# Spatial assessment of the potential of renewable energy: The case of Ecuador

Jaime Cevallos-Sierra[a,*] and Jesus Ramos-Martin[b]

a Universidad Andina Simón Bolívar, Quito, Ecuador

b Universidad Regional Amazónica Ikiam, Tena, Ecuador

* Corresponding autor: jaimec13@hotmail.com (J. Cevallos-Sierra)

**Abstract**

Although renewable energy represents a large share of the electric energy generation sources in Latin America, non-conventional sources such as solar or wind energies have not represented a big share of their electric energy systems. The first step to promote the use of these sources in the region is identifying the potential of each energy source, task that can be estimated with the use of spatial tools such as Geographic Information Systems (GIS). This study has reviewed a large list of GIS publications to select a methodology to identify suitable areas for the development of non-conventional renewable energy projects (REP), in order to estimate the maximum energy these technologies could contribute to a national electric energy system, and its applied to the Republic of Ecuador. By using GIS, it is sought to identify the sites where potential renewable energy plants could be located, and initially recommends geographic locations for the installation of measuring towers of solar and wind resources, in order to obtain more detailed information on their behavior. As a result, the areas with higher potential for the development of REP have been identified, and classified in spatial layers according its technology and location. These results show that solar PV is the technology with most suitable areas in the country and demonstrate particularly large potential in two regions: the Andes cordillera and Insular region, especially in the provinces of Loja, Pichincha and the Galapagos islands.

**JEL Classification**

O13; Q28; R32; Q42

**Keywords**

Renewable-energy; GIS; Ecuador; Multi-criteria analysis

## 1. Introduction

Whilst Non-Conventional Renewable Energy (NCRE) sources are increasing its share in most energy systems worldwide, the participation of these technologies in the majority of developing countries has not shown greater increase of installed capacity, and energy generated, during the last decade [1]. Besides Hydropower and biofuels, renewable energy has not played a significant role in the energy sector in the Latin-American region, although this trend has started to change thanks to the construction of some renewable energy projects, and public policies encouraging the development of clean energy generation projects [2]. If the goal of reducing greenhouse gas emissions is to be achieved, it is necessary to keep track to the growing economies of developing regions, which are projected to increase in energy demand and production.

Nowadays some countries in Latin America have achieved (or are close to) a complete renewable energy electricity grid, using a mix between hydropower and other NCRE. Examples of this are Costa Rica, Paraguay and Uruguay, which now satisfies more than 90% of their electric power demands using hydro, wind, or a mix of both [3]. Since 2016, Ecuador is trying to join these countries with an almost sustainable electric grid thanks to the construction of eight hydro power plants summing an installed capacity of 2.76 GWp and some minor capacity of NCRE [4]. As it can be seen in Fig. 1, Ecuador is a country filled with natural resources, and for decades has been able to use them to produce electricity. Despite the government has encouraged the expansion of renewable energy technologies in the country, through the issuance of various regulations that promote their participation [5–8], the share of NCRE power plants in the national energy balance was still below one percent in 2016. However, the few NCRE power plants that have been commissioned in the country have proven to be highly effective. One example of this is the Villonaco wind farm, which in 2014 showed a capacity factor of 53%, which is considerably high compared to the average capacity factor for this type of plants. Solar Photovoltaic plants have also shown high efficiencies, thanks to the privileged position of the country regarding the sun. Because of the high effectiveness of the projects mentioned, it is of great importance to promote the use of these technologies in the region.

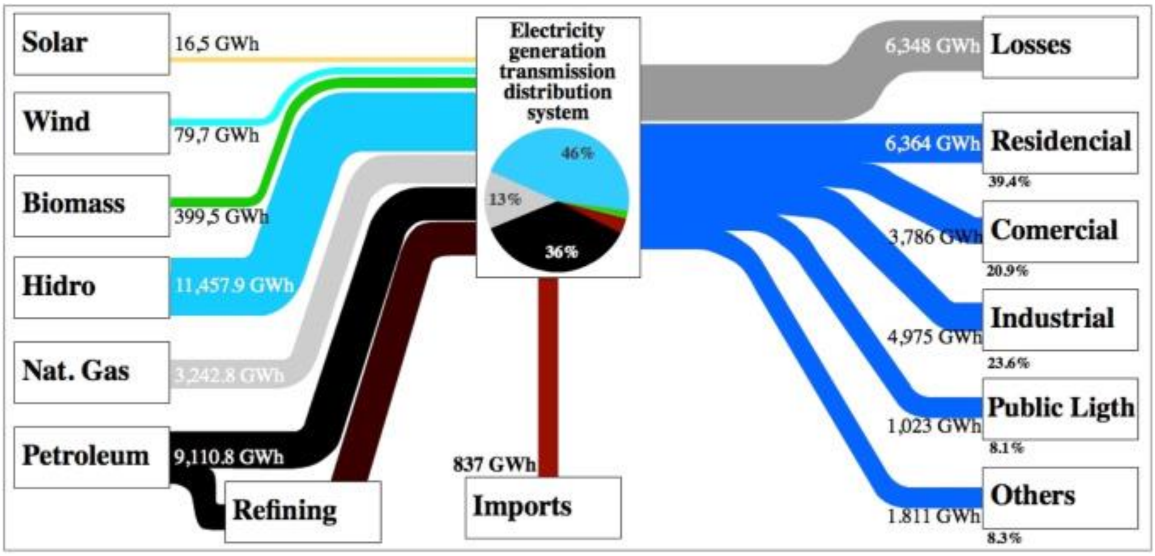


Fig. 1. Ecuadorean electric power system in 2014 [27].

Similar studies related to the location of suitable areas for different purposes can be found in almost every region of the planet. Studies carried out by Bravo et al. [9], and Ramachandra and Shruthi [10], have used Geographic Information Systems (GIS) approach to evaluate potential areas of multiple renewable energy technologies in Spain and Karnataka, India. Many other studies have focused in only one technology for the assessment of potential areas for RES projects. Although the methodology of each one varies according to the resource to be analyzed, most of them use GIS tools to carry out the processes required to determine the suitable areas of each technology. Assessments of the potential of Solar PV [11–13], and CSP [14–17], have been mainly performed in the regions with high solar radiation, most of them in North America, Africa, Australia, the Mediterranean and Middle East. Likewise, GIS assessments for the location of suitable areas are very popular for wind farm sitting [18–21], as it allows visualizing in advance the land surface where the plant will be implemented. The research performed by Tegou et al. [22], for instance, uses GIS tools to determine the suitability of land, for the construction of wind farms in the Lesvos island of Greece. In this case, the study uses multi-criteria analysis (MCA), and analytic hierarchy process (AHP), to evaluate each criterion according to its importance and establish a ranking among alternative sites.

This study focuses on the assessment of potential locations for the implementation of non-conventional renewable energy projects, in order to estimate the maximum theoretical amount of energy they could contribute to the Ecuadorean's energy system. By using Geographic Information Systems (GIS) tools, this study seeks to identify suitable areas where NCRE power plants could potentially be sited and classifies the results by regions. The evaluation can be used as a starting point to select the best locations for the installation of resource measuring towers, in order to obtain detailed behavioral data from these sources.

## 2. Materials and Methods

### *2.1 Description of the methodology*

The use of GIS has been widely accepted on the location of suitable areas for the implantation of RES power plants. Nath et al. [23] described in his study the nine steps to perform a GIS project and the main factors to be taken into account to carry them out correctly for the goal of locating suitable areas. It also included the description of various case studies, and some the methodologies applied in each case.

These nine stages are briefly described below:

a) Identifying the requirements of the project,

b) Formulation of specifications,

c) Development of the analytical framework,

d) Tracing data sources,

e) Organization and manipulation of the data,

f) Analysis of the data and outputs,

g) Evaluation of results.

The present study has followed these nine steps to identify the areas proposed in Section 1. Every step requires the participation of subject matter experts, GIS analysts and stakeholders in order to achieve accuracy in its results. Once each group of analysts has expressed their needs, they can begin to discuss how GIS can be used to fulfill them, also identifying the limitations of the use of these tools. Another important factor of the proposed model is the gathering of the necessary data to be used in the study, which typically consists of Vector and Raster images describing environmental, social, and economic information. These data can be obtained from primary sources like satellite and aerial imagery, or secondary sources like developed maps and layers of the region of study.

