaic and wind power than those that were considered suitable for use of biomass as a resource. This is associated with the agricultural vocation of the country and the large amount of waste generated that can be used.

5. Conclusions

The application of the multicriteria method for decision-making allowed the combination of technical, socio-environmental, and economic criteria, the opinion of experts, and the combination of GIS mapping for the identification of suitable municipalities in Colombia for the use of residual biomass for energy generation. The suitability values obtained with the application of the WLC method identified municipalities that are suitable for the use of agricultural and livestock residual biomass, considering the weighting and degree of importance of the sustainability indicators for the energy sector selected in this study.

A total of 127 municipalities were identified as suitable for the use of both agricultural and livestock residual biomass and 162 were suitable for livestock residual biomass. In the case of urban solid waste biomass, no municipality met the criterion of meeting the energy needs of at least 10% of the households in the generating municipality. However, this does not exclude the possibility of using residual biomass from urban solid waste at a larger scale through partnerships between municipalities, where biomass could be compiled at a single collection center and the resulting energy distributed according to the needs of each neighboring municipality.

Scenarios I and II had in common that the indicators of biomass energy potential (TJ/year) and GHGs were the most important for the proposed model. Under these indicators, the ideal municipalities for developing harvesting projects were Barrancabermeja, Tenjo, and Sabaneta in both scenarios. This is consistent with the conditions established to take advantage of residual biomass in municipalities that can supply more than 10% of their residential energy supply needs with this type of FNCES and that need to reduce the emission of GHGs.

The use of residual biomass to supply the energy needs of the region is an opportunity to take advantage of more than 450 thousand tons of waste generated per year in Colombia, where agriculture is one of the main economic activities. This would contribute to the generation of a local circular economy. However, it is essential to update the national baseline data on the amount of biomass produced annually and its energy potential for each type of biomass to develop models for its use with current data. This model will be helpful for decision-making in the public sector regarding the formulation of public policies and as a basis for the study of state and private investment projects, both national and international.

6. Recommendations

Some recommendations derived from this work, applying the multicriteria methods in renewable and sustainable energy generation to support the energy transition in Colombia, can be listed as follows:

* The scope of multicriteria analysis can be increased by increasing the number of ILs considering different ones or increasing the decision stages from 1 to 2 (even 3). Varying the MCDM applied at each decision stage is another interesting topic of study. On the other hand, it is advisable to include more indicators within the development of MCMD. However, care must be taken when selecting these indicators since data can be overestimated and underestimated, giving erroneous results.
* One or several MCDMs that help to decide a specific geolocation with more than one type of RNCES in the national territory beyond the municipal level can also be suggested.
* The research for technical-economic information can be expanded to build more suitable scenarios for official or private sectors interested in these analyses for the execution of public policies.
* The Inclusion of non-conventional renewable sources (such as tidal, wave, geothermal, hydrogen, fuel cells, etc.) in the MCDMs applied to the energy matrix transition is also interesting to develop in the future
* We also recommend that state entities and those that generate data centralize the information according to the field in consistently updated open database catalogs.

Author contribution statement

Maria Jisset CalvoSaad: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials analysis tools or data; Wrote the paper.

Walter MurilloArango: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Juan Sebastián Solís-Chaves: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.'

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e19874.

APPENDIX A

Table 10
Municipalities deemed suitable for agricultural biomass use under scenario I.

Department	Municipality ID	Municipality name	WLC Scenario I
Santander	68081	Barrancabermeja	0.813
Cundinamarca	25799	Tenjo	0.801
Antioquia	05631	Sabaneta	0.786
Cauca	19142	Caloto	0.786
Cundinamarca	25286	Funza	0.786
Valle Del Cauca	76892	Yumbo	0.786
Cundinamarca	25758	Sopó	0.772
Santander	68679	San Gil	0.772
Antioquia	05308	Girardota	0.771
Caldas	17001	Manizales	0.771
Cauca	19001	Popayán	0.771
Cesar	20400	La Jagua De Ibirico	0.771
Meta	50150	Castilla La Nueva	0.771
Norte De Santander	54001	San José De Cúcuta	0.771

(continued on next page)

Table 10 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario I
Quindio	63001	Armenia	0.771
Tolima	73268	Espinal	0.771
Valle Del Cauca	76130	Candelaria	0.771
Valle Del Cauca	76147	Cartago	0.771
Casanare	85001	Yopal	0.771
Boyacá	15176	Chiquinquirá	0.757
Caldas	17174	Chinchiná	0.757
Córdoba	23660	Sahagún	0.757
Cundinamarca	25873	Villapinzón	0.757
Meta	50573	Puerto López	0.757
Meta	50680	San Carlos De Guaroa	0.757
Norte De Santander	54498	Ocaña	0.757
Casanare	85139	Maní	0.757
Casanare	85410	Tauramena	0.757
Antioquia	05045	Apartadó	0.756
Caquetá	18001	Florencia	0.756
Cesar	20013	Agustín Codazzi	0.756
Córdoba	23001	Montería	0.756
Huila	41551	Pitalito	0.756
Meta	50001	Villavicencio	0.756
Risaralda	66170	Dosquebradas	0.756
Casanare	85010	Aguazul	0.756

Table 11
Municipalities deemed suitable for livestock biomass use under scenario I.

