04-007

STUDY OF THE POTENTIAL FOR ELECTRICITY GENERATION THROUGH RENEWABLE SOURCES IN THE DEPARTMENT OF LA PAZ, BOLIVIA

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One of the biggest environmental problems facing the planet is the depletion of natural resources. Due to exponential population growth, there is a greater need to cover various food and/or, productive demands. This implies greater use of natural resources for energy production. One way to reduce the impact on natural resources from an energy perspective is through production from renewable sources. This research evaluates the area of the department of La Paz in Bolivia, to determine its potential in energy production through renewable sources. It is necessary to denote that the study area presented an optimal level of radiation, wind speed records, and a distribution of geological characteristics that allow geothermal exploration and exploitation. Concluding that the altiplanics northern, and southern puna ecoregions present adequate conditions for three types of energy, wind, solar and geothermal. The areas with the greatest potential for use in the department cover 1143 km2, 5269 km2, and 18344 km2, for geothermal, wind, and solar energy, respectively. Concluding that there is a great territorial availability for the use of renewable energy sources in the department of La Paz.

Keywords: Geothermal energy; wind energy; solar energy; sustainability.

ESTUDIO DEL POTENCIAL DE GENERACIÓN DE ENERGÍA ELÉCTRICA A TRAVÉS DE FUENTES RENOVABLES EN EL DEPARTAMENTO DE LA PAZ, BOLIVIA

Uno de los mayores problemas ambientales que atraviesa el planeta, es el agotamiento de los recursos naturales. Debido al crecimiento poblacional exponencial, se tiene una mayor necesidad de cubrir diversas demandas alimentarias y/o productivas. Esto implica un mayor uso de recursos naturales, para la producción de energía. Una manera de reducir el impacto a los recursos naturales desde la perspectiva energética es a través de la producción por fuentes renovables. Esta investigación evalúa el área del departamento de La Paz en Bolivia, para determinar su potencialidad en la producción de energía a través de fuentes renovables. Es necesario denotar que, el área de estudio presento un óptimo nivel de radiación, registros de velocidad de viento y una distribución de características geológicas que permiten la exploración y explotación geotérmica. Concluyendo que, las ecorregiones altiplánicas, de puna norteña y sureña, presentan condiciones adecuadas para tres tipos de energías, eólica, solar y geotérmica. Las áreas con mayor potencial de aprovechamiento en el departamento abarcan 1143 km2, 5269 km2 y 18344 km2, para las energías geotérmica, eólica y solar, respectivamente. Concluyendo que existe una gran disponibilidad territorial para el aprovechamiento de las fuentes energéticas renovables en el departamento de La Paz.

Palabras clave: Energía geotérmica; energía eólica; energía solar; sostenibilidad.

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Agradecimientos: Los autores agradecen a la Universidad Católica Boliviana "San Pablo" - Sede La Paz, por la financiación de la formación doctoral de su docente investigadora del Centro de Investigación en Agua, Energía y Sostenibilidad (CINAES) perteneciente a la Carrera de Ingeniería Ambiental.

1. Introduction

According to the World Population Perspectives report, humanity is experiencing exponential growth at an impressive speed: Highlights (Naciones Unidas, 2019). The world population will increase by 2 billion people within the next 30 years, from currently having a population of 7.9 billion to 9.7 billion by 2050. Therefore, the natural resources demanded for all anthropogenic activities like energy generation, transportation, industrial, and daily activities will increase as well (Garrido, 2009).

Most of the mentioned activities infringe on the environment by generating significant quantities of waste, massive deforestation, greenhouse gas emissions, and reducing the availability of specific natural resources. One of the most critical aspects for the development of society is the generation of electricity, which makes all anthropogenic activities possible, helping economic growth all over the world. Despite its relevance, this activity has proven to be one of the most harmful to the environment since it´s generation implies the use mostly of non-renewable resources like fossil fuels (Garrido, 2009; Mohsen et al., 2015).

It is essential to understand the two main types of energy generation, non-renewable energy and renewable energy. The first one refers to the age of electrical power through natural resources found in restricted quantities, like fossil and nuclear fuels. On the other hand, renewable energy is based on virtually unlimited resources, like wind, solar, geothermal, and hydrological, among others. Besides their availability, these kinds of energy are considered clean for the environment (Mohsen et al., 2015; Robert, Parris, & Leiserowitz, 2005).