*2.2 Technologies considered in the study*

The proposed methodology can be applied to find potential areas for the implementation of all types of renewable energy projects. To meet the requirements of the model, for each technology, is necessary to have all the data needed to meet technical, environmental and social criteria. Each criterion will determine the minimum requirements in order to make each technology feasible; the lack of any of these criteria in the analysis could reduce the credibility of the results. Due to the availability of nationwide information from the solar and wind resources, the selected technologies for the analysis are: Wind energy, solar photovoltaic, and concentrated solar power, which are described next.

*2.2.1 Wind energy*

Wind is the most developed of the non-conventional RES, and its use has been spread in almost every country of the planet. This analysis takes into consideration only on-shore wind farms, because the resource raster files, containing national wind speeds, do not include wind speeds in marine regions of the country. According to various studies [20,22] a wind project needs at least monthly average wind speeds of 5 m/s (m/s), for a minimum period of 6 months per year, in order to become economically feasible.

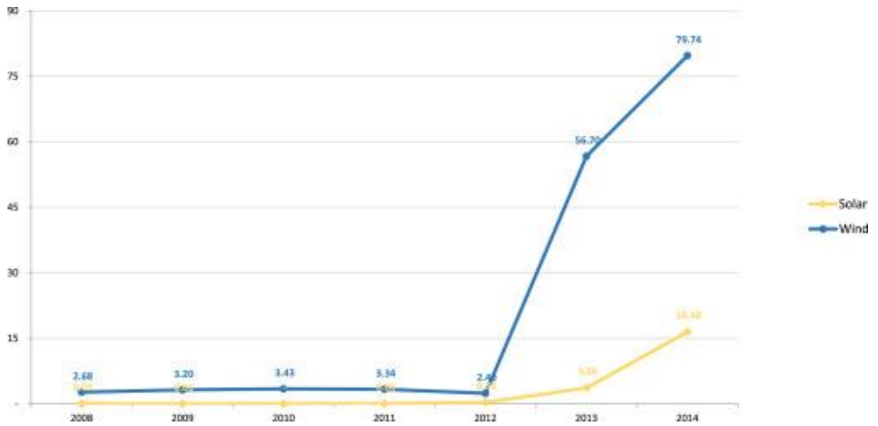


Fig. 2. Historical energy generation (GWh) of solar and wind technologies [27].

*2.2.2 Solar photovoltaic*

Solar photovoltaic (PV) technology generates Direct Current (DC) electricity from sunlight, but is capable to capture only a small portion of the large amount of energy irradiated to the surface of the planet (NREL, 2015) [24]. Although this technology was developed in 1960, the major barrier it has faced during its lifetime is its high investment costs, which have delayed its evolution. To date, various technologies have been developed helping to reduce the historical production and marketing costs on international markets. Unfortunately for the Ecuadorean population, this trend has not reached local markets yet, since actual marketing fees highly exceed international prices.

### *2.2.3 Concentrated solar power*

Unlike solar photovoltaic, Concentrated Solar Power (CSP) plants take advantage of the heat of the sun to produce electricity, also called Solar Thermal Electricity (STE). Unfortunately for our country, equatorial regions tend to have large concentration of clouds and greenhouse gases, causing the dispersion of DNI. Luckily, DNI is considerably higher at higher elevations, where the path of sunrays finds fewer obstructions (IEA, 2015) [25]. Affandi et al. [17], and Bravo et al. [9], have estimated suitable DNI amounts between 4 and 6 kW h/m per day, to be considered economically feasible.

## 3. Calculations

### *3.1. Area of study*

The Republic of Ecuador is located at the north-occidental region of South America, and it is surrounded by Colombia at the North, Peru at the South and East, and the Pacific Ocean at the West. The total territory covers an area of 256.4 thousand square kilometers, and it is formed by four natural regions: The Galapagos Islands, located about 1000 km off the west of the continental coast; the coastal region, located between the Pacific Ocean and the highlands; the Sierra region, which comprises the entire Andes cordillera; and the east region, covering the Amazonian forest [26].

The Ecuadorean Electricity System has two main features: the National Interconnected System (NIS), which is used to transport the electricity between the generation power plants and final consumers; and Isolated Independent Grids, where self-generating companies produce energy for their own consumption, or to supply communities nearby. In 2014, the national effective capacity summed a total of 5745 MW, where 87.2% is connected to the NIS, and the rest is used in remote areas such as the Amazon and Galapagos regions where this network cannot reach population. 45.7% of this capacity generates energy from renewable sources, where hydropower accounts for more than 95% of it; the remaining 5% is shared by biomass and wind technologies [27].

Since 2007, three Wind farms have been constructed in the country, two of them in the Galapagos Islands, and the other in the Andean territory of Loja. The first wind power plant was constructed in the San Cristobal Island with an installed capacity of 2.4 MWp, and it has demonstrated an average capacity factor of 15.2% in the last decade [27]. In 2013, the Villonaco Power plant started to operate with an installed capacity of 16.5 MWp, and has proven to be highly efficient due to its extraordinary capacity factor of 52.5% (Fig. 2). Recently, at the end of 2014, the Baltra's Eolic Park was inaugurated with an installed capacity of 2.25 MWp, and is expected to satisfy most of the electricity demand of Santa Cruz and Baltra islands. Although these three projects were developed in a relatively short period of time, the expansion plan of electricity generation does not show future projects to be undertaken in future years [28].

Until a few years ago, solar photovoltaic energy has not been used in the country for electric power generation. Since 2005, the electric company of Galapagos (ElecGalapagos S.A.) has used solar panels to provide electricity to households in Floreana and San Cristobal islands. To date, the photovoltaic capacity installed in the islands has increased largely thanks to the inauguration of the Puerto Ayora power plant with a power capacity of 1.5 MWp. In mainland, the first plant started to produce energy in 2011, and is located in the Amazonian region of Morona Santiago with an installed capacity of 0.37 MWp. Since then, the national installed capacity has been rapidly increasing its share, reaching in 2014 the summed capacity of 15.3 MWp, distributed in 24 plants located in various regions of the country [28].

### *3.2. Application of the methodology*

A brief description of each stage explains its application to meet the goals of the study.

#### *3.2.1. Identifying the requirements of the project*

The first stage of the method is to identify the needs that the project will have to satisfy. This study has identified as its primary need to identify potential sites for the construction of commercial scale renewable energy power plants, in Ecuador.

#### *3.2.2. Formulation of specifications*

Once the requirements of the project have been identified and understood, it is advisable to select a list of specifications to follow during the course of the study. The method proposed can be performed using any GIS tool with raster or vector capabilities. For the present study the tool chosen is ArcGIS 10.1, due to its high process reliability and availability of various spatial analysis tools. In this case raster analysis tools were selected due to the availability of official published data, like Digital Elevation Models (DEMs), wind and solar potential, urban settlements, electricity grid, road networks, and land cover collected for the two areas selected.

Usually, the information generated by the government, and public organizations, is classified in the following two groups: Region 1.- This area covers the three continental regions located between the Pacific Ocean, and the Colombian and Peruvian borders, and Region 2.- The Galapagos Archipelago, located at a considerably distance from the rest of the country. In these two regions the information available has different resolutions, for this reason a standard resolution for each region of 30 and 200 m respectively has been established. Frequently, available layers are developed using diverse coordinate systems, which have to be standardized into a single reference system.

