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Master Thesis

Geospatial assessment of the wind energy for an onshore project in the Caribbean region of Colombia.

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Geospatial assessment of the wind energy for an onshore project in the Caribbean region of Colombia.

This thesis was conducted between 10.02.2017 and 10.08.2017 and accounts for 30 ECTS of the “Master of Renewable Energy Systems” at the university of applied sciences “HAW Hamburg”.

Executive Summary

Colombia is setting a national renewable energy target providing a clear indication of the level of renewable energy development and the timeline envisioned by 2020 with almost the 7% of the energy production excluding large hydropower plants shall be generated from wind energy.

Wind potential of Colombia is outstanding. The Northern Caribbean region of the country alone has almost 20.000 MW of capacity (Huertas L., 2007). The real wind energy potential of all Colombia´s regions has to be defined yet. For this reason, this study is a useful start to generate research findings to uncover suitable sites for developing wind energy.

Additionally, the current energy access in Colombia and Latin America is described to illustrate the need for promoting the wind power penetration in the country and the continent. This thesis provides a more precise and differentiated assessment for an onshore wind energy farm in the Northern Caribbean region of Colombia selecting study areas of three Colombian’s departments (Atlantic, Magdalena and La Guajira).

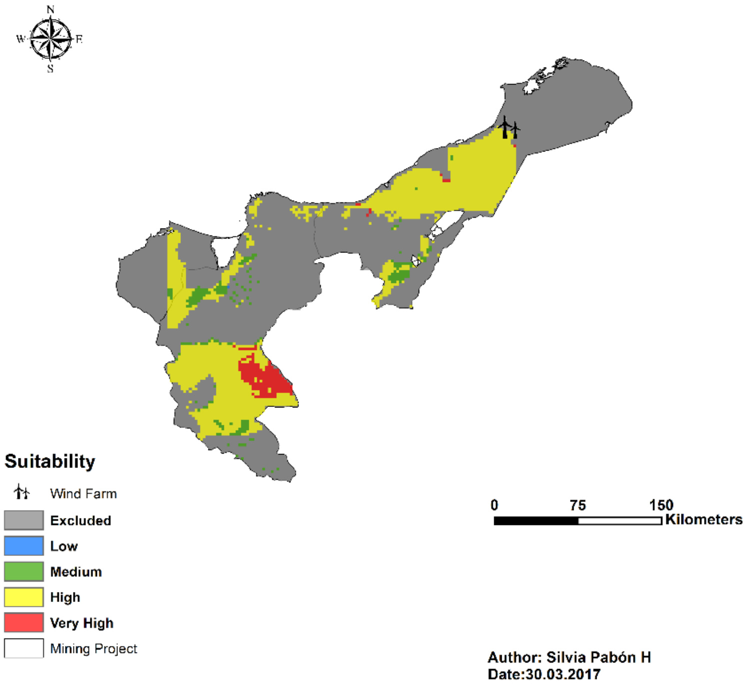
Wind energy potential assessment integrates socio-political, environmental and techno-economic criterion in a geographic information system (GIS) combining with a multi criteria decision making (MCDM) with its analytical hierarchy process approach.

The suitability model developed in this thesis generated a pre-assessment tool with a ready visual access to the onshore wind energy potential of the selected study area for investors, politicians, developers, researchers, students, and the public. It will be useful for a pre-assessment site selection of a utility-scale and largely distributed wind energy.

Likewise, the framework developed in this thesis successfully identified areas suitable for wind energy development based on a thorough set of seven criteria, including topography, wind power capacity, land use, proximity to the community, electricity grid access and natural reserve.

The figure “Executive Summary 1” below shows the wind energy suitability of the study areas. The majority of the areas with high suitability are located in La Guajira and the Magdalena departments.

Furthermore, with the result of the suitability model, the location of the “Jepirachi” wind farm in La Guajira department entirely overlaps with the areas identified as suitable which confirms the robustness of the results obtained.



Executive summary 1 Wind energy suitability of the study area, author´s map.

Altogether, 3.1% of the total study area is characterized as very high suitability (value score 5), 37.73% by high suitability (value score 4), 2% medium suitability, (value score 3), low suitability (value score 2), and 55.24% of the study area is excluded (value score 0).

Based on these findings, sufficient space is available for developing a wind farm in the Caribbean region of Colombia. The findings obtained from this study contributes to increasing the wind energy potential research in Colombia from the current low status.

The suitability model can be considered as a comprehensive pre-assessment wind energy tool, reducing the duration of assessment phase significantly from one or two years to 3 months when all the necessary data and criteria are available.

Furthermore, this research can have an extraordinary impact on the public through the production of interactive web-based maps, promoting wind energy planners and students of renewable energies to develop wind farms with different constraint and criteria, in a visualised manner recognising how a criterion can affect the assessment of a wind project.

Additionally, the publication of interactive web-based map in different interfaces such as through the ArcGIS Online interface can generate a free access to the wind suitability of the region, supporting the process of urban and regional planning of the departments.

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"Las máquinas no se rinden"

Statement

I hereby confirm that I am the author of the Master Thesis presented. I have written the Master Thesis as applied for previously unassisted by others, using only the sources and references stated in the text.

Hamburg, 29. July 2017

(Place, Date)

(Signature, Silvia Pabón Hernández)

Acronyms, Abbreviations and Units

AHP	Analytical Hierarchy Process
AWEA	American Wind Energy Association
COP	Colombia Currency (Pesos)
DANE	National Administrative Department for Statistics
DEM	Digital Elevation Model
EPM	Medellin Public Company (Empresas Públicas de Medellin)
EWEA	European Wind Energy Association
FENOGE	Fund for Non-Conventional Energies
GIS	Geographic Information System
GWEC	Global Wind Energy Council
IEA	International Renewable Energy Agency
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies
IGAC	Geographic Institute Agustin Codazzi
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
MCDM	Multi Criteria Decision Making
NPV	Net Present Value
NPVC	Net Present Value of Cost
O&M	Operation and Maintenance
REN21	Renewable Energy Policy Network for 21st Century
RES	Renewable Energy Siting
SIAC	Environmental Information System for Colombia
SPB	Simple Pay Back
USD	United States Dollars
UPME	National Commission of Mining and Energy Planning Unity
WRA	Wind Resource Assessment
WEC	World Energy Council
MW	Megawatt (1 MW = 1,000 kW = 1,000,000 or 106 watts)
GW	Gigawatt (1 GW = 1,000 MW = 1,000,000,000 or 109 watts)
kW	Kilowatt (1 kW = 1,000 watts)
m	Meter (the International System’s unit of length)
m/s	Meters per second (the International System’s unit for speed)

Financial units - exchange rates at (U.S. Department of Labor, 2016)

	1USD, 2010	*1USD, 2015*	*1USD, 2016*	*1 USD, 2017*
COP	0.000507	0.000536	0.000321	0.000345

1. Introduction

In a time of increasing electricity price, rising population, and climate change, renewable energies are becoming the focus to help mitigate the alarming consequence of an environmental degradation.

Renewable energies including solar energy, bioenergy, and hydropower and wind energy have been expanding around the world; wind energy has been the fastest growing resource of renewable energy during the past decade, and forecasts predict that this trend will continue for the next decade and beyond.

Countries like China, Denmark, Germany and United States of America; where the electricity demand is rising every minute, are world wind energy leaders,

The year 2015 was an unprecedented year for the wind industry as an annual installations crossed the 60 GW mark for the first time in history, and more than 63 GW of new wind power capacity was brought online. The last record was set in 2014 when over 51.7 GW of new capacity was installed globally (GWEC, 2016).

Likewise, the government of Germany with ambitious energy and climate policy targets aims at increasing the percentage of renewable energy consumption to 35% by 2020 and to 80% by 2050 to reduce greenhouse gas emissions to 40% and 80 - 95%, respectively, compared to 1990 (Fraunhofer, 2010).

In Latin America, the development of wind energy has gained momentum only during the last four years. There are a few wind farms along the continent particularly in countries such as Mexico, Brazil, Chile, Costa Rica and Uruguay; the last two countries are becoming leaders in Latin America with more than 80% of their electricity production comes from renewable energies (IRENA, 2016).

Colombia is setting a national renewable energy target providing a clear indication regarding the level of renewable energy development and the timeline envisioned by 2020 with almost the 7% of the energy production excluding large hydropower plants shall be generated from wind energy.

Additionally, the country has been making renewable energy laws providing a legal framework for the promotion of renewable energy as well as fiscal incentives, especially for investors and wind energy companies.

The wind potential of Colombia is outstanding especially in the Northern Caribbean region of the country with almost 20.000 MW of capacity (Huertas L., 2007).

However, the real potential for all Colombia´s region has to be not defined, for this reason, is convenient to start to generate research to identify the suitable sites.

The spatial and site analysis are the most important phases to build a wind project, and as a result, the wind project owner can easily take decisions in a real and a visualised manner, which is a substantial help to choose the most suitable place to develop the future wind farm.

Geospatial analysis is increasingly being acknowledged as an essential component to scale renewable energy projects, as well as it is a tool, geographic information system (GIS) has become fundamental to the wind power business, typical examples include real estate site selection, route/corridor selection, grid access, conservation and natural resource.

The purpose of this thesis is to find potential sites for build wind farms combining geographic information systems (GIS) and multi criteria decision making (MCDM) with the analytical hierarchy process (AHP) approach.

Since onshore wind energy siting is inherently multifaceted, an approach capable of evaluating several criteria simultaneously must be used.

Geographic information system(GIS) have the ability to assimilate, analyse, and visualise multiple spatial data sets that pertain to the different factors used for site selection, but GIS is limited in its capacity to assign values to these factors.

Thus, a multi-criteria decision-making (MCDM) must be generated since this approach has been shown to be an effective technique for assigning values to different criteria, and it is compatible with the functionality of GIS.

The outcome of the assessment of the wind energy of the Caribbean region of Colombia will not only contain technical issues such as reported below, additionally environmental, societal and economic aspects as well as the selection of the proper turbine for the study area.

Generating three models, the restriction model, which will indicate the areas excluded to develop wind farms, the rated model performing an evaluation of the different criteria used to develop a wind farm.

The suitability model will provide the best suitable sites for developing a wind farm, insight into the reliability and effectiveness of these models for locating potential sites. These may help decision makers understand which criteria are more sensitive to subjective input values.

Likewise, the suitability model can be an effective means of assessing the suitability of potential sites for wind energy development because they can be a cost-effective and visually powerful information source.

The result of these models can be easily displayed on the web to provide free, quick access for those interested in onshore wind energy siting, and increasing access to this type of information has been shown to enhance public participation in the siting process.

1.2 Objective

This thesis aims at providing a more precise and differentiated assessment for an onshore wind energy in the Northern Caribbean region of Colombia selecting a study area of three Colombia departments (Atlántico, Magdalena and La Guajira), by integrating social-political, environmental and techno-economic criteria in geographic information system (GIS) combining a multi criteria decision making (MCDM) with its analytical hierarchy process approach.

Likewise, a geospatial analysis presented in this thesis offer appraisal of the theoretical, geographical and technical wind energy potential in the study area, to indicate possible and optimal sites where onshore wind farms shall be built.