As in the rest of the world, Bolivia has experienced an important growth in its population, which has reached 11.6 million habitants, 2.8 million belonging to the department of La Paz (Instituto Nacional de Estadística [INE],2015). The current national demand is 1.511 MW, and as a comparison point, in 2005, this was 759 MW. On top of that, it is essential to acknowledge that energy generation in Bolivia is based mainly on non-renewable energy; as in fact, 58.9% of the energy production is through thermoelectric technology based on natural gas, 39.2% is from hydroelectric technology, and 1.7% biomass (Ministry of Hydrocarbons and Energy - Vice Ministry of Electricity and Alternative Energies 2011; Vice Ministry of Electricity and Alternative Energies 2014).

Bolivia has a variety of ecosystems and a diversity of ecoregions that meet the optimal conditions for implementing renewable energy production systems; some of these are the Andean ecoregions of the department of La Paz. Thanks to the levels of airspeed, solar irradiation and geological and geomorphological characteristics, this region is considered appropriate to implement energy projects like solar, wind, and geothermal (Ibisch et al., 2003).

This research is focused on analyzing the generation potential of three different types of renewable energy in the department of La Paz. It presents a baseline that can be used for future sustainable energy generation projects.

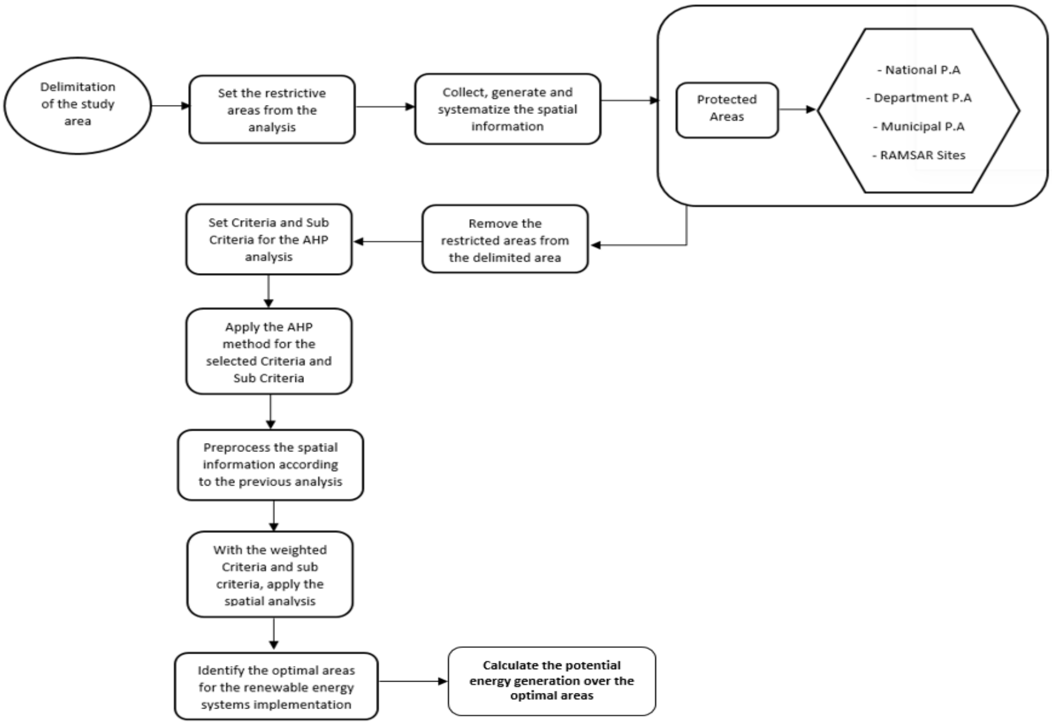
2. Objectives

This research aims to identify potential areas within the department of La Paz in Bolivia to implement three renewable energy systems (wind, solar, and geothermal).

3. Methodology

The information regarding this research has been represented through georeferenced layers in raster and shapefile format which have been manipulated for the main purpose of this analysis on a geographical information system (GIS) software. Spatial analysis such as the delimitation of the area and the detection of the restrictive areas have been carried out in this way, as well as the representation of the respective criteria for each the energy project and the application of the following Analytical Hierarchy Process to find the optimal areas to implement them. At the beginning of the spatial analysis, it was important to prepare the georeferenced layers. A process of standardization took place in which all the information was converted into the same coordinate system as well as quality control of them using the GIS software. The research was developed following the steps shown in Figure 1.

