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

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Abstract

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 social resistance that hydropower has been experiencing recently. Celsia, one of the main utility companies in the country, is aware of this and is leading the way in solar PV installations. Hence, their challenge is to find the best spots to set up solar projects.

Geographic Information System (GIS) are very helpful for site selection. 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 is linked to a detailed financial model to conduct the analysis from the perspective of the investor and identify the best locations considering the most relevant variables in a PV project.

The methodology is applied to a district in the southwest of Colombia, and for three voltage levels of grid connection. 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.

Resumo

A energia renovável está a crescer devido às preocupações com o aquecimento global. Na Colômbia, um país de tradicao hidrelétrica, a energia solar fotovoltaica está a se tornar a fonte de energia mais promissora devido ao alto potencial, à redução dos custos da tecnologia e à resistência ambiental e social que os projetos hidrelétricos vêm experimentando recientemente. A Celsia, uma das principais empresas de serviços públicos do país, está ciente dessa realidade e está a liderar o caminho em instalações de energia solar fotovoltaica. Por isso, o seu desafio é encontrar os melhores pontos para a instalação de projetos solares, ou seja, aqueles com maior rentabilidade, sem restriçoes ambientais ou sociais. O território da Colômbia tem 1.142.000 km2 (mais de 12 vezes a área de Portugal), o que torna esta uma tarefa complicada.

Os Sistemas de Informação Geográfica (SIG) pode ser muito útil para a seleção de locais, especialmente no setor de energia. Suas poderosas ferramentas de geoprocessamento permitem analisar o território a partir de diferentes perspectivas. Geralmente, eles tem sido usado com técnicas MCDM, nas quais as diferentes variáveis são ponderadas para definir a adequação de cada local avaliado. A novidade deste trabalho é que o SIG foi vinculado a um modelo financeiro detalhado para conduzir a análise sob a ótica do investidor e identificar os locais mais atrativos considerando todas as variáveis envolvidas, como temperatura do ar, radiação solar, declividade do terreno, custo da conexão à rede, restrições ambientais e sociais. Considera também todos os parâmetros financeiros utilizados pela empresa para avaliar seus projetos: investimento inicial, O & M, custo de capital, dívida, seguros, despesas regulatórias, entre outros.

A metodologia foi aplicada ao Valle del Cauca, um distrito no sudoeste da Colômbia, e para três diferentes níveis de tensão de conexão à rede: 13,2, 34,5 e 115 kV. Como resultado, a área viável foi reduzida para 1/10 da inicial, ajudando a empresa a focar sua busca.

Pode-se concluir que os mais promissores são os projetos de 10 MW conectados à rede a 13,2 kV, devido à ampla distribuição dessa rede no território, e os projetos de 80 MW conectados a 115 kV devido à economia de escala, em que o custo de conexão é dividido numa capacidade instalada maior.

Palavras chave: GIS, Solar PV, IRR

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ω	Hour angle
ω_s	Sunset hour angle
r_t	Ratio of hourly total to daily total radiation,
t_s	Solar time
t_{std}	Local standard time
L_{std}	Standard longitude
L_{loc}	Location longitude
n	Day of the year
δ	Declination angle
γ	Orientation angle
θ_Z	Zenith angle
φ	Latitude
γ_s	Solar azimuth angle
A_i	Anisotropy index
G_{on}	Extraterrestrial irradiance on a surface normal to the beam
R_b	Ratio of beam radiation on a tilted surface
$G_{T,d}$	Diffuse irradiance on the tilted panel
$F_{\tau,d}(\theta)$	Dirtiness factor

List of acronyms

AC	Alternating Current
ACG	Automatic Generation Control
AHP	Analytic Hierarchy Process
ALOP	Advanced Loss of Profits
ASTER	Advanced Spaceborne Thermal Emission And Reflection Radiometer
CAPEX	Capital Expenditure
CAPM	Capital Asset Pricing Model
CF	Capacity Factor
COD	Commercial Operation Date
COP	Colombian Peso
DC	Direct Current
DEM	Digital Elevation Model
DSCR	Debt Service Coverage Ratio
DST	Daily Saving Time
EBITDA	Earnings Before Interest, Taxes, Depreciations and Amortizations
ENSO	El Niño Southern Oscillation
FAHP	Fuzzy Analytic Hierarchy Process
FAZNI	Fondo de Apoyo a Zonas No Interconectadas
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
IGAC	Instituto Geográfico Agustín Codazzi
IRR	Internal Rate of Return
JPEG	Joint Photographic Experts Group
KMZ	Keyhole Markup Language Zipped
LSI	Land Suitability Index
MCA	Multi-Criteria Analysis
MCDM	Multicriteria Decision-Making
MRSID	Multi-Resolution Seamless Image Database
MTOE	Million Tons of Oil Equivalent
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development

OPEX	Operative Expenditure
PPP	Purchasing Power Parity
PV	Photovoltaics
T&D	Transmission and Distribution
TIFF	Tag Image File Format
TPES	Total Primary Energy Supply
UPME	Unidad de Planeación Minero-Energética
USD	United States Dollars
VAT	Value Added Tax
WACC	Weighted Average Cost of Capital

1. Introduction

1.1 Background

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.

1.2 Aim of the thesis

Utility companies operating in a certain country must focus their efforts on those projects which maximize their profits, complying with national and international laws, and fulfilling some requirements in terms of environmental and social performance according to their internal standards.

For Celsia, diversifying its portfolio of generation assets (2399 MW of installed capacity, 48% thermal plants, 50% hydropower plants, 2% solar PV and wind) is a strategic decision. Growing in solar PV and wind is a mandate from the board of directors and because of this, the company has set a goal of having 250 MW of solar energy in the next 2 years. Here is where the question arises: where to start looking for projects? Where are the most suitable locations to develop them? If a third party (external developer) is offering the company a project in a certain state of development (prefeasibility, feasibility, etc.), how to spend only the required resources and time to analyze the offer? The answer is mainly financial[1]. The way a private company decides whether or not to invest in a project is based on the IRR or the Net Present Value (NPV).

The aim of this thesis is to merge the capabilities of the GIS with an exhaustive financial model (considering the peculiarities of the company and of the Colombian electricity market) to produce a continuous surface (map) of IRR which helps the company to easily locate the regions with the highest economic potential, considering decision variables as the cost of connection infrastructure (based on

[11] In all the cases it is understood that despite the objective to maximize profit, it will be done under reasonable environmental and social standards.

the distance) and energy production (based on the solar radiation) and constraints such as slope of the terrain or National Natural Parks (NNP) and other sensible areas.

1.3 Thesis structure

This thesis will be composed of five main sections that will first describe the problem under consideration and later present the solution that has been developed. The main chapters of this thesis are:

- Introduction
- State of the art
- Description of the model
- Results
- Conclusions

The first section is the introduction in which a brief background of the topic is presented, followed by the objective of the work and the structure of the report. Then comes the state of the art, where a review on optimal site selection for energy projects is done. This section also includes a brief presentation on how the Geographic Information System works, and ends describing the energy context of Colombia, where the methodology will be applied.

The third section is the description of the model, starting with the primary data and continuing with the way this data was processed to get the secondary information that directly feeds the model, which is presented at the end of the chapter.

The results of simulations are presented and discussed in section 4 and the conclusions in section 5. Finally, since there is always room for improvements, some future work is suggested.

2 State of the art

2.1 Optimal site selection for energy generation projects

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.

2.2 Geographic Information Systems

According to [22] a Geographic Information System can be described as a database management system "designed for the capture, storage, analysis, and display of spatial (location defined) data for the purpose of decision making and research". Its power is the ability to process big amounts of data in different dimensions.

The data inside a GIS is organized by layers, all of them forming a database. In the case of this work the layers will be the variables used for the assessment of the solar PV projects which will be overlapped in the GIS software to process them according to the needs of the study. The common reference for all the layers is the coordinate system, in this way they are linked by the fact that they are representing different variables in the same region.

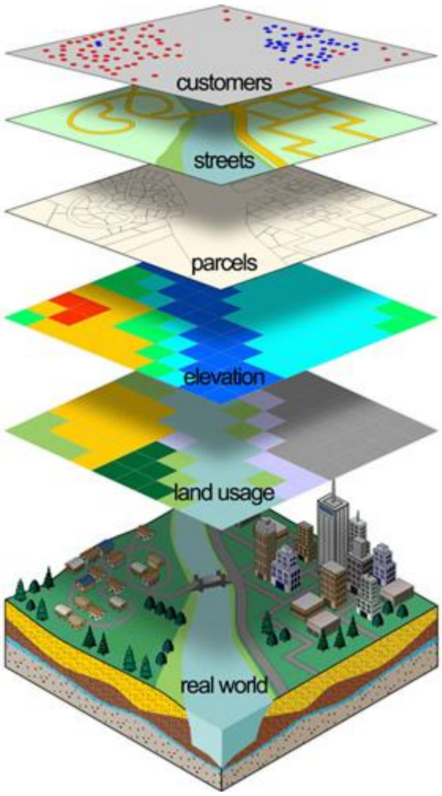


Figure 1 Example of layers forming a GIS data base [23]

As per [24], there are mainly two types of data models in GIS: vector and raster. The raster model is used to represent continuous variables, as it can be for example the land cover. In this format what lies behind the map reproduced by the GIS software is a rectangular matrix of numbers which can be operated in any way.

Each pixel in a raster file contains at least 3 values, the x and y coordinate (longitude and latitude) and the value of the variable its representing (e.g. land cover type, elevation, or other surface values). The grid layers are used to be stored in a wide range of various raster formats such as TIFF (Tag Image File Format), BMP (Bitmap Image File) or JPEG (Joint Photographic Experts Group). In case of GIS datasets, grid layers need to be embedded with geo-referencing data that include spatial localization and additional information about map projection. Thus, more specific raster formats must be used such as GeoTIFF, IMG-ERDAS IMAGINE, and Multi-resolution Seamless Image Database (MrSID) [25].

On the other hand, the vector model is better for representing points, lines, polygons and symbols, this format is suitable for representing linear infrastructure as for example roads and electric lines.

Figure 2 shows the difference between vector (points, lines and polygons) and raster format.

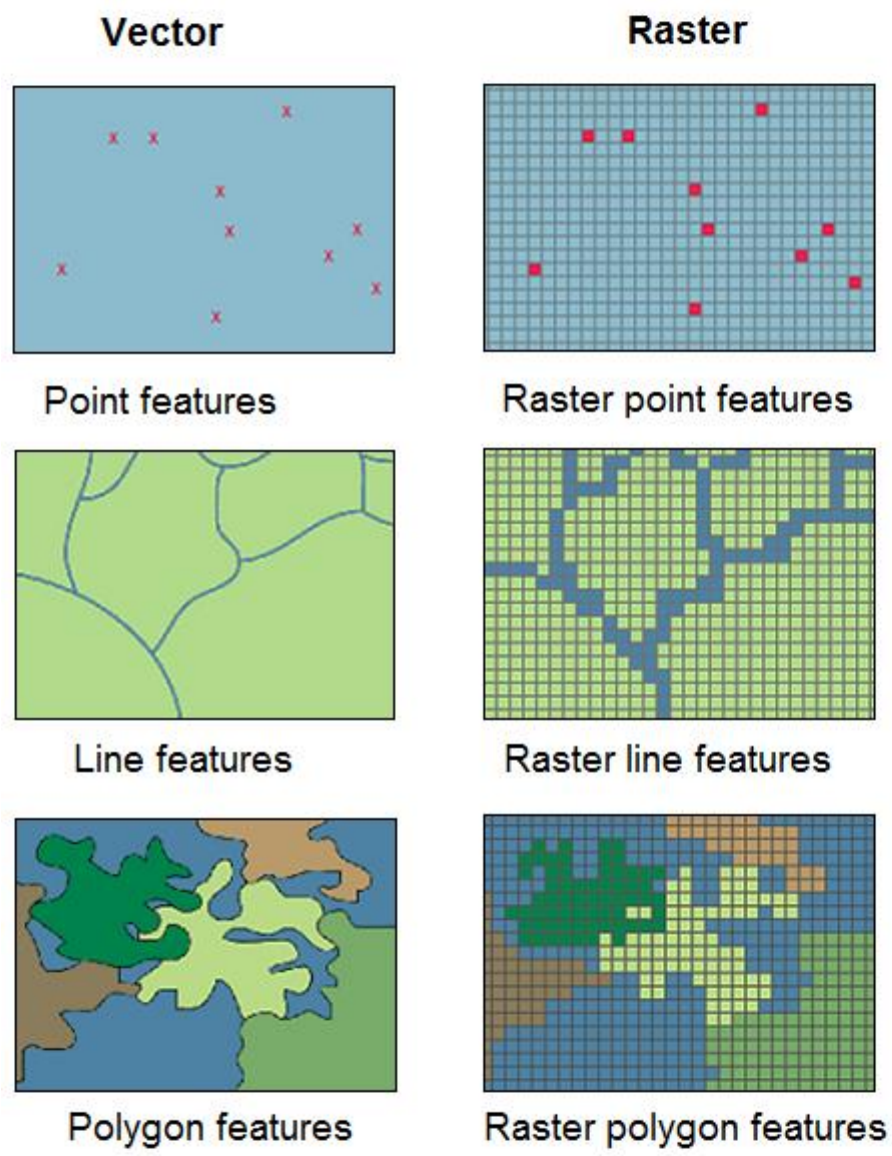


Figure 2 **Difference between vector and raster format (adapted from** [26]**)**

Since in this work we will be working mostly with continuous variables the raster format was chosen to perform the analysis, nevertheless some of the input information is available in vector format, so it will be converted using the appropriate tools.

2.3 Geographic limits of application

Since the analysis will be applied in Colombia, a brief description of the energy context in which the projects will be developed, is presented. Although the electrification rate in Colombia is higher than 99% [27] the electric system (as well as all the infrastructure of the country and almost all its population) is located in the Andean, Pacific and Caribbean regions [28], which comprises less than half of the area. This means that Orinoco and Amazonas regions are off-grid territories (the southeast of the country showed in Figure 3 with no connection lines) which can be excluded from the analysis.

Later on, in the report some of the calculations (those consuming a considerable amount of computational process power) will be done just for this region.

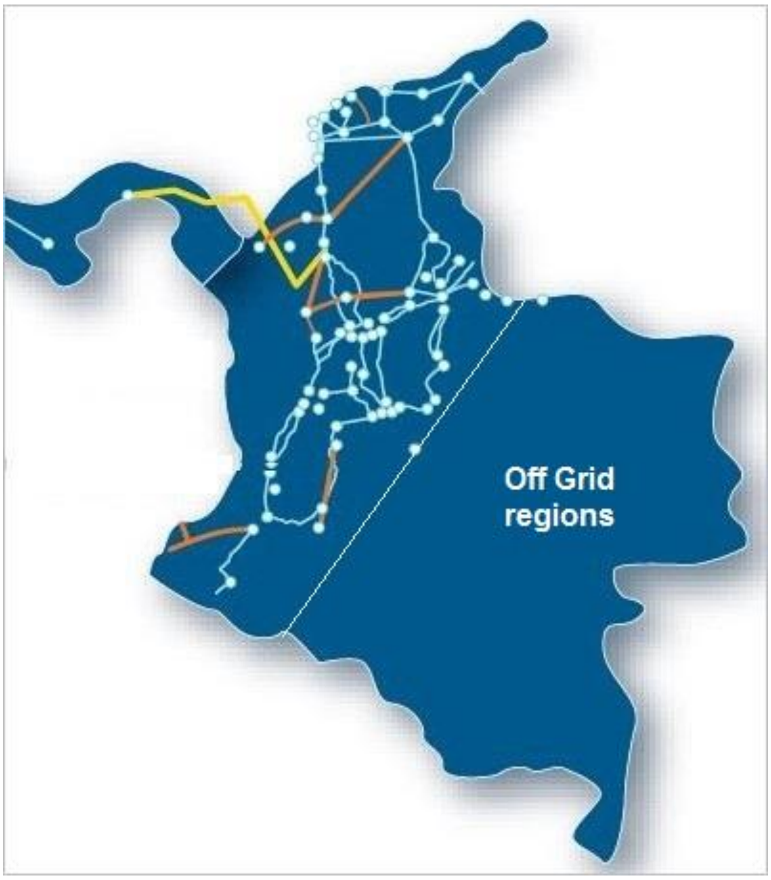


Figure 3 Scheme of the Colombian transmission system [28]

Moreover, the final methodology uses spatial information about the electric grid which is not publicly available yet, and is considered strategic for the DSO and so it remains private. Nevertheless, the law 030 2018, enforces the DSOs to make this information public by the end of this year. So far, the information available for the development of this thesis has been supplied by Celsia, from Valle del Cauca, a department in the southwest of Colombia (Figure 4) in which they have the monopoly of the distribution of electricity. The final methodology will be applied to this region, but can be extended to the rest of the country once the maps of the electric grid are publicly available.