The secondary objectives are:

- General assessment of environmental, techno-economic and social-political criteria of the study area in the Caribbean region of Colombia developing a restriction, rated and suitability model.
- Propose a wind farm in a suitable selected site, choosing a proper wind turbine model, in order to reach the maximum wind potential generated from the wind farm.
- Create an appropriate wind farm layout to visualise the potential and limitations of the selected site as well as the economic assessment of the wind farm.

1.3 Methodology

This thesis presents a GIS-based application for evaluating the potential suitability of an onshore wind energy farm to provide ready visual access to this information to investors, politicians, developers, researchers, students, and the public.

This application will be useful for a preliminary site selection of a utility-scale and largely distributed wind energy, the site suitability analysis based on a set of physical, economic, and environmental criteria.

The criteria including: topography, wind power capacity, land use, proximity to the community, power grid access and natural reserve are integrated into a Spatial Decision support systems (SDSS) as part of a multi-criteria analysis (MCA) approach to generated an onshore wind energy siting model, thus making it a valuable planning tool.

The first phase of the thesis is combining a geographic information system with the use of the software ArcMap 10.1 student desktop version, from the company Esri® and visualisation capabilities with MCA.

The MCA is an effective approach to “solving” complex spatial problems like wind energy siting, which must balance numerous geographic, technical, environmental, economic, and social variables.

The distinct evaluated criteria are obtained from five main research, public institutions of Colombia:

- Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, acronym in Spanish).
- Geographic Institute Agustin Codazzi (IGAC, acronym in Spanish).

- National Administrative Department of Statistics (DANE, acronym in Spanish).
- The Mining and Energy Planning Unit (UPME, acronym in Spanish).
- The Environmental Information System for Colombia (SIAC, acronym in Spanish).

The IDEAM is an institution that provides technical and scientific support to the national environmental system of Colombia, which generates knowledge, produces reliable, consistent and timely information on the state and dynamics of natural resources and the environment.

Furthermore, The Geographic Institute Augustin Codazzi, (IGAC, acronym in Spanish), is the entity responsible for producing the official map and the basic cartography of Colombia and develop the national property register creating the soil characteristics inventory; advancing geographic investigations in support of national development.

DANE is an official entity of Colombian origin founded in 1953 whose purpose is the production and dissemination of research and statistics in industrial, economic, agricultural, population and quality of life aspects aimed at supporting the decisions in the country

UPEM is an official institution that coordinates with the agents of the mining and energy sector, the use of mineral and energy resources of the country.

SIAC is an information system of the National Environmental System (SINA), is led by the ministry of environment and sustainable development in coordination with the environmental research institutes (IDEAM, SINCHI, HUMBOLDT, IIAP and INVEMAR), regional environmental authorities Regional Autonomous and Sustainable Development) and local, academic community.

When the GIS and the MCA are combined, the results are three assessment models including a restriction model, rated model and a suitability model. After generating the models, the second phase is performing a micro-siting evaluation, selecting a site in which a proposed wind farm should be developed.

However, to generate accurate data, it is necessary to confirm the calculated data with the result of the software windnavigator® student version from the company AWS Truepower, for the selected site, the windnavigator® generated a diverse accurate data such as wind speed, roughness and air density of the chosen location.

Once the micro-siting is performed, the third phase of the thesis is to generate an economic assessment for the proposed wind farm, which will give an overview of the cost of the project, the investment needed, and the revenue including payback generated from the wind farm and debt amortisation.

This phase answers the question of the profitability of the proposed wind farm in Colombia. The economic assessment will be beneficial for wind energy companies, public institutions, as well as potential shareholders with the intention of doing business and investment in Colombia.

2. Status of the energy market of Colombia and Latin America

Colombia is a country with abundant natural resources, reflected in the energy matrix rich in fossil fuels and renewable resources.

93% of the primary energy production is made up of fossil fuels, including (coal, oil and natural gas), 4% is from hydropower, and 3% is from biomass and residues, Figure 1 shows the share of primary energy resources in 2012.

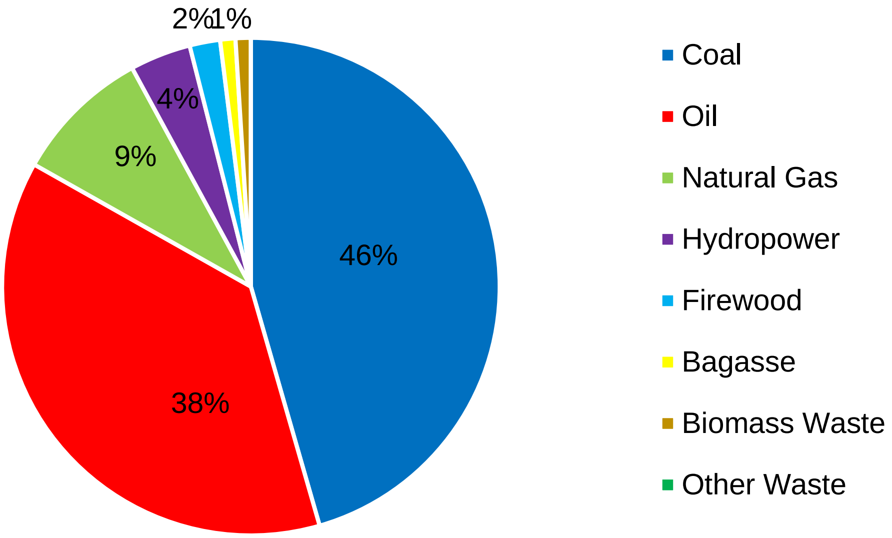


Figure 1. The share of primary energy resources in 2012, based on (UPME, 2015a).

In order to increase the share of non-renewable energies in Colombia´s energy matrix, the country is looking forward to transforming the energy from natural resources into secure energy supply systems, generating access to affordable and modern energy services and stimulate sustainable economic development, structuring a legal framework to increase the participation of renewables.

Furthermore, to promote private investment, the Colombian government has included constitutional and statutory provisions, measures, such as generation of a clear legal framework, easy access to markets, fair competition conditions, and stability for investors, and improvement of security (Zárate, Vidal, 2016).

Although 98% of Colombia has access to electricity, there are zones that still without power grid access, most of them are located the north part of the Guajira and South Colombia (Amazons).

With the intention to expand the power grid, Colombia has two main electricity cooperation projects-the interconnection with Panama and the Andean electrical interconnection system (SINEA, acronym in Spanish) among Colombia, Ecuador, Chile, Ecuador and Peru.

2.1 Colombia energy market structure

The primary energy market structure of Colombia is divided into non-renewable energy sources, such as oil, coal, natural gas and renewable energies corresponding to hydropower, biomass, wind and solar energy, Figure 2 shows the electrical generation capacity of the National Interconnect System (SIN, acronym in Spanish), with a wide representation of hydropower as renewable energy.

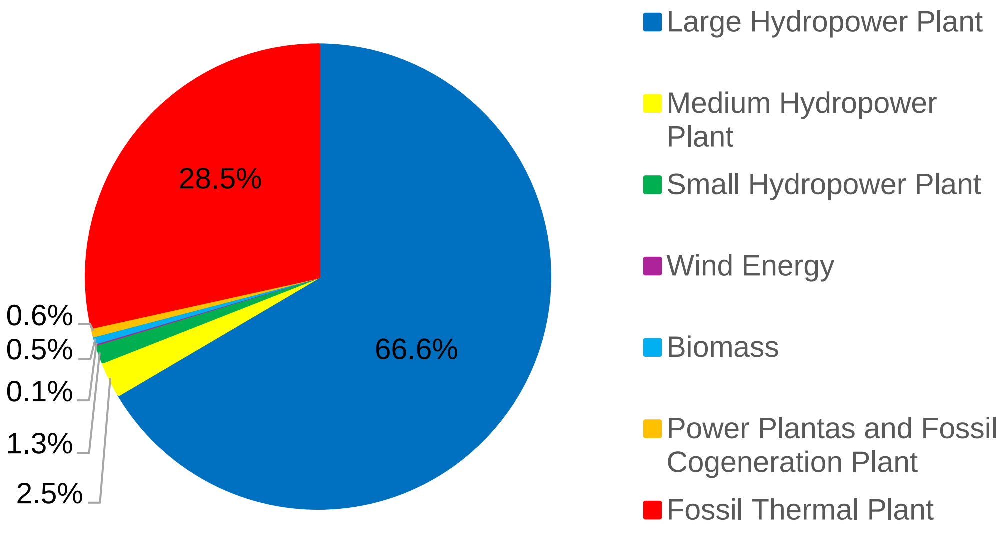


Figure 2. Electrical capacity generation of SIN in 2014, based on (UPME, 2015a).

2.1.1 Non-renewable energy resources

In 2006, Colombia accounted for 81 % of the total coal production in Central and South America. Furthermore, 94 % of Colombia's coal is of excellent quality and is classified as hard coal, with high heat-generating capacity. Coal has been Colombia's second-largest export since 2001.

The largest coal mines and the ones that generate the most exports are located in the north of the country, in the departments of La Guajira and César. *Cerrejón* is one of the largest open-pit coal mines in the world. There are also smaller coal mines scattered throughout the remainder of the nation (Hudson, 2010).

Likewise, 92% of thermal coal is exported to countries such as the Netherlands, Turkey, Spain, the United States, and others (SIMCO, 2016). Despite this significant coal production, only about 8% of installed electric power capacity corresponds to coal thermal power plants (UPME, 2016).

The main oil products produced in Colombia are gasoline, diesel oil, kerosene, fuel oil, jet fuel, propane, oil, asphalt and liquefied gas, with oil products being the leading source of supply for transport. (Ecopetrol, 2016)

Colombia exports about half of its production of oil, most of it to the United States. Although the share of oil in GDP has remained between 2 and 4 % since 1990, it shares in the total Colombian exports has been between 20 and 30 % since 1995. It generates significant revenues for the nation's public finances (Hudson, 2010).

The main natural gas reserves are in the basins of Llanos Orientales (50% of total production) and La Guajira (31%), and the remaining 19% is placed in the basins of Catatumbo, lower, middle and upper Magdalena Valley (UPME, 2015).

2.1.2 Renewable energy resources

Colombia has been concentrating on the investment, research and development of clean energy and energy efficiency.

The Law Number 1715 of 2014 determined the integration of alternative renewable energy into the domestic energy system and created tax incentives for investments in these sources. Since February 2016, the decree 2143 of (Ministry of Mines and Energy, 2015).

Additionally, the sale of electricity generated by wind resources has an exemption from income tax for 15 years from January 1st, 2003, as established in article 18 of law 788 of 2002 and decree 2755 of 2003.

Likewise, by the Article 428 of the Tax Statute, imports of machinery and equipment for the development of projects which contribute to reducing the emission of greenhouse gases, and therefore to sustainable development, are not subjected to VAT.

The exemption operates when the generator obtains and sells certificates of emission of carbon dioxide by the terms of the Paris Agreement, and invests at least 50% of the revenues in social benefits.

