Suitable location for renewable energy using GIS and a financial approach. Study case Valle del Cauca – Colombia

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Abstract

Renewable energy is booming worldwide due to global warming concerns. In Colombia, a country traditionally powered by hydroelectricity, solar Photovoltaic is becoming the most promising energy source due to the high potential, decreasing costs of technology and the environmental and social resistance that hydropower projects have been experiencing in the recent years. Celsia, one of the main utility companies in the country, is aware of this reality and is leading the way in solar PV installations. Hence, their challenge is to find the best spots to set up solar projects, i.e. the ones with the highest profit without any environmental or social restriction. Colombia's territory has 1,142,000 km2 (more than 12 times the area of Portugal) which makes this a complicated task.

Geographic Information System (GIS) can be very helpful for site selection, especially in the energy sector. Its powerful geoprocessing tools allow to analyze the territory from different perspectives. It usually has been used with Multi Criteria Decision Making techniques in which the different variables are weighted to define the suitability of each location assessed. The novelty of this work is that the GIS has been linked to a detailed financial model to conduct the analysis from the perspective of the investor and identify the most attractive locations considering all the variables involved such as the air temperature, solar radiation, slope of the terrain, cost of connection to the grid, environmental and social restrictions. It also considers all the financial parameters used by the company to assess their projects: initial investment, O&M, cost of capital, debt, insurance, regulatory expenses, among others.

The methodology was applied to Valle del Cauca, a district in the southwest of Colombia, and for three different tension levels of grid connection: 13.2, 34.5 and 115 kV. As a result, the feasible area was reduced to 1/10 of the initial one, helping the company to focus their search.

It can be concluded that the most promising are the projects of 10 MW connected to the grid at 13.2 kV, because of the wide distribution of this network on the territory, and the projects of 80 MW connected at 115 kV because of the scale of economy in which the connection cost is split into a bigger installed capacity.

Key words: Solar photovoltaics, Geographic Information Systems, financial analysis.

1. Introduction

According to [1], in recent years, the Geographic Information Systems (GIS) have become popular for various site selection assessments, especially in the energy field. Looking for possible sites for renewable energy projects is a strategic process as suggested by different studies and organizations as the National Renewable Energy Laboratory (NREL). This, combined with the increasing interest in renewable energy due to global warming, led to a boost in studies using these tools to find the best locations for projects.

In the study conducted by [2], 54 scientific papers published in this field were analyzed, thereby describing the applied technique, the renewable sources involved in the study and the location. The results show that the main technique used is MCDM (Multi-Criteria Decision-Making) combined with GIS capabilities. In most of the cases the technology analyzed is solar PV (photovoltaics) and wind, and the main countries in which these studies have been done are China, Spain and India.

One of the general conclusions in these papers is that developing a decision support model that integrates GIS with multicriteria can promote determining the ideal location for renewable energy, improving the performance of the projects, maximizing the generated output power and contributing to minimal project costs.

In Latin America, few research has been done regarding this topic. [3] identified suitable areas in Ecuador for the development of non-conventional renewable energy projects (solar and wind in this case), in order to estimate the maximum energy that these technologies could contribute to the national electric energy system; on the other hand [4] did the same for Argentina, also including other sources such as hydropower and biomass.

Colombia has been traditionally supplied by hydropower plants [5], and therefore, has a clear understanding of this resource and the feasible potential (including technical, economic and environmental variables). Other renewable resources like wind and solar are just taking off (20 MW of wind and 10 MW of solar PV out of 17 GW of total electric installed capacity, less than 1% [6]). To date, no study has been done to evaluate from a spatial perspective the real potential and prioritize the opportunities considering environmental and social restrictions, availability of resources, land, closeness to infrastructure (such as roads or substations), etc. The information is scarce and scattered, and should be gathered from many different governmental, national and international institutions.

Once all the geographic information is collected, a methodology should be defined to process it in the proper way to identify the location of the untapped potential. The proposal in this case is to implement a business approach, in which the final goal is to find the locations with the highest Internal Rate of Return (IRR) for a project of this kind. This is the metric used by developers and utility companies to decide whether to invest in a project or not. This, in turn, means that most of the variables involved in the analysis of a renewable generation plant can be related amongst themselves based on the impact that they have on the IRR. This removes the subjectivity linked to the MCDM approach. For example, to decide if it is better to be closer to the electric substation or further but in a sunnier location, the relation between these two variables would be defined in an economic way. The study is developed with the support of Celsia (http://www.celsia.com/), one of the main utility companies in Colombia, with participation in the generation, transmission, distribution and retail of electricity. The methodology is applied to solar PV.