Department	Municipality ID	Municipality name	WLC Scenario I
Cundinamarca	25214	Cota	0.816
Santander	68081	Barrancabermeja	0.813
Cundinamarca	25799	Tenjo	0.801
Antioquia	05631	Sabaneta	0.786
Boyacá	15759	Sogamoso	0.786
Boyacá	15238	Duitama	0.786
Cauca	19142	Caloto	0.786
Cundinamarca	25126	Cajicá	0.786
Cundinamarca	25286	Funza	0.786
Cundinamarca	25817	Tocancipá	0.786
Cundinamarca	25175	Chía	0.786
Cundinamarca	25473	Mosquera	0.786
Valle Del Cauca	76892	Yumbo	0.786
Boyacá	15491	Nobsa	0.772
Cundinamarca	25758	Sopó	0.772
Cundinamarca	25793	Tausa	0.772
Santander	68679	San Gil	0.772
Antioquia	05308	Girardota	0.771
Antioquia	05615	Rionegro	0.771
Caldas	17001	Manizales	0.771
Cauca	19001	Popayán	0.771
Cesar	20400	La Jagua De Ibirico	0.771
Cundinamarca	25269	Facatativá	0.771
Cundinamarca	25430	Madrid	0.771
Cundinamarca	25899	Zipaquirá	0.771
Cundinamarca	25307	Girardot	0.771
Cundinamarca	25290	Fusagasugá	0.771
Meta	50150	Castilla La Nueva	0.771
Nariño	52001	Pasto	0.771
Norte De Santander	54001	San José De Cúcuta	0.771
Quindío	63001	Armenia	0.771
Santander	68307	Girón	0.771
Santander	68276	Floridablanca	0.771
Santander	68547	Piedecuesta	0.771
Sucre	70001	Sincelejo	0.771
Tolima	73268	Espinal	0.771
Valle Del Cauca	76130	Candelaria	0.771
Valle Del Cauca	76147	Cartago	0.771
Casanare	85001	Yopal	0.771
Atlántico	08078	Baranoa	0.757
Boyacá	15176	Chiquinquirá	0.757
Caldas	17174	Chinchiná	0.757

(*continued on next page*)

Table 11 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario I
Córdoba	23660	Sahagún	0.757
Cundinamarca	25200	Cogua	0.757
Cundinamarca	25873	Villapinzón	0.757
Meta	50573	Puerto López	0.757
Meta	50680	San Carlos De Guaroa	0.757
Norte De Santander	54498	Ocaña	0.757
Santander	68406	Lebrija	0.757
Casanare	85139	Maní	0.757
Casanare	85410	Tauramena	0.757
Antioquia	05045	Apartadó	0.756
Antioquia	05088	Bello	0.756
Atlántico	08433	Malambo	0.756
Boyacá	15572	Puerto Boyacá	0.756
Caquetá	18001	Florencia	0.756
Cesar	20013	Agustín Codazzi	0.756
Córdoba	23001	Montería	0.756
Huila	41551	Pitalito	0.756
Meta	50001	Villavicencio	0.756
Risaralda	66170	Dosquebradas	0.756
Casanare	85010	Aguazul	0.756
Antioquia	05380	La Estrella	0.755

Table 12
Municipalities deemed suitable for livestock biomass use under scenario II.

Department	Municipality ID	Municipality name	WLC Scenario II
Santander	68081	Barrancabermeja	0.960
Cundinamarca	25214	Cota	0.947
Cundinamarca	25799	Tenjo	0.927
Antioquia	05631	Sabaneta	0.907
Boyacá	15759	Sogamoso	0.907
Boyacá	15238	Duitama	0.907
Cauca	19142	Caloto	0.907
Cundinamarca	25126	Cajicá	0.907
Cundinamarca	25286	Funza	0.907
Cundinamarca	25817	Tocancipá	0.907
Cundinamarca	25175	Chía	0.907
Cundinamarca	25473	Mosquera	0.907
Valle Del Cauca	76892	Yumbo	0.907
Antioquia	05308	Girardota	0.887
Antioquia	05615	Rionegro	0.887
Caldas	17001	Manizales	0.887
Cauca	19001	Popayán	0.887
Cesar	20400	La Jagua De Ibirico	0.887
Cundinamarca	25269	Facatativá	0.887
Cundinamarca	25430	Madrid	0.887
Cundinamarca	25899	Zipaquirá	0.887
Cundinamarca	25307	Girardot	0.887
Cundinamarca	25290	Fusagasugá	0.887
Meta	50150	Castilla La Nueva	0.887
Nariño	52001	Pasto	0.887
Norte De Santander	54001	San José De Cúcuta	0.887
Quindio	63001	Armenia	0.887
Santander	68307	Girón	0.887
Santander	68276	Floridablanca	0.887
Santander	68547	Piedecuesta	0.887
Sucre	70001	Sincelejo	0.887
Tolima	73268	Espinal	0.887
Valle Del Cauca	76130	Candelaria	0.887
Valle Del Cauca	76147	Cartago	0.887
Casanare	85001	Yopal	0.887
Boyacá	15491	Nobsa	0.880
Cundinamarca	25758	Sopó	0.880
Cundinamarca	25793	Tausa	0.880
Santander	68679	San Gil	0.880
Antioquia	05380	La Estrella	0.880
Antioquia	05045	Apartadó	0.867
Antioquia	05088	Bello	0.867
Atlántico	08433	Malambo	0.867