Renewable energies in Colombia are based on hydropower, wind energy, biomass and solar energy, currently the electric matrix, which produces approximately 17% of the final energy consumed in the country, has the vast participation of hydropower as a renewable resource, which represents between 70% and 80% of generation, as reported by the variations in annual hydrology, and 70% of installed capacity by December 2014.

The dependence of Colombia on hydropower generate a high risk for the nation due to the “El Niño” phenomenon is characterised by dry seasons.

“El Niño” phenomenon disturbs the electricity production of hydropower plants. The occurrence of such dry periods has resulted in the increase in energy prices in 1992 and 1993 or more recently in 2009, 2010, 2013 and 2014. Moreover, recent studies have predicted that vulnerability to droughts will grow up significantly due to the climate change.

The most notable progress in renewable energy in Colombia is the “*Jepirachi*” the first power system connected wind farm with a capacity of 19.5 MW produced by 15 turbines of approximately 60 m hub height.

Likewise, the geothermic project Colombia - Ecuador, which in 2005 produced 49.358 Megawatt-hours (MWh) of power and generated net revenue of COP 3. 741 million ($1. 5 million), it is situated on the Guajira peninsula in the northernmost region of Colombia very close to the Venezuelan border (Ledec et al., 2011).

Additionally, in 2010 the Ministry of Mines and Energy of Colombia and the Ministry of Electricity and Renewable Energy of Ecuador signed a bilateral agreement to produce the project ‘tufiño-chiles-cerro negro’, the main objective of this task is to generate electricity from geothermal resources in the border between the two countries with an energy potential around 114 MW, and implies the investment of around $150 million.

2.2 The energy market in Latin America

Rapid growth in energy demand amid energy security concerns and increasing climate impacts present Latin American countries with an opportunity to rethink their energy mix; the region is endowed with vast energy resources, both fossil and renewables.

The prominence of oil and gas in the energy mix of the region is largely derived from the role of Latin America as a key oil and gas producer with some of the world's top 10 oil exporters besides oil, accounting for 46% of the of the total primary energy supply in 2013, holding a share higher than the world average of 31% (REN21, 2016).

Non-renewable resources are used mainly transport (especially oil), whereas its use in other sectors has decreased, in the power sector, oil has been substituted primarily by natural gas, which makes up 23% of primary energy supply, Figure 3 shows the total primary energy's share in the region in 2013.

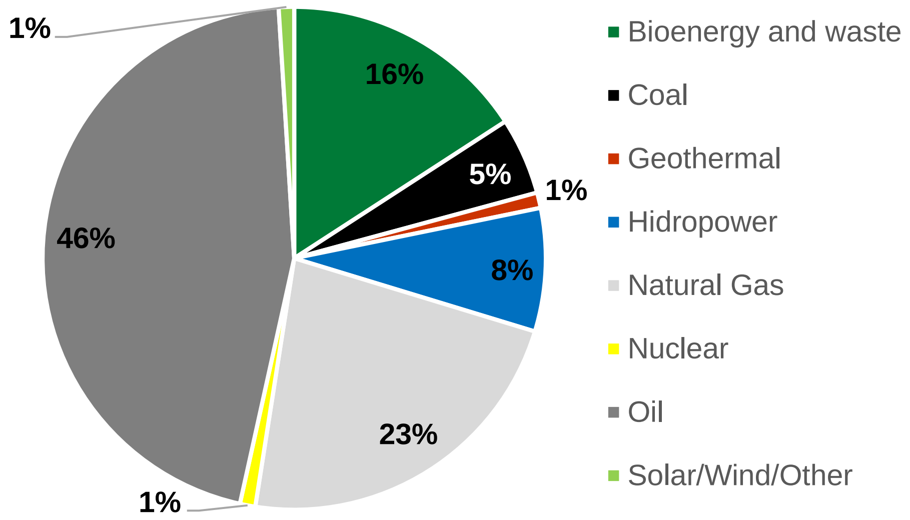


Figure 3.Primary energy share of the region in 2013, based on (IEA, 2015)

Furthermore, the electricity demand growth has been driven mostly by economic development, urbanisation, higher living standards and the successful expansion of electricity access, which currently reaches close to 95% of the population.

2.3 Renewable energies in Latina America

Although, Latin America is considered a new market into renewable energies, there are countries of the region with a prominent share of electricity generation from renewable sources, targets.

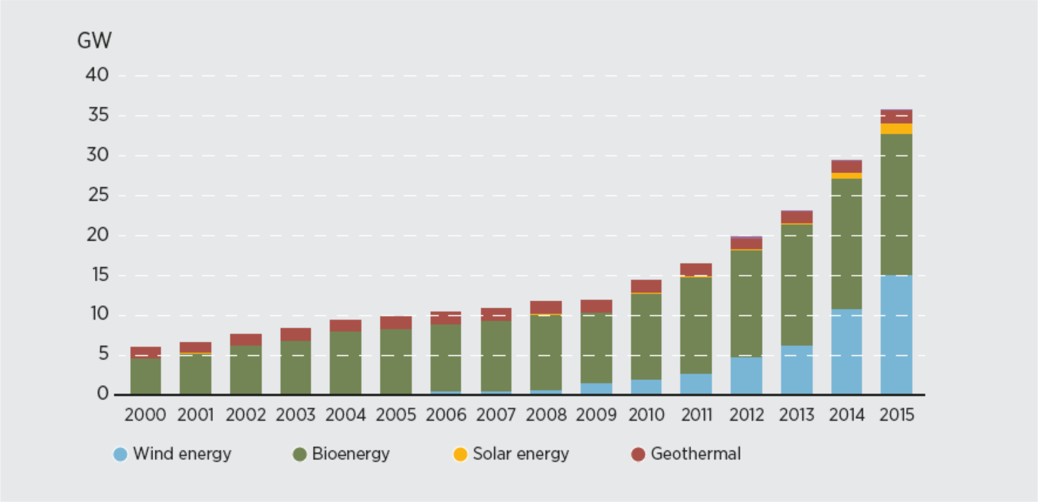
Lead by Costa Rica with 100% of its energy production by 2030, as well as Uruguay with an ambitious target by 2017 reached a 95% of its energy production by 2017, Belize 85% by 2027, Guatemala 80% by 2030 and Bolivia which 79% by 2030, Lower shares were targeted in Brazil, Chile and Paraguay and Colombia (REN21, 2016)

Latin America has one of the world's highest shares of renewable energy, due to the significant historical development of hydropower and the role of bioenergy in the transport, residential and industrial sectors, which stand out as distinct features of the region, for example, Brazil generates the 40% of total regional electricity from hydropower.

Nevertheless, the relative percentage of hydropower in total renewable capacity has been steadily going down, from 95% in 2000 to 83% in 2015, due to slower capacity additions and the worries created by major droughts across the area.

Hence, recent years have witnessed impressive growth in non-hydropower renewable, whose installed capacity has more than tripled between 2006 and 2015, from 10 GW to 36 GW. Figure 4. shows the renewable power capacity of the region excluding large hydropower from it (IRENA, 2012).

Countries across the region achieved high shares of their electricity generation with renewable energies: for example, Costa Rica generated 99% of its electricity with renewable sources, Uruguay generated 92.8%, and Chile has quickly gone by several long-term targets. Figure 4 shows the renewable power capacity and generation, excluding large hydropower.



Source: IRENA, 2016a

Figure 4. Renewable power capacity and generation, excluding large hydropower, based on (IRENA, 2016).

Latin America remained one of the fastest growing markets for wind energy and solar PV in 2015; Brazil is the second globally for new hydropower and fourth for wind power capacity although, transmission capacity has been unable to keep pace with wind power capacity.

Nevertheless, Mexico was one of the few countries worldwide to add geothermal power capacity in 2015, Guatemala bring its first wind power plant online, as well as countries including Chile, and Peru held successful tenders in 2015 and early 2016, resulting in some of the world's lowest bid prices, due to the vast renewable energy resources of the region (REN21, 2016).

The levelized cost of energy (LCOE) in the continent has fallen by over 50% for solar PV since 2012, and by around 20% of hydropower and onshore wind since 2010, ranking among the lowest globally.However, hydropower has historically been and still is, one of the most cost-efficient technologies in the region.

The competitiveness of solar PV is contributing to achieving record-low costs, such as in the recent PV auctions in Mexico and Peru with prices of $36/MWh and $48/MWh (REN21, 2016), respectively for the lowest bids.

Technological progress underpins these reductions, local supply chain development, resource quality, reduced financing costs and growing sector maturity.

Regarding solar energy, Latin America and the Caribbean added an estimated 1.1 GW in 2015 to more than double regional capacity, Chile installed over 0.4 GW, mostly in very large-scale projects, with a year-end total exceeding 0.8 GW.

Solar PV has become the country’s cheapest source of electricity while Honduras emerged as an important market and, Chile is among the top 15 countries worldwide for new installations, the country added nearly 0.4 GW (REN21, 2016).

Brazil is the second largest biofuel producer of the world, increased both ethanol and biodiesel production during 2015, due to good sugar cane harvests and blending mandates.

However, in Argentina, a leading producer in years past, output fell by 20% due to constrained export markets. Colombia, the region’s third-largest biofuel producer, raised its ethanol production by nearly 12% over 2014 levels, but its biodiesel production decreased slightly (REN21, 2016).

Likewise, onshore wind energy has seen a strong positive evolution in the region, led by deployment in Brazil, the installed costs of onshore wind in 2010 ranged between $2.500 kW and $3.250 kW, with a weighted average, installed cost of $2.900 kW.

However, with a small number of projects In 2014, the ranges decreased to between $1.000 /kW and $2.990 /kW.(IRENA, 2016c), Figure 5 shows the wind energy installed capacity in Latin America.

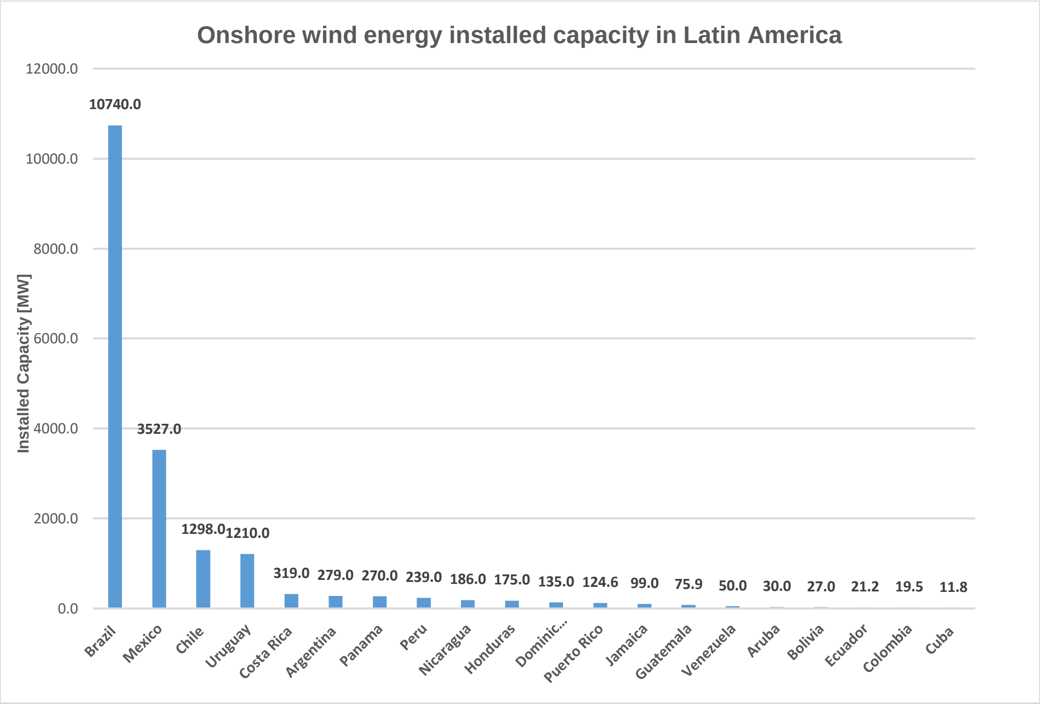


Figure 5. Onshore wind energy installed capacity in Latin America, author´s diagram based on data from (IRENA, 2016).