Figure 4 Valle del Cauca, Colombia

2.3.1 Colombian energy context

Colombia is in the northern part of South America. It possesses numerous fossil fuel and natural resources. The country has productive petroleum reserves, extensive coal reserves (the largest in South America), significant but largely untapped natural gas reserves, and extensive hydroelectric resources. A large amount of potentially productive oil and natural gas areas remain unexplored. Demand for energy (petroleum, natural gas, and electricity) is expected to grow 3.5% per year through 2020 [29]. Table 1 shows a summary of the main indicators.

Table 1 Main energy indicators for Colombia [30]

Main Facts		**Energy indicators per cápita**	
Population (millions)	48	TPES[2]/Population (toe/capita)	0.71
GDP (billion 2010 USD)	349	TPES/GDP (toe/thousand 2010 USD)	0.1
GDP PPP (Billion 2010 USD)	597	TPES/GDP PPP (toe/thousand 2010 USD)	0.06
Energy production (Mtoe)	127	Electricity cons. / Population (MWh/capita)	1.29
Net exports (Mtoe)	88	CO_2/TPES (tCO_2/toe)	2.13
TPES (Mtoe)	34	CO_2/population (tCO_2/capita)	1.52
Electricity consumption (TWh)	62	Access to electricity (%)[31]	97
CO_2 emissions (Mt of CO_2)	73		

[2] Total Primary Energy Supply

As it can be seen from Table 1, Colombia is a privileged country in terms of resources, with high exports of different forms of energy. Nonetheless, it has low levels of energy consumption (0,71 toe vs 1,35 toe for Non-OECD countries average).

2.3.2 Electricity production

Unlike, primary energy production, electricity generation is mainly based on renewable resources; hydropower represents 70% of the 17,000 MW of the Net Effective Capacity, while the other 30% is based on fossil fuels (Figure 5). There is an important potential for wind (up to 1 kW/m^2 yearly average at a height of 50 meters [32]) and solar (up to 7 kWh/m^2/day [33]) but it has been hindered by the cost of hydropower, which historically had been cheaper. However, the recent drop in solar and wind costs, and the social resistance to new hydropower plants (due to its social and environmental impacts) create new opportunities for these technologies, and there are different developers working on this kind of projects.

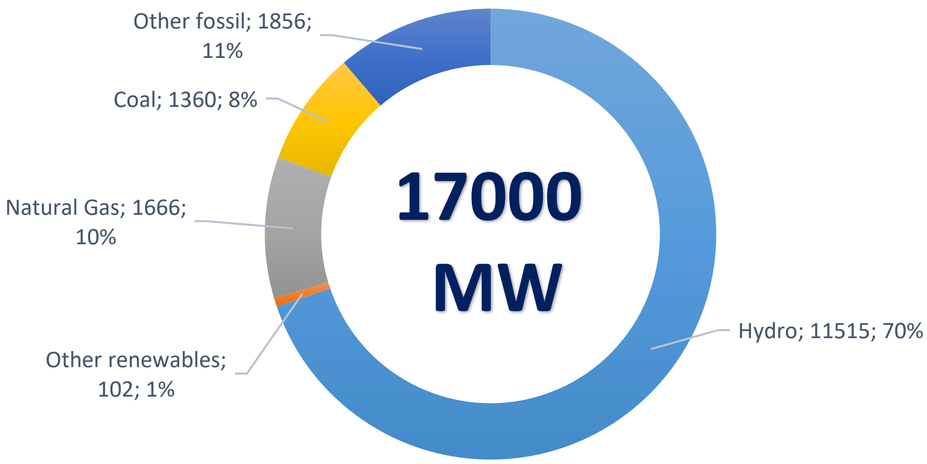


Figure 5 Installed capacity by resource. Self-elaboration based on [34]

The electricity generation is highly dependent on the weather. It is affected by local phenomena and by global climate oscillations as the ENSO (El Niño Southern Oscillation). As an example, under the El Niño phenomenon, rainfall in Colombia suffers an important decrease, and the contrary happens on La Niña phase. Lower rainfall leads to more thermal generation with expensive and polluting fuels, which at the end means high energy prices during these seasons. Figure 6 shows the historical generation by source, and the CO_2 emissions. It can be clearly identified that during La Niña most of the generation was from hydropower which led to low fossil generation and to a reduction in CO_2 emissions. As it was mentioned, prices are affected as well, an example of this is that the average price in the period 2011-2012 was 5,86 USD Cents/kWh, while in the period 2014-2015 was 13,11 USD Cents/kWh.

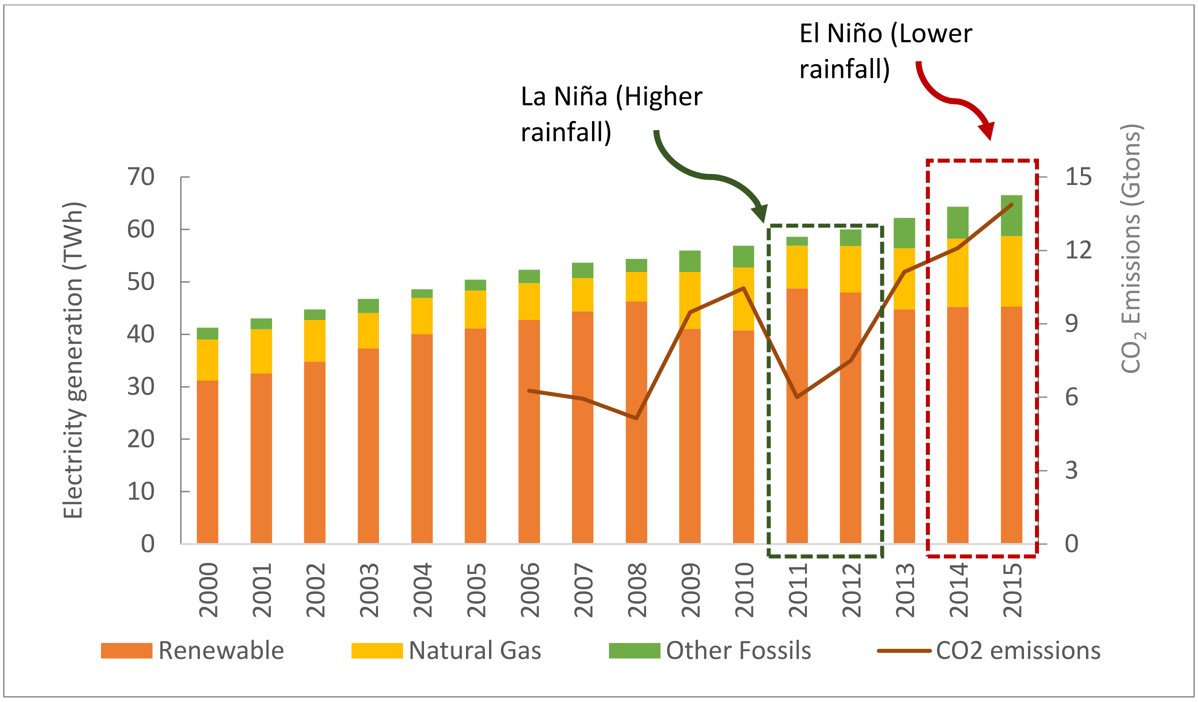


Figure 6 **Electricity generation by source. Self-elaboration based on** [34]

From this analysis it can be concluded that the electrical system of Colombia relies on hydropower, which is clean and cheap but at the same time this is highly vulnerable to weather. The backup system is based mainly on Natural Gas, which until this year had been produced internally. During one of the recent El Niño event (2014) a shortage in NG forced the country to build a liquefaction plant in the Caribbean to import LNG from Trinidad & Tobago and the Gulf of México (there are also plans to build another one in the pacific by the year 2020 to feed the interior of the country).

2.3.2.1 Conventional Renewables (Large hydropower plants)

Hydropower is already extensively used in Colombia and an estimated 56 GW of hydroelectric capacity is still to be developed [35]. According to statistics of Interconexion Electrica S.A (ISA), the country has a global hydroelectric potential of 93 GW (regardless of environmental restrictions) of which 9,185 MW (9.86%) is already installed in large hydropower plants and 533 MW (0.57%) in small plants (less than 20MW capacity). The energy expansion plan from 2011 to 2025 aims to increase the installed capacity by 7914 MW [36].

2.3.2.2 Non-conventional Renewables

The development of new technologies and fuel price uncertainty have motivated the search for an energy portfolio of minimum cost and risk, to improve the security and reduce CO_2 emissions. The

“Indicative Plan 2010-2015” established targets for unconventional renewable energies. The target for 2015 was an increase of renewable energies participation in the energy matrix. In Colombia, small hydroelectric (< 10 MW), wind, solar, biomass, geothermal and wave energy are considered unconventional renewable resources [35].

In 2010 there was around 9 MW peak (MWp) of solar photovoltaic capacity, belonging to private systems [35]. The development of photovoltaic systems in Colombia had been mainly focused on the rural sector off grid, where the high cost of generation due to fuel prices and the cost of maintenance and operation make solar seem more reliable and economic on the long term. Since 1979, PV has become essential for rural telecommunication. Celsia built in 2017 the first utility scale solar PV plant connected to the grid with 10 MW of installed capacity in Valle del Cauca (southwest), as of April 2018 is finishing the construction of another plant the same size in the north of the country, and has more than 200 MW in the pipeline to be built in 2018 – 2019. The UPME (Unidad de Planeación Minero Energética) has registered 352 solar PV projects of different sizes, ranging from a few kW to hundreds of MW, for a total of 3,773 MW, it does not mean that all of them will be built in the short term, but is clear indicator of the interest of the developers [37].

With an average speed of 9 m/s, the potential of wind power is estimated to be around 49.5 GW [35]. Although wind power is intermittent and usually more expensive to produce, in some areas of Colombia it is the most abundant resource. So far the installed capacity of the country (grid connected) is 20 MW, but the main utility companies and several developers are working on wind projects, and the UPME has 15 projects totaling a capacity of 2,269 Installed MW [37].

3 Description of the model

3.1 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).

The information presented in this section is taken from different national and international information services or directly from Celsia. The secondary information, calculated based on this, is presented in the following section.

3.1.1 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[3]. 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. It covers the land areas of Colombia including an approximately 10 km buffer zone. The data is available in the raster (grid) format that is suitable for use in Geographic Information Systems (GIS) for:

- Processing, analyzing and querying in the region
- Spatial analysis and expertise with other data sources
- Creating custom maps or applications.

The solar radiation data are derived by Solargis algorithms from original 30-minute time series of satellite images and auxiliary atmospheric datasets. Data layer is projected to Geographical coordinate system (EPSG:4326) and calculated in 30 arc-sec resolution (nominally 1 km).

Metadata are delivered in separate files according to ISO19139 standards in two formats:

- PDF - human readable
- XML - for machine-to-machine communication

A preview of the information is shown in Figure 7

[3] SolarGIS is a company which provides weather data and software for solar power investments

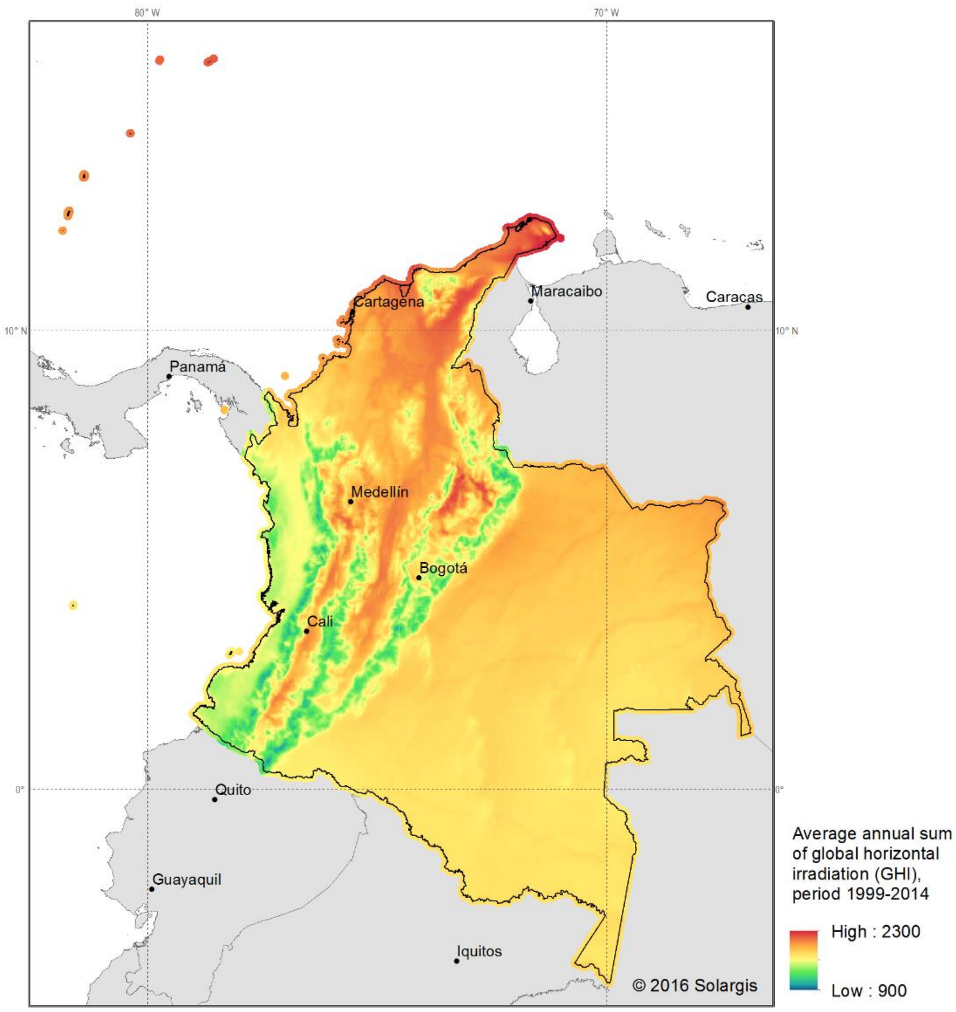


Figure 7 Solar resource in Colombia

3.1.2 Digital Elevation Model (DEM)

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was created by NASA and the Japanese aerospace exploration agency. "As part of this project emerged the ASTER Global Digital Elevation Model (GDEM) which boasted a global resolution of 90m" [38].

The ASTER GDEM is distributed as Geographic Tagged Image File Format (GeoTIFF) files with geographic coordinates (latitude, longitude). The data are referenced to the 1984 World Geodetic System (WGS84)/ 1996 Earth Gravitational Model (EGM96) geoid. To simplify calculations with the DEM it was projected to a local coordinate system (MAGNA Colombia Bogota).

The different tiles (grid files) for Colombia were downloaded from [26] and then merged in to a single raster by using the appropriate GIS tools.