Figure 1: Methodological scheme



AHP: Analytical Hierarchy Process
Source: Own elaboration,2022.

3.1. Delimitation of the study area

In the first place, the study area was delimited as the full extension of the department of La Paz, as shown in Figure 2.

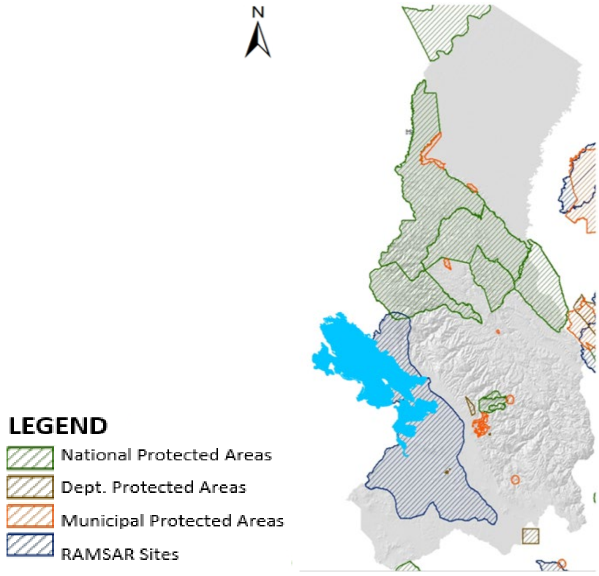
For the delimitation of the study area, an extraction by mask process was applied to all layers regarding the analysis in order to base the results over its limits.

3.2. Restrictive Areas

One of the fundamental points of this research is to maintain the idea of implementing projects under the concept of sustainable development; therefore, following national environmental laws, some areas were excluded from the analysis. Protected Areas at federal, departmental, and municipal levels and RAMSAR sites were considered restrictions (Kimball, 2010; Höfer et al., 2014; Noorollahi et al., 2016). Figure 2, shows the restricted areas within the study.

In this case, we considered the restrictive areas as places where the research and further analysis cannot take place, in this sense, all the mentioned areas where cut off from the limits of the study areas applying a clip process with the GIS software.

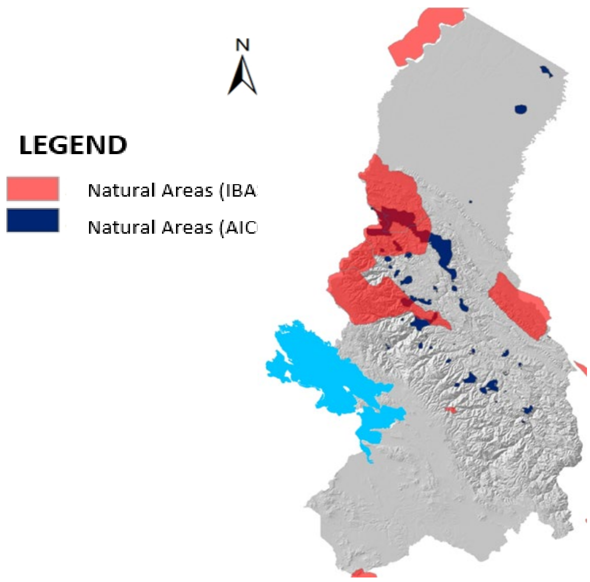
Figure 2: Delimitation of the study area with restrictions



Source: SERNAP, 2018; VMA, 2020

For wind energy projects, two important areas were considered as restrictions. Due to the mechanical technology required for constructing this kind of project, such as wind turbines, it is found that the blades of the rotors that compound them can harm flying species like birds and bats. Thus, spatial analysis has been done to crop the areas where birds and bats are more likely to be found and their familiar track, according to the information developed by Important Bird and Biodiversity Area (IBA) and Important Areas and Sites for the Conservation of Bats (AICOMS), as shown in Figure 3 (IBAS, 2009; Vargas et al., 2010; Höfer, 2014; Elmahmoudi et al., 2019; Zalhaf et al., 2021).