3. Wind farm siting using a geospatial analytic process

One of the most challenging phases of developing a wind farm is to find the most appropriate location to build it; this step can easily take years of feasibility studies.The principal objective of the siting process is to locate a wind turbine (or turbines) such that net revenue is maximised while minimising issues such as noise, environmental and visual impacts and overall cost of energy (Manwell et al., 2009)

With the aim of developing a successful wind project, the measurement of wind speed should be produced as accurately as possible; there are a variety of models to estimate wind speed such mesoscale and microscale models.

The mesoscale model is included in the computational fluid dynamics (CFD) and the micro scale model well-known as Atlas analysis and the application program (Wasp), is highly renowned due to the extent used to it in tools like windPRO and Windfarm.

Additionally, there is a diversity of technical parameters necessary to consider in developing an appropriate wind resource assessment (WRA), such wind resource map, average annual wind energy density by direction (wind rose), average of turbulence intensity, average of wind shear, parameters for the distribution of wind speed (Weibull) and average annual energy production for choosing turbines of a wind farm (Jain, 2011).

3.1 Renewable energy siting (RES)

Geographic information systems have been widely used to assist in searching for suitable sites for wind farms, by combining different layers, ArcMap, its dynamic tool, provides the functionalities of integrating a large spectrum of geospatial information into the decision making of wind energy development.

Additionally, application of GIS-RES includes wind farm siting, photovoltaic electrification, biomass evaluation, visual impact, assessment of wind park (Ramachandra, Shruthi, 2007).

Combining GIS with MCDM is a successful approach that generated useful and efficient information as well as improves the decisions making process:

GIS contributes with the spatial and temporal analysis of the resources, further the outstanding capacity of spatial problems visualizing, besides MCDM combining distinct categories of criteria such techno-economic, socio-political and environmental originating a real evaluation of potential suitability sites, in the case of this thesis MCDM is focused on evaluating the suitability sites where a wind farm should be developed.

The following is a review of some prominent worldwide studies related to location, suitability or optimisation of wind energy project development; these have some similarities and discrepancies in methodologies and performance results.

(Baban, Parry, 2001) The analysis is suited within the boundary of Lancashire, England; Conducted a postal questionnaire targeting public and private sectors, 112 questionnaires were sent, 100 to the public and 12 to a private organisation.

The output (60 out 100 and four out 12) was used to identify criteria and policy factors that frequently various agencies in the UK apply to determine suitable areas for locating wind farms.

The study includes eight restriction layers (topography, wind speed and direction, land use/cover, population, access, hydrology, ecology and resources). Considering that a similar outline and a pairwise comparison of criteria were utilised.

(Rodman, Meentemeyer, 2006) utilise the framework rule-based spatial analysis to assess different scenarios for big and small-scale wind turbines; the study estimated the nine-county area of the greater San Francisco Bay Area, United States; Due to the densely populated area and severe geographical constraints the region generated a challenge to develop and siting wind farms.

Four models are created: A physical model, including three factors (average annual wind speed, obstacles and terrain), an environmental model, including three factors (vegetation/land use, presence of endangered plant species and precedence of wetlands) a human impact model (urban and recreational areas) and a combined model.

(Tegou et al., 2010) evaluated land suitability for siting wind farms, combining multi-criteria analysis (MCA) and geographical information system (GIS), for the island of Lesvos in Greece, based on five-stage procedure.

The study includes a variety of criteria such wind power potential, land cover type, electricity demand, visual impact, land value and distance from the electricity grid.

Additional is created a pairwise matrix comparison applying the analytical hierarchy process (AHP) to estimate the criteria weight.

One of the most comprehensive reviewed studies, the only disadvantage is that the weight assigned to the criteria is no explained, it means that the authors assigned the criteria weight by his knowledge, and not because of the literature review or evaluation of experts or decision makers.

(Van Haaren, Fthenakis, 2011) a novel method of site selection for wind farms in the New York State, in the United States of America, based on spatial cost-revenue optimization with a three-stage framework, the analysis evaluates a large area (141.300 km²) and include an economic part that usually is not included in most of the studies of this type.

The first stage is based on excludes sites that are unsuitable for siting wind farms including physical constraints such (urban areas, federal lands, Indian lands, roads, lakes, slope and karts (porous ground and caves), additionally in the second stage identified the best available sites based on an economic evaluation.

(Höfer et al., 2014) improve the siting assessment by providing a holistic, multicriteria decision-making approach that incorporates techno-economic, social-political and environmental criteria in the Städteregion Aachen, Germany; the analysis combined geographical information system and analytical hierarchy process, with a three-stage framework.

Likewise, the second stage consists of the selection of analytical hierarchy process criteria and assigned the weights for each criterion, the weights assigned to the criteria were extracted from a survey among 22 local, regional wind power experts from the Städteregion Aachen, the expert fill out a questionnaire of pairwise comparison of nine criteria, the third stage is a consolidation of exclusion area and rated area generating the potentially suitable area.

The results obtained indicate that the study area still available for wind energy development, focus on the north part of the region which offers a high suitability potential.

An overview of the most important criteria considered in the development of wind farms is summarised in Table 1.

Table 1.Summary of criteria considered in the literature reviewed.

Criteria / Constraint	Baban and Parry (2001)	Rodman and Meentemeyer (2006)	Tegou et al. (2010)	Van Haaren and Fthenakis (2011)	T. Höfer et al. (2014)
Wind energy potential	restriction	restriction	x	x	x
Distance from roads	x	n.c	x	x	x
Distance from electricity grid	restriction	n.c	x	x	x
Slope terrain	x	x	x	x	restriction
Distance from urban areas	x	restriction	x	restriction	x
Airports	n.c	n.c	restriction	n.c	n.c
Electricity demand	n.c	n.c	x	x	n.c
Places of interest	x	n.c	x	n.c	x
Natural environments	x	restriction	restriction	n.c	restriction
Avian habitat	n.c	n.c	n.c	restriction	
Water bodies	x	n.c	x	n.c	
Wetlands	n.c	restriction	restriction	n.c	
Land cover	restriction	x	x	x	restriction
Forest areas	x	x	x	n.c	x
Soil type	n.c	n.c	n.c	n.c	n.c
Surface roughness	n.c	n.c	n.c	n.c	n.c
Elevation	restriction	n.c	n.c	restriction	n.c

Note: the abbreviation "n.c" stands for not considered, "x" stands for considered.

3.2 Multicriteria decision making

Multi-criteria decision making (MCDM) is primarily concerned with how to combine the information from several criteria to form a single index of evaluation, as well as MCDM, is a successful method for evaluating the relative importance of multiple variables as input criteria for making complex decisions (Chen et al., 2010).

Likewise, MCDM main concept is to determine, identify and assesses the proposed criteria regarding the value or weight of the influence the criteria have on the final decision; decision support systems are usually combined with geoinformation systems(GIS).

One of the most common GIS-based strategies that have been designed to facilitate decision making in site selection, land suitability analysis and resources evaluation is multi-criteria analysis (MCA)(Tegou et al.).

The analytical hierarchy process(AHP) is original describe by the Professor Thomas L.Saaty in 1977 as a general theorem of measurement; provides a means of decomposing the problem into a hierarchy of subproblems which can easily be comprehended and subjectively evaluated, the subjective evaluation are converted into numerical values and processed to rank.

This approach is one of the most commonly used by decisions makers and planner for evaluation multi criteria decisions; it provides a calculable consistent factor (regarding a ratio) that contribute to the decisions makers a high level of confidence in the criteria weighting process**.**

Based on the description by (Saaty, 1977), (Saaty, 1987) and (Saaty, 1990), the methodology of the AHP can be explained in four main steps as follows:

1. Structuring the hierarchy: Arrange in a hierarchy structured in terms of goal, criteria and alternatives, reflecting the relationship between criteria of one level with those of the level immediately below.

   In this thesis the **goal** is to *find optimal wind farm site*, the selected six **criteria** are exposed in section 3.4, in which their characteristics and importance are defined, in the level immediately below are the **alternatives**, called in this thesis suitability sites, this structure is shown schematically in Figure 7.

2. Performing paired comparisons between criteria/sub-criteria: construct a pairwise matrix comparison of criteria/sub-criteria applying the judgment matrix, Equation(1), where the entries indicated the dominance of one criterion/sub-criteria above another.

   The scale applied to make this pairwise comparison is provided in Table 2, and the calculation of this process is demonstrated in Appendix A, the comparisons in AHP enables decision makers, shareholders, stakeholders and experts to make qualitative judgments.

   The number of judgments required for such matrix is *n (n-1) /2*, where n is the number of criteria, the matrix A= $[C_{ij}]$ ∀ i, j=1, 2,..., n can be constructed for the n criteria affecting the selection of one of the available alternatives.

   The judgment matrix “A” Equation (1) is given below, where C_{ij} is the relative importance of criterion C_i over criterion C_j $[C_{ij} = 1/C_{ji}]$.

$$A = \begin{pmatrix} C_{11} & C_{12} & C_{1(n-1)} & C_{1n} \\ C_{21} & C_{22} & C_{2(n-1)} & C_{2n} \\ \vdots & \ddots & \vdots & : \\ C_{n1} & \cdots & C_{n(n-1)} & C_{nn} \end{pmatrix} \qquad \textit{Equation(1)}$$

Table 2. Pairwise evaluation scale, based on (Saaty, 1990)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favour one activity over other
5	Essential or substantial importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate importance	When compromise is needed

3. Calculating the priority vector: to generate the importance of the different criteria is necessary to calculate the priority vector applying Equation (2), the priority vector indicates the importance of each criterion where *w* is the principal eigenvector of the matrix A.

As well as λ_{max} is the maximum eigenvalue of the judgment matrix, in Appendix C: Priority Vector and Consistency of matrix is shown the calculation of it.

$$A \times w = \lambda_{max} \times w \qquad \textit{Equation(2)}$$

4. The consistency of A matrix: with the proposed of verifying the consistency of the A matrix, two parameters must be evaluated: The Consistency Index (***CI***) and the consistency ratio (***CR***).