#### *3.2.3. Development of the analytical framework*

This step involves the participation of energy and GIS specialists in order to develop a framework that allows to satisfy the needs defined previously. The analytical framework designed to fulfill this goal uses operators and procedures to classify and merge spatial layers according to the selected specifications. The structure of the analytical framework has been built using the following procedure:

a) Product layers were created from primary and secondary data, which were classified in two main groups: Evaluation Layers, and Constraint Layers.

b) The first group uses parametric classification (assigning values between 0 and 1) to assume a percentage of suitability; and the second group uses Boolean classification (assigning values of 0 and 1) to assume land suitability.

c) Each layer of group one has a weight assigned proportional to its importance in the analysis. Once each individual layer has been normalized, they are merged multiplying each layer with its assigned weight, and summing their results. This process returns another parametric layer representing land suitability, where regions with highest values represent areas with great suitability for the installation of renewable energy power plants.

d) Layers of group two have the same importance in the analysis, as their negative value represents a serious obstruction in the development of feasible projects. These group of layers are merged using the multiply operator, returning another Boolean layer representing only the areas that fulfill every requirement previously set.

e) Finally, multi-objective land allocation is applied to remove every area that presents a potential conflict with other commercial and economic purposes. This task is performed joining both constraint and evaluation layers, causing the removal of every value in the evaluation layer that is considered non-suitable in the constraint layer. This process was repeated for each technology considered in the study.

### *3.2.4. Tracing data sources*

Diverse layers have been identified as relevant data for the study, and the analysis layers are derived from them. The layers used for the analysis have been derived from the following basic data:

• Raster DEM of region 1 with pixel size of 30 m, and DEM of region 2 with pixel size of 200 m [29].

• Raster layers with monthly and annual average wind speeds for both regions, at 30, 50, and 80 m above ground level [30]. Each layer has a pixel resolution of 200 m.

• Raster layers with monthly and annual average direct, diffuse and global solar radiation, with 1 km resolution, for region 1 [31]; and a worldwide vector layer with monthly and annual average direct and global solar radiation, with 1° resolution, for region 2 [32].

• Vector layers of nationwide urban settlements, rural communities, electric transmission lines, and primary and secondary roads, National Parks, among others [33].

• Vector layers of land cover from region 1 and from region 2 [34].

Due to the great distance between the two areas, each region requires its own coordinate system in order to ensure a correct display and process of each layer. For the continental region (region 1) the system most widely used is the **WGS84: UTM_Zone_17_Southern_Hemisphere**, and for the insular region (region 2) is the **WGS 1984: UTM_Zone_15_Southern_Hemisphere**. It is necessaryto transform the coordinate system of each layer to match the selected system for each region (In the case of ArcGIS this process can be performed using the ArcToolBox tools: ***Project*** and ***Define Projection***).

### *3.2.5. Data organization and manipulation*

Once all relevant information has been collected, it is necessary to organize and manipulate it according to the specifications defined previously. The following sub-sections describe the steps performed to obtain the evaluation and the constraint layers, until the suitability layer of each technology is obtained (Tables 1–6) obtained.

**Table 1**
Weighted overlay for wind scenario - Region 1.

| | T. SLOPE | VISUAL I. | D. TRANS. | D. ROUTES | L. COVER | WIND F. | WIND R. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|---|---|---|
| TERRAIN SLOPE | 1.000 | 1.000 | 0.500 | 0.333 | 0.250 | 0.200 | 0.167 | 0.493 | 4.22% |
| VISUAL IMPACT | 1.000 | 1.000 | 0.500 | 0.500 | 0.333 | 0.250 | 0.200 | 0.540 | 4.63% |
| D. TRANS | 2.000 | 2.000 | 1.000 | 1.000 | 0.333 | 0.250 | 0.200 | 0.969 | 8.30% |
| D. ROADS | 3.000 | 2.000 | 1.000 | 1.000 | 0.500 | 0.333 | 0.250 | 1.155 | 9.89% |
| LAND COVER | 4.000 | 3.000 | 3.000 | 2.000 | 1.000 | 0.333 | 0.333 | 1.952 | 16.71% |
| WIND FREQUENCY | 5.000 | 4.000 | 4.000 | 3.000 | 3.000 | 1.000 | 1.000 | 3.000 | 25.68% |
| WIND RESOURCE | 6.000 | 5.000 | 5.000 | 4.000 | 3.000 | 1.000 | 1.000 | 3.571 | 30.57% |

**Table 2**
Weighted overlay for solar PV scenario - Region 1.

| | D. ROUTES | D. TRANS. | L. COVER | T. SLOPE | GHI FREQ. | GHI RES. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|---|---|
| D. ROADS | 1.000 | 1.000 | 0.500 | 0.250 | 0.200 | 0.167 | 0.519 | 5.16% |
| D. TRANS. | 1.000 | 1.000 | 0.333 | 0.250 | 0.200 | 0.200 | 0.497 | 4.94% |
| LAND COVER | 2.000 | 3.000 | 1.000 | 0.500 | 0.500 | 0.250 | 1.208 | 12.01% |
| TERRAIN SLOPE | 4.000 | 4.000 | 2.000 | 1.000 | 0.500 | 0.500 | 2.000 | 19.88% |
| GHI FREQUENCY | 5.000 | 5.000 | 2.000 | 2.000 | 1.000 | 1.000 | 2.667 | 26.51% |
| GHI RESOURCE | 6.000 | 5.000 | 4.000 | 2.000 | 1.000 | 1.000 | 3.167 | 31.48% |

**Table 3**
Weighted overlay for solar CSP scenario – Region 1.

| | L. COVER | D. ROUTES | D. TRANS. | T. SLOPE | DNI FREQ. | DNI RES. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|---|---|
| LAND COVER | 1.000 | 0.250 | 0.250 | 0.167 | 0.143 | 0.125 | 0.322 | 2.40% |
| D. ROADS | 4.000 | 1.000 | 0.500 | 0.200 | 0.200 | 0.143 | 1.007 | 7.49% |
| D. TRANS. | 4.000 | 2.000 | 1.000 | 0.333 | 0.250 | 0.167 | 1.292 | 9.61% |
| TERRAIN SLOPE | 6.000 | 5.000 | 3.000 | 1.000 | 0.333 | 0.250 | 2.597 | 19.32% |
| DNI FREQUENCY | 7.000 | 5.000 | 4.000 | 3.000 | 1.000 | 0.333 | 3.389 | 25.21% |
| DNI RESOURCE | 8.000 | 7.000 | 6.000 | 4.000 | 3.000 | 1.000 | 4.833 | 35.96% |

**Table 4**
Weighted overlay for wind scenario – Region 2.

| | L. COVER | T. SLOPE | WIND F. | WIND R. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|
| LAND COVER | 1.000 | 0.500 | 0.333 | 0.250 | 0.521 | 9.29% |
| TERRAIN SLOPE | 2.000 | 1.000 | 0.500 | 0.333 | 0.958 | 17.10% |
| WIND FREQ. | 3.000 | 2.000 | 1.000 | 0.500 | 1.625 | 29.00% |
| WIND RES. | 4.000 | 3.000 | 2.000 | 1.000 | 2.500 | 44.61% |

**Table 5**
Weighted overlay for solar PV scenario – Region 2.

| | T. SLOPE | L. COVER | GHI F. | GHI R. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|
| TERRAIN SLOPE | 1.000 | 0.333 | 0.333 | 0.333 | 0.500 | 9.30% |
| LAND COVER | 3.000 | 1.000 | 0.500 | 0.500 | 1.250 | 23.26% |
| GHI FREQ. | 3.000 | 2.000 | 1.000 | 0.500 | 1.625 | 30.23% |
| GHI RES. | 3.000 | 2.000 | 2.000 | 1.000 | 2.000 | 37.21% |

**Table 6**
Weighted overlay for solar CSP scenario – Region 2.

| | L. COVER | T. SLOPE | DNI F. | DNI R. | P. VECTOR | WEIGHTS |
|---|---|---|---|---|---|---|
| LAND COVER | 1.000 | 0.333 | 0.333 | 0.333 | 0.500 | 9.52% |
| TERRAIN SLOPE | 3.000 | 1.000 | 0.500 | 0.500 | 1.250 | 23.81% |
| DNI FREQ. | 3.000 | 2.000 | 1.000 | 1.000 | 1.750 | 33.33% |
| DNI RES. | 3.000 | 2.000 | 1.000 | 1.000 | 1.750 | 33.33% |

#### *3.2.5.1. Evaluation Layers (EL)*

In this step, the evaluation criterion of Tables 7 and 8 is assigned to each layer in order to define the areas with higher suitability for the desired purpose. A total of seven ELs were selected based on the data available and relevant criteria of previous literature [22]. Each layer is described below:

• EL-1. Resource potential: a layer showing the areas with the potential of each resource was calculated using the annual and monthly average layers of each resource. In this case, a grading value is applied for an area that could harvest energy using a specific technology. The grading values range between 0, where no energy can be produced with that amount of resource, and 10, where the maximum power output can be produced with the selected technology. This layer is built using the tool Reclassify, which is used to reassign values according to the evaluation criteria showed in Tables 9–11.