2. State of the art

A GIS is an efficient tool for the selection of optimal locations for several kinds of activities [7], [8], [9]. Applications of GIS and sustainable energy source planning include wind farm siting and visual impact assessment, solar electrification, biomass and waste evaluation, etc. [10].

One of the most popular GIS-based strategies designed to help in decision making for site assessment is Multi-Criteria Analysis (MCA), [11] cited by [10]. The Analytic Hierarchy Process (AHP) method that was introduced by Saaty (1980) "is a flexible and easily implemented MCA technique and its use has been largely explored in the literature with many examples in locating facilities and land suitability analysis" [10]. It has been proposed as a method to "distill measures associated with widely different qualitative and quantitative criteria into a single measure. AHP allows a decision-maker to value the decision criteria differently via criteria weights" [12].

Different studies have applied these techniques with some variations, including in some cases more precise and complex analysis. For example, [13] studied how GIS can be combined with MCDM to evaluate the suitability of a certain set of locations for renewable energy projects in Morocco. In his case four criteria were used: orography, location, climate and land use. AHP was used to calculate the weight of each criteria. On the other hand, [14] identified areas suitable for solar and wind projects applying multi-criteria GIS modelling techniques in Colorado, US.

In Iran, [15] used GIS to identify the suitability of different regions for solar projects, 11 defined criteria were weighted using Fuzzy Analytic Hierarchy Process (FAHP), which is an improvement addressing "the vagueness, imprecision and uncertainty associated with the process" of traditional hierarchy process.

[16] applied a model considering several factors, such as technical and economic variables, with the purpose of getting maximum power while minimizing the cost of the project. An AHP was applied to weigh the criteria and compute a Land Suitability Index (LSI) to evaluate potential locations.

There is a great variety of studies in both MCDM and GIS applied to energy. [17] selected and reviewed 196 published papers, from 1995 to 2015 in 72 important journals related to energy. Hybrid MCDM and fuzzy MCDM methods were ranked as the first ones in use, and GIS was integrated to the analysis in several of them. At this point it is clear that GIS and MCDM have been widely used to site energy generation projects with a holistic perspective, including both qualitative and quantitative variables.

There have been some studies with a more specific focus on economic variables: [18] did a spatial and techno-economic analysis for wind energy planning in Greece; despite GIS was used in the research, this is not a continuous analysis on space but a set of discrete options (locations) that were evaluated. [19] assessed standalone photovoltaic system for major cities of United Arab Emirates based on simulated results, including a spatial approach considering financial variables. [20] studied the financial feasibility of on grid photovoltaic systems in 14 cities in Bangladesh, and [21] compared the financial returns and cost for PV arrays installed by companies in different places in the USA, the study concluded that costs and financial returns of PV systems change drastically depending on the location where they are installed.

In general terms, from the literature review, it can be concluded that there are studies assessing the economic performance of renewable energy projects based on their location, but none of them (to the best knowledge of the author) combines a continuous geographic approach (supported by GIS) with an orthodox financial assessment.

3. Primary data

The model proposed is a combination of spatial information, relevant for the assessment of renewable energy generation projects, linked with a financial model from the perspective of a utility company. The data used is mainly the energy resource (solar radiation), the conditions of the terrain (land cover, slope), meteorological variables (temperature), and location of infrastructure (transmission lines and electrical substations).

- **Solar radiation**: The solar resource data in GIS format for Colombia was one of the main inputs for the analysis, this was provided by Celsia, which bought it from SolarGIS. According to the company, the information contains a layer of Global Horizontal Irradiation (GHI), presented as an average annual sum for the period 1999-2014.

- **Digital Elevation Model (DEM)**: The DEM used is the ASTER Global Digital Elevation Model (GDEM) with a resolution of 90 m

- **Base cartography of Colombia**: maps with political division, natural protected areas and roads are taken from the IGAC (Instituto Geográfico Agustín Codazzi), the governmental geographic institute of the country.