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \textit{Equation(3)}$$

$$CR = \frac{CI}{RI} \qquad \textit{Equation(4)}$$

Table 3.Random index values, based on (Saaty, 1990).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The consistency index is evaluated with the Equation(3), where λ_{max} is the maximum eigenvalue of the judgment matrix, n is the number of criteria; Likewise, the Consistency Ratio is evaluated applying the Equation (4).

Where RI is the random index (***RI***), RI is obtained from Table 3, is used to calculate the CR and usually vary according to the matrix size, in this thesis is a 6x6 matrix with six selected criteria (see Table 6) it means that the *RI* is 1.24 , the pairwise evaluation scale is given in Table 2.

The consistency matrix evaluation is based on the result of CR, if CR is smaller than 0.1, the matrix A is considered consistent nevertheless, if CR exceeds the threshold, the matrix A is seen as inconsistent. The calculation of this process is demonstrated in Appendix A, B and C.

3.3 Data and AHP framework

3.3.1 Study area

Three Colombian departments (La Guajira, Magdalena and Atlántico) make part of the selected “Area of Study” in which the wind potential, as well as different characteristic for developing a wind farm, are evaluated, with a total projected area of 38.835 km^2 and 68 municipalities (Dane, 2015), the spatial overview of the study area is shown in Figure 6.

La Guajira Department, located at the northernmost tip of South America, sharing borders with the Caribbean Sea and Venezuela, with a projected area of 17.408 km^2, 985.498 inhabitants and 15 municipalities (Dane, 2015) is one of the less dense regions of Colombia, well known for its outstanding wind potential and its natural and cultural wealth.

Likewise, as mentioned before in La Guajira is located the first wind farm in Colombia, “The Jepirachi” a wind farm with a production capacity of 19.5 MW (Ledec et al., 2011).

Magdalena department with a projected area of 17.408 km^2, 1,272.278 inhabitants and 30 municipalities, is located in the northeast and share fluvial borders with the Guajira department and the Cesar department.

La Guajira own specials naturals and geographical characteristics, such several water resources, natural parks and two of the highest mountains of the country:

The Pico Cristobal Colon is the highest peak in Colombia standing at an elevation of 5.776 meters; the Pico Simon Bolivar closely follows the peak at an altitude of 5.638 meters (Sawe, 2017) which are located in the Natural Park “The Sierra Nevada de Santa Marta”.

Finally, Atlántico department is located north in the country, share borders with the Magdalena Department and Bolivar department, with 2,489.709 inhabitants, total surface of 3.649 km^2 and 23 Municipalities.

The Atlántico is considered by the densest departments in Colombia, the department owns a strategic geographic position, surrounded by the Magdalena River and the Atlantic Ocean (Caribbean Sea), makes the department very attractive regarding logistics and supply chain.

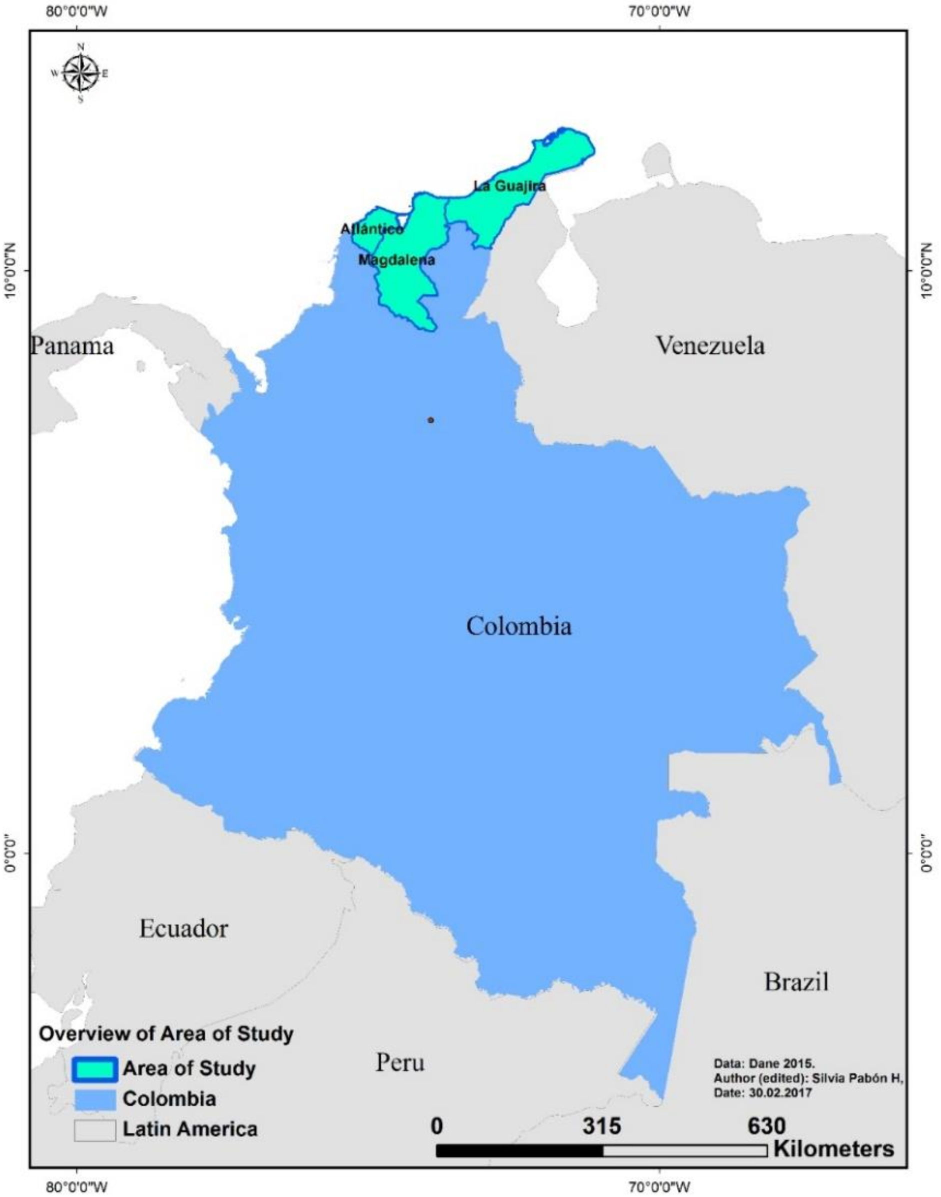


Figure 6.Overview of the study area and spatial location, author’s map based on data from (Dane 2015).

3.3.2 Methodological framework

The methodological framework of the wind siting assessment applied in this thesis to find suitability sites to (or “intending to”) the schematic methodological framework for developing a wind farm is explained in Figure 7.

The procedure involves five steps. First, the literature review and selection of the different criteria, following by the creation of data geoformation system, subsequent the exclusion area is calculated as well as the rated area and finally, with the combination of the exclusion area and the rated area the suitability area is found.

In general, the methodological framework applied in this thesis has a similar structure to the Tegou et al. (2010) and the T. Höfer et al. (2014) studies.

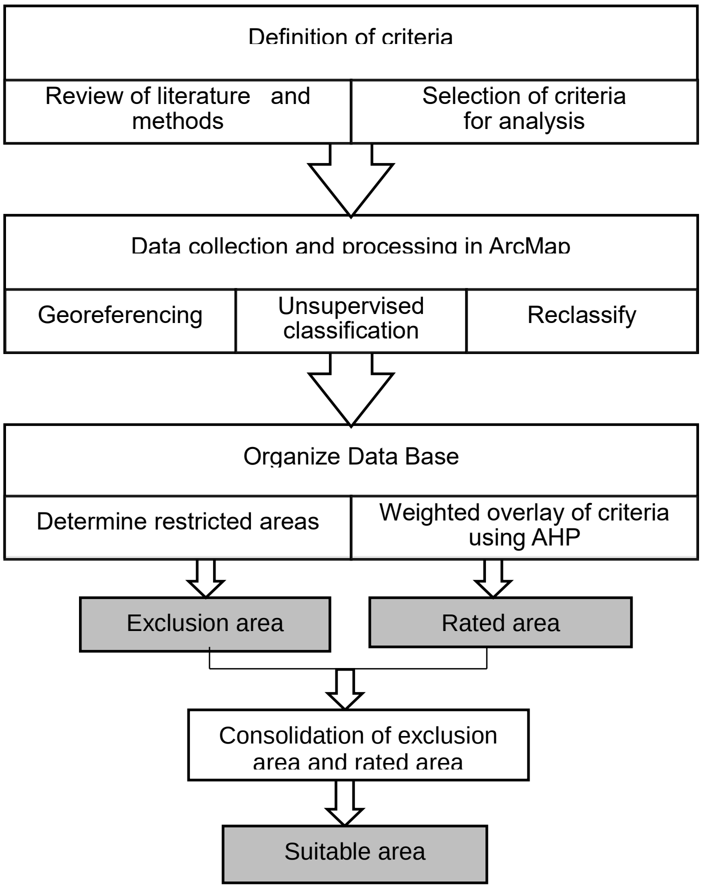


Figure 7.Schematic methodological framework, author´s diagram.

3.3.3 Selection of criteria and data

A set of eight criteria were chosen for generating a wind energy suitability model, the criteria selection begging with an extensive literature review and based on it the most used criteria describe in consideration of the different studies already mentioned.

Additionally, the data are projected into a geographic coordinate system: GCS_WGS_1984 converted into a raster data structured and resampled to a common cell of (22 m).

The original criteria data feature is in PDF and vectors files, particularly the vectors files are the representation of the world using points, lines, and polygons. Vector models are useful for storing data that has discrete boundaries, such as country borders, land parcels, and streets.

However, for creating Geographic information systems, all the feature data have to be translated into a rated model, which is a representation of the world as a surface divided into a regular grid of cells.

Raster models are useful for storing data that varies continuously, as in an aerial photograph, a satellite image, a surface of chemical concentrations, or an elevation surface (McCoy, Johnston, 2010).

Raster also features the ideal data representation for spatial modelling. Table 4 describes the characteristics of the criteria, justification and the original data source as well as the final feature type.

Table 4. Criteria and data sources used to model wind farm suitability.