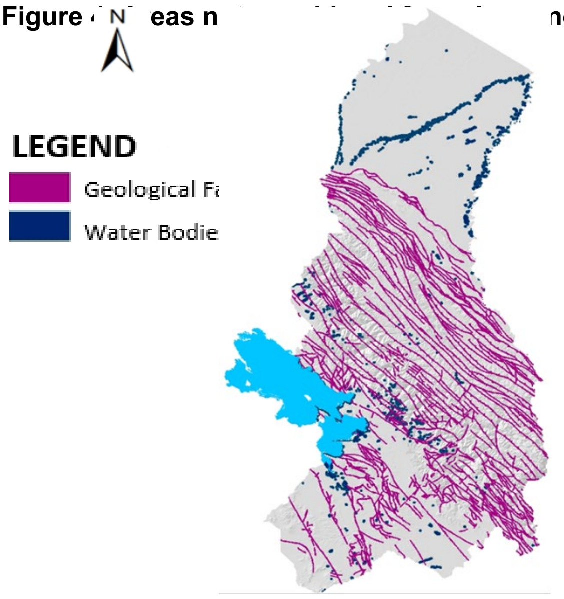
Figure 3: Areas not considered for wind generation



Source: IBAS,2009; AICOMS, 2003

Another technical consideration took place for the area restriction analysis for solar energy. There are some specific places where solar panels and their other components for the development of the project cannot be applied due to their territorial conditions (Asakereh et al., 2014; Noorollahi et al., 2016; Albraheem et al., 2021).

Figure eas n neration



Source: SERGEOTECMIN 2000a y 2000b.

As shown in Figure 4, the main areas in which it is impossible to implement solar energy projects are places where geological faults and water bodies exist. This is because the ground instability in these areas may not be appropriate for the solar panels and the technological machinery because of the instability of the ground that can endanger the systems and affect the solar energy harvesting (Noorollahi et al., 2016).

3.3. Analytical Hierarchy Process (AHP)

The next step focused on developing the Analytical Hierarchy Process (AHP). This procedure is applied to make supported decisions by considering various criteria and weighted by their level of importance related to the final decision (Hurtado et al., 2015). In this research, the main idea is to support technically and territorially the decision of implementing renewable energy projects on specific sites around the extension of the department of La Paz. Each of the studied energy projects has its criteria to determine a particular place optimal for its development (Hurtado et al., 2015).

To organize the variables in an AHP, the Saaty (1980) evaluation matrices are used to represent the relationship between the criteria and the alternatives and allow placing scores or weights for each of them by the level of importance. They must consist of the central column, criteria, and the other options in the main row. This matrix can have various names such as scores, effectiveness, project-effect, or evaluation (Saaty, 1980; Frau, Valenzuela, & Rojas, 2006). Table 1 presents an example of this type of matrix.

Table 1: Evaluation matrix

		ALTERNATIVES (j)			
		1	2	3	…j
CRITERIA (i)	1	WEIGHT OF THE CRITERIA (x_{ji})			
	2				
	3				

	(i)	

Source: Saaty 1980.

To obtain the desired values, it is advisable to have previous references and experience on the part of the decision-making center since they will be in charge of assigning these quantitative values (Hurtado et al., 2015). The result of the evaluation process is given at this stage.

To know if the entered values are adequate for the evaluation, a consistency index is calculated, which measures how logically consistent the assessments of the participants in the review are. The tolerance level for this index must be less than 10% (0.1) to be considered correct. Scores are provided on a 9-point continuous scale, as shown in Table 2.

Table 2: Weighting scale according to attributes

1/9	1/7	1/5	1/3	1	3	5	7	9
Extreme	**Strong**		**Moderate**	**Equal**	**Moderate**		**Strong**	**Extreme**
LESS IMPORTANT				**MORE IMPORTANT**				

Source: Saaty 1980.

In this sense, for the three types of renewable energy projects studied, the criteria were selected and weighted separately and are presented in the following sections (Saaty, 1980; Frau, Valenzuela, & Rojas., 2006).