- **Transmission lines, distribution lines and substations:** Celsia has the monopoly of the distribution of electricity in the southwest of the country (Valle del Cauca district), where operates around 20 thousand km of electric lines and serves more than 600 thousand customers in the retail market [22], they supplied the information (maps) about the grid infrastructure.

Secondary Data

Starting from the primary data, secondary variables necessary for the development of the project were derived based on certain models and with the help of the tools of ArcGIS. The variables calculated and the way they are used in the model is as follows

- **Yearly average temperature:** In Colombia, the temperature is strongly correlated to the height above sea level. The regionalization method proposed by Cenicafé (Chávez & Jaramillo 1998, cited by [23]) is a good way to estimate the long-term average. The results of the application of this method to the DEM are presented in Figure 1.

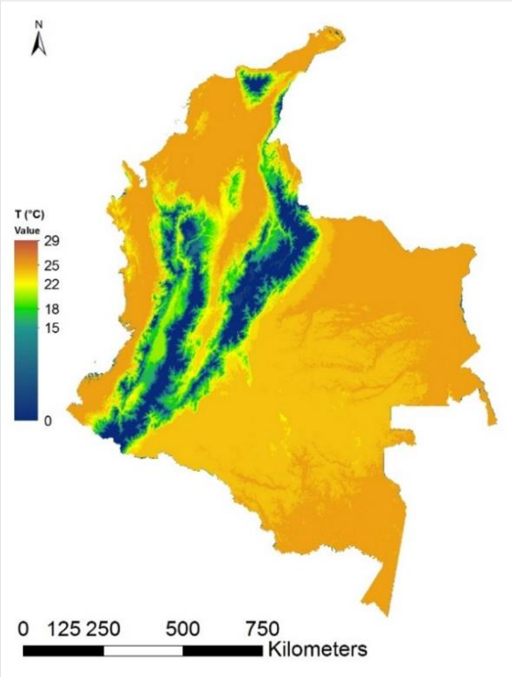

Figure 1 Air temperatures based on Cenicafé equations.

- **Slope of the terrain:** The slope is one of the criteria selected to define the suitability of the terrain for installation of a PV plant. According to the Celsia, they do not build this kind of projects in terrains with slopes higher than 15 degrees. This has been cross checked with literature references, for example [24] stated that slope higher than 16° is considered poorly suitable for PV projects in Europe.

The raster of terrain slope for the country is generated from the DEM using the tool Slope from the Spatial Analyst Toolbox from ArcGIS. After this is done, with the Raster Calculator, all the pixels with a slope higher than 15° will be turned into 'No Data' values to exclude them from the subsequent analysis. The result is showed in Figure 2.

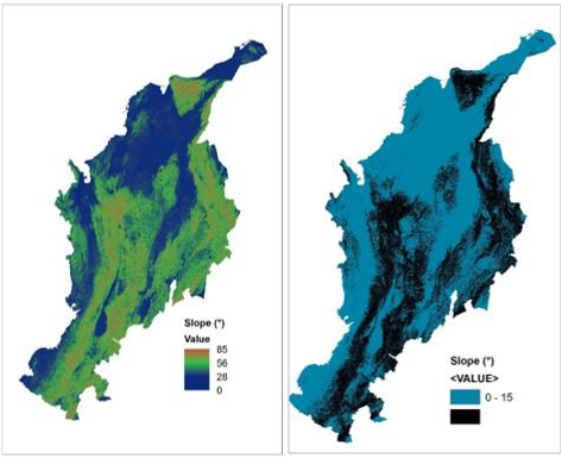

Figure 2 Slope raster

For some of the variables the analysis is done excluding the southeast of the country which lacks electric infrastructure.

- **Solar energy production:** The electricity production from the PV modules is calculated from the solar radiation information described in the primary data and the air temperature. First, the equations proposed by Collares-Pereira and Rabl [45] are used to downscale the average daily radiation value into hourly resolution. Then the HDRK model was applied to calculate the radiation on the tilted surface (the one which maximizes the production of a module sited on a certain location i.e. the latitude).

Finally, the radiation on a tilted surface is applied to the JKM330P [25] Jinko PV module to calculate the electricity production in terms of the capacity factor:

$$CF = \frac{\sum_{1}^{8760} P_{ACi}}{P_{peak} * 8760}$$

Having the capacity factor, the yearly average production of a power plant of any size can be derived. Results are shown in Figure 3.