(*continued on next page*)

Table 12 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario II
Boyacá	15572	Puerto Boyacá	0.867
Caquetá	18001	Florencia	0.867
Cesar	20013	Agustín Codazzi	0.867
Córdoba	23001	Montería	0.867
Huila	41551	Pitalito	0.867
Meta	50001	Villavicencio	0.867
Risaralda	66170	Dosquebradas	0.867
Casanare	85010	Aguazul	0.867
Atlántico	08078	Baranoa	0.860
Boyacá	15176	Chiquinquirá	0.860
Caldas	17174	Chinchiná	0.860
Córdoba	23660	Sahagún	0.860
Cundinamarca	25200	Cogua	0.860
Cundinamarca	25873	Villapinzón	0.860
Meta	50573	Puerto López	0.860
Meta	50680	San Carlos De Guaroa	0.860
Norte De Santander	54498	Ocaña	0.860
Santander	68406	Lebrija	0.860
Casanare	85139	Maní	0.860
Casanare	85410	Tauramena	0.860
Valle Del Cauca	76895	Zarzal	0.853
Antioquia	05129	Caldas	0.847
Antioquia	05318	Guarne	0.847
Valle Del Cauca	76113	Bugalagrande	0.847
Cesar	20045	Becerril	0.847
La Guajira	44035	Albania	0.847
Arauca	81001	Arauca	0.847
Antioquia	05212	Copacabana	0.840
Atlántico	08296	Galapa	0.840
Bolívar	13836	Turbaco	0.840
Bolívar	13430	Magangué	0.840
Caldas	17380	La Dorada	0.840
Cauca	19698	Santander De Quilichao	0.840
Cesar	20178	Chiriguaná	0.840
Cesar	20011	Aguachica	0.840
Córdoba	23417	Lorica	0.840
Cundinamarca	25386	La Mesa	0.840
Cundinamarca	25839	Ubalá	0.840
Cundinamarca	25740	Sibaté	0.840
Meta	50124	Cabuyaro	0.840
Meta	50313	Granada	0.840
Nariño	52356	Ipiales	0.840
Norte De Santander	54874	Villa Del Rosario	0.840
Santander	68615	Rionegro	0.840
Santander	68575	Puerto Wilches	0.840
Casanare	85250	Paz De Ariporo	0.840
Antioquia	05664	San Pedro De Los Milagros	0.833
Antioquia	05440	Marinilla	0.827
Antioquia	05649	San Carlos	0.827
Antioquia	05686	Santa Rosa De Osos	0.827
Boyacá	15806	Tibasosa	0.827
Boyacá	15837	Tuta	0.827
Meta	50568	Puerto Gaitán	0.827
Nariño	52835	San Andrés De Tumaco	0.827
Antioquia	05079	Barbosa	0.820
Antioquia	05376	La Ceja	0.820
Atlántico	08638	Sabanalarga	0.820
Huila	41885	Yaguará	0.820
La Guajira	44430	Maicao	0.820
Santander	68190	Cimitarra	0.820
Casanare	85230	Orocué	0.820
Casanare	85325	San Luis De Palenque	0.820
Putumayo	86568	Puerto Asís	0.820
Antioquia	05756	Sonsón	0.813
Cauca	19455	Miranda	0.813
Tolima	73449	Melgar	0.813
Córdoba	23189	Ciénaga De Oro	0.813
Antioquia	05154	Caucasia	0.807
Boyacá	15690	Santa María	0.807
Huila	41298	Garzón	0.807

(*continued on next page*)

Table 12 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario II
Quindio	63130	Calarcá	0.807
Valle Del Cauca	76122	Caicedonia	0.807
La Guajira	44078	Barrancas	0.800
Arauca	81065	Arauquita	0.800
Antioquia	05034	Andes	0.800
Antioquia	05250	El Bagre	0.800
Antioquia	05579	Puerto Berrío	0.800
Huila	41524	Palermo	0.800
Huila	41132	Campoalegre	0.800
Antioquia	05887	Yarumal	0.793
Cundinamarca	25183	Chocontá	0.793
Cundinamarca	25843	Villa De San Diego De Ubaté	0.793
Magdalena	47980	Zona Bananera	0.793
Santander	68755	Socorro	0.793
Cesar	20770	San Martín	0.787
Meta	50287	Fuente De Oro	0.787
Meta	50689	San Martín	0.787
Santander	68077	Barbosa	0.787
Santander	68820	Tona	0.787
Casanare	85440	Villanueva	0.787
Cesar	20710	San Alberto	0.780
Norte De Santander	54405	Los Patios	0.780
Santander	68655	Sabana De Torres	0.780
Guainía	94001	Inírida	0.780
Antioquia	05736	Segovia	0.780
Antioquia	05893	Yondó	0.780
Antioquia	05895	Zaragoza	0.780
Cesar	20238	El Copey	0.773
Córdoba	23162	Cereté	0.773
Córdoba	23555	Planeta Rica	0.773
Bolívar	13244	El Carmen De Bolívar	0.767
Boyacá	15516	Paipa	0.767
Caldas	17042	Anserma	0.767
Caldas	17614	Riosucio	0.767
Cesar	20250	El Paso	0.767
Norte De Santander	54261	El Zulia	0.767
Norte De Santander	54518	Pamplona	0.767
Valle Del Cauca	76616	Riofrío	0.767
Casanare	85225	Nunchía	0.767
Casanare	85430	Trinidad	0.767
Antioquia	05490	Necoclí	0.760
Bolívar	13052	Arjona	0.760
Sucre	70215	Corozal	0.760
Valle Del Cauca	76622	Roldanillo	0.760
Antioquia	05264	Entrerríos	0.753
Bolívar	13744	Simití	0.753
Boyacá	15632	Saboyá	0.753
Huila	41001	Neiva	0.753
Risaralda	66001	Pereira	0.753
Tolima	73001	Ibagué	0.753
Valle Del Cauca	76111	Guadalajara De Buga	0.753
Valle Del Cauca	76520	Palmira	0.753
Valle Del Cauca	76834	Tuluá	0.753