Criteria	**Data Sources**	**Reasons for Selection**	**Original Data Source**	**Final Feature Type**
Wind energy potential	IDEAM[1], wind energy potential at 90 m.	An estimation of the wind resource at potential projects sites is the heart of the siting process (Manwell et al., 2009).	PDF	Raster
Land use	IGAC[2], land use map.	Access to land is necessary to install and operate wind turbines(Wizelius, 2007).	PDF	Raster
Distance from urban areas	DANE[3], population center.	Public concerns regarding visual and noise impacts(Rodman, Meentemeyer, 2006).	Vector, Polygon	Raster
Distance from power grid	UPEM[4], transmissions lines map.	Reducing the cost of building new transmissions lines(Baban, Parry, 2001).	Vector, Polyline	Raster
Distance from road network	DANE, access (roads).	The access road has been able to bear heavy lorries with trailers and a heavy mobile crane(Wizelius, 2007).	Vector, Polyline	Raster
Natural environment	SIAC[5], bird reserved and natural park and wetlands	The impact of the wind farm, including its construction, on the local flora and fauna, needs to be considered(Burton, 2011).	Vector, Polygon	Raster
Hydrographic resource	SIAC, hydrographic resource(Rivers)	Depending on the site it may be necessary to evaluate the impact of the project on water courses and supplies(Burton, 2011).	Vector, Polyline	Raster
Digital elevation model	SIAC, contour lines.	Avoid areas of a steep slope. The wind on steeps slopes tends to be turbulent and has a vertical component that can affect the turbine(Zobaa, Bansal, 2011).	Vector, Polyline	Raster

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[1] *IDEAM - Institute of Hydrology, Meteorology and Environmental Studies (http://www.ideam.gov.co)*

[2] *IGAC- Geographic Institute Augustin Codazzi (http://www.igac.gov.co)*

[3] *DANE- the National Administrative Department for Statistics (http://www.dane.gov.co)*

[4] *UPEM- Mining/Energy Planning Unit (http://www1.upme.gov.co/)*

[5] *SIAC-Environmental Information System of Colombia (http://www.ideam.gov.co/web/siac/index)*

3.4 Description of criteria

The different criteria evaluated in this thesis are wind energy potential, land use, distance from urban areas, distance from the power grid, distance from road network, and distance from the natural environment including hydrographic resource and digital elevation and slope data.

3.4.1 Wind energy potential

Wind resource is almost always a key consideration, the better the resource, the greater the potential power production and project revenues (Brower, 2012), the average wind speed criterion is widely used in all studies found in the literature and considers the most important criteria.

Wind energy potential at 90 m map was obtained from the IDEAM, in 2012 the IDEAM created an interactive Wind Atlas in which are explained the different characteristic of the wind potential in Colombia in it are included wind speed, density, roughness, wind direction, among other resources.

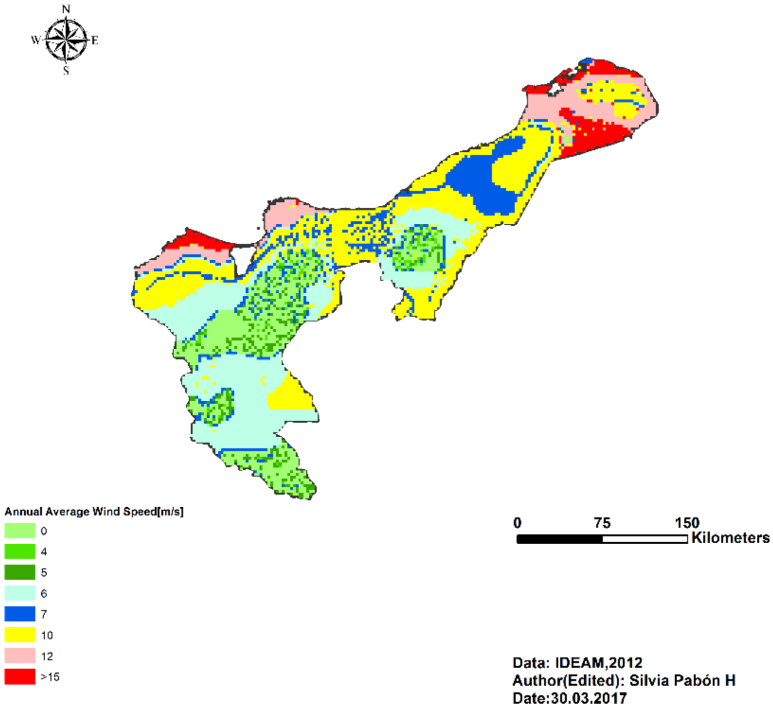
The wind atlas data are based on 111 meteorological measurement stations, 10 of them are sitting in the related study area, the measurements are from a period of 29 years, between 1961 and 1990 (IDEAM, 2002).

Additionally, the wind energy map was obtained in format PDF; since all the maps must be in format Raster for generating a better performance in the result of the suitability model, subsequently In ArcMap were created two additional processes.

GEOREFERENCING is mainly to add control points which are the georeferenced to the figure and *UNSUPERVISED CLASSIFICATION* which is used to find the spectral classes of the map, after the performance, the two conversions process the result is the wind potential in format raster with a cell size of 22 m.

The annual average wind speed in the study is shown in Figure 8, based on the figure is evident the high wind energy potential of the study area, especially in the Guajira department with a higher wind speed of 15 [m/s] in the northern part.

As well as in the Atlántico department with different wind speed class from 6 until 15 [m/s]; Wind speed, lower than 5 [m/s] are not taken into consideration for suitable sites.



Data: IDEAM,2012
Author(Edited): Silvia Pabón H
Date:30.03.2017

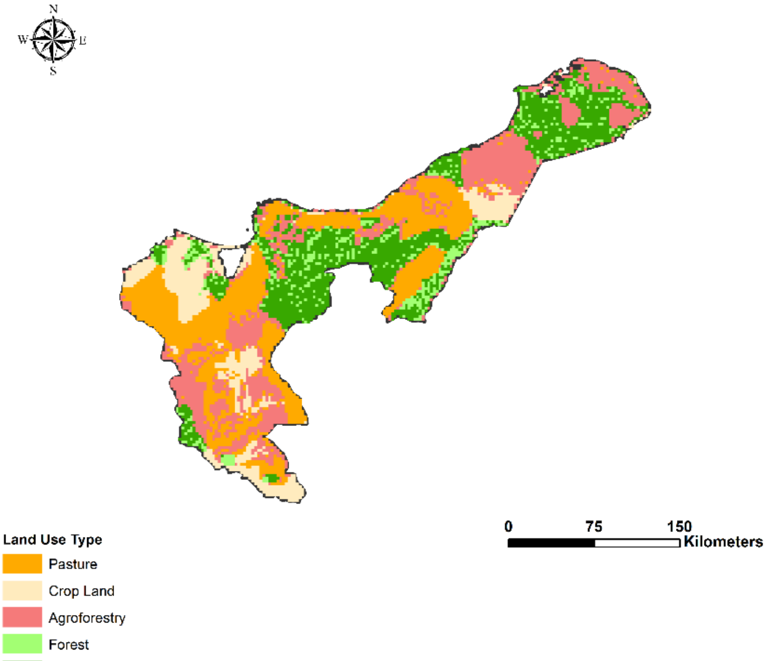
Figure 8.Annual average wind speed [m/s] at 90 m, author´s map based on data from (IDEAM, 2002).

3.4.2 Land use/cover type

One of the main advantages of wind power, in comparison with most other forms of energy development, is that pre-existing land uses such as crop and grazing can be combined without problems. Wind turbines should be installed on the land with the lowest disruption to the existing land (Miller, Li, 2014).

The land use data were derived from the IGAC, in a format PDF like the wind potential map the land use map went through the same transformation process, *GEOREFERENCING* and *UNSUPERVISED CLASSIFICATION*.

The land use map also called by the IGAC purpose use of the land, is shown in Figure 9, the study area present different types of existing land used such as pasture, cropland, agroforestry, forest and reserve, since the goal is to find the most suitable site for build a wind farm the land use forest and reserve as an exclusion.



Data: IGAC,2013
Author(Edited): Silvia Pabón H
Date:30.03.2017

Figure 9. Land use type, author´s map based on data from (IGAC, 2013)

3.4.3 Distance from urban areas

Some parameters need to be evaluated before sitting a wind farm nearby urban areas such as sound propagation, shadows and reflections, visual impact on the landscape and public acceptance (Wizelius, 2007), these parameters involve an extensive review of standards, laws and regulations of the specific assessment site.

According to the Colombia existing resolution, the maximum sound pressure level allowed during the day is 65 dB and 45 dB at night (Ministry of Health, 1983), The noise limits in Colombia are similar to those used in Europa.

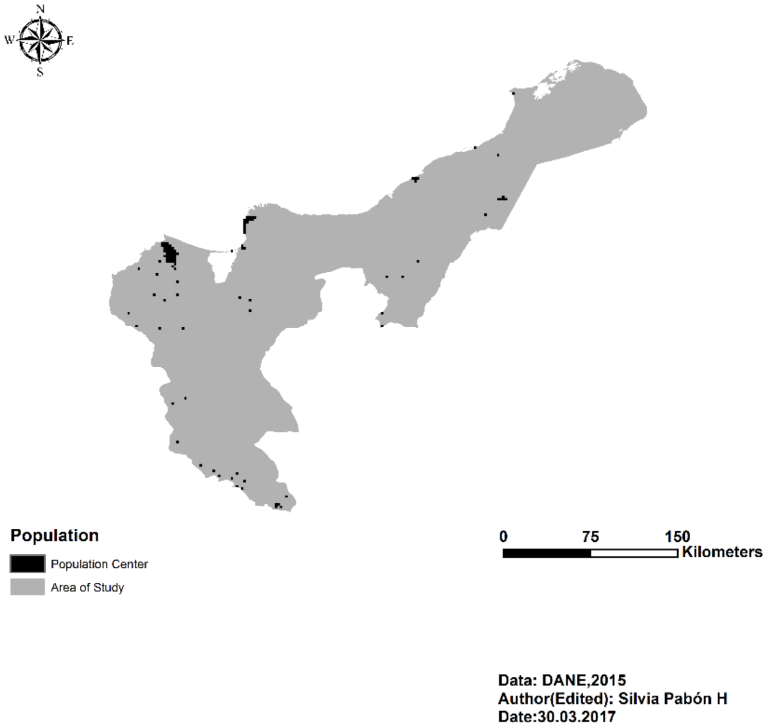
The impact of the noise and rotating from wind turbines can be annoying to neighbours if the turbines are installed too close or in the opposite direction about dwellings or holiday cottage (Chen et al., 2010).

In the proposed suitability model, areas closer than 550 m to residential areas are considered excluded, the population centre of the study area is shown in Figure 10.

The criteria distances from urban areas provide a visualization of the population center of the study area, most of the large cities are in the Atlantic department, unlike the Guajira department that represents a large surface, but with very reduce urban area, this department own one of the biggest deserts of Colombia and its population is centered in two small cities.

Distances from urban areas as a vector file called “population centre” is derived the from DANE, the process in ArcMap of these criteria reduced to two steps.

First used the *CLIP* tool to cut out a piece of the feature class, in this case, the “study area” and second using the conversion tools, transform the information from vector to raster using the tool *TO RASTER* (polygon to raster).



Data: DANE,2015
Author(Edited): Silvia Pabón H
Date:30.03.2017

Figure 10. Population centre, author´s map based on data from (Dane, 2015).

3.4.4 Distance from power grid

Although wind projects vary in scale, the same general components comprise any size project, the typical modern wind energy project consists of three major systems: wind turbines mounted on towers, an electrical collection system, and transmission/interconnection facilities, most projects also include access roads, O&M facilities, and meteorological towers (Wizelius, 2007).

Wind turbines are connected to three of electricity networks: transmissions, distribution and directly to the delivery point, the distinction between the three is based on the line voltage, the current-carrying capacity depends on the size of the conductor (Jain, 2011).

The structure of the power system in Colombia consists of a national transmission grid with a voltage level between 500 and 220 kV, this high voltage transmission network is used to transport large amounts of power over long distances.