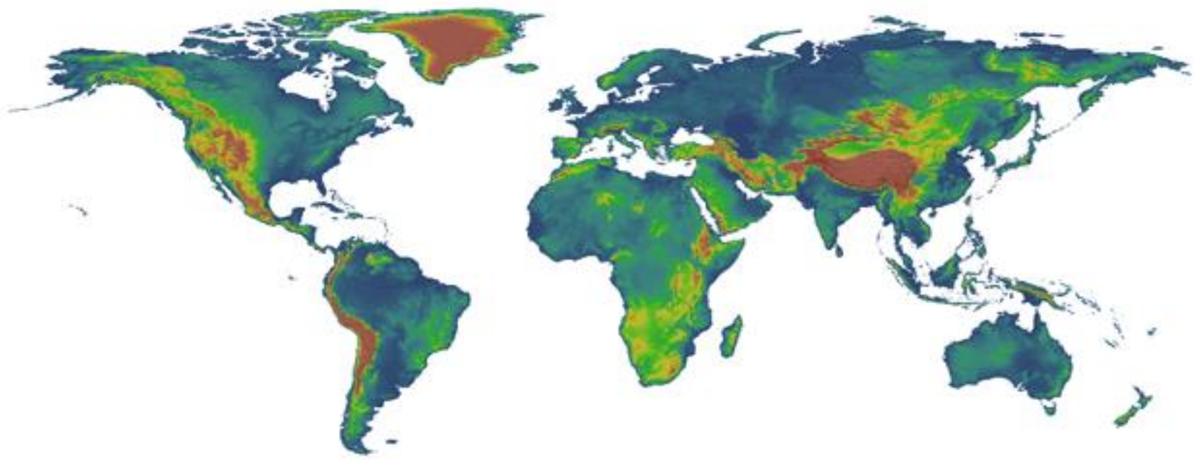


Figure 8 Digital Elevation Model 90m pixel [26]

3.1.3 Base cartography of Colombia

The Geographic Institute Agustín Codazzi (Spanish: Instituto Geográfico Agustín Codazzi, IGAC), is the entity of the Government of Colombia in charge of producing the official maps and basic cartography of the country. It distributes geographic data through its online portal, SIGOT [39]. The information obtained from this source was land cover, political map, roads, environmental and social restrictions.

With the online tool [40] is possible to download the cartographic information in vector format. A schematic view of the maps is presented in Figure 9 to Figure 13.

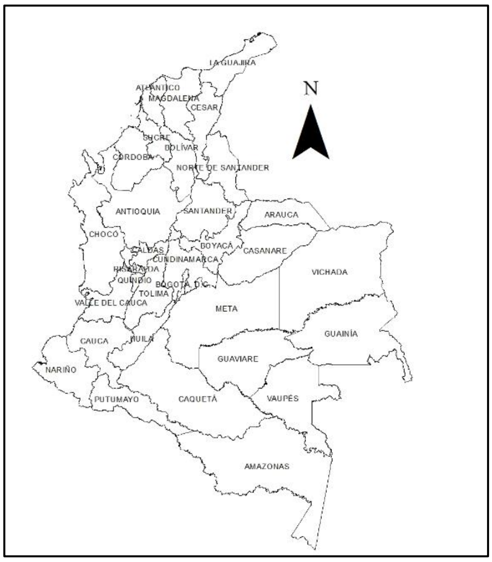


Figure 9 Political map (districts)

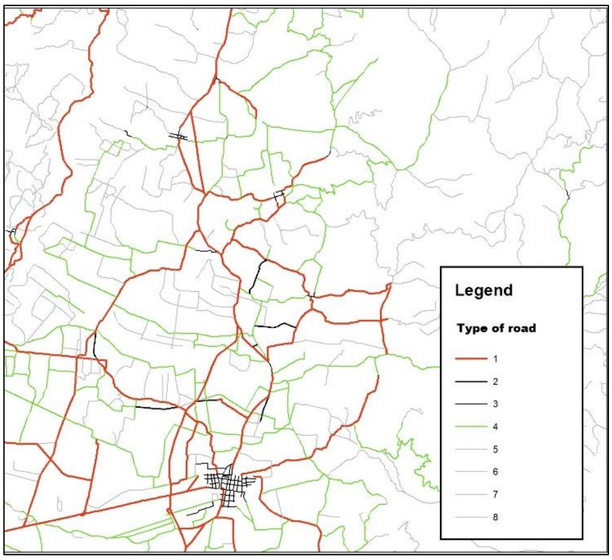


Figure 10 Roads

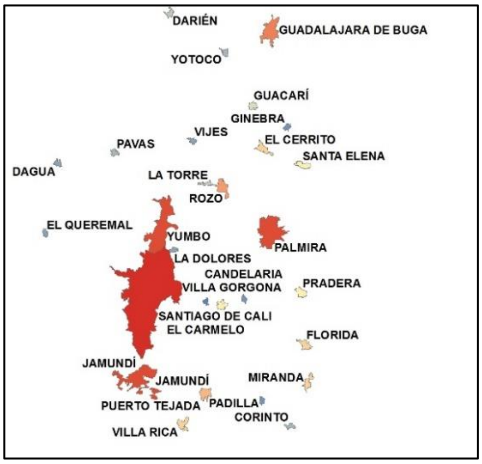


Figure 11 Centers of population

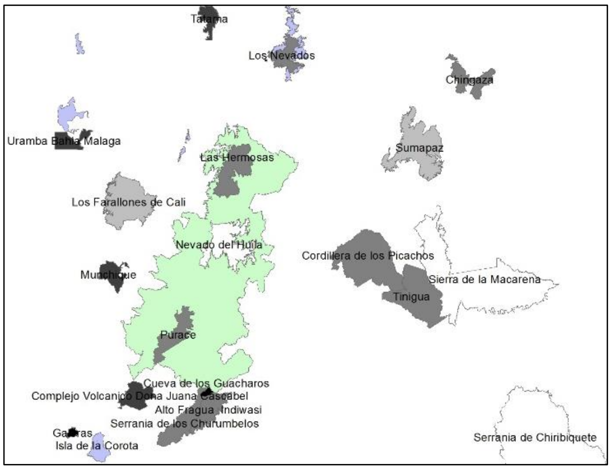


Figure 12 National protected areas

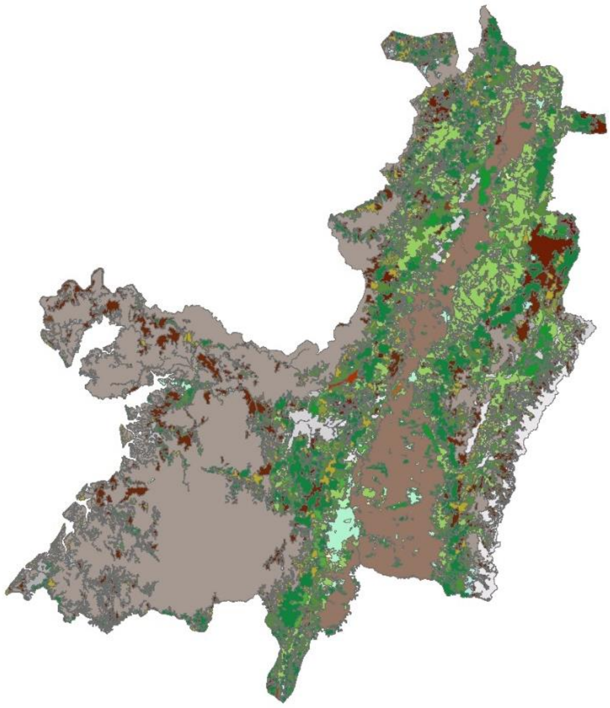


Figure 13 Land cover

3.1.4 Transmission lines, distribution lines and substations.

Celsia is the 4th utility company in the country by installed capacity, and 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 [41]. The detailed number of their distribution assets is shown in Table 2.

Table 2 Celsia transmission and distribution assets

T&D Infrastructure	Year 2017
Transmission Substations	16
km of transmission lines (>220 kV)	291
Distribution substation (115 Kv)	84
Distribution substation (34.5 - 13.2 kV)	52
km of distribution lines (<220 kV)	20473
Transformers in the distribution network	29343

They provided the KMZ[4] files with all the distribution lines in the different voltage levels (i.e. 13.2, 34.5 and 115 kV) and an excel list with the substations and its characteristics (including location), which was used to create the shapefile shown in Figure 14.

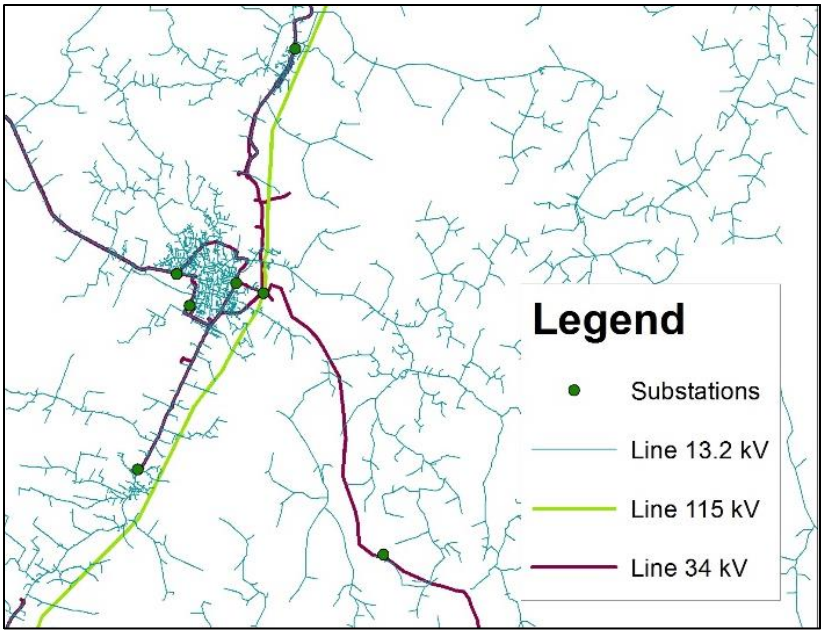


Figure 14 Transmission lines and substations

3.2 Secondary data

Starting from the primary data presented in section 3.1, 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.

- Average air temperature: Needed to calculate the capacity factor of the PV modules.
- Slope of the terrain: Pixels (terrains) with slope higher than certain value are not suitable for the installation of solar PV plants.
- PV capacity factor: Needed to calculate the electricity production of the modules (and hence the incomes of the project).
- Connection cost: Needed to calculate the total Capex (initial investment) necessary to set up the solar PV plant.

3.2.1 Calculating the 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 [42]) is a good way to estimate the

[4] KMZ is a file extension for a placemark file used by Google Earth. KMZ stands for Keyhole Markup Language Zipped. It is a compressed version of a KML (Keyhole Markup Language) file. KMZ files can contain placemarks featuring a custom name; the latitudinal and longitudinal coordinates for the location, and 3D model data.

long term average. Such method was applied to the different regions of the country (i.e. Amazonas, Caribe, Pacifico, Orinoquia, Andina, see Figure 15) based on the registers of average air temperature of 1002 weather stations spread along the national territory. The results are shown in the equations below:

Andean Region: $T_{average} = 29.42 - 0.0061 * H$

Atlantic region: $T_{average} = 27.72 - 0.0055 * H$

East region (Orinoquía y Amazonía): $T_{average} = 27.37 - 0.0057 * H$

Pacific region: $T_{average} = 27.37 - 0.0057 * H$

Figure 15 Geographic regions of Colombia

Following this methodology, a raster of temperatures for the whole country was built using the DEM and the equations shown before for each region. Temperatures range from 0°C in the high peaks above 5000 m.a.s.l. to 29 °C (yearly average) in the low lands, especially in the Caribbean region. The resolution and characteristics of this raster are the same as the DEM (geographic projection is MAGNA Colombia Bogota, with a pixel size of 90m), the result is shown in Figure 16.

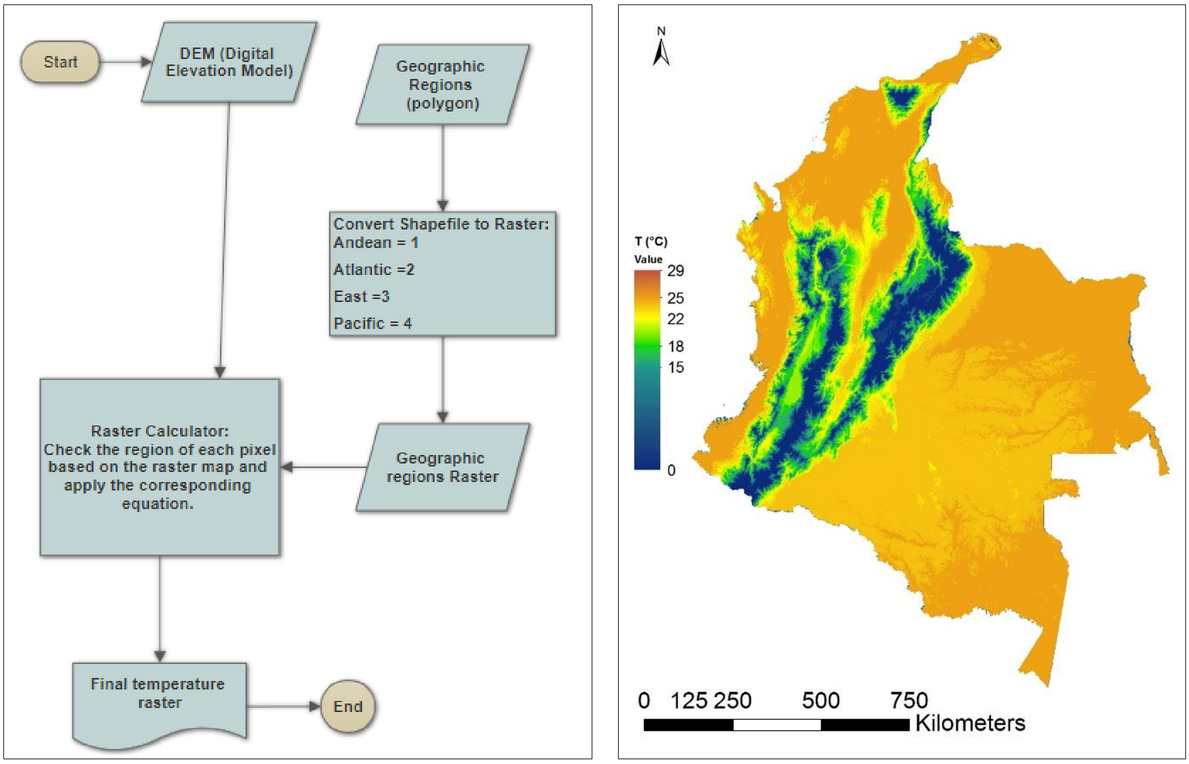


Figure 16 Process and final raster of air temperature (Cenicafé equations)

3.2.2 Calculating the 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 [43] 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. As explained in [44], for each cell, the Slope tool calculates the maximum rate of change in value from that cell to its neighbors. Basically, the maximum change in elevation over the distance between the cell and its eight neighbors identifies the steepest downhill descent from the cell. After this is done, with the Raster Calculator[5] all the pixels with a slope higher than 15° will be turned into 'No Data' values to exclude them from the subsequent analysis, the process is described in Figure 17 and the result are showed in Figure 18.

[5] The Raster Calculator tool allows to create and execute a Map Algebra expression that will output a raster[53].