• EL-2. Resource frequency: the availability of resources during a year is necessary to determine the feasibility of the construction of an Energy Power Plant. Here, monthly average resource layers are used to determine the areas meeting the minimum requirement of resources for more months during the year, as it is shown in Table 12.

• EL-3. Terrain Slope: The slope is a technical factor for the construction of RE plants, where each technology requires different minimum inclination for an optimum performance. Current technologies, like solar CSP, require flat surfaces for the installation of panels and mirrors. This requirement become less important for other technologies like wind turbines, which can be located in steep surfaces (Table 13). The procedure to built the terrain slope layer is described below:

• EL-4. Land Cover: The vegetation and infrastructure cover influences the potentiality of a power plant as it can cause obstruction for the path of the resource (Tables 14 and 15). Tall vegetation may cause shade over solar panels, reducing considerably their efficiency. Likewise, forests may cause turbulence in the wind, reducing its speed, and scattering its direction.

• EL-5. Distance to transmission lines: This is considered an economic factor, as the evaluation of this requirement will affect the final cost of the investment (Table 16). If the locations with high technical suitability are located in regions far from inhabited regions, away from transmission lines, the implementation of a power plant may cause higher construction costs, due to the need of transmission lines to transport the energy produced.

• EL-6. Distance to roads: Is also considered an economic factor, but it also could be considered as a technical factor for wind technology, as the construction of wind farms in some locations could be considered nonviable due to lack of access to certain locations (Table 17). The process performed to generate this layer is similar to the one executed to calculate layer E-5.

• EL-7. Visual Impact: This evaluation layer has been considered only for wind technology, as the construction of high altitude towers could affect landscape (Table 18).

**Table 7**
Evaluation layers criteria – Region 1.

| Evaluation | Code | Wind | CSP | SPV |
|---|---|---|---|---|
| **Resource Potential** | EL1 | 30.57 | 35.96 | 31.48 |
| **Resource Frequency** | EL2 | 25.68 | 25.21 | 26.51 |
| **Terrain Slope** | EL3 | 4.22 | 19.32 | 19.88 |
| **Land Cover** | EL4 | 16.71 | 2.4 | 12.01 |
| **Distance to transmission lines** | EL5 | 8.30 | 9.16 | 4.94 |
| **Distance to roads** | EL6 | 9.89 | 7.49 | 5.16 |
| **Visual Impact** | EL7 | 4.63 | – | – |

**Table 8**
Evaluation layers criteria – Region 2.

| Evaluation | Code | Wind | CSP | SPV |
|---|---|---|---|---|
| **Resource Potential** | EL1 | 33.33 | 33.33 | 44.61 |
| **Resource Frequency** | EL2 | 33.33 | 33.33 | 29.00 |
| **Terrain Slope** | EL3 | 23.26 | 9.30 | 17.10 |
| **Land Cover** | EL4 | 9.30 | 23.26 | 9.29 |

**Table 9**
CSP Resource potential criteria.

| Direct Normal Irradiance (kW h/m$^2$/day) | Grade |
|---|---|
| < 3.5 | 0 |
| 3.5–4 | 3 |
| 4–4.5 | 6 |
| 4.5–5 | 8 |
| > 5 | 10 |

**Table 10**
SPV Resource potential criteria.

| Global Horizontal Irradiance (kW h/m$^2$/day) | Grade |
|---|---|
| < 3.8 | 0 |
| 3.8–4 | 4 |
| 4–4.5 | 6 |
| 4.5–5 | 8 |
| > 5 | 10 |

Finally, once every EL has been generated, they have to be standardized to allow direct comparability between them [22]. The process performed for the normalization of the ELs has implied using the open-source programming language Python, which was introduced in ArcGIS 9.0. This platform allows the user to perform data analysis, conversion, management and automation, helping to increase productivity and reduce time process [35]. The following algorithm describes the code used to normalize an EL:

```
 >> import arcpy
... from arcpy import env
... from arcpy.sa import *
... env.Workspace = "My_WorkSpace_root"
... inRaster = arcpy.Raster("input_raster")
... outRaster = (inRaster - inRaster.minimum) /
                (inRaster.maximum - inRaster.minimum)
... outRaster.save("output_raster_name")
```

Where My_workspace_root relates to the complete Hard Drive root location of the Geodatabe, input_raster refers to the EL to be normalized, and output_raster_name indicates the name of the resulting layer of the process. This process may lead to failure for various reasons such as insufficient space in the Hard Drive, input Raster layer internal errors, or existing output file name. If the procedure completes correctly, it will return a standardized layer with values between 0 and 1 (Fig. 3).

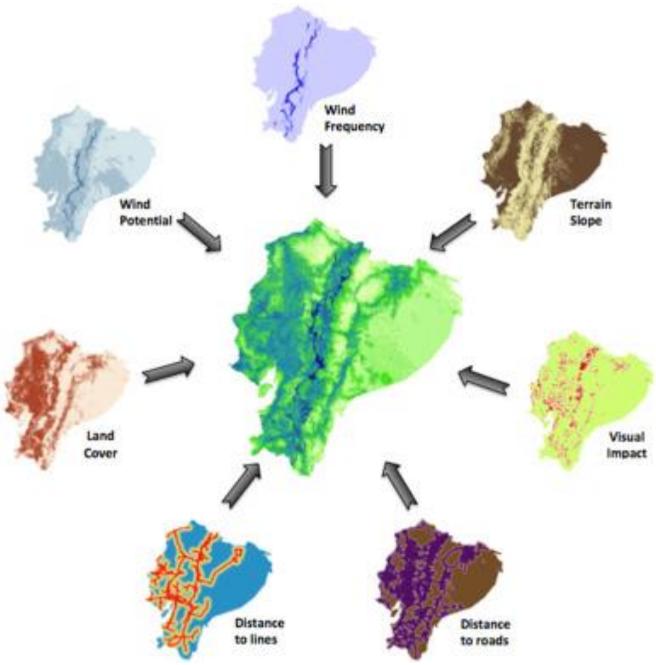


Fig. 3. Evaluation layers and result of wind technology.

*3.2.5.2. Constraint layers (CL)*

The constraint map is built to define the areas where a RE project cannot be developed, due to technical, environmental or social obstacles. Each technology generated its own constraint map, as each one has different requirements. The constraint map is derived form the collection of layers into one, which includes the sum of all unsuitable areas in each layer. As it is shown in Table 19, a total of eight restriction layers were identified, which are described below:

• CL-1: Resource Potential and Frequency

• CL-2: Wetlands

• CL-3: Altitude

• CL-4: Terrain Slope

• CL-5: Distance to transmission lines

• CL-6: Distance to roads

• CL-7: Distance to urban settlements

• CL-8: National Parks

Each layer was transformed to binary using the Spatial Analyst tool ***Reclassify***, and the restriction criteria showed in Table 7, assigning a value of 1 (true) to the regions meeting the minimum requirements for each layer. Subsequently all the layers are merged into one constraint layer using the tool Raster Calculator and the operator OR. This process has not included layer C-8 since local regulation allows the construction of RE power plants inside National Park areas (Fig. 4).