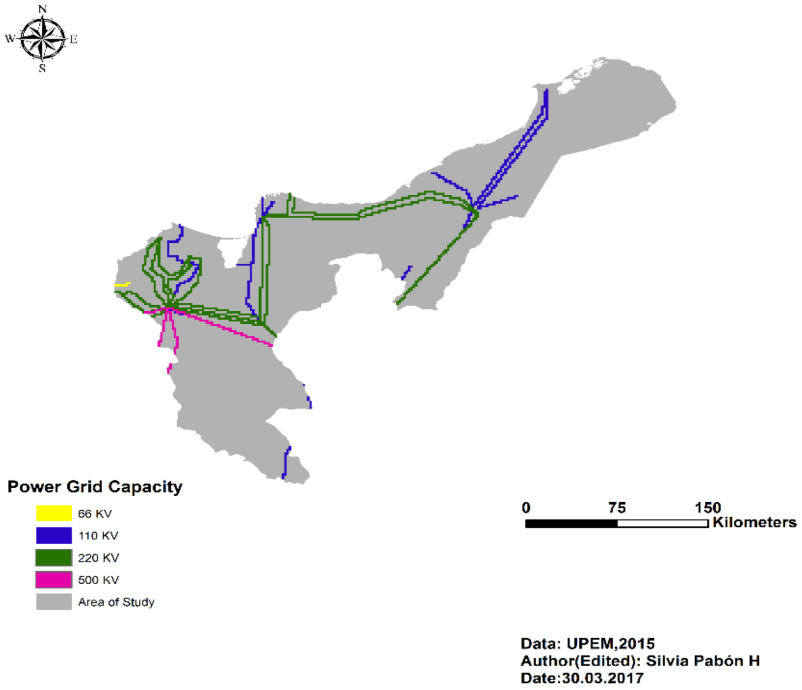
The next level is the regional transmission grid with a voltage of 110 kV, which transmits power to the local distribution network.

The criteria distance from electricity grid was obtained from UPEM, the map called “actual transmission national system from 2016”, show the power grid distribution type of the country.

The original data source was in PDF, from this source was necessary, do a three-measure procedure to translate it in a raster feature finally.

The first step is *GEOREFERENCING*; the second phase recreated the vector lines with the tool *CREATE FEATURES* (Line) and finally applying the conversion tools, transform the information from Vector to Raster using the tool *TO RASTER* (polyline to raster).

Based on Figure 11 power grid capacity is possible to observe that La Guajira department is the department from the study area with the lowest access to the power grid, even though the department owns an outstanding wind potential the technical resource in this case grid power is very limited, leading to suitability problems.



Data: UPEM,2015
Author(Edited): Silvia Pabón H
Date:30.03.2017

Figure 11. Power grid capacity, author´s map based on data from (UPME, 2015b).

3.4.5 Distance from road network

With the purpose of reducing the construction cost of new access roads and avoid soil sealing, wind turbines should be located as closely as possible to the existing road network; roads must have a minimum width of 4 m and a soil pavement (van Haaren, Fthenakis, 2011).

The criterion distance from road network was derived from the DANE, in format Vector, the original type was polyline in this criterion are include all the roads of Colombia.

This data source is not divided into categories for the type of road, hence is necessary check the information in open tools like Google maps, Figure 12 shows the access road in the study area.

The process of transformation is the following; first *CLIP* subsequently was using the conversion tools, transform the information from vector to raster using the tool *TO RASTER* (polyline to raster) with the purpose of generating the raster format.

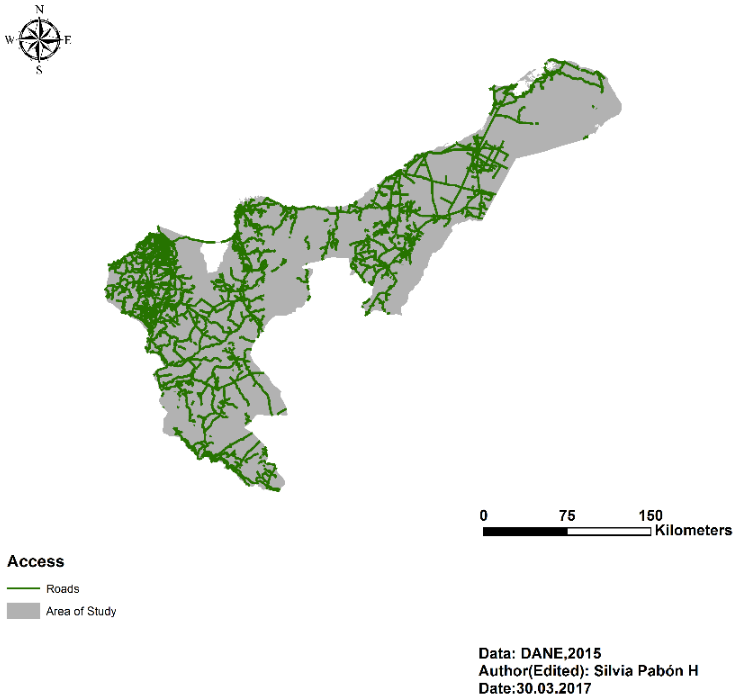


Figure 12. Access roads, author´s map based on data from (Dane, 2015).

3.4.6 Distance from natural environments and hydrographic resource

The potential negative impacts of wind energy can be summarised into avian/bat interaction with wind turbines, the visual impact of wind turbines, wind turbine noise, electromagnetic interference effects of wind turbines, the land-use impact of wind power systems (Manwell et al., 2009).

Likewise, the presence of wind farms may affect bird life in the following ways: collision, due displacement turbulence, barrier effect and habitat change and loss (Burton, 2011).

The criteria distance from natural environments comprises regionals natural parks, bird reserve, natural, civil reserve and the hydrographic resource, the natural environment type in the study area is shown in Figure 13.

The data was derived from the SIAC in vector format; the original feature was a polygon, the process of transformation of this criterion was made in three steps first with the tool *CLIP* to cut out the feature and visualise it in the study area.

Subsequently was using the *conversion tools* to transform the information from vector to raster using the tool *TO RASTER (*polygon to raster*)* with the purpose of generating the raster format.

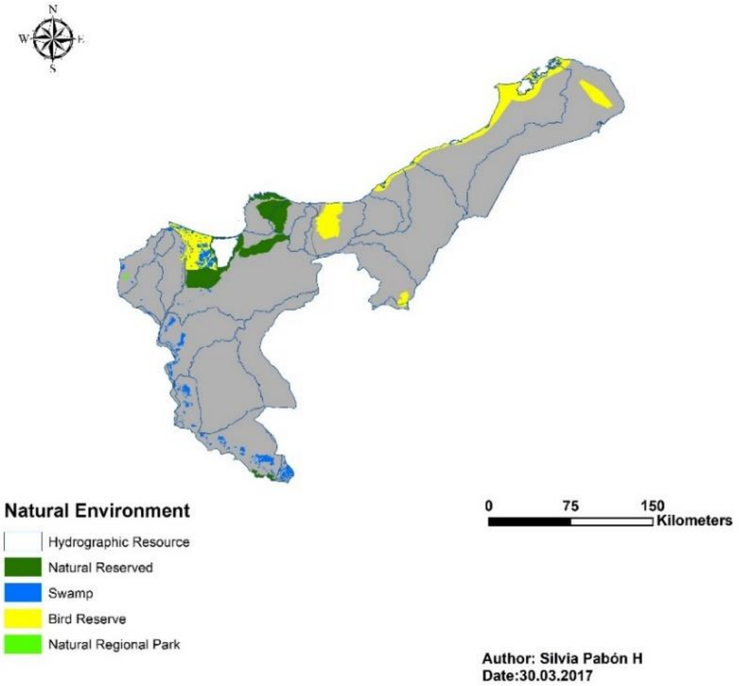


Figure 13. Natural environment type, author´s map based on data from (SIAC, 2016).

3.4.7 Digital elevation and slope data

In the wind industry one distinguishes between the roughness of the terrain, the influence from obstacles and the influence from the terrain contour, the more pronounced the roughness of the earth´s surface, the more the wind will be slowed (Jain, 2011).

Steep slopes of a surface can reduce the accessibility of cranes and trucks and increase building cost, specific recommendations for the maximum slope restriction is very complicated to find, in the literature review two studies applied a limitation for slope greater than 30% (Höfer et al., 2014) and (Tegou et al.) based on them in this thesis slopes larger or equal to 30% are excluded.

With the purpose of generating the slope feature, is necessary to create the digital elevation model (DEM). Therefore the contour lines derived from SIAC were selected. The slope present in the study area is shown in Figure 14.

The following steps describe the transformation process: first, the triangulated irregular networks (TIN) are created with the tool *CREATE TIN*, the TIN is converted to raster generated the DEM.

Once the DEM is generated the second step is creating the slope of the terrain, in *3D Analysis Tool, RASTER SURFACE* (Slope), and for the third step is necessary to classify the values into a percentage and at least five categories.

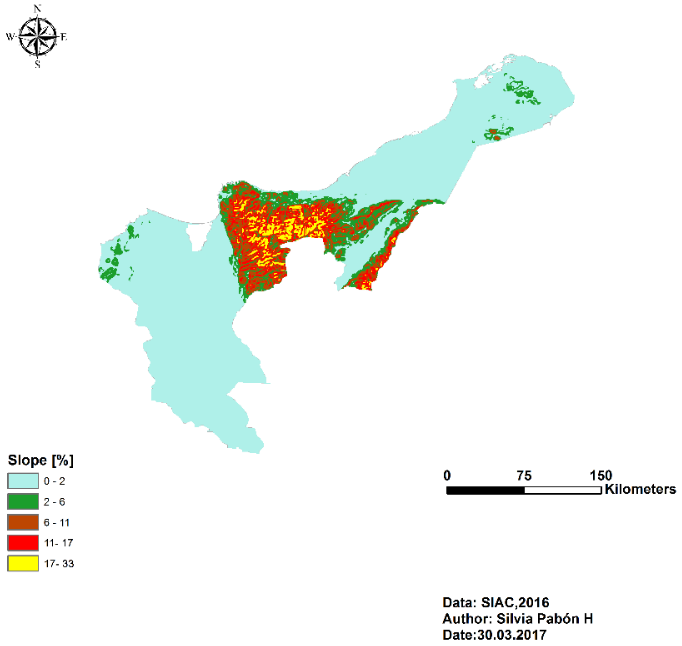


Figure 14. Slope, author´s map based on data from (SIAC, 2016).

3.5 Exclusion areas

Following the methodological framework proposed in figure 7, the next step is determinate the restricted area also called *exclusion areas*, these areas are determinate according to the legal regulation, wind assessment standards and literature review. Table 6 exposes the different exclusion parameters corresponding to each selected criterion.

In the case of wind energy potential all the values below to 5 m/s are excluded, for natural environment parameters (forest, regional natural park, civil reserve and bird reserve) all are excluded:

In the case of the slope criteria, the exclusion was defined as follows “all terrain with a slope greater than 30% are excluded” as well as land used (agroforestry, reserve and forest).