Table 13
Municipalities deemed suitable for agricultural biomass use under scenario II.

Department	Municipality ID	Municipality name	WLC Scenario II
Santander	68081	Barrancabermeja	0.960
Cundinamarca	25799	Tenjo	0.927
Antioquia	05631	Sabaneta	0.907
Cauca	19142	Caloto	0.907
Cundinamarca	25286	Funza	0.907
Valle Del Cauca	76892	Yumbo	0.907
Antioquia	05308	Girardota	0.887
Caldas	17001	Manizales	0.887
Cauca	19001	Popayán	0.887
Cesar	20400	La Jagua De Ibirico	0.887
Meta	50150	Castilla La Nueva	0.887

(*continued on next page*)

Table 13 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario II
Norte De Santander	54001	San José De Cúcuta	0.887
Quindio	63001	Armenia	0.887
Tolima	73268	Espinal	0.887
Valle Del Cauca	76130	Candelaria	0.887
Valle Del Cauca	76147	Cartago	0.887
Casanare	85001	Yopal	0.887
Cundinamarca	25758	Sopó	0.880
Santander	68679	San Gil	0.880
Antioquia	05045	Apartadó	0.867
Caquetá	18001	Florencia	0.867
Cesar	20013	Agustín Codazzi	0.867
Córdoba	23001	Montería	0.867
Huila	41551	Pitalito	0.867
Meta	50001	Villavicencio	0.867
Risaralda	66170	Dosquebradas	0.867
Casanare	85010	Aguazul	0.867
Boyacá	15176	Chiquinquirá	0.860
Caldas	17174	Chinchiná	0.860
Córdoba	23660	Sahagún	0.860
Cundinamarca	25873	Villapinzón	0.860
Meta	50573	Puerto López	0.860
Meta	50680	San Carlos De Guaroa	0.860
Norte De Santander	54498	Ocaña	0.860
Casanare	85139	Maní	0.860
Casanare	85410	Tauramena	0.860
Valle Del Cauca	76895	Zarzal	0.853
Antioquia	05129	Caldas	0.847
Valle Del Cauca	76113	Bugalagrande	0.847
Cesar	20045	Becerril	0.847
La Guajira	44035	Albania	0.847
Arauca	81001	Arauca	0.847
Antioquia	05212	Copacabana	0.840
Atlántico	08296	Galapa	0.840
Bolívar	13836	Turbaco	0.840
Bolívar	13430	Magangué	0.840
Cauca	19698	Santander De Quilichao	0.840
Cesar	20178	Chiriguaná	0.840
Cesar	20011	Aguachica	0.840
Córdoba	23417	Lorica	0.840
Cundinamarca	25386	La Mesa	0.840
Cundinamarca	25839	Ubalá	0.840
Meta	50124	Cabuyaro	0.840
Meta	50313	Granada	0.840
Norte De Santander	54874	Villa Del Rosario	0.840
Santander	68615	Rionegro	0.840
Santander	68575	Puerto Wilches	0.840
Casanare	85250	Paz De Ariporo	0.840
Antioquia	05649	San Carlos	0.827
Antioquia	05686	Santa Rosa De Osos	0.827
Boyacá	15806	Tibasosa	0.827
Boyacá	15837	Tuta	0.827
Meta	50568	Puerto Gaitán	0.827
Nariño	52835	San Andrés De Tumaco	0.827
Antioquia	05079	Barbosa	0.820
Antioquia	05376	La Ceja	0.820
Huila	41885	Yaguará	0.820
La Guajira	44430	Maicao	0.820
Santander	68190	Cimitarra	0.820
Casanare	85230	Orocué	0.820
Casanare	85325	San Luis De Palenque	0.820
Putumayo	86568	Puerto Asís	0.820
Antioquia	05756	Sonsón	0.813
Cauca	19455	Miranda	0.813
Tolima	73449	Melgar	0.813
Córdoba	23189	Ciénaga De Oro	0.813
Antioquia	05154	Caucasia	0.807
Boyacá	15690	Santa María	0.807
Huila	41298	Garzón	0.807
Quindio	63130	Calarcá	0.807
Valle Del Cauca	76001	Cali	0.807

(*continued on next page*)