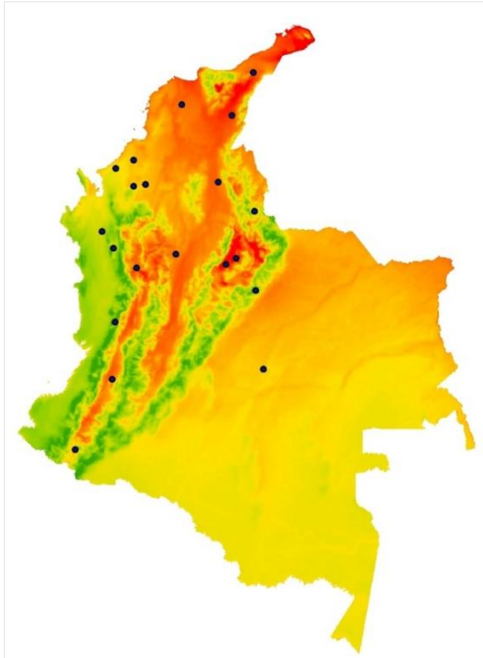

Figure 3 Capacity factor

Since the electricity production (represented by the capacity factor) is the most important input to the financial model, it was validated with the process that the company uses to assess their projects: with the online paid tool PV Planner of SolarGIS. Twenty points (locations) given by the company (Figure 3) were used to compare the error between the two tools:

$$Error(\%) = \left(\frac{CF_{ArcGIS} - CF_{PVplanner}}{CF_{PVplanner}}\right) * 100$$

The results are quite satisfactory, with errors ranging from 0.3% to 6.9% (in absolute values) and an average error of 1.4%.

- **Connection cost:** One of the key points in a project of this kind is the grid connection, a middle or high voltage transmission line should be built to connect the plant with the national or regional grid to feed the electricity produced into the system and to be delivered to the consumers. In general terms the project can be connected either to an electrical substation or directly to a transmission or distribution line (depending on the voltage level). After conversations with employees of the company from the T&D (Transmission and Distribution) department, it was agreed to split the cost into two: firstly the cost of building a new line from the location of the project to the connection point, which is a unitary cost per km; and secondly the cost of the work that has to be done at the connection point (transformers, bays, etc.) which is a unitary cost per MW of installed capacity and depends on whether the connection is done to an existing line or connecting to the substation. Table 1 shows the cost per km of building the new line (at each voltage level) which will connect the project with the existing grid.

Table 1 Cost of new transmission line

Tension level (kV)	USD/km
13.2	80,000
34.5	100,000
115	200,000

Table 2 shows the unitary costs per MW of installed capacity, if the project is connected to an existing line.

Table 2 Cost of connecting to an existing line

Voltage(kV)	Max. MW	USD/kWp
13,2	10	23.5
34,5	20	37
115	80	94

Table 3 shows the unitary cost of connecting the project to an existing substation.

Table 3 Cost of connecting to an existing substation

Voltage (kV)	Max. MW	USD/kWp
13,2	10	35
34,5	20	52
115	80	108

It is important to understand that Table 1 represents the cost of building a new line, which is necessary in all the cases, while Table 2 and Table 3 show the cost of the infrastructure that must be built to connect the new line to the existing infrastructure (either line or substation). The unitary cost presented in the tables above is in ideal conditions, i.e. flat terrain and grass or similar land cover, however, Colombian territory is far from that conditions in most of the cases. On agreement with Celsia these two additional factors were included in the cost estimation. That means that the cost of building a new line through each pixel on the map will depend on the slope and the land cover. With this information and using a powerful algorithm included in ArcGIS the least cumulative cost for each pixel is calculated. In other words, it finds for each pixel in the map, which is the cheapest way to connect to the existing grid considering the slope and land cover of the chosen path. The result of this procedure applied to the grid of 34.5 kV is shown in Figure 4 (environmental restrictions are shown in black), the same was done for the grid at 13.2 and 115 kV.