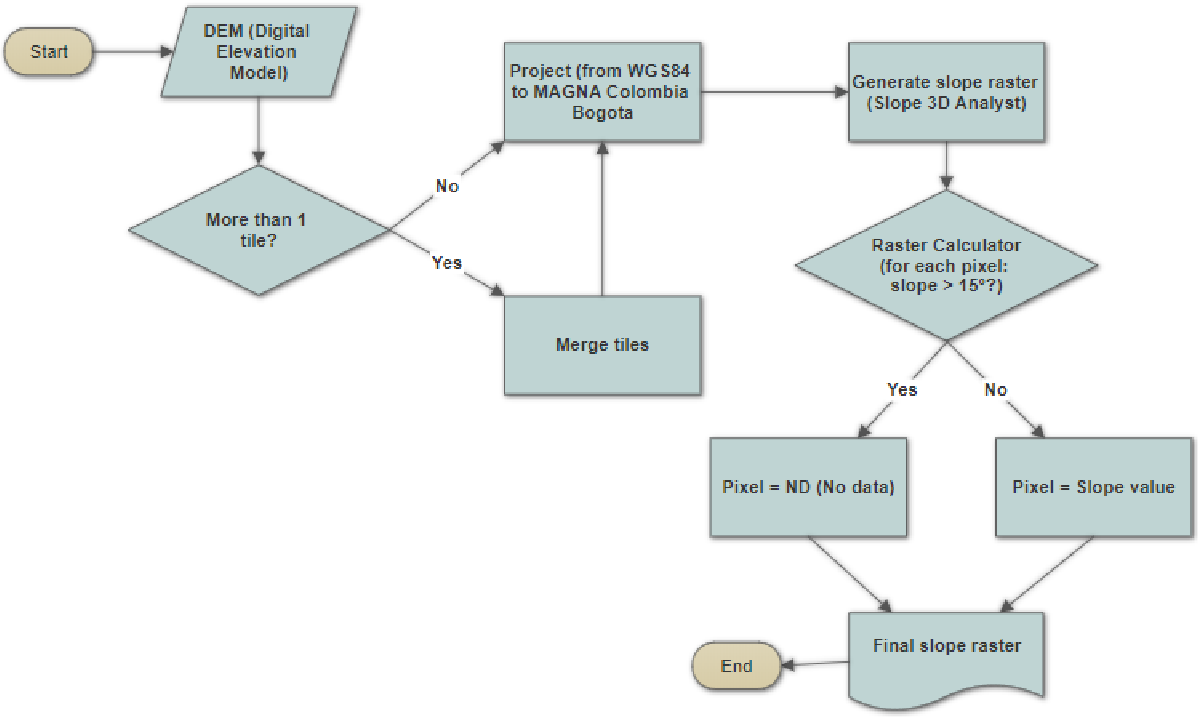


Figure 17 Process to generate the slope raster

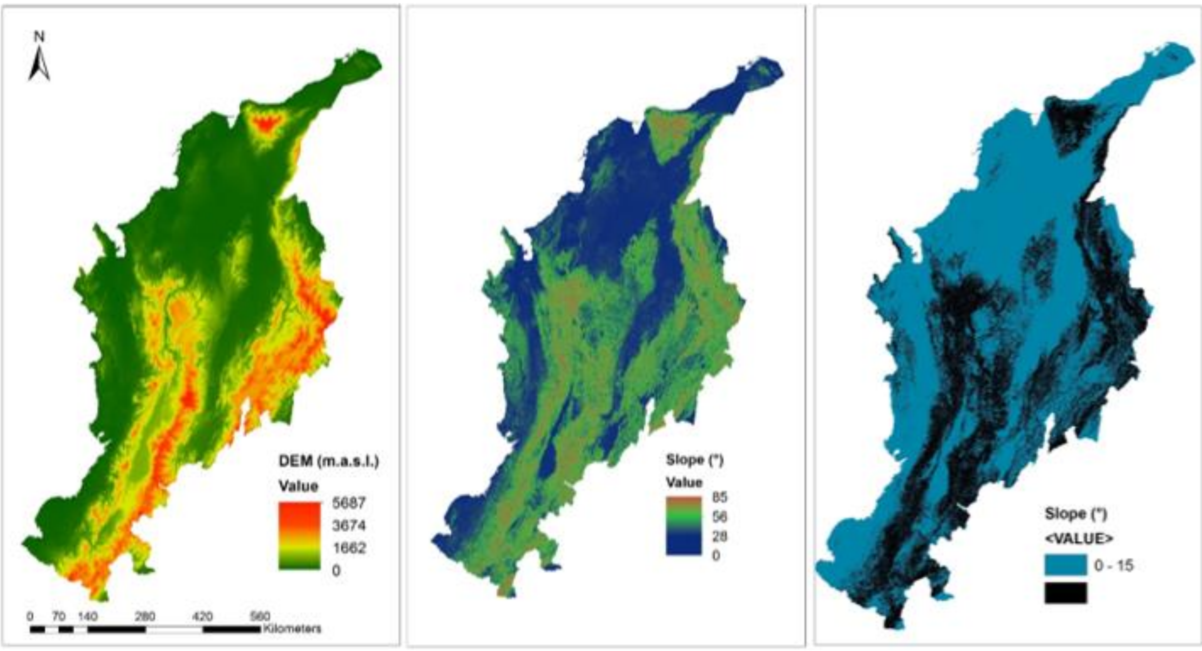


Figure 18 From elevation to slope (suitable land on blue, right map)

The result is in MAGNA Colombia Bogota projection, with a pixel size of 90m, same as the DEM from which it is generated. With this criterion 31% of the territory is discarded (black pixels in right map in Figure 18) and 69% is suitable land. As mentioned in section 2.3, for some of the variables the analysis is done excluding the southeast of the country which lacks electric infrastructure.

3.2.3 Solar energy production simulation

The calculation of the electricity production of the PV system starts with the Average Annual Global Horizontal Radiation presented in section 3.1.1. Since this information is an average annual value and the HDKR model works with hourly data, some assumptions were made and some equations used to downscale the data to hourly resolution: On the first hand, the simulation was performed for an average day; that means that the total daily radiation was calculated dividing the annual average by 365. As a second stage, to build the hourly radiation from the total daily value, the model presented by Collares-Pereira and Rabl (1979) and cited by [45] was used. According to the authors, when "hour-by-hour performance calculations for a system are to be done, it may be necessary to start with daily data and estimate hourly values from daily numbers. Statistical studies of the time distribution of total radiation on horizontal surfaces through the day using monthly average data for a number of stations have led to generalized charts of the ratio of hourly total to daily total radiation, as a function of day length and the hour in question":

$$r_t = \frac{\pi}{24}(a + b cos\omega) \cdot \frac{cos\omega - cos\omega_s}{sin\omega_s - \frac{\pi \cdot \omega_s}{180} \cdot cos\omega_s} \qquad (1)$$

The coefficients a and b are given by

$$a = 0.409 + 0.5016 \cdot sin(\omega_s - 60) \qquad (2)$$

$$b = 0.6609 - 0.4767 \cdot sin(\omega_s - 60) \qquad (3)$$

In these equations ω is the hour angle in degrees for the time in question (i.e., the midpoint of the hour for which the calculation is made) and ω_s is the sunset hour angle. Figure 19 shows an example of the result of applying the equations to a specific location in the study zone.

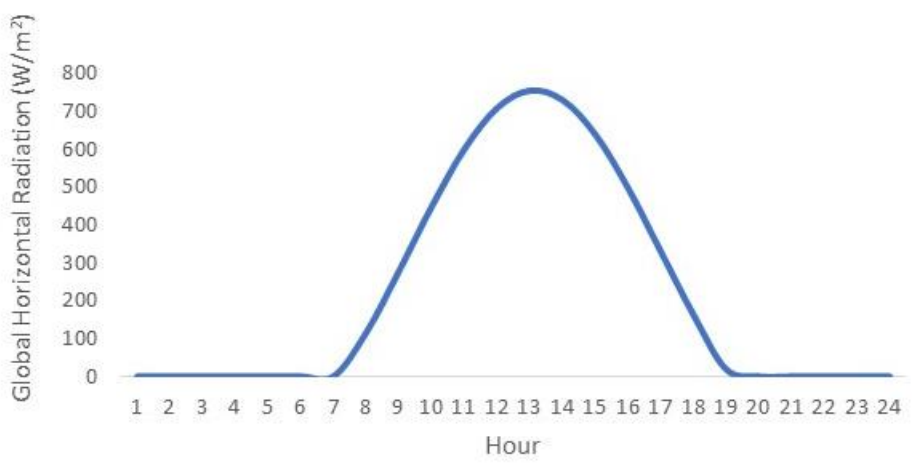


Figure 19 Hourly distribution of radiation based on [45]

3.2.3.1 Solar angles

The calculation for solar radiation takes into account geographic and astronomic parameters. Radiation is influenced by the latitude, longitude, inclination and orientation of the panel. Furthermore, relative position between Sun and Earth is considered: variations due to Earth rotation, revolution etc.

As reference for calculations, coordinates are considered positive in latitude due North, and positive in longitude due West. A scheme of the solar angle is available in Figure 20.

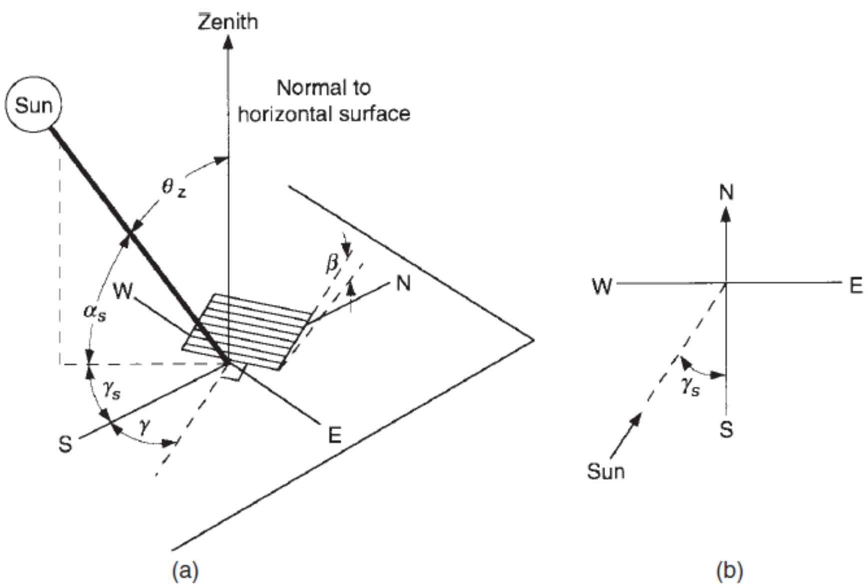


Figure 20 **Solar angles scheme** [28]

All the angles are expressed in radians.

3.2.3.1.1 Solar time

Solar time differs from local standard time (clock time). The equation to switch one into the other is:

$$t_s - t_{std}\ [min] = E + 4(L_{std} - L_{loc}) - 60\ DST \qquad (4)$$

Where L_{std} and L_{loc} are the standard and location longitudes, DST is the daily saving time, 0 or 1 according to the location and the period of the year (In Colombia there is no saving time, so this parameter will always be zero).

$$E = 2.292(0.0075 + 0.1868 \cos B - 3.2077 \sin B - 1.4615 \cos 2B - 4.089 \sin 2B) \qquad (5)$$

$$B = (n-1)\frac{360}{365} \qquad (6)$$

Where n is the day of the year according to the Gregorian Calendar.

3.2.3.1.2 Declination angle δ

It represents the angle between the earth orbit and the equatorial plane, and it can be calculated as:

$$\delta = 0.006918 - 0.399912\cos B + 0.070257\sin B - 0.006758\cos 2B + 0.000907\sin 2B - 0.002697\cos 3B + 0.00148\sin 3B \qquad (7)$$

3.2.3.1.3 Orientation angle γ

The orientation angle indicates the orientation of the tilted surface with respect to the South direction. In the considered case, γ=0.

3.2.3.1.4 Hour angle ω

The hour angle depends on the solar time and the equation is:

$$\omega = \frac{\pi}{12}(t_s - 12) \qquad (8)$$

3.2.3.1.5 Zenith angle θ_Z

The zenith angle is the angle between the vertical direction of the ground (zenith) and the position of the Sun. In other words, it represents the angular distance of the sun from the zenith.

$$\theta_Z = \arccos(cos\,\delta\, cos\,\omega\, cos\,\phi + sin\,\delta\, sin\,\phi) \qquad (9)$$

Where φ is the latitude in radians.

3.2.3.1.6 Solar azimuth angle γ_s

The solar azimuth angle represents the angle between the Sun and the South direction. It can be expressed as:

$$\gamma_s = sign(\omega)\left|\arccos\left(\frac{\cos\theta_Z \sin\phi - \sin\delta}{\sin\theta_Z \cos\phi}\right)\right| \qquad (10)$$

3.2.3.1.7 Incidence angle θ

The incidence angle is the angle between the direction normal to a tilted surface and the direction of the sun.

$$\theta = \arccos(sin\,\delta\, sin\,\phi\, cos\,\beta - sin\,\delta\, cos\,\phi\, sin\,\beta\, cos\,\gamma + cos\,\delta\, cos\,\phi\, cos\,\beta\, cos\,\omega + cos\,\delta\, sin\,\phi\, sin\,\beta\, cos\,\gamma\, cos\,\omega + cos\,\delta\, sin\,\beta\, sin\,\gamma\, sin\,\omega) \qquad (11)$$

3.2.3.2 HDKR model application

The radiation model applied is the HDKR model (Hay, Davies, Klucher, Reindl). It is an evolution with respect to the isotropic sky model, which is simpler but underestimates the diffuse radiation. The model was firstly developed by Hay and Davies (1980), estimating the fraction of the circumsolar diffuse radiation, and considering it as it is coming all from the beam direction. Reindl proposed to add a horizon-brightening term (1990) following the proposal of Klucher (1979).

$$\frac{I_T}{I} = \left[1 - \frac{I_d}{I}(1 - A_i)\right] R_b + \frac{I_d}{I}(1 - A_i)\left(\frac{1 + cos\beta}{2}\right)\left[1 + \sqrt{\frac{I_b}{I}} sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g\left(\frac{1 - \cos\beta}{2}\right) \qquad (12)$$

In particular, A_i is the anisotropy index, a function of the transmittance of beam radiation of the atmosphere. It determines the portion of the horizontal diffuse radiation that can be considered forward scattered, with the same incidence angle of beam radiation.

$$A_i = \frac{I_b}{I_0} \qquad (13)$$

When conditions are of clear sky, A_i is high and most of the diffuse radiation is forward scattered. In overcast conditions, when there is no beam radiation, A_i is zero and all the diffuse radiation is isotropic.

The same formula is used in this case considering irradiance values:

$$\frac{G_T}{G} = \left[1 - \frac{G_d}{G}(1 - A_i)\right] R_b + \frac{G_d}{G}(1 - A_i)\left(\frac{1 + cos\beta}{2}\right)\left[1 + \sqrt{\frac{I_b}{I}} sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g\left(\frac{1 - \cos\beta}{2}\right) \qquad (14)$$

The extraterrestrial irradiance on a surface normal to the beam can be estimated as:

$$G_{on} = 1367\,(1{,}00011 + 0{,}034221\cos B + 0{,}00128\sin B + 0{,}000719\cos 2B + 0{,}000077\sin 2B)$$

The result can be projected to obtain the extraterrestrial irradiance on a horizontal surface:

$$G_o = G_{on}\cos\theta_Z \qquad (15)$$

The ratio of beam radiation on a tilted surface to that of a horizontal surface is:

$$R_b = \frac{\cos\theta}{\cos\theta_Z} \qquad (16)$$

The clearness index can be calculated using the measurement of the global horizontal irradiance of the pyranometer, and the extraterrestrial irradiance on a horizontal surface:

$$k_T = \frac{G}{G_0} \qquad (17)$$

3.2.3.2.1 Beam and diffuse components of the irradiance

Once the clearness index has been calculated as presented above, the next step is to correlate Id/I, the fraction of the hourly radiation on a horizontal plane which is diffuse, with k_t, the hourly clearness index. This is made based on correlations presented in the literature, for example Figure 21 shows the diffuse irradiance vs the clearness index in Florida, US (Reindl, 1988).