3.3.1. Solar Energy

For solar energy projects, the most important criteria are related to climate parameters like solar radiation, temperature, humidity, and cloud coverage (Noorollahi et al., 2016). These criteria are essential specifically for the solar panel devices that are in charge of acquiring the solar energy for its transformation into electric power; the more solar radiation the area presents and less cloud coverage and humidity, the more point is going to be gathered, as well as the less cloud coverage. At an average temperature, the more efficient will be the solar panels. Other important criteria considered are the ground conditions; at a higher altitude, it is more likely to have powerful radiation, and the less slope the terrain presents, the more optimal is going to be the operation of solar panels, and the importance of land cover in which it is recommended to implement these projects on bare soil. It is more likely to install solar energy plants next to rods, interconnected systems, and populated centers for economic purposes. Finally, it is important to consider air quality; the more contaminated it can be, the less energy a solar panel can obtain. Table 3 presents the criteria and their weights according to their level of importance (Wong et al., 2016; Huld, 2015; Noorollahi et al., 2016; Ruiz et al., 2020; Tempa et al., 2020).

Table 3: Criteria and Weights – Solar Energy

Criteria	Weighing (%)
Annual Mean Solar Radiation	27.5
Mean Annual Temperature	7.1
Proximity to the National Interconnected System	11.2
Proximity to the Fundamental Road Network	8.2
Proximity to Populated Centers	8.1
Ground Elevation	8.1
Slope	8
Land Cover	7
Annual Mean Cloud Coverage	5.8
Mean Annual Relative Humidity	4.1

Suspended Particles pm 2,5	4.8
TOTAL	100

Source: Own elaboration,2022.

3.3.2. Wind Energy

Wind energy projects are more likely to be installed in areas with a good wind speed, which is why this is the most important criteria (Höfer, 2014; Jangid et al., 2016; Taoufik et al., 2021, Nasery et al., 2021). Table 4 shows the requirements weighted for wind energy systems.

Table 4: Criteria and Weights – Wind Energy

Criteria	Weighing (%)
Annual Mean Wind Speed	23.52
Proximity to Populated Centers	20.42
Proximity to Natural Areas (Bats)	11.16
Proximity to Natural Areas (Birds)	11.16
Proximity to the National Interconnected System	9.92
Proximity to the Fundamental Road Network	9.32
Land Cover	7.92
Slope	6.52
TOTAL	100

Source: Own elaboration,2022.

As seen in Table 4, it is important to mention that it is better to consider the annual mean wind speed for more supported decision-making for installing wind energy systems. It is imperative to consider the proximity to populated centers; the more populated it may be and the closer a wind system can be, the more likely it is to present noise contamination harmful to people. Another fundamental aspect is the proximity of natural areas; the more protected a site is due to its species density (bats and birds), the less feasible it is to implement a wind energy project. It is relevant to mention that the most protected natural areas regarding this criteria are considered like restrictions. For technical considerations, ground criteria are considered, such as slope and land cover. It is better to implement a wind-energy turbine on a plain terrain and bare soil without forests that can affect the wind speed. For economic considerations, the proximity to roads and the interconnected system is very important. (Höfer, 2014; Pamučar et al., 2017).

3.3.3. Geothermal Energy

Geothermal energy projects take into account specific factors to consider a feasible area to implement these systems. The three main macro factors for geothermal energy are temperature, permeability, and structure (Kimball, 2010; Şener et al., 2021; Dong et al.,2022). The temperature factor is related to the underground conditions in which high-temperature indicators such as geothermal temperature, hot springs, volcanic centers, and volcanic geological periods are found. On the other hand, Permeability indicates the possibility of extracting geothermal energy at the underground or surface level. The indicators related to it are geological faults and epicenters of earthquakes. For the macrostructure factor, the roads and the interconnected system are considered for the structural implementation and economic considerations (Kimball, 2010; Noorollahi & Itoi, 2007; Yousefi et al., 2010; Yalcin et al., 2017). The macro criteria and indicators are weighted and are presented in Table 5.

Table 5: Criteria and Weights – Geothermal Energy

Geothermal Resource Factor 80%	
Temperature Factor (80%)	
Criteria	**Weighing (%)**
Geothermal Temperature	53.57
Volcanic Centers	27.63
Hot Springs	11.03
Geological Volcanic Periods	7.77
TOTAL	100
Permeability Factor (20%)	
Criteria	**Weighing (%)**
Geological Faults	89.89
Earthquake Epicenters	11.11
TOTAL	100
Structure Factor 20%	
Structure Factor (20%)	
Criteria	**Weighing (%)**
Proximity to the Fundamental Road Network	50
Proximity to the National Interconnected System	50
TOTAL	100

Source: Own elaboration,2022.