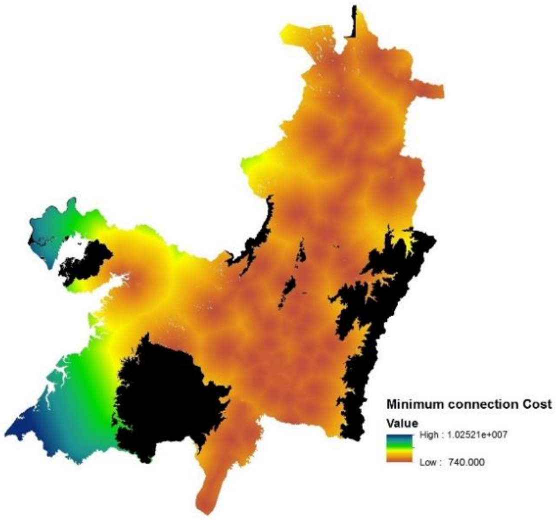

Figure 4 Cost of connection to the grid of 34.5 kV

Description of the simulation

The next step is the financial simulation of a PV plant located in each feasible pixel of the territory under assessment. The main inputs for the simulation will be the solar PV production and the connection cost, considering the constraints defined by the slope of the terrain and the environmental restrictions. The forecast of the electricity price in the wholesale market, which is another important input, was supplied by Celsia.

All the costs and expenses, both operative, financial, or regulatory were agreed with the company and considered in the simulation. Based on this a DCF (Discounted Cash Flow) model was built including all the financial statements, optimizing for each project the capital structure (% debt, % equity) and calculating the WACC and finally the IRR (Internal Rate of Return) to the equity. It is important to mention that the model considers the benefits of the law 1715 of 2014, which gives a tax exemption of 50% of the invested capex and the possibility of applying accelerated depreciation.

Results

The resultant maps are shown in the following figures. In all the cases the ocher (dark yellow) color represents lower values of IRR while the dark blue represents the highest. Natural Parks or other places with environmental or social restrictions are shown in gray, while land with slope higher than 15° is shown in black. Pixels in which the IRR < 15%, i.e. where the NPV is negative and hence does not comply with the minimum profitability demanded by the company, are shown in red.

10 MW plant connected at 13.2 kV

Figure 5 shows the result of a PV power plant of 10 MW connected to the grid at 13.2 kV (either substation or directly to the line). It can be noticed that the feasible region is now reduced to the center of the valley: flat lands close to the electric grid, far from the influence of the Pacific Ocean, which brings clouds to the western part of the department [26].

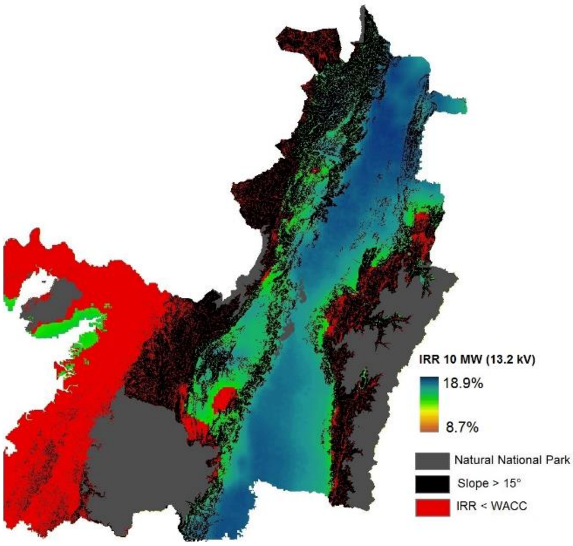

Figure 5 IRR for a 10 MW PV (13.2 kV)

Putting together all the restrictions, the area can be narrowed to 6.774 km2, this is 33% of the initial one (20.481 km2). This process is shown in Figure 6. It should be noticed that one pixel can have more than one restriction, for example, being part of a Natural Park, having a slope higher than 15° and an IRR lower than 15%, in this case the criteria were applied in the following order:

first the Environmental Restrictions were removed, then from the remaining area, the same was done with those pixels with slope higher than 15°, and finally the regions with IRR lower than 15% were discarded.