Table 13 (*continued*)

Department	Municipality ID	Municipality name	WLC Scenario II
Valle Del Cauca	76122	Caicedonia	0.807
La Guajira	44078	Barrancas	0.800
Arauca	81065	Arauquita	0.800
Antioquia	05034	Andes	0.800
Antioquia	05250	El Bagre	0.800
Antioquia	05579	Puerto Berrío	0.800
Huila	41524	Palermo	0.800
Huila	41132	Campoalegre	0.800
Antioquia	05887	Yarumal	0.793
Magdalena	47980	Zona Bananera	0.793
Santander	68755	Socorro	0.793
Cesar	20770	San Martín	0.787
Meta	50287	Fuente De Oro	0.787
Meta	50689	San Martín	0.787
Santander	68077	Barbosa	0.787
Santander	68820	Tona	0.787
Casanare	85440	Villanueva	0.787
Cesar	20710	San Alberto	0.780
Norte De Santander	54405	Los Patios	0.780
Santander	68655	Sabana De Torres	0.780
Guainía	94001	Inírida	0.780
Antioquia	05893	Yondó	0.780
Antioquia	05895	Zaragoza	0.780
Cesar	20238	El Copey	0.773
Córdoba	23162	Cereté	0.773
Córdoba	23555	Planeta Rica	0.773
Bolívar	13244	El Carmen De Bolívar	0.767
Caldas	17042	Anserma	0.767
Caldas	17614	Riosucio	0.767
Cesar	20250	El Paso	0.767
Norte De Santander	54261	El Zulia	0.767
Valle Del Cauca	76616	Riofrío	0.767
Casanare	85225	Nunchía	0.767
Casanare	85430	Trinidad	0.767
Antioquia	05490	Necoclí	0.760
Bolívar	13052	Arjona	0.760
Valle Del Cauca	76622	Roldanillo	0.760
Bolívar	13744	Simití	0.753
Boyacá	15632	Saboyá	0.753
Huila	41001	Neiva	0.753
Risaralda	66001	Pereira	0.753
Tolima	73001	Ibagué	0.753
Valle Del Cauca	76111	Guadalajara De Buga	0.753
Valle Del Cauca	76520	Palmira	0.753
Valle Del Cauca	76834	Tuluá	0.753

References

[1] J. Lelieveld, K. Klingmüller, A. Pozzer, R.T. Burnett, A. Haines, V. Ramanathan, Effects of fossil fuel and total anthropogenic emission removal on public health and climate, Proc. Natl. Acad. Sci. U.S.A. 116 (2019) 7192–7197, https://doi.org/10.1073/pnas.1819989116.

[2] UPME, Ministerio de Minas y Energía de la República de Colombia, BID, FMAM, Integración de las Energías Renovables No Convencionales en Colombia, 2015. http://www.upme.gov.co/Estudios/2015/Integracion_Energias_Renovables/INTEGRACION_ENERGIAS_RENOVANLES_WEB.pdf.

[3] Q. Fu, S. Álvarez-Otero, M.S. Sial, U. Comite, P. Zheng, S. Samad, J. Oláh, Impact of renewable energy on economic growth and CO2 emissions - evidence from BRICS Countries, Processes 9 (2021), https://doi.org/10.3390/pr9081281.

[4] Independent statistics and analysis U.S, in: Energy Information Admistration, Electricity, 2022. (Accessed 11 January 2023).

[5] UN - climate change, Energías renovables: energías para un futuro más seguro, 2022. https://www.un.org/es/climatechange/raising-ambition/renewable-energy. (Accessed 11 January 2023).

[6] DNP (Departamento Nacional de Planeación), Colombia avanza en más del 72% de cumplimiento de los ODS, 2022. https://www.dnp.gov.co/Prensa_/Noticias/Paginas/colombia-avanza-en-mas-del-72-de-cumplimiento-de-los-ods.aspx#:~:text=La%20reciente%20publicaci%C3%B3n%20del,respecto%20a%20la%20meta%202030. (Accessed 25 January 2023).

[7] A. Armin Razmjoo, A. Sumper, A. Davarpanah, Energy sustainability analysis based on SDGs for developing countries, Energy Sources, Part A Recovery, Util. Environ. Eff. 42 (2020) 1041–1056, https://doi.org/10.1080/15567036.2019.1602215.

[8] A.Q. Al-Shetwi, Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges, Sci. Total Environ. (2022) 822, https://doi.org/10.1016/j.scitotenv.2022.153645.

[9] CEPAL, OLADE, GTZ, Energía y desarrollo sustentable en América Latina y El Caribe: Guía para la formulación de políticas energéticas, Naciones unidadas, Santiago de chile, 2003.

[10] I.A.E.A. International Energy Agency (IEA), Energy Indicators for Sustainable Development: Guidelines and Methodologies, 2007, pp. 1–140. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1222_web.pdf.