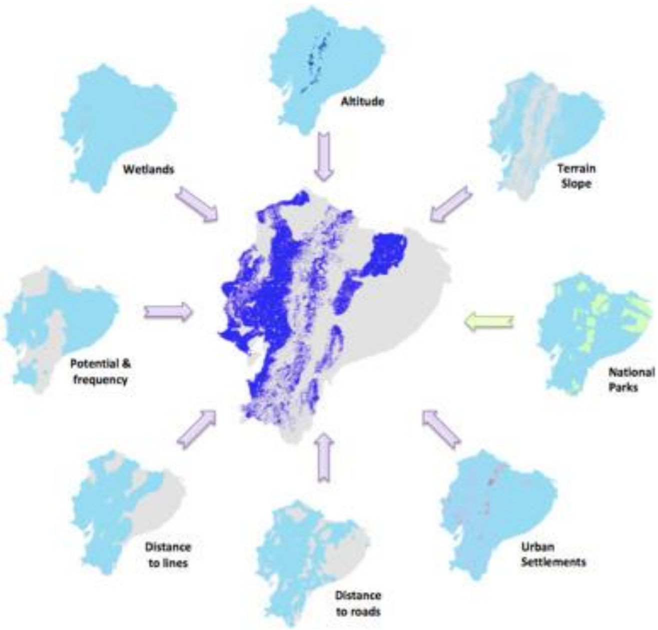


Fig. 4. Constraint layers and result of solar photovoltaic technology.

*3.2.5.3. Suitability layers (SL)*

Once both EL and CL have been developed, they were merged using the tool ***Raster Calculator***, as described in Fig. 5. The process multiplies each pixel in both layers, and removes the values where the CL has a value of zero (0); leaving the remaining pixels unchanged. This process is performed, for each technology, to remove all the areas previously assumed to be unsuitable due to technical, social, or economic factors.

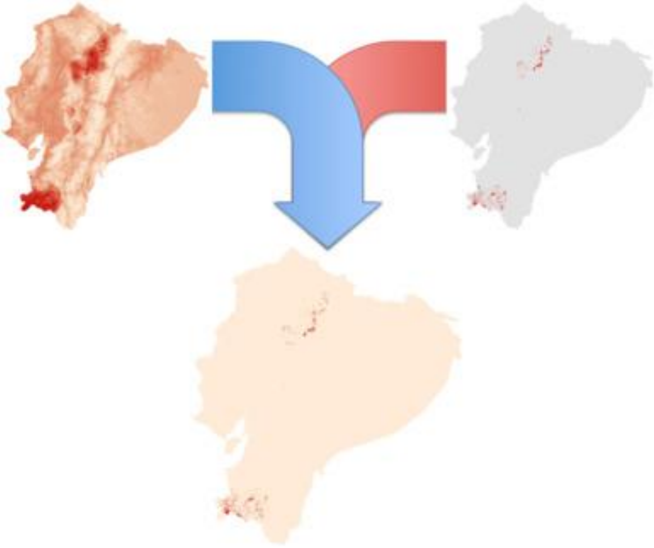

Fig. 5. Suitability layer generation for CSP technology.

*3.3 Sensitivity analysis*

In order to confirm the robustness of results, a sensitivity analysis was performed to confirm the results of each suitability layer, especially in the areas identified with high suitability. This study used the sensitivity analysis to generate four scenarios repeating the process of Section 3.2., to identify the areas of influence of each group of layers, according to its factor. The resulting suitability layer has been compared with these case scenarios:

**Scenario 1** each layer is assigned the same weight,

**Scenario 2** the weights of the Environmental/Social factors are equal to zero (0),

**Scenario 3** the weights of the Economical factors are equal to zero (0),

**Scenario 4** the weights of both Environmental/Social and Economical factors are equal to zero (0). This scenario takes into consideration only Technical factors such as resource potential, frequency and terrain slope.

In practice, this step has been useful to identify areas as suitable, for which the high score is the result of the sum of minor factors, other than technical factors. As it is seen in Fig. 6, the wind suitability layer (light blue) locates suitable areas in different locations of the areas with high technical suitability (dark blue). As a result, it was possible to identify areas with effective results and eliminate areas without technical potential.

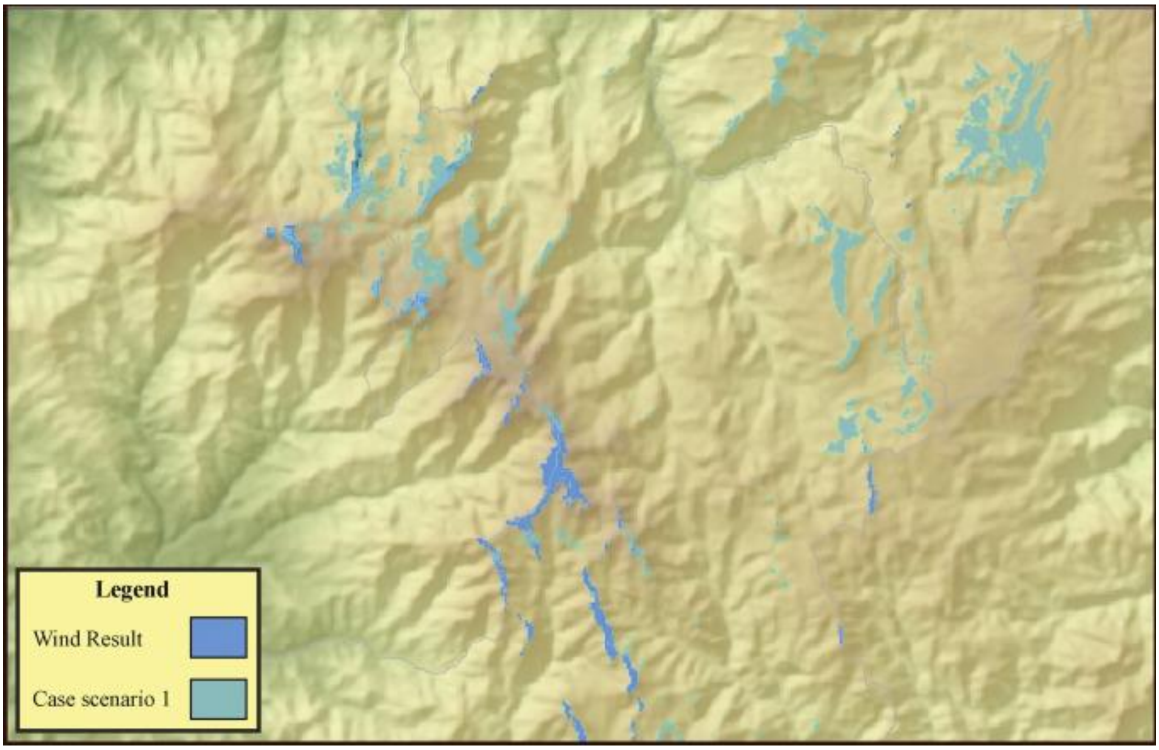


Fig. 6. Sensitivity analysis, comparison of wind result and case 1 scenario.

**Table 11**
Wind Resource potential criteria.

| Wind Speed (m/s) | Grade |
|---|---|
| ≤ 2 | 0 |
| 3 | 1 |
| 4 | 2 |
| 5 | 3 |
| 6 | 4 |
| 7 | 5 |
| 8 | 6 |
| 9 | 7 |
| 10 | 8 |
| 11 | 9 |
| 12 | 10 |
| > 13 | 10 |

**Table 12**
Resource frequency criteria.

| (Months/annum) | Wind | CSP | SPV |
|---|---|---|---|
| **0–3** | 0 | 0 | 0 |
| **3–6** | 4 | 4 | 4 |
| **6–9** | 8 | 7 | 7 |
| **9–12** | 10 | 10 | 10 |

**Table 13**
Terrain slope criteria.

| Percentage rise | Wind | CSP | SPV |
|---|---|---|---|
| **≤ 2%** | 10 | 10 | 10 |
| **2–5%** | 10 | 8 | 10 |
| **5–10%** | 9 | 5 | 7 |
| **10–20%** | 7 | 2 | 4 |
| **20–30%** | 5 | 0 | 2 |
| **> 30%** | 0 | 0 | 0 |