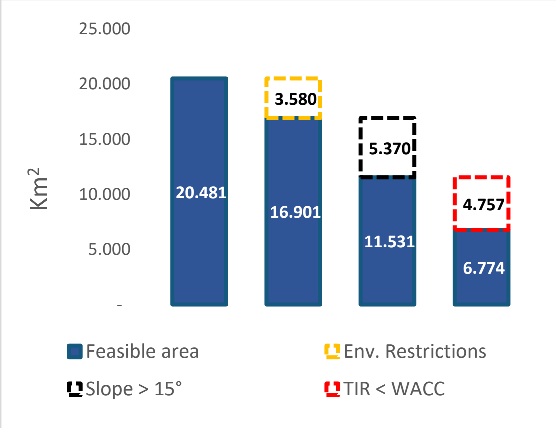

Figure 6 Feasible area (10 MW / 13.2 kV)

20 MW plant connected at 34.5 kV

Figure 7 shows the result for a 20 MW solar PV plant connected to the grid at 34.5 kV of tension. From the three levels of tension analyzed this is the one with the poorest performance (lowest values of IRR). It is because the grid is not as dense as the one for 13.2 kV, so points in general are further away. It can be seen that the feasible region is narrower than the others (blue pixels).

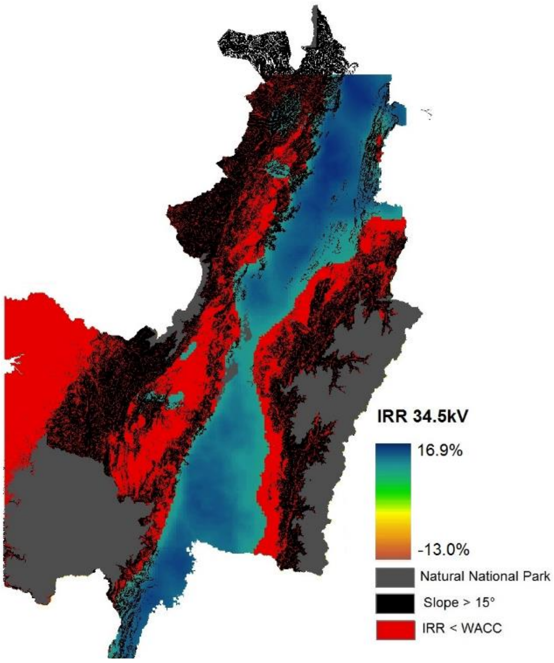

Figure 7 IRR for a 20 MW PV (34.5 kV)

In this case, the red area in (b) is 70% of the original map, nevertheless combining all the restrictions the area discarded goes up to 75% (from 17.275 km2 to 4.471 km2) as shown in Figure 8.

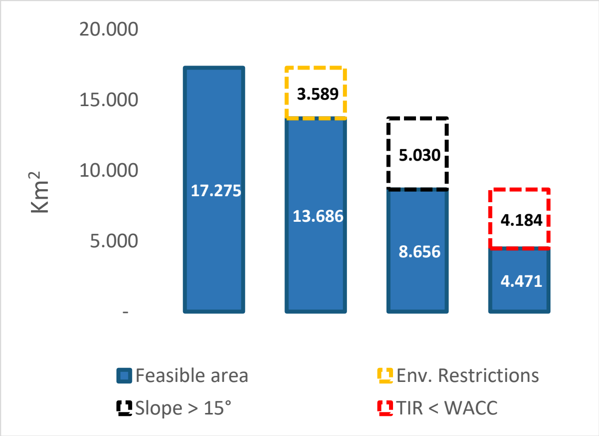

Figure 8 Feasible area (20 MW / 34.5 kV)

80 MW plant connected at 115 kV

In Figure 9, it can be seen the same result for a project of 80 MW connected to the grid of 115 kV. Here the feasible area increases again due to the economy of scale, in which, despite the total connection cost being higher, it is split into 80 MW, making the unitary value lower. (USD/MW). The feasible area at this point is 6.689 km2 out of the initial 17.046 km2