After the AHP analysis application, with all the criteria regarding the different energy projects on this research weighted by level of influence, a layering process was carried out through a map algebra procedure with the raster calculator tool on the GIS software, after converting all the layers to raster format, in order to obtain the optimal areas within the limits of the study area.

3.4. Potential Energy Generation Estimation

Another important finding, after determining the most suitable areas for the three energy projects, is to quantify how much energy can be produced in them. Each of the systems applies different kinds of technology for harvesting energy, which are based on physical and thermodynamical numerical models that allows all the machinery and equipment to work properly towards energy generation (Li, 2015). The three models for each energy system are presented below.

3.4.1. Wind Energy

To calculate how much energy can be produced through the air, it is important to consider the wind turbines with a specific length of the blades, wind speed, air density, efficiency coefficient, and air density in normal conditions (1,225 kg/m^3). (Sarkar et al., 2012; Lee et al., 2012). In this case, the wind speed was taken from the criteria regarding the AHP and spatial analysis, following the physical numerical model:

$$P = 1/2 * \rho * v3 * \pi * r2 * Cp \quad (1)$$

Where:

P = Energy Power (watts)

Ƥ = Wind density on normal conditions = 1,225 kg/m^3

V = Wind Speed (m/s)

r = Wind turbines blade length (m)

3.4.2. Solar Energy

In the case of solar energy, to calculate the energy generation, it is important to consider the area that solar panels can cover and their efficiency coefficient. (Swain, 2017), (Schoenmaker, 2014). Another fundamental aspects to consider is the solar radiation parameters that are related to how much solar energy can solar panels gather to be transformed; the following numerical physical model was applied:

$$E = A*r*H*QR \qquad (2)$$

Where:

E = Energy Power (mwh/year)

A = Total coverage area of solar panels

r = Solar panel efficiency (%)

H = Accumulated average solar radiation (kwh/year)

QR = Quality Ratio (%)

3.4.3. Geothermal Energy

To calculate the energy power that a geothermal reservoir can produce, it is important to take into consideration the phenomenon of heat flow, which refers to the transfer of heat from the interior of the soil to the surface, based on convection and conduction processes, this phenomenon is studied to find the energy power through the following numerical thermodynamical model (Akin et al., 2014; Franco et al., 2017):

$$q = k*dT/dZ \qquad (3)$$

Where:

q = Heat Flux (mW/m^2)

k = Thermal Conductivity

dT/dZ = vertical temperature gradient

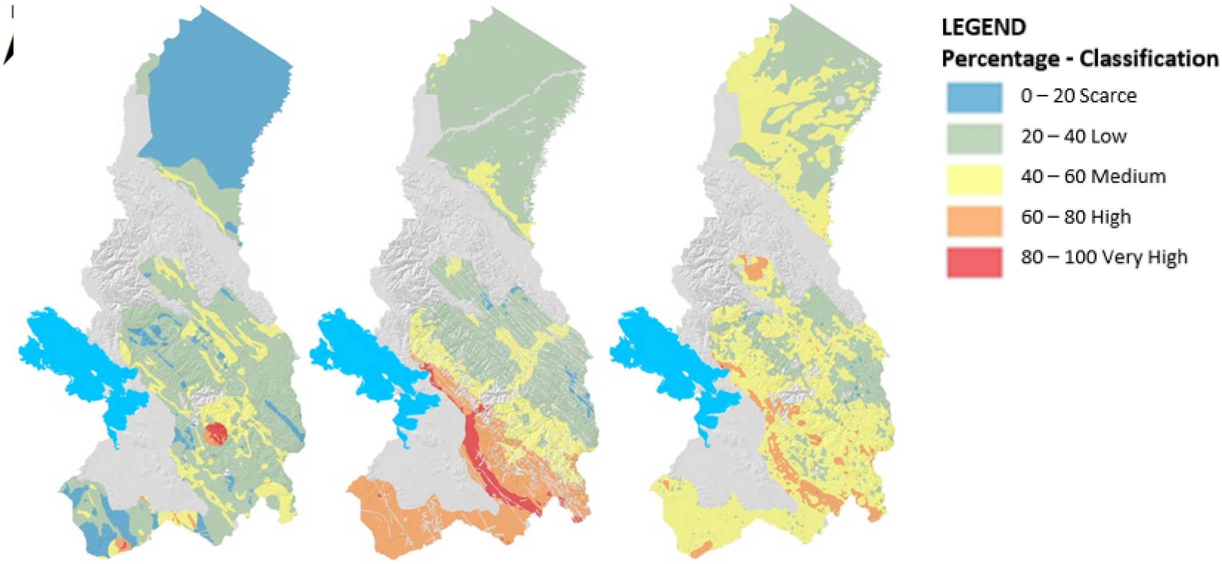
4. Results

This section presents the results obtained following the proposed methodology.