**Table 14**
Land cover criteria – Region 1.

| Land Cover | Wind | CSP | SPV |
|---|---|---|---|
| **Native Forest** | 0 | 0 | 0 |
| **Forest plantation** | 0 | 0 | 0 |
| **Pastureland** | 10 | 10 | 10 |
| **Shrubbery** | 10 | 9 | 9 |
| **Moor** | 4 | 4 | 4 |
| **Herbaceous vegetation** | 10 | 8 | 8 |
| **Natural area** | 0 | 0 | 0 |
| **Artificial area** | 0 | 0 | 0 |
| **Populated areas** | 0 | 0 | 6 |
| **Infrastructure** | 0 | 0 | 0 |
| **Area without plant cover** | 10 | 10 | 10 |
| **Glacier** | 0 | 0 | 0 |
| **Annual crop** | 8 | 6 | 6 |
| **Semi-permanent crop** | 8 | 6 | 6 |
| **Permanent crop** | 8 | 6 | 6 |
| **Other agricultural areas** | 10 | 8 | 8 |
| **Agricultural mosaic** | 10 | 8 | 8 |

**Table 15**
Land cover criteria – Region 2.

| Land Cover | Wind | CSP | SPV |
|---|---|---|---|
| **Rocky outcrops** | 8 | 7 | 7 |
| **Wetlands** | 0 | 0 | 0 |
| **Shrubbery** | 7 | 3 | 5 |
| **Timberline** | 4 | 0 | 0 |
| **Cultivated area** | 6 | 6 | 6 |
| **Invasive species** | 10 | 8 | 8 |
| **Herbaceous vegetation** | 8 | 6 | 6 |
| **Infrastructure** | 0 | 5 | 8 |
| **Mangrove swamp** | 0 | 0 | 0 |
| **Pioneer vegetation** | 2 | 2 | 2 |
| **Bare soil** | 10 | 10 | 10 |

**Table 16**
Distance to transmission lines criteria.

| Distance (km) | Grade |
|---|---|
| ≤ 2 | 10 |
| 2–3 | 9 |
| 3–4 | 8 |
| 4–5 | 7 |
| 5–6 | 6 |
| 6–8 | 5 |
| 8–10 | 5 |
| 10–15 | 4 |
| 15–20 | 4 |
| 20–25 | 2 |
| 25–30 | 2 |
| > 30 | 0 |

**Table 17**
Distance to routes criteria.

| Distance (km) | Grade |
|---|---|
| ≤ 1 | 10 |
| 1–2 | 9 |
| 2–4 | 8 |
| 4–6 | 6 |
| 6–8 | 4 |
| 8–10 | 2 |
| > 10 | 0 |

**Table 18**
Visual impact criteria.

| Distance (km) | Visibility | Grade |
|---|---|---|
| > 1 | Visible | 0 |
| 1–2 | Visible | 2 |
| 2–3 | Visible | 4 |
| 3–4 | Visible | 6 |
| 4–5 | Visible | 8 |
| ≥ 5 | Non visible | 10 |

## 4. Results and discussion

This step represents the conclusion in the development of the analytical framework, which has identified, located and organized data for its analysis [22]. The suitability layer, for each technology, contains pixels with grading values between zero (0) and one (1), representing the percentage of suitability of any area located in regions 1 and 2. The results of the suitability layers have been grouped according to their score, in order to identify the areas that are closer to meet all requirements. This process has been performed using the suitability criteria of Table 20, and the tool Reclassify. The results can be better visualized modifying the colors of each class according to the Color criteria also in Table 20, and removing the color of every unsuitable area. This process can be done using the Symbology tab of the properties option of each layer.

**Table 19**
Constraint list.

| Constraints | Code | Wind | CSP | SPV |
|---|---|---|---|---|
| **Resource potential and frequency** | CL1 | (Wind speed ≥ 5 m/s) ≥ 6 months/a. | (DNI ≥ 4 kW h/m$^2$/day) ≥ 6 months/a. | (GHI ≥ 4 kW h/m$^2$/day) ≥ 6 months/a. |
| **Wetlands** | CL2 | Rivers, lakes, lagoons, flooded areas, ponds, and aquatic farms. | | |
| **Altitude** | CL3 | ≤ 4 km | ≤ 3 km | ≤ 4 km |
| **Terrain slope** | CL4 | ≤ 30% | ≤ 10% | ≤ 20% |
| **Distance to transmission lines** | CL5 | ≤ 30 km | ≤ 30 km | ≤ 30 km |
| **Distance to roads** | CL6 | ≤ 4 km | ≤ 10 km | ≤ 10 km |
| **Distance to urban settlements** | CL7 | ≤ 5 km | ≤ 1 km | ≤ 1 km |
| **National Parks** | CL8 | 47 National Parks located Nationwide | | |

**Table 20**
Suitability criteria.

| Suitability | Grade | Color |
|---|---|---|
| 0–50% | Not suitable | No color |
| 50–75% | Suitable | Light |
| 75–100% | Highly Suitable | Dark |

**Table 21**
Identified suitable areas with its geographical location and coordinates.

| Location/Tech. | Province | Canton | Parish | Longitude | Latitude |
|---|---|---|---|---|---|
| **Wind** | | | | | |
| Location 1 | Loja | Zapotillo | Garzareal | 585743,086 | 9525545,551 |
| Location 2 | Loja | Macará | Sabiango | 631913,196 | 9516445,626 |
| Location 3 | Loja | Paltas | Yamana | 644176,686 | 9555578,338 |
| Location 4 | Cotopaxi | Sigchos | Sigchos | 734696,074 | 9925032,210 |
| Location 5 | Pichincha | Quito | Calacali | 780040,109 | 10004279,676 |
| **SPV** | | | | | |
| Location 1 | El Oro | Las Lajas | La victoria | 602964,343 | 9580813,287 |
| Location 2 | Imbabura | Ibarra | Salinas | 817787,942 | 10052066,959 |
| Location 3 | Imbabura | A. Ante | Imbaya | 815272,820 | 10042285,929 |
| Location 4 | Pichincha | Quito | Puembo | 791950,455 | 9983915,914 |
| Location 5 | Sto. Domingo | Sto. Domingo | Alluriquin | 715227,963 | 9971637,943 |
| **CSP** | | | | | |
| Location 1 | Loja | Loja | Loja | 704229,557 | 9547187,38 |
| Location 2 | Cañar | Cañar | Juncal | 722364,775 | 9719629,912 |
| Location 3 | Chimborazo | Alausí | Achupallas | 756562,239 | 9751842,998 |
| Location 4 | Bolivar | Guaranda | San Simon | 734691,737 | 9820846,469 |
| Location 5 | Cotopaxi | Pujilí | Zumbahua | 728897,351 | 9899904,127 |

Once the model has been run, and its outcomes have been analyzed, its results are summarized for the selection of the areas with highest suitability, so that resource measurement towers can be installed. The location of suitable areas for the development of RE projects with each technology, and as seen in Figs. 7–9, the technology with greater areas around the country is solar photovoltaic, due to the increased availability of GHI. Wind and CSP technologies have suitable locations in the Andean and Insular regions. Table 21 shows the five locations with greatest potential for each technology, with its political and geographical location and coordinates.