[11] I. Gunnarsdottir, B. Davidsdottir, E. Worrell, S. Sigurgeirsdottir, Review of indicators for sustainable energy development, Renew. Sustain. Energy Rev. 113 (2020), 110294, https://doi.org/10.1016/j.rser.2020.110294.
[12] ONU, Objetivos de Desarrollo sostenible. https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/, 2022. (Accessed 12 February 2023).
[13] G.S. Cardoso De Lima, P.T. Leite, B.C. Canesso, K.L. Zambon, Location of distributed generation by the perspective of sustainable development, in: IYCE 2015 - Proceedings: 2015 5th International Youth Conference on Energy, 2015, pp. 1–6, https://doi.org/10.1109/IYCE.2015.7180819.
[14] K.L. Zambon, , A.A. de F.M. Carneiro, A.N.R. da Silva, J.C. Negri, Análise de decisão multicritério na localização de usinas termoelétricas utilizando SIG, Pesqui. Oper. 25 (2005) 183–199, https://doi.org/10.1590/S0101-74382005000200002.
[15] C. de Lima, Análise Multicritério E Aplicação Sig Para Localização Do Potencial Eólico , Visando O Desenvolvimento Análise Multicritério E Aplicação Sig Para Localização Do Potencial Eólico, Visando O Desenvolvimento, 2017.
[16] A. Kumar, B. Sah, Y. Deng, X. He, P. Kumar, R.C. Bansal, Application of multi-criteria decision analysis tool for design of a sustainable micro-grid for a remote village in the Himalayas, J. Eng. (2017) 2108–2113, https://doi.org/10.1049/joe.2017.0702.
[17] A. Deepanjali, H.S. Kumar, I. Karunasagar, I. Karunasagar, Seasonal variation in abundance of total and pathogenic Vibrio parahaemolyticus bacteria in oysters along the southwest coast of India, Appl. Environ. Microbiol. 71 (2005) 3575–3580, https://doi.org/10.1128/AEM.71.7.3575-3580.2005.
[18] C. Ghenai, M. Albawab, M. Bettayeb, Sustainability indicators for renewable energy systems using multi-criteria decision-making model and extended SWARA/ARAS hybrid method, Renew. Energy 146 (2020) 580–597, https://doi.org/10.1016/j.renene.2019.06.157.
[19] R.W. Saaty, The analytic hierarchy process - what it is and how it it used 9 (1987) 161–176. https://www.sciencedirect.com/science/article/pii/0270025587904738. (Accessed 11 January 2023).
[20] Meng Shao, Yuanxu Zhao, Jinwei Sun, Zhixin Han, Zhuxiao Shao, A decision framework for tidal current power plant site selection based on GIS-MCDM: a case study in China, Energy 262 (2023), 125476, https://doi.org/10.1016/j.energy.2022.125476. ISSN 0360-5442.
[21] Gustavo Pires da Ponte, Rodrigo Flora Calili, Reinaldo Castro Souza, Energy generation in Brazilian isolated systems: challenges and proposals for increasing the share of renewables based on a multicriteria analysis, Energy for Sustainable Development 61 (2021), https://doi.org/10.1016/j.esd.2020.12.007, 74-88, ISSN 0973-0826.
[22] S. Yalcinkaya, O.S. Kirtiloglu, Application of a geographic information system-based fuzzy analytic hierarchy process model to locate potential municipal solid waste incineration plant sites: a case study of Izmir Metropolitan Municipality, Waste Manag. Res. 39 (1) (2021) 174–184, https://doi.org/10.1177/0734242X20939636.
[23] Geovanna Villacreses, Javier Martínez-Gómez, Diego Jijón, Martin Cordovez, Geolocation of photovoltaic farms using Geographic Information Systems (GIS) with Multiple-criteria decision-making (MCDM) methods: case of the Ecuadorian energy regulation, Energy Rep. 8 (2022) 3526–3548, https://doi.org/10.1016/j.egyr.2022.02.152. ISSN 2352-4847.
[24] Felipe Henao, A. Judith, Cherni, Patricia Jaramillo, Isaac Dyner, A multicriteria approach to sustainable energy supply for the rural poor, Eur. J. Oper. Res. 218 (Issue 3) (2012) 801–809, https://doi.org/10.1016/j.ejor.2011.11.033. ISSN 0377-2217.
[25] R. Quijano H, S. Botero B, J. Domínguez B, MODERGIS application: integrated simulation platform to promote and develop renewable sustainable energy plans, Colombian case study, Renew. Sustain. Energy Rev. 16 (Issue 7) (2012) 5176–5187, https://doi.org/10.1016/j.rser.2012.05.006. ISSN 1364-0321.
[26] T.L. Saaty, Decision Making with the Analytic Hierarchy Process, 2008.
[27] S. Ghosh, M. Majumder, M. Pal, Application of metaheuristic algorithm to identify priority parameters for the selection of feasible location having optimum wave energy potential, Energy Environ. 29 (1) (2018) 3–28, https://doi.org/10.1177/0958305X17737341.
[28] Juan Miguel Sánchez-Lozano, Adela Ramos-Escudero, C. Isabel, Gil-García, M Socorro García-Cascales, Angel Molina-García, A GIS-based offshore wind site selection model using fuzzy multi-criteria decision-making with application to the case of the Gulf of Maine, Expert Syst. Appl. 210 (2022), 118371, https://doi.org/10.1016/j.eswa.2022.118371. ISSN 0957-4174.