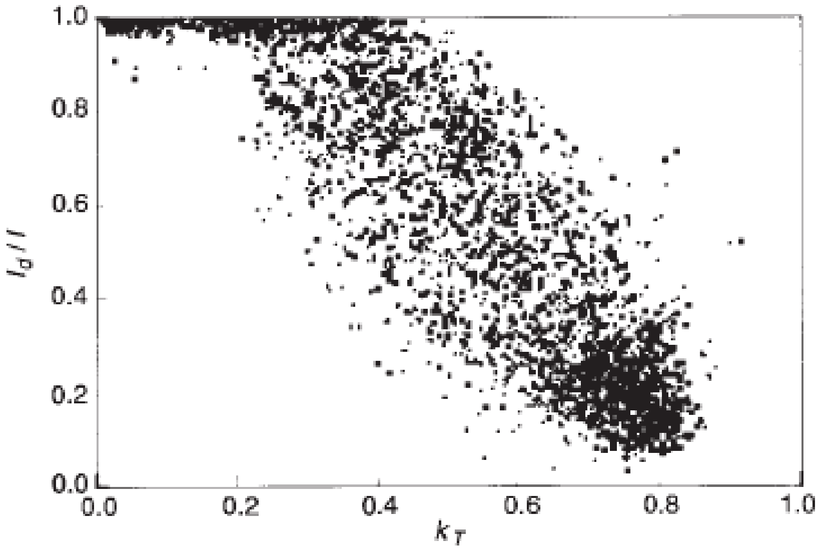


Figure 21 A sample of diffuse fraction versus clearness index data from Cape Canaveral, FL. Adapted from Reindl (1988) [28]

The equations used were the following:

$$\frac{G_d}{G} = \begin{cases} 1 - 0.09k_t \; for \; k_t \le 0.22 \\ 0.9511 - 01604k_t + 4.388{k_t}^2 - 16.638{k_t}^3 + 12.336{k_t}^4 \; for 0.22 < k_t \le 0.8 \\ 0.165 \; for \; k_t > 0.8 \end{cases} \quad (18)$$

3.2.3.3 Effects of the Angle of Incidence and of Dirt

The different components of the irradiance on the tilted surface must be corrected to consider additional losses, and to have a more precise estimation of the effective irradiance.

The diffuse irradiance on the tilted panel can be written as:

$$G_{T,d} = G_{T,d,iso} + G_{T,d,cs} \quad (19)$$

$$G_{T,d,iso} = G_d(1 - A_i)\left(\frac{1 + \cos\beta}{2}\right)\left[1 + \sqrt{\frac{I_b}{I}} sin^3\left(\frac{\beta}{2}\right)\right] \quad (20)$$

$$G_{T,d,cs} = G_d A_i R_b \quad (21)$$

The direct components of the radiation are the beam and the circumsolar diffuse, and they can be corrected by a factor that depends on the incidence angle and dirtiness:

$$F_{\tau,b}(\theta) = 1 - \frac{\exp\left(-\frac{\cos\theta}{a_r}\right) - \exp\left(-\frac{1}{a_r}\right)}{1 - \exp\left(-\frac{1}{a_r}\right)} \quad (22)$$

Where a_r depends on the dirtiness degree of the panel. The factor can be applied to correct the irradiance:

$$\frac{G_{b,eff}}{G_b} = \frac{\tau_{dirt}(0°)}{\tau_{clean}(0°)} F_{\tau,b}(\theta) = (G_{beam} + G_d A_i) R_b \frac{\tau_{dirt}(0°)}{\tau_{clean}(0°)} F_{\tau,b}(\theta) \quad (23)$$

Some recommendations are available to estimate the parameters of the equation:

Table 3 Parameters for the correction of the irradiance

Dirtiness degree	$\tau_{dirt}(0°)/\tau_{clean}(0°)$	a_r
Clean	1	0.17
Low	0.98	0.20
Medium	0.97	0.21
high	0.92	0.27

For the calculation, a medium dirtiness degree has been considered. The isotropic diffuse component of radiation can be corrected by a factor of $F_{\tau,d}(\theta) = 0.9$.

The final equation to estimate the corrected irradiance on the tilted surface is:

$$G_{T,corr} = (G_b + G_d A_i) R_b \cdot 0.97 \cdot F_{\tau,b}(\theta) + 0.9\, G_{T,d,iso} + \rho_g \left(\frac{1 - \cos\beta}{2}\right) \quad (24)$$

In this thesis it is assumed that the PV modules are installed in such a way that they maximize the annual electricity production, that means that they are oriented to the equator (south in this case that the locations are in the northern hemisphere) and tilted with a slope equal to the latitude. To summarize this section of the report, it can be said that the solar angle calculations and the HDKR model are used to calculate the Global Tilted Radiation in the optimum plane for the modules (which, as explained, is related with the latitude of each pixel in the raster).

3.2.3.4 Electricity production

From the Global Tilted Radiation and the specifications of the PV module, the electricity production can be estimated. For this sake the JKM330P [46] from Jinko was used[6], the technical specifications are shown in Table 4.

Table 4 Specifications of the PV module [46]

SPECIFICATIONS

Module Type	JKM310P		JKM315P		JKM320P		JKM325P		JKM330P	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	310Wp	230Wp	315Wp	233Wp	320Wp	237Wp	325Wp	241Wp	330Wp	245Wp
Maximum Power Voltage (Vmp)	37.0V	34.4V	37.2V	34.7V	37.4V	34.7V	37.6V	35.0V	37.8V	35.3V
Maximum Power Current (Imp)	8.38A	6.68A	8.48A	6.71A	8.56A	6.83A	8.66A	6.89A	8.74A	6.94A
Open-circuit Voltage (Voc)	45.9V	42.7V	46.2V	42.8V	46.4V	43.0V	46.7V	43.3V	46.9V	43.6V
Short-circuit Current (Isc)	8.96A	7.26A	9.01A	7.28A	9.05A	7.35A	9.10A	7.40A	9.14A	7.45A
Module Efficiency STC (%)	15.98%		16.23%		16.49%		16.75%		17.01%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	15A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.41%/℃									
Temperature coefficients of Voc	-0.31%/℃									
Temperature coefficients of Isc	0.06%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

The energy produced by a PV module depends on the temperature of the cells, which is a function of the radiation, the ambient temperature and the NOCT[7] (Normal Operating Cell Temperature), which is 45 °C for this module.

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20°C}{0.8}\right) * G \qquad (25)$$

$$Derate_{temp} = 1 - Temp_{coefficient_{P_{max}(T_{cell}-25)}} \qquad (26)$$

The $Temp\_coefficient\_P_{max}$ reflects how the efficiency of the module is affected by the temperature of the cell.

$$P_{AC} = G_t * \eta_{inv} * Derate_{temp} * \eta_{cell} * area \qquad (27)$$

[6] This is the module used by Celsia in their projects
[7] Is the expected cell temperature when the ambient is 20°, solar irradiance 0.8 kW/m^2 and wind speed is 1 m/s.

Where G_t is the global radiation in the tilted surface, η_{inv} the efficiency of the inverter (Euro - eta), η_{cell} the efficiency of the PV module.

The inverter used for the calculations is the PVS800-57-1000kW-C from ABB [47] with an efficiency of 98.6%. With the P_{AC} of the module the capacity factor can be calculated:

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

Where P_{AC} is the AC power produced by the module in each hour (since it has hourly resolution, power and energy have the same magnitude in kW and kWh), P_{Peak} is the peak power of the module and 8760 are the hours in one year.

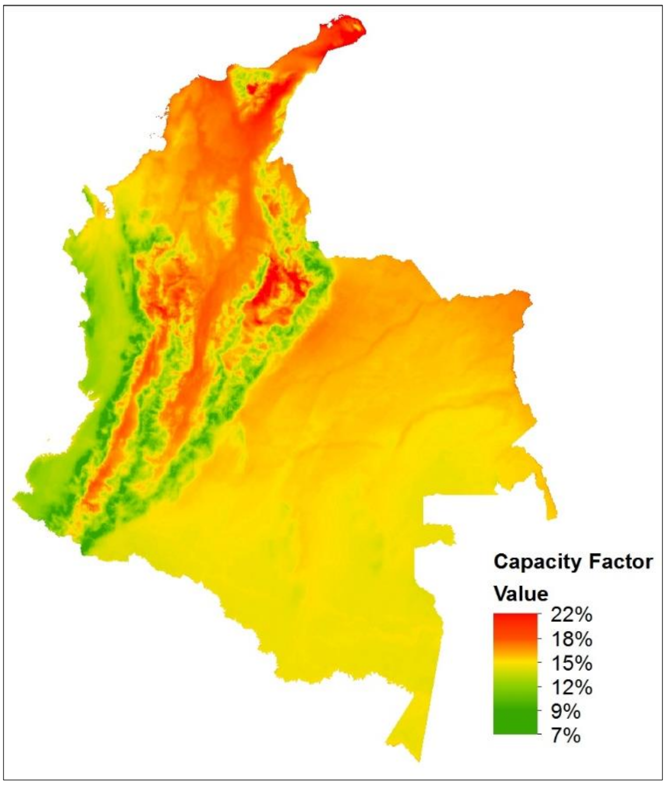


Figure 22 Capacity factor of a module PV.

3.2.4 Validation of the results

The electricity produced by the panel (represented in this case by the capacity factor) is the most important input in the financial model, since it defines the income of the project during its lifetime. Therefore a validation of the results is done to identify the accuracy of the map that was built following the steps described in section 3.2.1. This is done comparing the capacity factor obtained with the one obtained by the company from the PV Planner of SolarGIS (which is the way it is presently done).

The PV planner of SOLARGIS is a "tool to make reliable calculations of PV electricity potential without having to invest too much time or resources. It helps streamline the pre-feasibility process by providing access to reliable PV potential information. The software makes use of validated solar radiation data that has lower uncertainty compared to other satellite derived irradiation data sources" [48]. It is to be noted that the company pays more than 3 thousand euros per year for this online service.

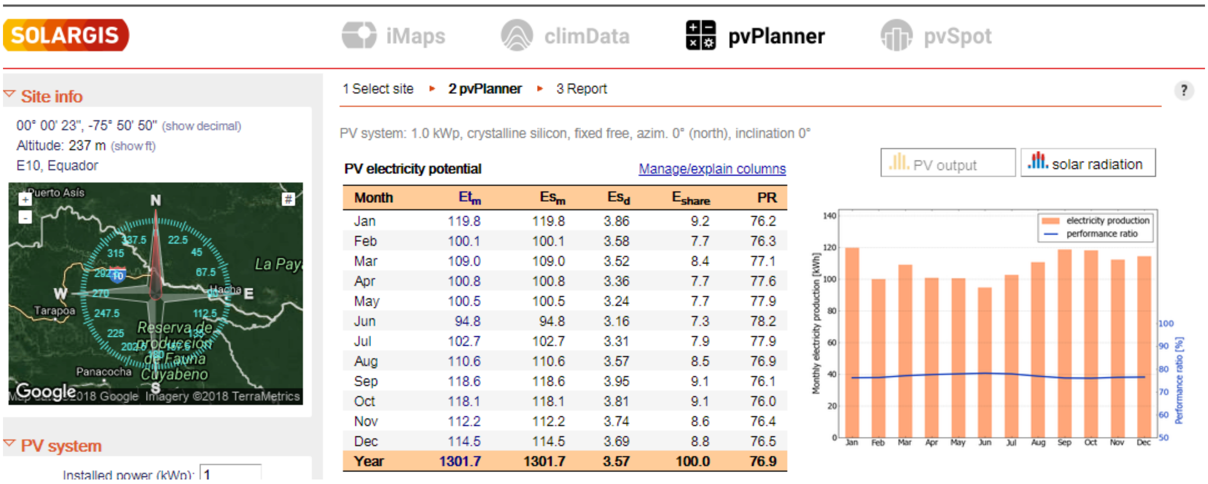


Figure 23 Screenshot of the PV Planner from SolarGIS

From the software the monthly and yearly electricity production for a certain installed capacity can be obtained. Using this information, the capacity factor is calculated.

Twenty points (locations) given by the company (Figure 24) were used to compare the error between the two tools:

$$Error(\%) = \left(\frac{CF_{ArcGIS} - CF_{PVplanner}}{CF_{PVplanner}} \right) * 100 \qquad (28)$$

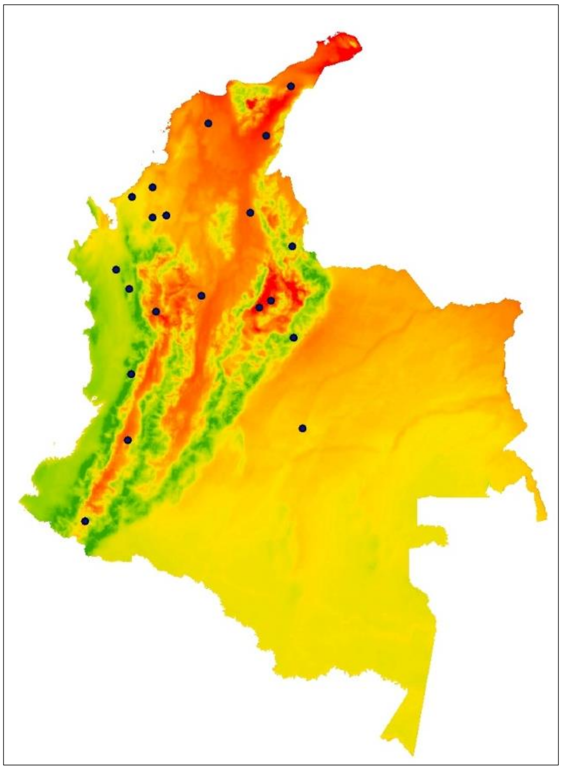


Figure 24 Points used for the validation with PV Planner of SolarGIS

Results are shown in Table 5, it can be seen that the validation points cover an important part of the territory, going from 1.2 to 11.2 degrees north in latitude and from -77.58 to – 72.48 degrees west in longitude. The results are quite satisfactory, with errors ranging from 0.3% to 6.9% (in absolute values) and an average error of 1.4%.

Table 5 Capacity factors and comparison with PV Planner of SOLARGIS

Latitud	Longitud	CF SOLARGIS (PV Planner)	CF ArcGIS	Error
6.12	-73.48	16.96%	16.82%	-0.8%
4.57	-76.42	10.20%	10.26%	0.6%
6.38	-74.80	17.51%	17.69%	1.0%
6.55	-76.47	14.80%	14.65%	-1.0%
6.27	-73.22	18.40%	18.52%	0.6%
6.01	-75.85	18.56%	18.00%	-3.0%
8.22	-75.61	16.26%	16.16%	-0.6%
7.52	-72.72	15.61%	15.47%	-0.9%
8.18	-75.93	16.02%	15.87%	-0.9%
6.99	-76.78	14.37%	14.26%	-0.8%
8.29	-73.68	17.59%	17.72%	0.7%
10.06	-73.32	18.71%	18.62%	-0.5%
11.20	-72.75	16.66%	17.81%	6.9%
10.35	-74.65	17.17%	17.72%	3.2%

Latitud	Longitud	CF SOLARGIS (PV Planner)	CF ArcGIS	Error
8.88	-75.93	16.28%	16.16%	-0.7%
3.32	-72.48	16.13%	16.08%	-0.3%
3.05	-76.50	17.99%	17.94%	-0.3%
5.41	-72.69	12.87%	12.78%	-0.7%
8.66	-76.41	15.84%	15.63%	-1.3%
1.20	-77.48	15.76%	15.11%	-4.1%

After validating the accuracy of the model, this tool turns into the first useful product of the thesis which can be used by everyone in the company, without access to the SolarGIS license, to calculate the capacity factor of a PV plant in any point of the country with high accuracy in just one click. Nevertheless, since not everyone has access to a GIS software, an MS Excel file is built (by exporting the geographic values to csv[8]) in which the user just enters the coordinates (Latitude and Longitude) of the point and the excel model returns the capacity factor and the slope of the terrain in that spot.