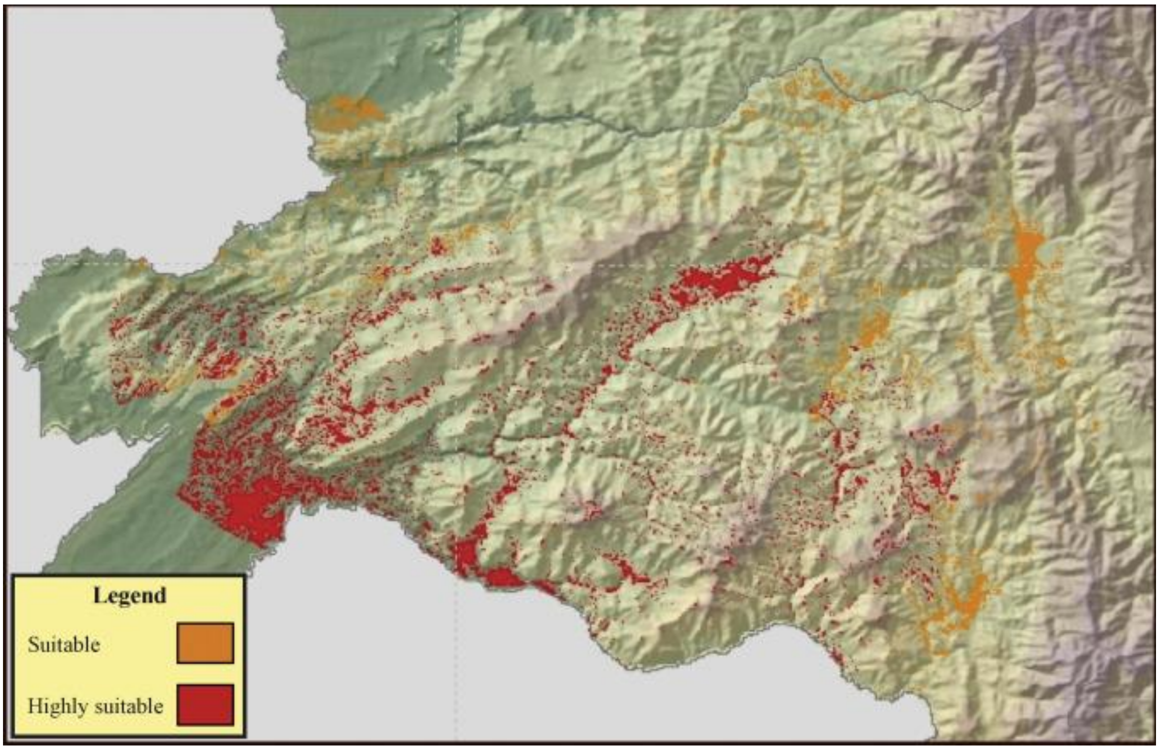


Fig. 7. Suitability map for CSP technology, region 1.

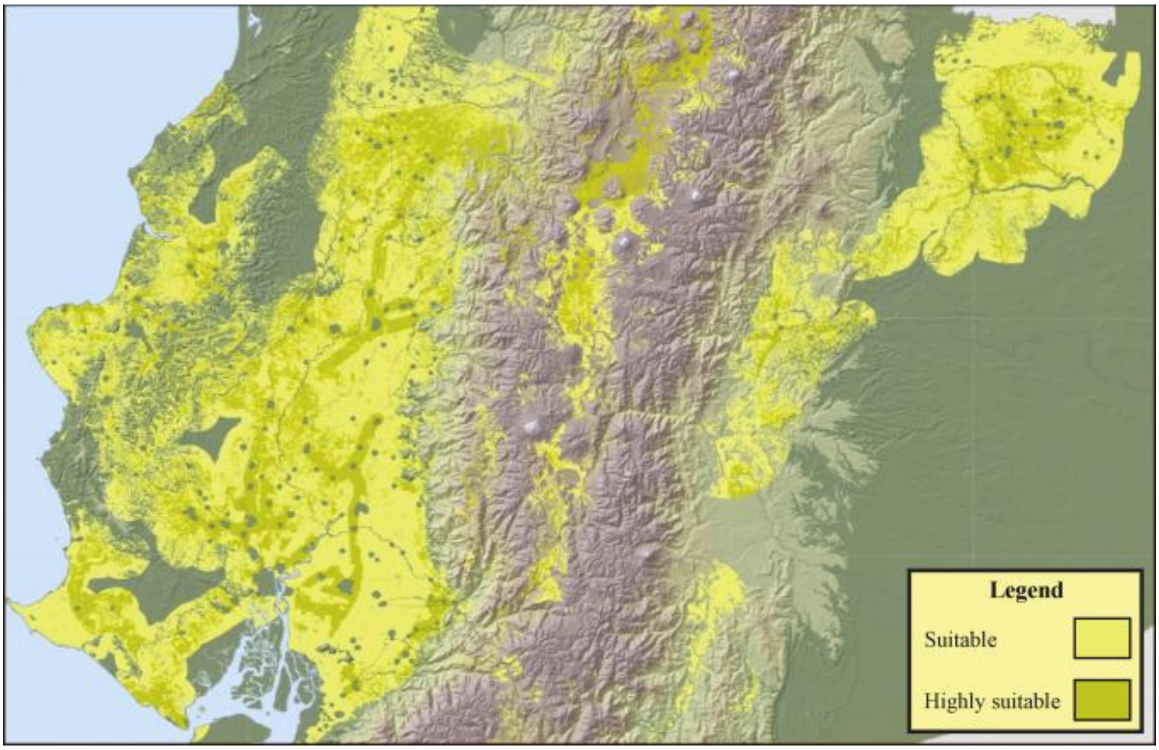


Fig. 8. Suitability map for SPV technology, region 1.

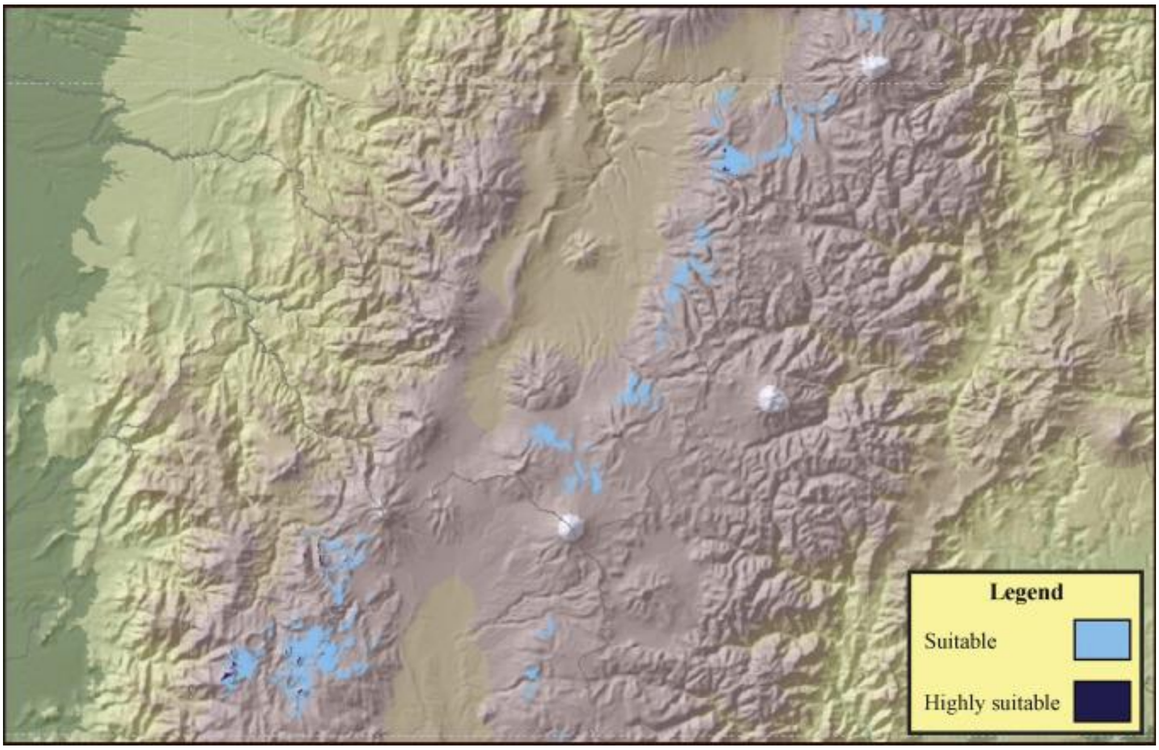


Fig. 9. Suitability map for Wind technology, region 1.

Results show the provinces with the most suitable areas are located in the Andean and Insular regions. Here it can be observed that appropriate locations vary with each resource, however these are concentrated in only few provinces. The provinces of Loja, Pichincha, and Galapagos are the most benefited from the solar resource. It is in these provinces where optimal areas for implementation of SPV and CSP technologies are found. Provinces benefited with wind resources are distributed in the Andean region, however potential locations are limited to the provinces of Loja, Cañar, Chimborazo, Cotopaxi and Pichincha only.

The layers used for the study have been assumed to be completely valid and reliable. In the model, resource potential and frequency were taken as layers of great importance (and weight), therefore it is crucial to be able to confirm the veracity of each resource. This can be achieved as the number of resource measurement towers increases across the country. Although the results have been confirmed by sensitivity analysis and field verification, the evaluation criteria used in the model to rate the importance of each layer can be modified, according to end user requirements. The exact selection of weights for each evaluation criterion will be achieved as the understanding of how each technology increases in our region.