[29] Lamya Albraheem, Lama AlAwlaqi, Geospatial analysis of wind energy plant in Saudi Arabia using a GIS-AHP technique, Energy Rep. 9 (2023) 5878–5898, https://doi.org/10.1016/j.egyr.2023.05.032. ISSN 2352-4847.
[30] Heni Susiati, Moh Dede, Millary Agung Widiawaty, Arif Ismail, Pande Made Udiyani, Site suitability-based spatial-weighted multicriteria analysis for nuclear power plants in Indonesia, Heliyon 8 (3) (2022), E09088, https://doi.org/10.1016/j.heliyon.2022.e09088. MARCH.
[31] Bahaa Elboshy, Mamdooh Alwetaishi, M. Reda, H. Aly, Amr S. Zalhaf, A suitability mapping for the PV solar farms in Egypt based on GIS-AHP to optimize multi-criteria feasibility, Ain Shams Eng. J. 13 (3) (2022), 101618, https://doi.org/10.1016/j.asej.2021.10.013. ISSN 2090-4479.
[32] M.A. Coronado, C. García, G. Montero, et al., Assessment and potential-site determination of a wheat straw power plant by Aspen Plus and multi-criteria GIS model, Waste Manag. Res. 39 (7) (2021) 985–994, https://doi.org/10.1177/0734242X20978288.
[33] Enrique Ángel-Sanint, Simon García-Orrego, Santiago Ortega, Refining wind and solar potential maps through spatial multicriteria assessment, Case study: Colombia, Energy for Sustainable Development 73 (2023) 152–164, https://doi.org/10.1016/j.esd.2023.01.019. ISSN 0973-0826.
[34] Yasel Costa, Alexandra Duarte, William Sarache, A decisional simulation-optimization framework for sustainable facility location of a biodiesel plant in Colombia, J. Clean. Prod. 167 (2017) 174–191, https://doi.org/10.1016/j.jclepro.2017.08.126. ISSN 0959-6526.
[35] Soumya Ghosh, Mrinmoy Majumder, Manish Pal, Application of metaheuristic algorithm to identify priority parameters for the selection of feasible location having optimum wave energy potential, Energy Environ. 29 (1) (2018) 3–28, https://doi.org/10.1177/0958305X17737341. February.
[36] Pérez Rodríguez, Claudia Patricia, et al., Harnessing residual biomass as a renewable energy source in Colombia: a potential gasification scenario, Sustainability 14 (19) (2022), 12537.
[37] A. Younis, "Using integrated systems analysis to inform the prospects of the bio-based economy: the case of Colombia, in: Progress)." Groningen, The Netherlands, 2018.
[38] W. Reyes-Calle, J.W. Grimaldo-Guerrero, Drivers of biomass power generation technologies: adoption in Colombia, in: IOP Conference Series: Materials Science and Engineering, vol. 844, IOP Publishing, 2020. No. 1.
[39] A. Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 6 (2019) 962–979, https://doi.org/10.18331/BRJ2019.6.2.3.
[40] UPME, IDEAM, COLCIENCIAS, Universidad Industrial de Santander, Atlas del Potential Energético de la Biomasa Residual en Colombia, 2015.
[41] S.S. Siwal, Q. Zhang, N. Devi, A.K. Saini, V. Saini, B. Pareek, S. Gaidukovs, V.K. Thakur, Recovery processes of sustainable energy using different biomass and wastes, Renew. Sustain. Energy Rev. 150 (2021), https://doi.org/10.1016/j.rser.2021.111483.
[42] Ramirez-Contreras, Nidia Elizabeth, PC Faaij André, A review of key international biomass and bioenergy sustainability frameworks and certification systems and their application and implications in Colombia, Renew. Sustain. Energy Rev. 96 (2018) 460–478.
[43] Tomás Gómez-Navarro, David Ribó-Pérez, Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia, Renew. Sustain. Energy Rev. 90 (2018) 131–141.
[44] D.A.L. Silva, et al., A systematic review and life cycle assessment of biomass pellets and briquettes production in Latin America, Renew. Sustain. Energy Rev. 157 (2022), 112042.
[45] Quintero, Juan Sebastián Gamarra, A. Carlos, Díaz Gonzalez, and Leonardo Pacheco Sandoval. "Exergoeconomic analysis of a simulated system of biomass gasification-based power generation with surplus syngas storage in a rural zone in Colombia.", Sustain. Energy Technol. Assessments 44 (2021), 101075.
[46] F. Medina, Panorama de Micro Generación de Energía Fotovoltaica en Colombia", Tesis de Maestría en Ingeniería Mecánica, Universidad ECCI, Bogotá, Colombia, 2020.
[47] J. Ospina, Emplazamiento Sustentable de Sistemas de Microgeneración Eólica en Colombia desde la Perspectiva del Desarrollo Sustentable", Tesis de Maestría en Ingeniería Mecánica. Bogotá, Universidad ECCI, Colombia, 2020.
[48] DANE, Encuesta Nacional Agropecuaria por departamentos, 2019. https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/encuesta-nacional-agropecuaria-ena/encuesta-nacional-agropecuaria-por-departamentos. (Accessed 7 January 2023).