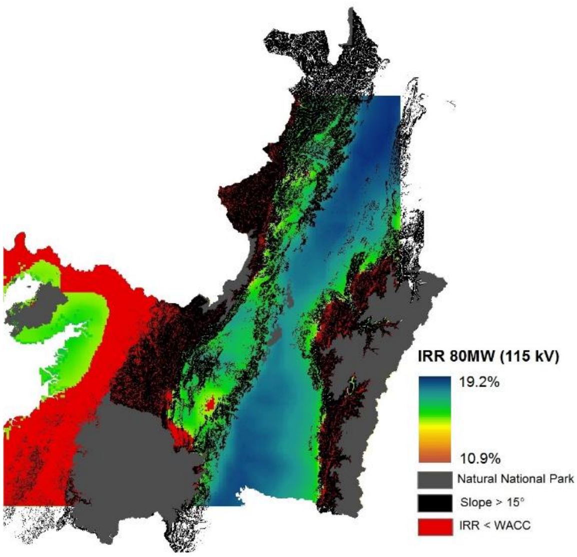

Figure 9 Feasible area (80 MW / 115 kV)

Since the area of feasible projects is still very wide and the company is looking to narrow it down as much as possible, a forward step can be taken by including the layer of land cover once again. This variable is not easy to include directly in the economic analysis, for example defining the cost or availability of the land based on the vegetation is complicated and can introduce noise (in the model). Anyway, the ideal condition is to find land with a low natural value i.e. no forests, wetlands, etc. and with low economic value i.e. lands without profitable crops. The first condition will minimize the environmental impact of the power plant and hence will facilitate obtaining the permits, the second one will avoid expensive lands in which the power plant will have to compete with highly profitable crops. In the region of study one good example is the sugar cane, which is an industrialized crop with high yields. According to the experience of the company the land cover that better fits these conditions is the pasture for livestock, it has very low value from both perspectives: biodiversity and economic. The result of excluding all the other land covers and leaving just pastures is shown Figure 10.

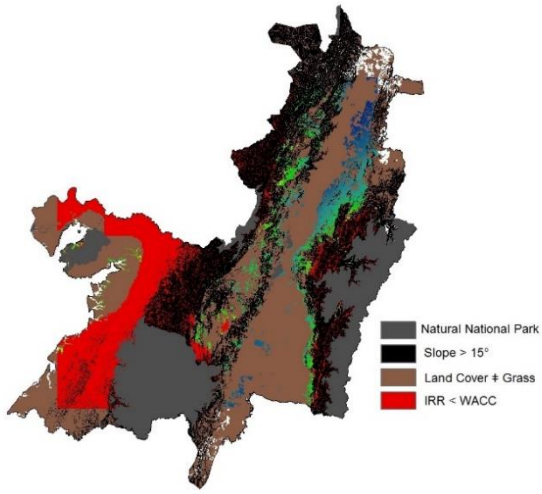

Figure 10 Including land cover

Figure 11 represents the process of reducing the area, from the initial 17.000 km2, to the final 1.190 km2. The first 3 parameters are considered as exclusions (environmental restriction, slope and minimum IRR), while the last one, land covers different from pastures, is not an exclusion, but a desired condition.

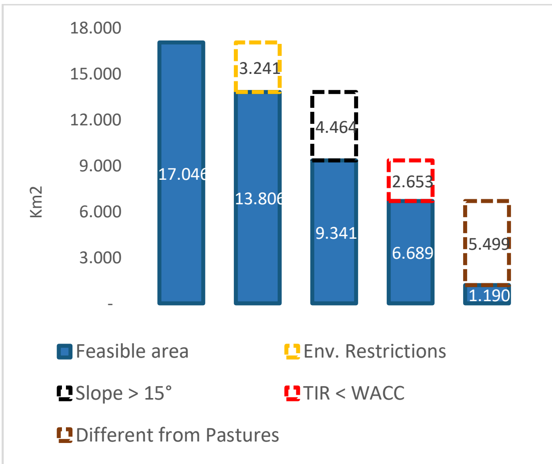

Figure 11 Feasible area (80 MW / 115 kV)

At this point the area has been reduced to less than 10% of the starting point, but it is still too large to start a specific search in the field. In order to narrow it even more, just the pixels over the percentile 90 in IRR (from those feasible and in pasture) are taken (b).

Figure 12 shows the polygons corresponding to the pixels selected before, they correspond to 121 Km2 in the northwest of the department, with high solar radiation represented by an average capacity factor of 16.7% corresponding to the percentile 77 in the study region and low cost of connection (average of 2.7 MUSD, percentile 38). From this land in "ideal" conditions, the company can start a more detailed analysis, involving all the experts in the different fields: environmental, social, transmission and distribution, regulatory, land acquisition, etc. to define the best specific spots and start the tasks of land negotiations with the owners.