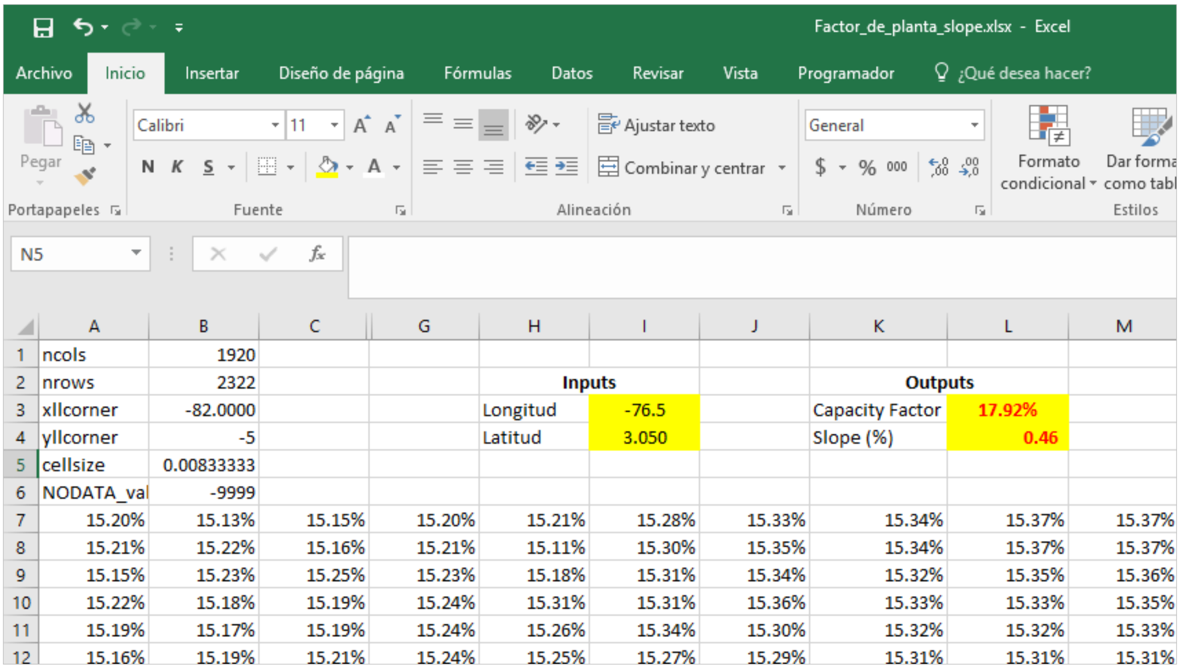


Figure 25 Screenshot of excel file to get solar PV capacity factor and slope of the terrain

3.2.5 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

[8] CSV, comma separated value

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, depending on the voltage of the line; 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. Both options are possible as far as the connection limits are respected and there is free capacity in the circuit. This last issue can be easily included into the analysis if the company generates a map with the idle capacity of all the lines and substations, even tough, since this information is not yet available, no restrictions are assumed.

Table 6 shows the unitary cost (USD/kWp) that the project should assume for connecting either to the line or to the substation. The maximum capacity (MW) that can be connected to each voltage level is also stated, this will be the parameter used to size each project in the financial analysis.

Table 6 Unitary cost of connection

Voltage (kV)	Max. connection capacity (MW)	Connection to substation		Connection to the line	
		USD/kWp	Total USD	USD/kWp	Total USD
13.2	10	23.5	$235,000	35	$350,000
34.5	20	37	$740,000	52	$1,040,000
115	80	94	$7,520,000	108	$8,640,000

On the other hand, Table 7 presents the unitary cost (USD/km) of the transmission line of the project

Table 7 Linear cost of the transmission line

Voltage level (kV)	USD/km	Cost/m
13.2	$ 80,000	$ 80
34.5	$ 100,000	$ 100
115	$ 200,000	$ 200

This means, that for example, a project with 20 MWp of installed capacity, located 8 km away from the closest point of the 34.5 kV line will need to invest in connection:

$$1'840,000\, USD = 20\, MW * \frac{1000\, kW}{1\, MW} * \frac{52\, Usd}{kW} + 8km * \frac{100,000\, USD}{km}$$

3.2.5.1 *Effect of land cover and land cover*

The unitary costs mentioned above are in ideal conditions, that means flat terrain and grass or similar land cover, however, Colombian territory is far from that conditions in most of the cases. The company suggested to include an extra cost equal to the slope of the terrain in degrees (e.g. if certain path of a connection line passes through a pixel with a slope of 11°, the cost of this pixel would be 11% higher than the one in flat land).

Additionally, the land cover should also be considered, is not the same to build a transmission line over grass than in tropical forest or crossing wetlands, rivers or cities. To do this, the map of land covers presented in section 3.1.3 was converted into raster format (Figure 26).

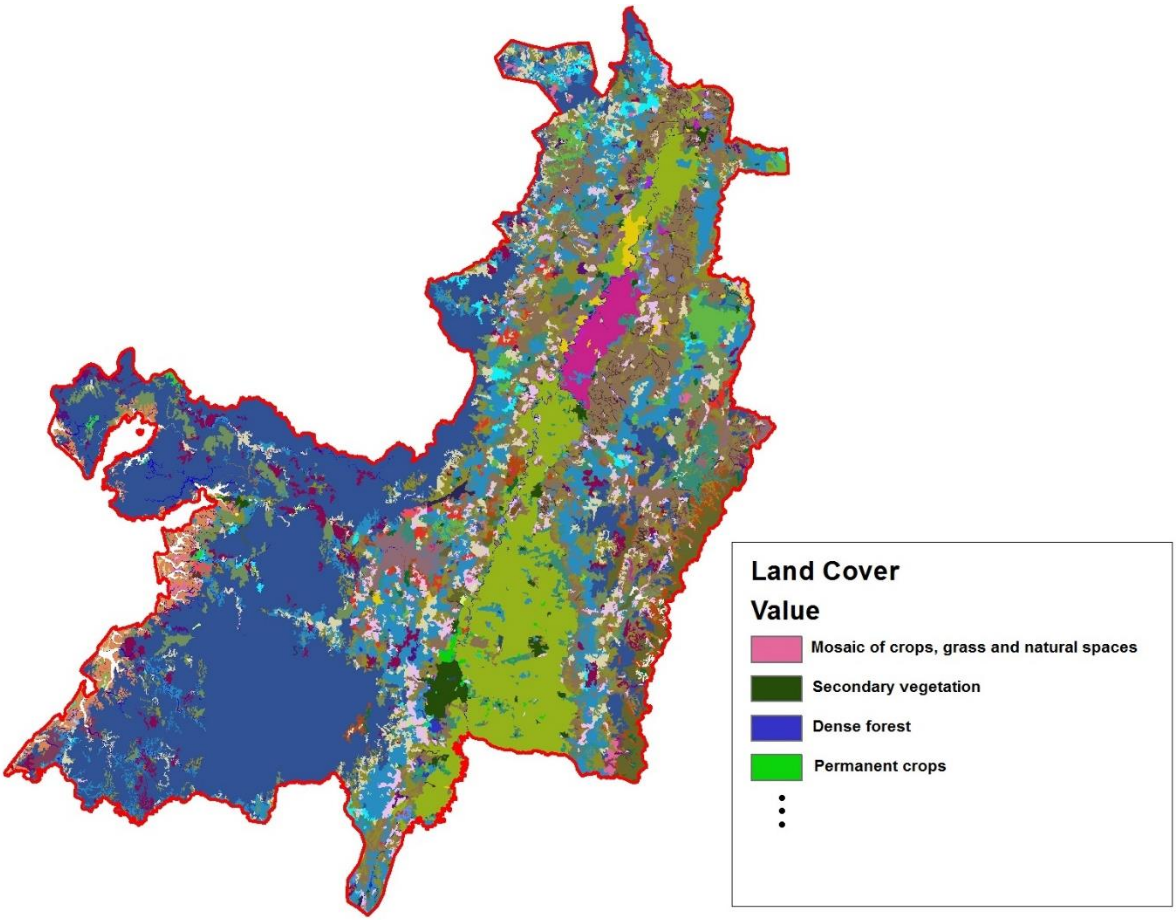


Figure 26 Land cover map

With the help of the company some factors were assigned to each type of cover, the most representative are shown in Table 8, this will prevent the algorithm from choosing the least cost path overlapping with urban or industrial regions where transmission lines cannot be physically set up or would be too expensive.

Table 8 Cost factor by land cover type

Land cover	Factor
Urban	5
Semi urban	2
Industrial and commercial	3
Ports	3
Crops	1.2
Grass	1
Forestry plantation	2
Natural forest	3
Rivers	3

With these factors (slope and land cover) a new map of costs for each pixel is built, Figure 27 shows the cost of passing by each pixel for a line of 34.5 kV. Have in mind that from Table 7 we have that the value by pixel in ideal conditions is 100 USD/m, it can be seen that this value can go up to 662 USD/m, especially in dense urban areas. The same map was made for 13.2 and 115 kV.

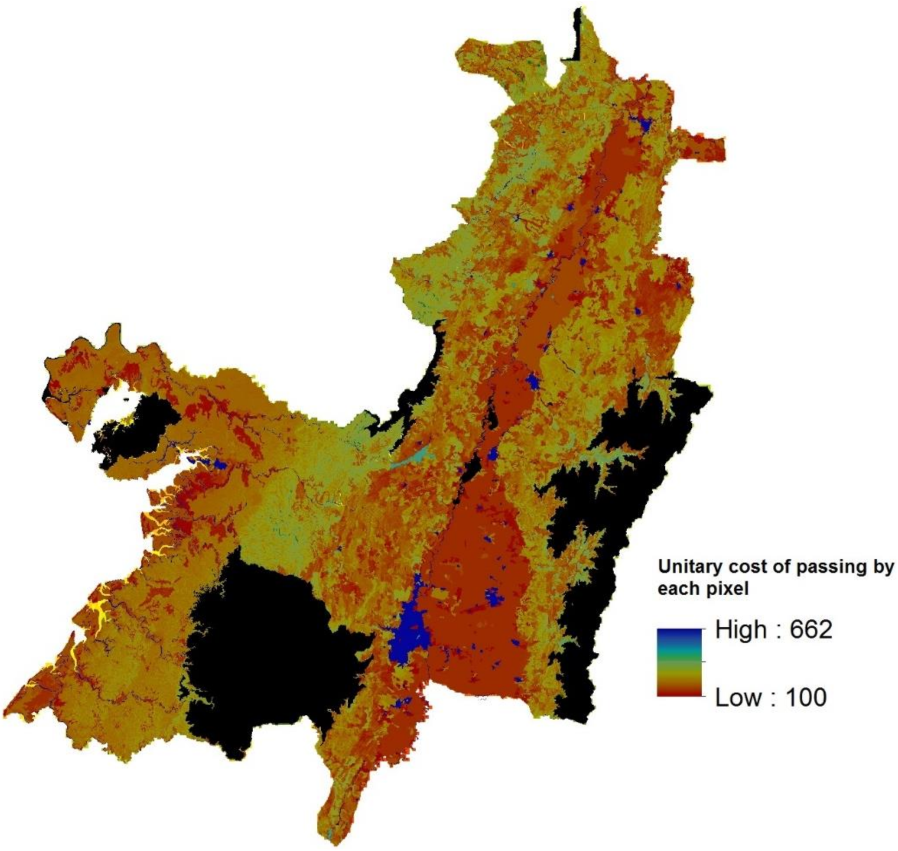
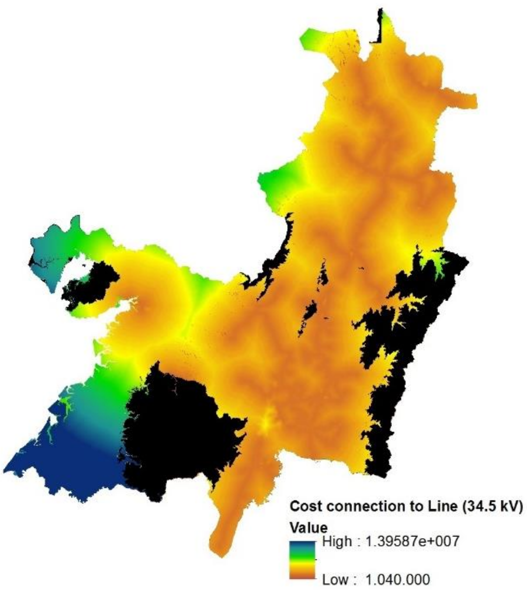


Figure 27 Unitary cost of the transmission line 34.5 kV (USD/m)

Finally, to get the final cost of connection, a powerful algorithm included in ArcGIS is used. It calculates the least accumulative cost distance for each cell to the nearest source over a cost surface. In other words, it finds for each pixel in the map, which is the cheapest way to connect to the electric line considering the slope and land cover of the chosen path. In Figure 28 the cost of connection to the line of 34.5 kV is shown. It means that each pixel has the value of the total cost of building a line from that point to the "closest[9]" point of the existing grid. Figure 29 shows the same but for the substations and finally, Figure 30 shows the minimum of the 2 previous maps, this is the value used in the financial simulations as the cost of the connection. Regions with environmental restrictions are shown in black, the algorithm is avoiding these pixels. This same procedure was done for the lines of 13.2 kV and 110 kV.

[9] In terms of cost not distance



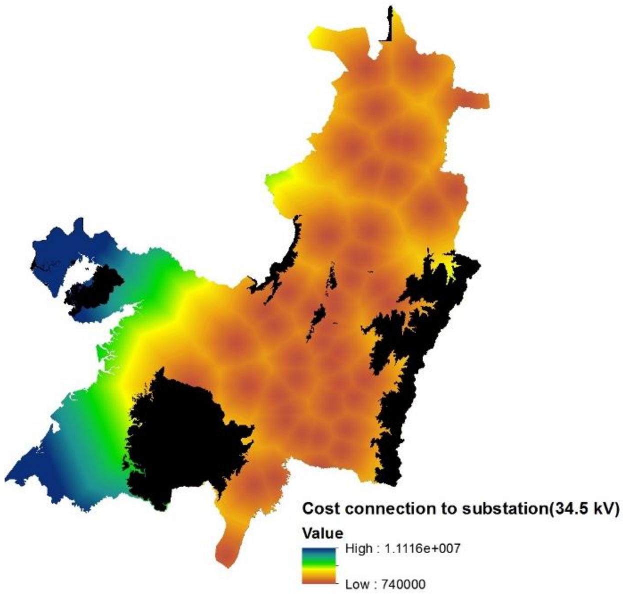


Figure 28 Cost of connection from each pixel to the line of 34.5 kV

Figure 29 Cost of connection to the 34.5 kV substations

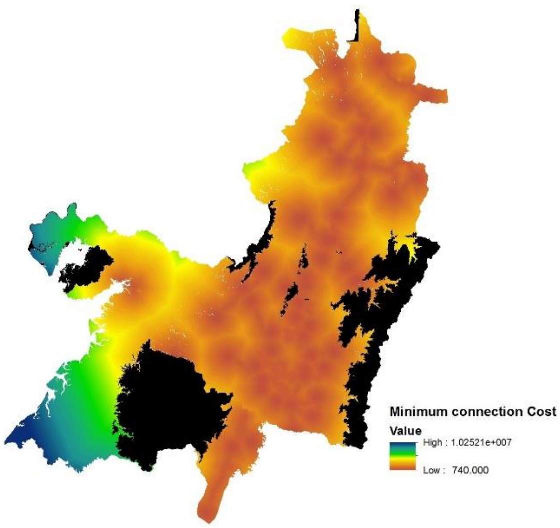


Figure 30 Minimum cost of connection to the 34.5 kV system (line or substation)

3.3 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 calculated in section 3.2.3.4 and the connection cost presented in section 3.2.5, considering the constraints defined by the slope of the terrain (3.2.2) and the environmental restrictions (3.1.3).