4.1. AHP and Spatial Analysis

The results of the AHP and the spatial analysis are presented in Figure 5. It is possible to see the spatial distribution of the areas considered the best to implement solar, wind, and geothermal energy production systems in the department of La Paz.

Figure 5: Areas considered the best to implement solar, wind, and geothermal energy systems



Source: Own elaboration,2022.

As presented in the maps, the areas colored in orange are considered with high potential and the red ones with very high potential for implementing the three types of renewable energy. On the other hand, yellow areas are regarded as medium potential, and light blue and blue areas are considered low and very low potential, respectively.

In the present analysis, it is perceived that the southern part of the department of La Paz territory is more suited to implement the energy projects. It is essential to mention that the gray areas are the ones that are not considered in the analysis due to the restrictions presented before. Therefore, in the case of geothermal energy, 66.7% (85,494 km^2) of the total of the department of La Paz was suitable for wind energy 65.5% (84,147 km^2) and solar energy, 58% (74,327 km^2). Table 6 shows the spatial distribution of each category over the full extension of the department.

Table 6: Criteria and Weights – Wind Energy

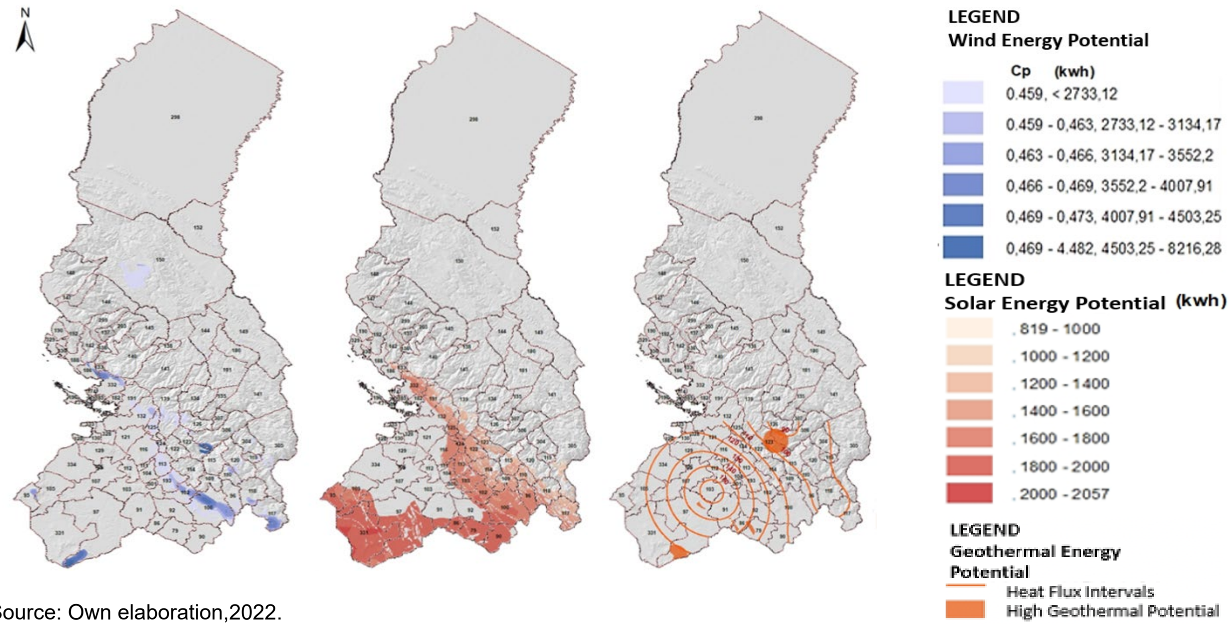
Classification	Geothermal Potential Areas Distribution		Wind Potential Areas Distribution		Solar Potential Areas Distribution	
	Area (Km^2)	Percentage (%)	Área(Km^2)	Porcentaje (%)	Área (Km^2)	Porcentaje (%)
Scarce	32,177.25	37.64	164.28	0.20	604.78	0.81
Low	40,512.30	47.39	28,634.01	34.03	44,615.09	60.03
Medium	11,661.06	13.64	50,079.30	59.51	10,763.15	14.48
High	675.22	0.79	5,255.87	6.25	15,625.99	21.02
Very High	468.15	0.55	13.30	0.02	27,18.21	3.66
TOTAL	85,493.99	100	84,146.77	100	74,327.23	100