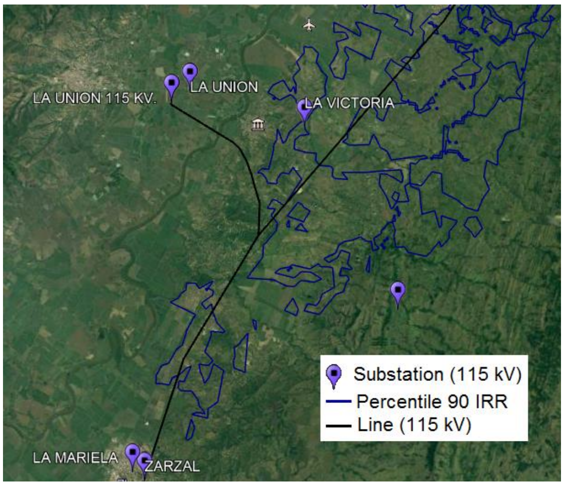

Figure 12 Polygons technically feasible, in grass land cover

The same exercise can be done for the tension levels of 13.2 kV and 34.5 kV.

There are several players interested in the sector of renewable energies in Colombia and the company continuously receives offers from developers and land owners with potential sites for the development of PV projects. The IRR map built in this thesis allows Celsia to make a quick first review of the offering, without investing too much time and resources to decide whether it is worth it to analyse it more in detail.

Conclusions

It has been demonstrated once again that GIS is an ideal tool for the selection of optimal sites for the installation of solar photovoltaic power plants at a utility scale. Its powerful geoprocessing tools allow for analysis of the territory from different perspectives, including the most impacting variables in a project of this kind.

Even though there have been several studies using GIS to find suitable locations for renewable energy plants, most of them use MCDM (multicriteria decision-making) in which a weight is given to each variable e.g. air temperature, solar radiation, distance to infrastructure, slope of the terrain, etc. and a suitability map is produced based on these relations.

The novelty of this work, is linking the GIS capabilities, with a detailed financial model including all the parameters considered by the company in their projects. This assures that the relations among variables are modeled exactly in the way the company needs it.

A model to calculate the Capacity Factor (average energy production) of a PV plant with accuracy just by introducing the coordinates of the location has been developed, this can be used for everyone in the company with any specific knowledge or access to specialized software. The same can be done for the IRR.

By applying some constraints, as environmental sensitive areas, reasonable slope for implementing the projects, adequate land covers to facilitate land acquisition and environmental licenses, and discarding those locations in which a project would not comply with the minimum profitability expected by the company, the original area can be reduced to 1/10. Over this area some more criteria can be applied to narrow it down according to the preferences of the company.

According to the analysis done, in general terms, the most profitable projects are the ones of 10 MW of installed capacity connected to the grid at 13.2 kV and the 80 MW connected at 115 kV. The first one is because the grid is very dense (distance to the grid is usually short), while the second is because of the high installed capacity, in which the total connection cost is divided into a higher number of MW, decreasing the unitary cost.

The main variable in the analysis is the solar radiation, which defines (with some influence of the temperature) the energy production of the plant. The cost of the connection plays an important role as well, but is secondary compared to the availability of the resource.

Future Work

The Net Present Value can be used as the decision variable instead of the Internal Rate of Return, this will simplify the analysis, since the cash flows will be discounted with the respective WACC and in that way all the pixels will have the same basis, regardless the percentage of debt.

The same analysis can be applied to other renewable sources like wind, hydropower and other kinds of solar energy as CSP, whose potential is distributed throughout the territory. It can also be used in hybrid systems.

The methodology can also be adapted to reflect the economics of distributed generation at small scale, using the appropriate decision variables.

The cost and availability of land is one of the most important variables in a renewable energy project after the ones considered in this thesis. Therefore, including this variable in the analysis would give additional important information.

The methodology proposed can be implemented with a Multi Criteria Decision Making model, in which the final IRR is compared with variables that cannot easily be included in a financial analysis as regulations, policies, social dynamics, or the land cover treated as a decision variable.

The availability of the capacity connection in the grid can be included if the information is spatially available, thereby considering technically feasibility of connecting the project to the grid and not just the cost to the closest point.

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