The whole analysis in this thesis is performed from the perspective of an investor (e.g. the utility company), which decides whether to invest or not based on the profitability of a portfolio including different options. In this case the options correspond to all the possible (technically and environmentally feasible) locations in which a solar photovoltaic plant can be set up. The profitability of each option (each pixel in the raster) is defined by the IRR of a solar farm installed there.

According to [49] the best way to assess a project is by using discounting methods in which the value of money in time is considered. One of the most used is the Discounted Cash Flow (DCF), which as per [50] is an analysis to identify the present value of an individual asset or portfolio of assets. This is equal to the discounted value of expected net future cash flows, with the discount reflecting the cost of waiting, risk and expected future inflation. This is the chosen methodology to assess the financial performance of the different alternatives.

3.3.1 Inputs for the model

The company facilitated a series with monthly price of electricity for 30 years (Figure 31), this series is generated by them based on simulations of a Stochastic Dual Dynamic Programing model, in which the whole electric system of the country can be simulated. It includes the evolution in the cost of fuels (natural gas, coal, diesel, etc.), and the evolution of the generation assets, shutdown of plants or new installations. The model gives as an output the minimum cost for running the system in each month. This is the standard way in which long term electricity prices are forecasted in Colombia.

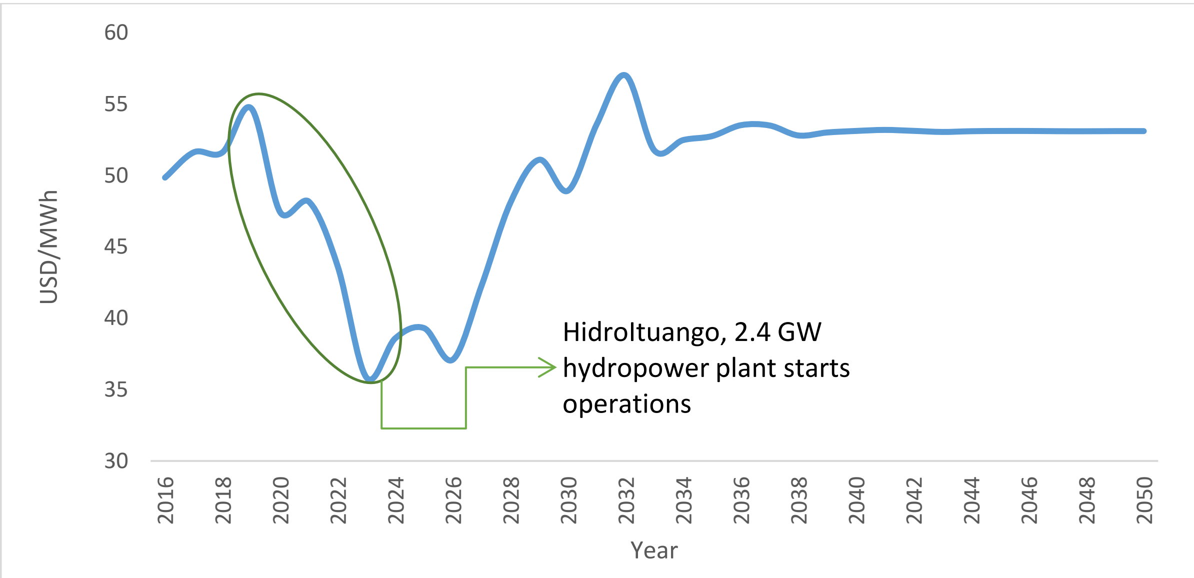


Figure 31 Electricity price in Colombia in the wholesale market (35 years)

There are several inputs for the financial model that should be accurately calculated if possible, or assumed based on reasonable hypothesis, according to the reality of the market and the company. Table 9 shows the operative values assumed in the assessment: The Capex of development is the money that the company must invest to bring the project to the stage “ready to build”, this includes environmental and social studies, connection assessment, etc. Commercial Operation Date (COD) is the date in which it will start operation, and the degradation[10] of the modules is split in 2 (2.5% for the first year, and 1% for the next years until the end of the lifetime) according to the experience of the company in their projects already in operation.

Table 9 Operative assumptions for the financial model

Variable	Value
Capex of development (USD/MW)	15,000
Capex of construction (USD/MW)	1,300
DC Installed capacity (Peak)	Depending on the connection[11]
Life time (years)	30
COD (comercial operation date)	jul-19
PV degradation of first year	2.5%
PV degradation year 2 on	0.7%

There are other financial assumptions presented in Table 10 which affect the assessment because they impact the working capital (as the accounts receivable, accounts payable and inventories), and the taxes (as depreciation, VAT, etc.).

It is important to mention that the analysis performed is considering the benefits of the law 1715 of May 13th 2014, from the Ministry of Mines and Energy which "encourages the integration of alternative energy in the Colombian Energy mix. This law aims to incentivize private capital investment in renewable energy integration. The law provides fiscal incentives, establishes a dedicated fund and creates the legal basis for development of renewable energy support initiatives, thus paving the way for further policy and regulatory action"[51]. The most important effect of this law is the tax exemption of 50% of the invested capex and the possibility of applying accelerated depreciation which is a method used for accounting purposes that allows greater deductions in the earlier years of the life of an asset [27], having a positive impact in the cashflows of the first years which are the ones that affect the most the IRR. The 1715 law also excludes from the payment of the VAT on the equipment used to generate clean electricity.

The exchange rate, used to convert the cost of the equipment and some regulatory costs which are defined in USD to Colombian Pesos, is taken from the consensus of Bloomberg.

[10] Reduction in the capacity of producing electricity
[11] See Table 6

Table 10 Financial assumptions

Variable	Value
Depreciation years (Accelerated, benefit law 1715)	5
VAT (benefit law 1750)	No VAT
50% discount of the investment from taxes	Yes
Cash and Banks (Days of costs)	15
Accounts Receivable (Days of income)	30
Accounts payable (Days of costs)	15
Inventories (% of Capex)	0.5%
Exchange rate (COP/USD)	Consensus Bloomberg 2016

3.3.2 Financial statements

The economic assessment was done by building the financial statements with the information presented above. It starts with the initial investment, goes through the incomes and operative costs, considers taxes and loans, and finally gets to the free cash flow of the project and the investor, which are the ones used to calculate the IRR.

The Profit and Loss financial statement (also referred to as Income statement) is developed in detail in the model, starting with the incomes of the plant, due to the sales in the spot market. The electricity production is taken from the map presented in section 3.2.3.4 (Figure 22) and the price is the one presented in Figure 31.

$$Incomes\ (COP) = Electricity\ produced\ (MWh) * Cost\ \left(\frac{USD}{MWh}\right) * exchange\ rate\ (\frac{COP}{USD})$$

The EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization) is calculated as follows, being the total cost the sum of all the costs and expenses presented in Table 11.

$$EBITDA = Total\ Incomes - Total\ Costs$$

Table 11 Costs assumptions

Cost	Value
Fixed regulatory costs (COP/MW)	3,054,000
Variable regulatory costs (COP/kWh)	5.33
FAZNI[12] (COP/kWh)	1.9
AGC[13] (% of the spot price of electricity)	2.40%
Cost O&M (USD/kW)	11

[12] Fund of support for Off grid zones.

[13] Automatic Generation Control

Cost	Value
Insurance Property risk (% CapEx)	0.40%
Insurance ALOP (% EBITDA)	0.60%
Land rent (COP / Ha /year)	5,000,000
Land needed (Ha)	MW of capacity DC x 1.2
Management fees (% de sales)	1.5%
Cost of transactions in the electricity market (% income)	0.56%

The net utility starts from the EBITDA and includes depreciation, interest payment, and rent taxes. The balance sheet is simulated as well to calculate the working capital. Finally, according to the indebtedness policy of the company, the project should keep at least a DSCR[14] (Debt Service Coverage Ratio) of 1.3, in that way in every project evaluated, the capital structure is optimized to maximize the amount of debt that the project can handle, while respecting the constraint.

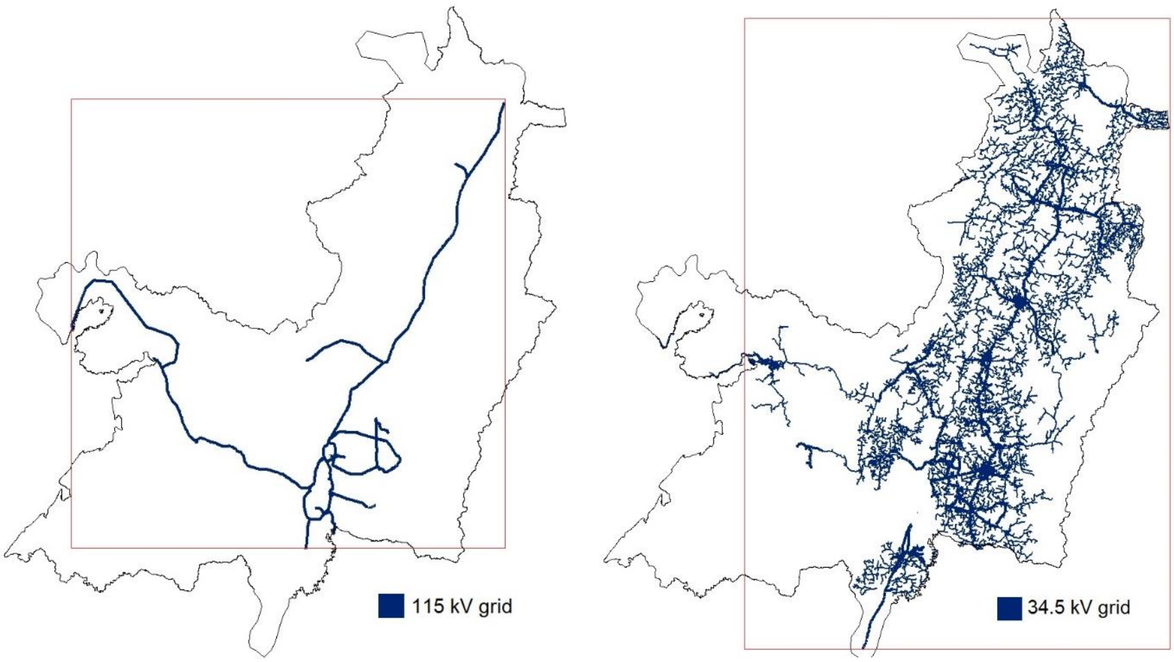
The cost of capital is calculated using the CAPM (Capital Asset Pricing Model) considering the risk of the country and the electric sector. The WACC (Weighted Average Cost of Capital) is calculated for every project according to the capital structure (% debt) and the cost of the debt, which in this case is 10.25%.

The reference to decide whether the project complies with the financial requirements of the company is if the IRR is higher than the WACC, that means that the NPV is positive and the project is creating value. As mentioned previously the WACC can slightly change in different projects because it is a function of the percentage of debt, which depends on the incomes (and finally on the solar radiation of the location). In any case it is very close to 15% and for simplicity it will be said that projects with IRR above 15% are interesting for Celsia.

[14] The DSCR is a measure of the cash flow available to pay current debt obligations

4 Results

The model is run in each pixel along the study region, for each simulation it considers the energy production as well as the cost of the connection and optimizes the capital structure (equity/debt) and calculates the IRR. This is done for the different voltage levels (13.2, 34.5 and 115 kV) producing one map of IRR per case. The initial area for each case is different because the financial model is not run in the whole district but in the minimum rectangle containing the electric grid and substations for that voltage level (as shown in Figure 32). This is done to save time in the simulation, considering that the IRR decreases rapidly out of the limits of this region.



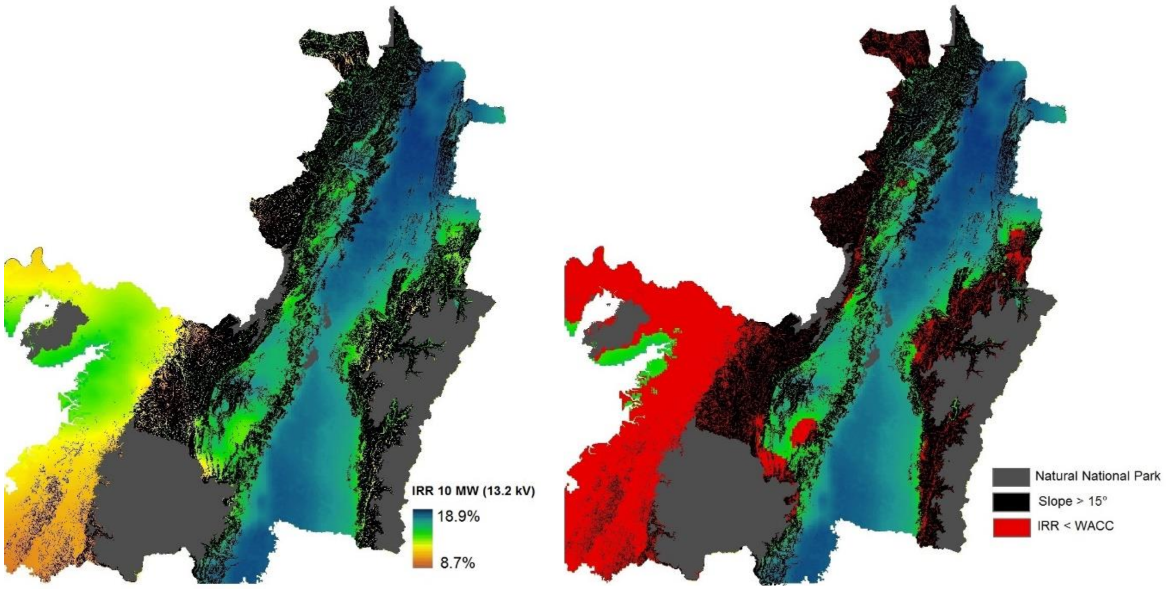
a) Region simulated for the 115 kV grid   b) Region simulated for the 13.2 kV grid

Figure 32 Example of minimum rectangle used for the simulation

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. In (b), all the 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.

4.1 10 MW plant connected at 13.2 kV

Figure 33 (a) 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 [52].



a) All technically feasible points

b) Feasible Technically and financial

Figure 33 IRR for a 10 MW PV project connected to the 13.2 kV system

The frequency histogram shown in Figure 34 is the statistical representation of the map of IRRs, it can be concluded, that even before applying any additional restriction, almost 50% of the territory can be discarded because of financial reasons (IRR < 15%).

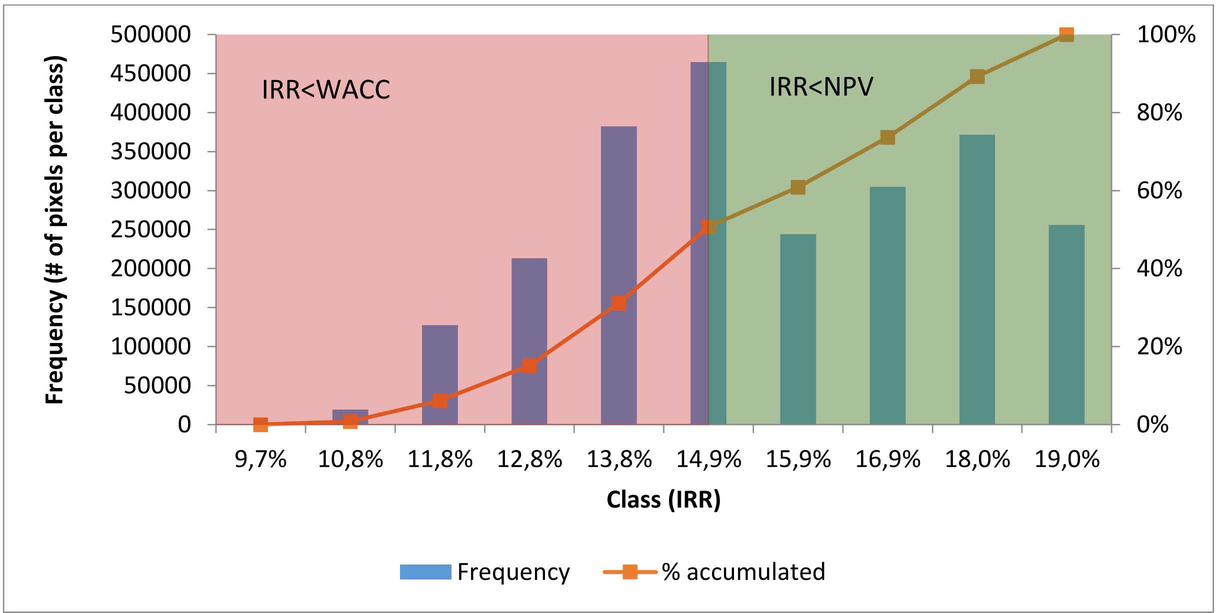


Figure 34 Frequency histogram of IRR (10 MW / 13.2 kV)

Putting together all the restrictions, the area can be narrowed to 6.774 km^2, this is 33% of the initial one (20.481 km^2). This process is shown in Figure 35.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.