[49] Banco Mundial, y T. C, de C. Ministerio de Vivienda, S.A.S. Mag Consultoría, Tratamiento de residuos sólidos en el marco del servicio público de aseo. https://www.minvivienda.gov.co/sites/default/files/documentos/20210806-entregable-1-v5-definitiva_0.pdf, 2021. (Accessed 7 January 2023).
[50] P.C. de Oliveira Campos, T. da Silva Rocha Paz, L. Lenz, Y. Qiu, C.N. Alves, A.P.R. Simoni, J.C.C. Amorim, G.B.A. Lima, M.P. Rangel, I. Paz, Método de decisão multicritério para a gestão sustentável de cursos de água em áreas urbanas, Sustainability (2020) 12. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85089799819&doi=10.3390%2Fsu12166493&partnerID=40&md5=980ceae1860066a9f877c071b357f77e.
[51] A. Kumar, Y. Deng, X. He, P. Kumar, A Multi Criteria Decision based rural electrification system, IECON Proceedings (Industrial Electronics Conference) (2016) 4025–4030, https://doi.org/10.1109/IECON.2016.7793640.
[52] DNP, Informe anual de avance en la implementación de los ODS en Colombia, 2021, 2021, www.dnp.gov.co.
[53] IPSE, Informe mensual de localidades sin telemetría de las ZNI - Noviembre 2022, 2022. https://ipse.gov.co/documentos_cmn/documentos/informe_mensual_localidades_sin_telemetria/2022/11-INFORME%20LOCALIDADES%20SIN%20TELEMETR%C3%8DA%20ZNI%20NOVIEMBRE-2022.pdf. (Accessed 8 January 2023).
[54] IPSE, Informe mensual de localidades con telemetría de las ZNI - Noviembre 2022, 2022. https://ipse.gov.co/documentos_cmn/documentos/informe_mensual_localidades_sin_telemetria/2022/11-INFORME%20LOCALIDADES%20SIN%20TELEMETR%C3%8DA%20ZNI%20NOVIEMBRE-2022.pdf. (Accessed 8 January 2023).
[55] IPSE, Informe Telemetría Mensual Noviembre 2022, 2022. https://ipse.gov.co/blog/2022/12/30/informe-de-la-demanda-de-energia-registrada-en-las-localidades-de-las-zni/.
[56] IPSE, Informe mensual de la prestación de servicios de energía eléctrica en las localidades sin sistemas de telemetría de las zonas no interconectadas - ZNI, Noviembre (2022) 2022. ipse.gov.co/blog/2022/12/30/informe-de-la-demanda-de-energia-registrada-en-las-localidades-de-las-zni/.
[57] S. de S.P. Domiciliarios, Diagnóstico Anual de la Prestación del Servicio de Energía Eléctrica en las Zonas no Interconectadas, Diagnóstico De La Prestación Del Servicio De Energía Eléctrica 2017, 2017, p. 43. https://www.superservicios.gov.co/sites/default/archivos/SSPD Publicaciones/Publicaciones/2018/Sep/diagnosticozni-superservicios-oct-2017.pdf.
[58] UNDP, Human Development Reports, Human Development Index (HDI), 2023. https://hdr.undp.org/data-center/human-development-index#/indicies/HDI.
[59] H. Duque-Sandoval, P. Garizado-R, Colombia, Medición del Índice de Desarrollo Humano Municipal, 2020.
[60] Environmental Protection Agency - EPA US, Overview of Greenhouse Gases, 2020. https://www.epa.gov/ghgemissions/overview-greenhouse-gases. (Accessed 14 January 2023).
[61] Parques Naturales Nacionales de Colombia, Categorías de áreas protegidas - Parques Nacionales Naturales de Colombia, 2021. https://www.parquesnacionales.gov.co/portal/es/sistema-de-parques-nacionales-naturales/categorias-de-areas-protegidas/. (Accessed 14 January 2023).
[62] Congreso de Colombia, Función Pública: Ley 1551 de 2012, 2012. https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=48267#:~:text=La%20presente%20ley%20tiene%20por,cumplir%20sus%20competencias%20y%20funciones.&text=.,-Los%20municipios%20gozan. (Accessed 14 January 2023).
[63] DANE, Metodología para calcular el Indicador de Importancia Económica Municipal Cuentas Departamentales-CD, 2016. https://www.dane.gov.co/files/investigaciones/fichas/metodologia_importancia_economica_CD-02_V5_15-07-16.pdf. (Accessed 15 January 2023).
[64] DNP, Colombia potencia mundial de la vida, Bases Plan Nacional de Desarrollo, 2022, 2022- 2026, https://colaboracion.dnp.gov.co/CDT/portalDNP/PND%202022/Bases-PND2022-2026_compilado-CEVC15-10-2022.pdf. (Accessed 15 January 2023).
[65] Climate Change 2022: Impacts, Adaptation and Vulnerability | Climate Change 2022: Impacts, Adaptation and Vulnerability, (n.d.). https://www.ipcc.ch/report/ar6/wg2/(accessed April 5, 2023).
[66] National Geographic, Revolución energética en Alemania, cómo combatir el cambio climático, 2021. https://www.nationalgeographic.com.es/ciencia/grandes-reportajes/revolucion-energetica-en-alemania-2_9762. (Accessed 11 January 2023).
[67] UN, Ensure Access to Affordable, Reliable, Sustainable and Modern Energy, 2022. https://www.un.org/sustainabledevelopment/energy/. (Accessed 11 January 2023).