## 5. Conclusions and recommendations

This study has used GIS tools to identify the locations, with the greatest potential, for the development of medium-scale and largescale, wind and solar, power plants. This assessment represents the first step to determine the real potential of renewable energy in Ecuador, and can be extended to other energy sources as more resource information is published. Future studies will use these results to estimate the maximum amount of energy that certain technology could produce in a chosen area. Those studies in the future will require the installation of resource measuring towers in the locations that have been identified here, in order to increase the understanding of the behavior of each resource in those areas.

Historically, Ecuador is not a country that has taken advantage of solar and wind resources for power generation, and according to various experts, the topographical and meteorological conditions of the country are not adequate for the implementation of renewable energy power plants. However, most of NCRE power plants commissioned in the country, in the last decade, have demonstrated considerably high capacity factors, if they are compared to other plants in the world.

The outcomes of the study are considered as a starting point to feed future studies, related with renewable energy potential, with reliable sources. These results can be used in future projects requiring to locate the regions with potential for harnessing solar and wind energies nationwide. Future analysis will include energy production and cost comparison (per MW installed and per MWe produced) for the implementation of any technology meeting the evaluation criteria of the model. Further analysis may include social and environmental evaluations of the effects of the implementation of renewable energy power plants in the locations selected as suitable.

## Acknowledgements

The authors acknowledges the support from the project "Centro de Prospectiva Estratégica, CUP00101819" from the Republic of Ecuador, and the support of the Military Geographic Institute of Ecuador, the Ministry of Agriculture, Livestock, Aquaculture and Fisheries, and the Ministry of Electricity and Renewable Energy for providing the dataset and information required for the study. Jesus Ramos-Martin acknowledges support from the project HAR2016-76814-C2-1-P (AEI/FEDER, UE) from the Ministry of Economics, Industry and Competitiveness of Spain

## References

[1] BP Statistical Review of World Energy. London – UK; 2016.

[2] Castro M. Hacia una matriz energética Diversificada en Ecuador. Quito – Ecuador: Centro Ecuatoriano de Derecho Ambiental; 2011.

[3] Heart G. Global list of countries powered 100% by renewable energy, or close to it. Green Road J 2017, [Retrieved from] ⟨http://www.agreenroadjournal.com/2016/05/global-list-of-countries-powered-100-by.html⟩.

[4] Matriz energetica. Ministerio Cordinador de Sectores Estrategicos. Quito – Ecuador. Retrieved from: ⟨https://www.celec.gob.ec/enernorte/images/PDF/Supleok.pdf⟩; 2013.

[5] Regulacion No. 004/11. Tratamiento para la energia producida con Recursos Energeticos Renovables No Convencionales. Consejo Nacional de Electricidad. Quito – Ecuador; 2011.

[6] Regulacion No. 001/13. La participacion de los generadores de energia eléctrica producida con recursos Energéticos Renovables No Convencionales. Consejo Nacional de Electricidad. Quito – Ecuador; 2013.

[7] Codificación de la Regulacion No. 001/13. La participacion de los generadores de energia electrica producida con recursos Energéticos Renovables No Convencionales. Consejo Nacional de Electricidad. Quito – Ecuador; 2013.

[8] Regulacion No. 002/13. Procedimiento de Calificacion y Registro de los Proyectos de Generacion de Energias Renovables No Convencionales. Consejo Nacional de Electricidad. Quito – Ecuador; 2013.

[9] Bravo J, Casals X, Pascua I. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. Energy Policy 2007;35:4879–92.

[10] Ramachandra T, Shruthi B. Spatial mapping of renewable energy potential. Renew Sustain Energy Rev 2005;11:1460–80.

[11] Carrión J, Estrella A, Toro M, Rodriguez M, Ridao A. Environmental decisionsupport systems for evaluating the carrying capacity of land areas: optimal site selection for grid-connected photovoltaic power plants. Renew Sustain Energy Rev 2008;12:2358–80.

[12] Jain A, Mehta R, Mittal S. Modeling impact of solar radiation on site selection for solar PV power plants in India. Int J Green Energy 2011.

[13] Barman J. Design and feasibility study of PV systems in Kenya, a case study. Department of energy and environment. Chalmers University of Technology; 2011.

[14] Fluri T. The potential of concentrating solar power in South Africa. Energy Policy

2009;37:5075–80.

[15] Kronshage , et al. Country analysis for solar thermal power stations using remote sensing methods. Cologne, Germany: World Renewable Energy Congress VII; 2002.

[16] Ummel K, Wheeler D. The economics of solar termal electricity for Europe, North Africa, and The Middle East. Center for Global Development; 2008, [Working Paper Number 156].

[17] Affandi R, Ab Ghani M, Ghan C, Jano Z. A review of concentrating solar power (CSP) in Malaysian environment. Int J Eng Adv Technol 2013;3(2).

[18] Baban S, Parry T. Developing and applying a GIS-assisted approach to locating wind farms in the UK. Renew Energy 2000;24:59–71.

[19] Gamboa G, Munda G. The problem of wind farm location: a social multi-criteria evaluation framework. Energy Policy 2006;35:1564–83.

[20] Dimcev V, Najdenkoski K, Stoilkov V, Kokolanski Z. Wind energy potential of the Republic of Macedonia. J Energy Power Eng 2011;5:324–30.

[21] Grassi S, Chokani N, Abhari R. Large scale technical and economical assesment of wind energy potential with a GIS tool: case study Iowa. Energy Policy 2012;45:73–85.

[22] Tegou L, Polatidis H, Haralambopoulos D. Environmental management framework for wind farm siting: methodology and case study. J Environ Manag 2010;91:2134–47.

[23] Nath S, Bolte J, Ross L, Aguilar J. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. Aqua-Cult Eng 2000;23:233–78.

[24] Learning about renewable energy: Solar photovoltaic technology basis. National Renewable Energy Laboratory; 2015. Retrieved from ⟨http://www.nrel.gov/learning/re_photovoltaics.html⟩.

[25] International Energy Agency . Wind 2015 annual report. Colorado, United States: PWT Communications, LLC; 2016.

[26] Republic of Ecuador´s Profile. Ministry of Foreign Trade and Integration. PRO ECUADOR, Quito – Ecuador. Retrieved from; 2011. ⟨http://www.ecuadorenchina.org.ec/ecuador/perfil-del-ecuador/situacion-geografica-superficie-agricola-yclima⟩.

[27] ARCONEL Estadísticas del Sector Eléctrico Ecuatoriano, año 2014. Consejo Nacional de Electricidad. Quito – Ecuador; 2015.

[28] CONELEC Plan Maestro de Electrificación 2013 – 2022. Consejo Nacional de Electricidad. Quito – Ecuador; 2013.

[29] Secretaria Nacional de Planificacion y Desarrollo. Modelos de Elevacion Digital del Ecuador; 2014.

[30] Corporation for Energy Research . Solar Atlas of Ecuador, for power generation purposes. Quito – Ecuador: National Electricity Council; 2008.

[31] AWS Truepower . Eolic Atlas of Ecuador, for power generation purposes. Quito – Ecuador: Ministry of Electricity and Renewable Energy (MEER); 2013.

[32] Surface Meteorology and Solar Energy. Direct, Diffuse and Global Solar Radiation, data and information. National Aeronautics and Space Administration. Retrieved from: ⟨https://eosweb.larc.nasa.gov/project/sse/sse_table⟩; 2015.

[33] Instituto Geografico Militar del Ecuador. Cartografia base del Ecuador. Retrieved from; 2014. ⟨http://www.igm.gob.ec/index.php/en/servicios/productoscartograficos-on-line⟩.

[34] Tapia L, Ponce J, Terán C, Bucheli V. Mapa de Covertura y Uso de la Tierra. Ministerio de Agricultura, Ganaderia y Pezca.

[35] ESRI. ArcGIS for Desktop. What is Python? Learning Python; 2015. Retrieved from ⟨http://desktop.arcgis.com/en/desktop/latest/analyze/python/what-is-python-.htm⟩.