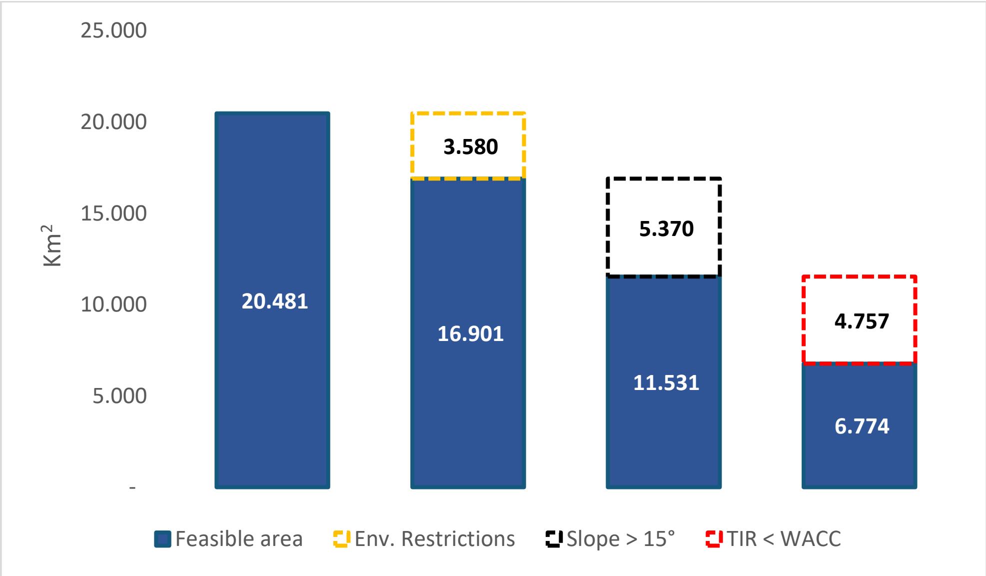
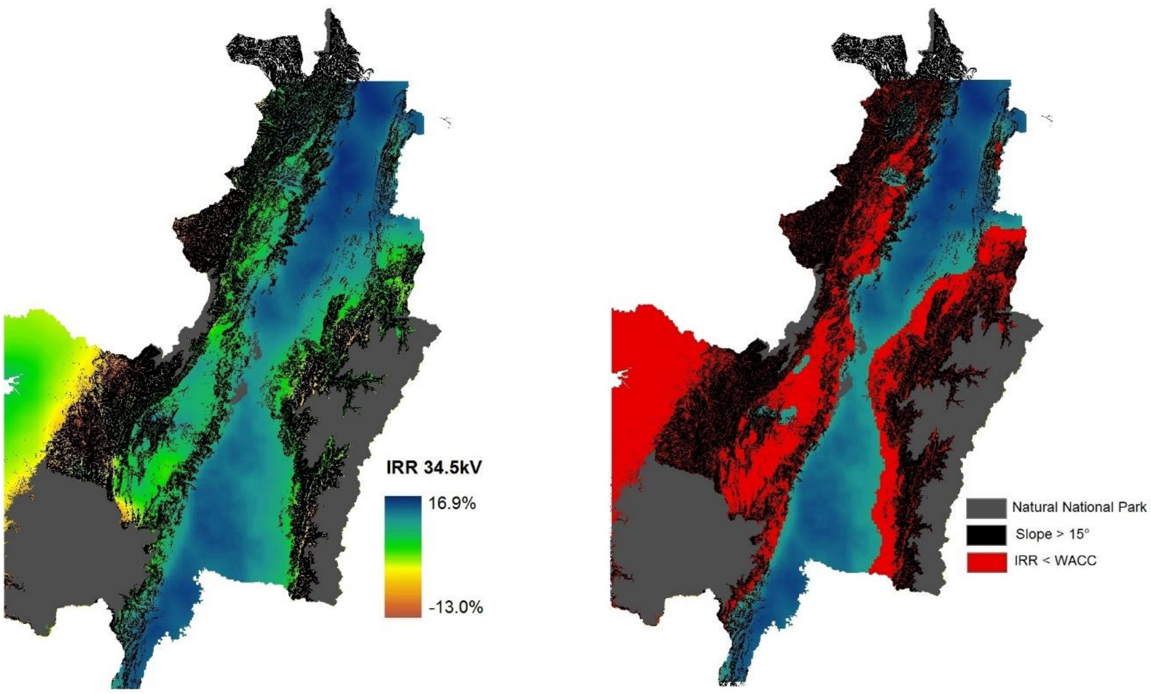


Figure 35 Process of narrowing the feasible area (10 MW / 13.2 kV)

4.2 20 MW plant connected at 34.5 kV

Figure 36 shows the result for a 20 MW solar PV plant connected to the grid at 34.5 kV of voltage. From the three levels of voltage 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 in (b)).



a) All technically feasible points b) Feasible technical and economical

Figure 36 IRR of a solar PV plant of 20 MW connected to a 34.5kV line.

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 km^2 to 4.471 km^2) as shown in Figure 37.

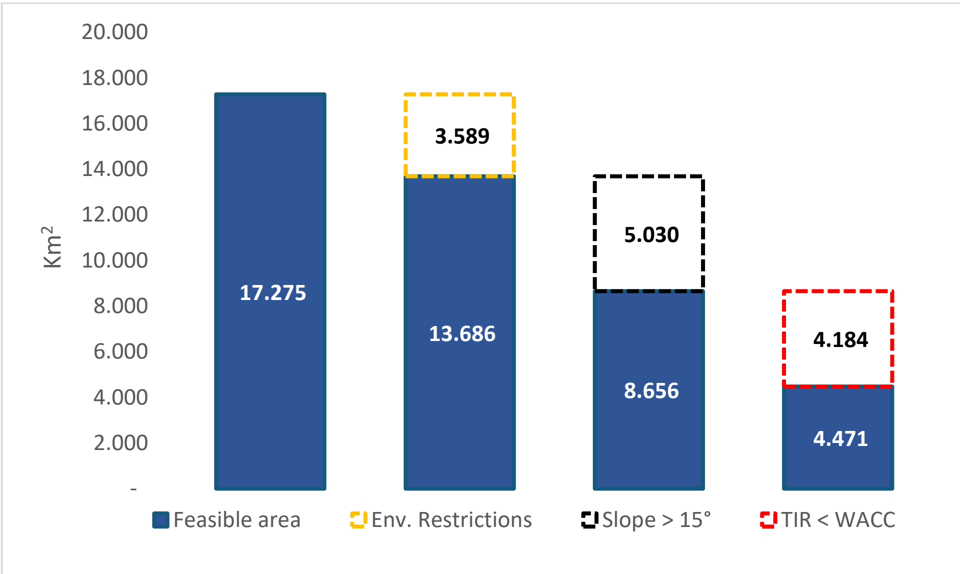
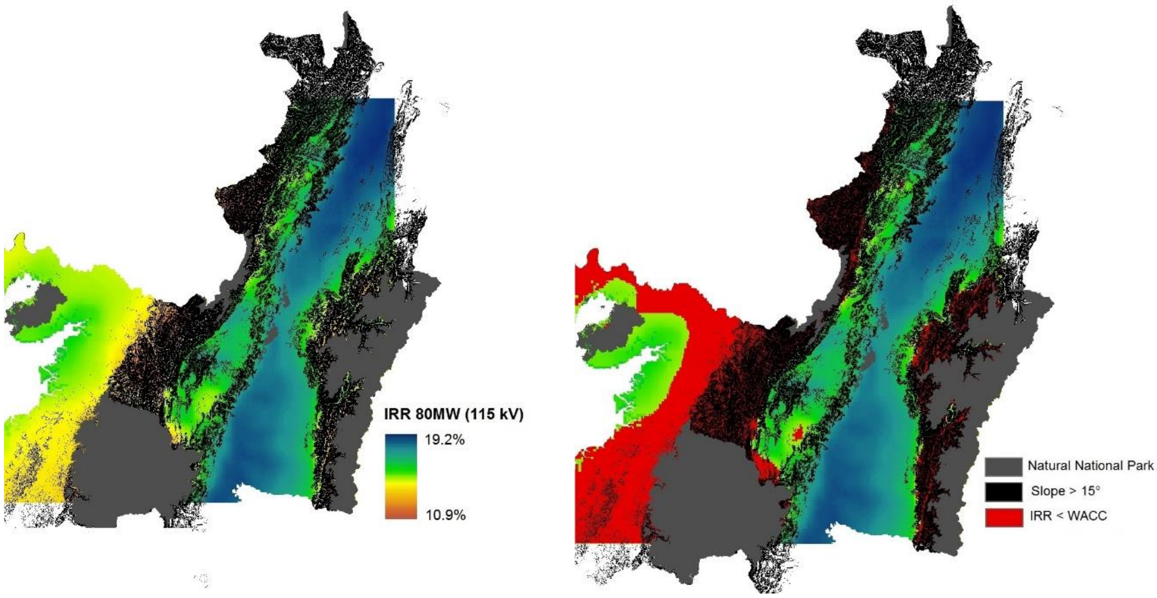


Figure 37 Process of narrowing the feasible area (20 MW / 34.5 kV)

4.3 80 MW plant connected at 115 kV

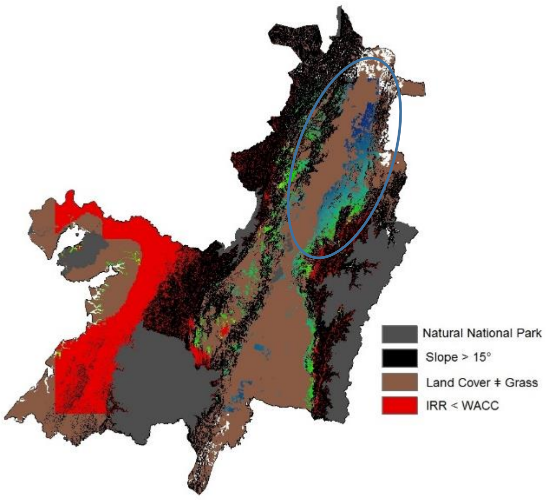
In Figure 38 it can be seen the same result for a project of 80 MW connected to the grid of 115 kV. Here the feasible area increases again due to the economy of scale, in which, despite the total connection cost being higher, it is split into 80 MW, making the unitary value lower. (USD/MW). The feasible area at this point is 6.689 km^2 out of the initial 17.046 km^2.



a) All technically feasible points b) Feasible technically and economical

Figure 38 IRR for an 80 MW PV project connected to the 115-kV system

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 in Figure 39 (a).



a) Feasible locations in pasture land cover

b) Percentile 90 IRR, in pasture land cover

Figure 39 Feasible locations in pasture and (b) percentile 90 of IRR

Figure 40 represents the process of reducing the area, from the initial 17.000 km^2, to the final 1.190 km^2. 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.

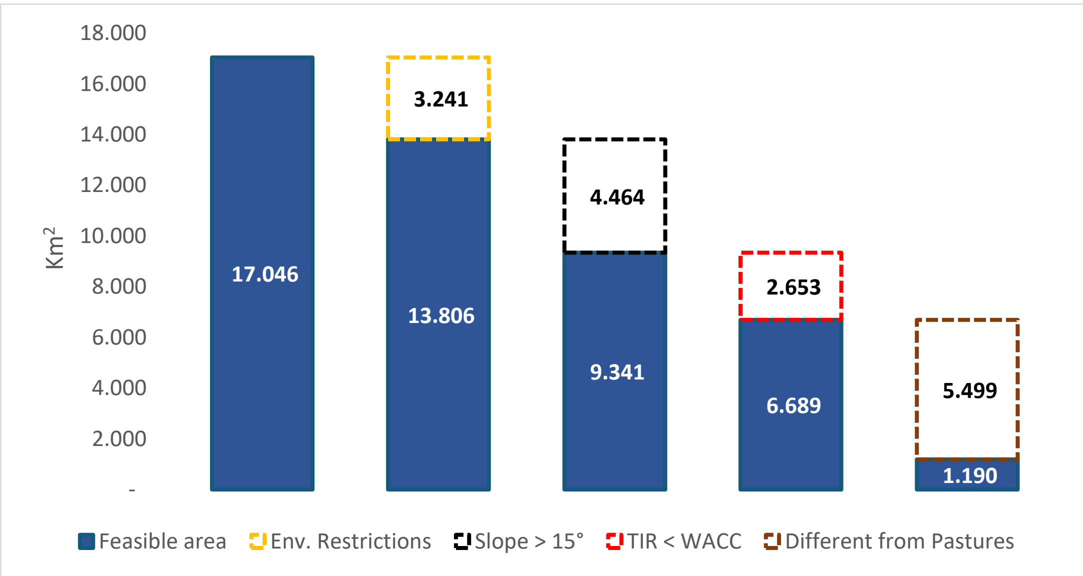


Figure 40 Reduction of the feasible area (80 MW/ 115 kV)

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 41 shows the polygons corresponding to the pixels selected before, they correspond to 121 Km^2 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.

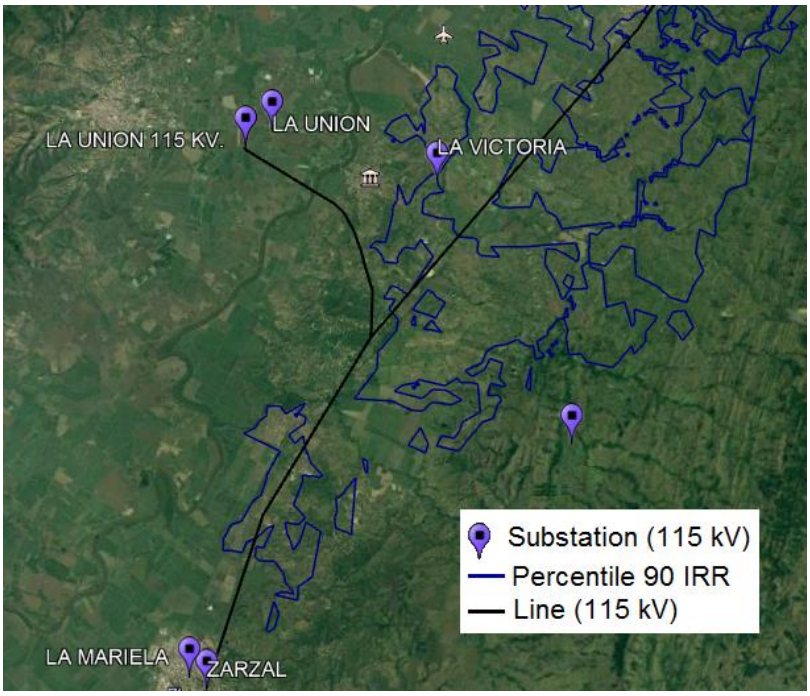


Figure 41 Polygons technically feasible, in grass land cover, with IRR in percentile 90.

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

As it was expressed in section 1.2, 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.

5 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.

5.1 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.

6 References

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