Source: Own elaboration,2022.

4.2. Energy Power Estimation

Figure 6 shows the estimation of electricity generation for the tree energy systems.

Figure 6: Estimation of Electricity Generation Potential solar, wind, and geothermal energy systems



Source: Own elaboration,2022.

After applying the numerical models to estimate the generation of electrical energy for each renewable energy system in the optimal zones, another spatial analysis was carried out to analyze the variation in the intensity of energy production over these zones, obtaining the spatial distribution presented in Figure 6. In the previous maps, we can see the different ranges of energy power that can be produced with the three types of energy systems. Wind energy has the potential to make energy from 2,733 to 8,216 (kwh) every year; solar energy, on the other hand, can produce from 819 to 2,057 (kwh). In the case of geothermal energy, the analysis showed the heat flux intervals, which allows us to take this as an indicator of the energy power that can be obtained in the potential areas, which as a result, showed a range of 90 to 160 mW/m^2, indicating that these sites are very likely to obtain an adequate quantity of energy, it is important to mention that to calculate precisely how much energy can be produced is important to make a deeper field analysis.

5. Discussion

In recent years, life on earth has accelerated; with populations' growth and energy demands, the planet's non-renewable resources have been depleted. The current energy supply will no longer be sufficient to cover global market in the coming decades. For this reason, the transition from non-renewable sources to renewable has become a priority for the sustainable development of the world.

Bolivia has been carrying out projects related to his matter, such as the Cobija Solar power generation plant with an operating area of 0.3 km^2 and 5.2 MW of power (ENDE,2014), the Laguna Colorada pilot geothermal plant with an area of 4 km^2 and 5MW of power (Empresa Eléctrica CORANI S.A, 2016)), the Qollpana wind farm with 0.11km^2 and 24MW capacity (Empresa Eléctrica CORANI S.A 2015), among others. The preceding demonstrates Bolivia´s predisposition to generate clean energy through renewable resources, following the same line as many countries that seek to optimize their resources. In this regard, this research emphasizes the availability of areas within the country that can be considered optimal for energy production through renewable sources, such as the department of La Paz. This department has the territorial conditions and the necessary resources to implement renewable energies. This information becomes especially useful in energy management systems and helps decision-makers evaluate the implementation of power generation projects.

6. Conclusions

The main conclusion of this research is that the sites with good potential for renewable energy systems are found mainly in the southern and northern puna ecoregions, approximately from the middle of the department of La Paz to the south. The areas with the greatest solar, wind, and geothermal energy potential are 18,344.21 km^2, 5,269.17 km^2, and 1,143.38 km^2, respectively. The information shows the existence of territorial availability in the department of La Paz to take advantage of three types of renewable energy simultaneously.

Applying the AHP methodology for the decision-making on selecting or finding optimal areas for the three studied energy production systems has been very important to understanding the dynamics of the interaction of technical, territorial, and environmental criteria. The results of wind, solar and geothermal energy in the department of La Paz shows that in addition to being a sustainable technology, it can be used promptly, for energy production, covering areas with little access to electricity, or carrying out the energy transition from conventional sources to renewable sources.

This research will allow making decisions and creating strategies to respond to the increase in energy demand within the framework of sustainable development, considering sensitive environmental variables, such as biodiversity, resource protection as bodies of water, and protected areas, among others, in addition to the necessary consideration for the acceptance of society based on the protection of public health.

Future research can continue this work by evaluating the energy potential of the other departments of Bolivia. This type of study can also help rethink the energy matrix of other parts of the world that want to optimize their resources and seek clean energy generation sources.

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Comunicación alineada con los Objetivos de Desarrollo Sostenible