In particular cases such as urban centre and rivers are created Buffer zones i.e. minimum distance around each parameter.

Table 5.Exclusion parameters.

Criteria	Exclusion Parameter	Buffer Zone
Wind energy potential	< 5 m/s	-
Distance from urban areas	Urban centre, municipality	550 m
Infrastructure	Roads Transmission lines	100 m 100 m
	Water bodies	100 m
Natural environment	Forest Regional natural park Natural, Civil Reserve Bird reserve	-
Slope of terrain	≥30%	-
Land Use	Agroforestry Reserve Forest	-

3.5.1 Restriction model

The restriction model aim is to generate an approximation evaluation of the exclusion area of the study area following the exclusion parameters exposed in Table 6.

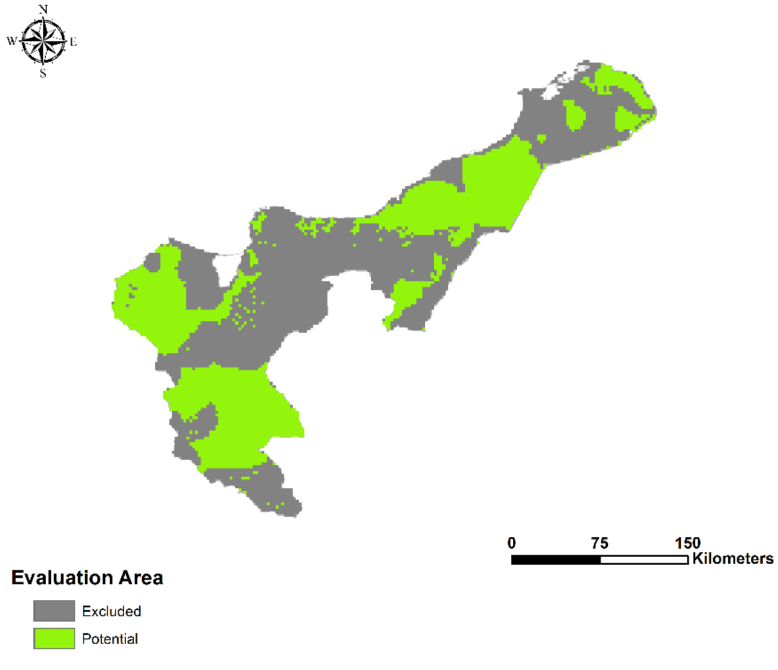
Through ArcMap, the restriction model is created, with the support of this software and it different spatial tools, such as *BUFFER* to generate the minimum distance from urban areas, transmission lines and roads, after the BUFFERS are created.

The following process is called *RECLASSIFY* in this process all criteria values are reclassified in two classes zero or one, zero indicates an unsuitable value and 1 is a suitable value.

For example, the slope´s criteria, all the values greater or equal to 30% are classified as zero; it means that these values are excluded, as well as in the wind potential criteria all the values greater than 5 [m/s] the value of one is given.

Finally, the criteria are reclassified into two values zero (excluded area) and one (potential area) the tool *RASTER CALCULATOR*, which enables the construction and execution of a single map algebra expression in Python syntax, generating the new map features.

The evaluation area in Figure 15. Shown that the excluded area with almost 21.455 km^2 (55.24%) is remarkably greater than the potential area of 17.38 km^2 (44.75%) due to environmental and technical constraints, the region generated an economical challenged to develop wind farms due to the low power grid access, the restriction model flow is exposed in Appendix F.



Author: Silvia Pabón H
Date:30.03.2017

Figure 15. Restriction model, author´s map.

3.6 Rated potential model

The rated potential model potential model is performed, creating a rated potential model, this evaluation considered the six from the eight criteria defined in Table 6, as well as the rated potential model flow, is shown in Appendix G.

Table 6. Rated criteria.

Criteria

- Wind energy potential
- Distance from road network
- Distance from electricity grid
- Distance from urban areas
- Distance from natural environment
- Land use

The rated potential model process starts in ArcMap where the criteria are evaluated; three tools are applied to perform a successful model, *EUCLIDEAN DISTANCE, RECLASSIFY* and *WEIGHT OVERLAY*.

The first step is performed the *EUCLIDEAN DISTANCE* tool, which calculates the distances range of distance-dependent criteria, here each criterion generated a distance range, according to its characteristics.

For the criteria wind, energy and land using the Euclidean distance are not performed due to the criteria are classified according to velocity and type of land use.

RECLASSIFY is the second step, this tool is used to evaluate the importance of the criteria, with a scale factor of one to five, where one is, the less critical value and five are the most significant value, the evaluation of the different criteria using the scale factor is shown in Table 7.

The third step of generated the rated potential model is combining all the input criteria with the *WEIGHT OVERLAY* tool combine the assigned value scores for each criterion with their relative importance. Accordingly, the rated are map will display the distribution of value scores across the study area (Höfer et al., 2014).

Considering each Criterion's weight finding the most suitable areas for developing a wind farm project.

Table 7.Criteria and values scores.

Value Score	Rated potential area	Wind energy potential	Land use	Distance from natural environments	Distance from urban areas	Distance from power grid	Distance from road network
		[m/s]	[type]	[m]	[m]	[m]	[m]
0	Excluded	<5.00	Reserve	0-100	0-550	0-100	-
1	Low	-	Forest	100-184	550-650	>1,515	>2,281
2	Low	5-6	-	184-413	550-650	610-1,515	882-2,281
3	Medium	6-7	Agroforestry	413-658	650-1,0044	308-610	454-882
4	High	7-8	Cropland	658-984	1,0044-2,5208	154-308	178-454
5	Very high	>8	Pasture	>984	>2,5208	0-154	0-178

After the performance evaluation of the different criteria in the study area is easy to visualise the result, Table 7 describes the Values scores of the rated potential model which are divided into six categories from excluding (value score of 0) to very high (value score of 5).

Where category very high is for all these sites with a wind energy greater than 8 m/s, a land use type pasture, these sites are quite far from the natural environment and urban areas, however; these suitable sites are near to the power grid and roads.

In addition, Figure 16. Shows the result of the rated potential area; it can be clear, observe that the "*Jepirachi* Wind farm" in La Guajira is located in an estimated area classify as medium.

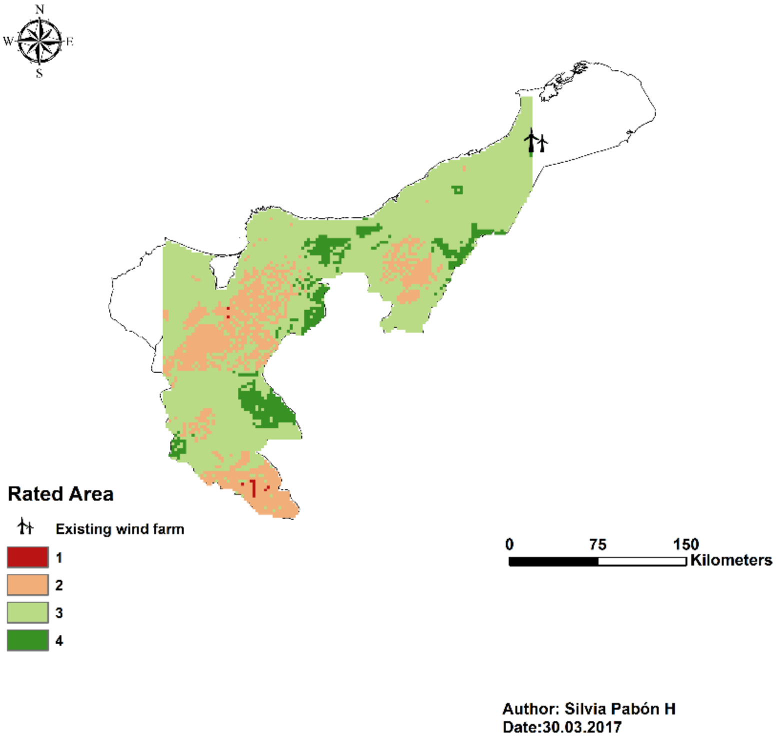


Figure 16. Rated model, author´s map.

3.6.1 AHP weights

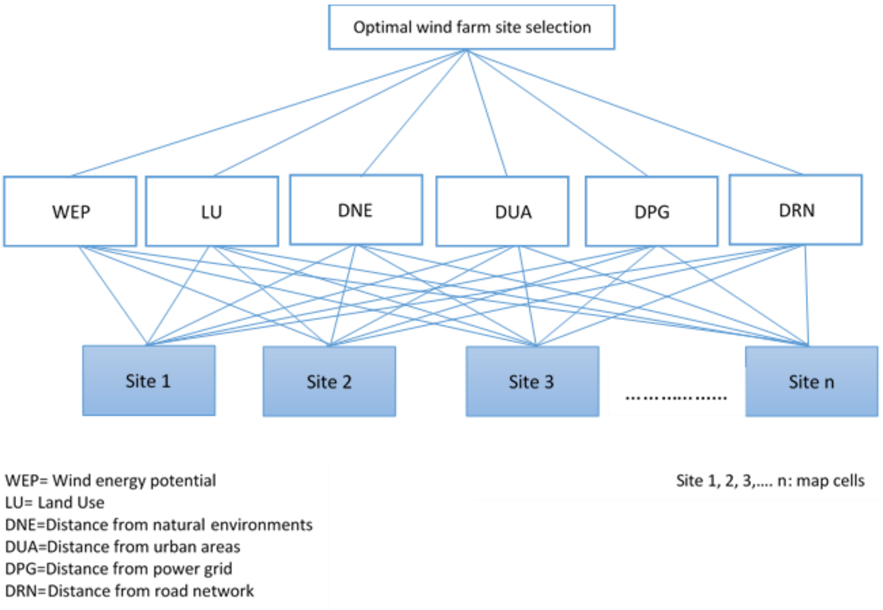
The last step of the suitability study is the consolidation of exclusion area and rated area; the consolidation process has to be performed with the analytic hierarchy process approach, Figure 17. Provides the overview of the process for the selection of the optimal wind farm sites in a hierarchical structure.

Where, the optimal wind farm site selection is considered the *goal*, for instance, is at the top level, the criteria that influence the goal achievement are on the second level (*criteria*), and the bottom level of the structure is the potentially suitable sites as *alternatives*.

The relative importance of the criteria in this thesis is generated from three sources, first the review of literature and "State of the Art" concerning assessment of wind farms,

Second a consulting with a wind energy assessment expert, who shared his experience related to the essential criteria for build a wind farm and the third resource the application of the knowledge acquired by the author in the master.

The processing of data and information to generate the relative importance or weight is illustrated in Appendix B: Standardized Matrix, where the weights, as well as the consistency matrix index, are calculated.



WEP= Wind energy potential
LU= Land Use
DNE=Distance from natural environments
DUA=Distance from urban areas
DPG=Distance from power grid
DRN=Distance from road network

Site 1, 2, 3,…. n: map cells

Figure 17.Schematic of the hierarchical structure of the evaluation criteria, author´s diagram based on Saaty (1990).

Table 8 describes the result obtained; the relative importance results are quite similar with the information found in the literature review, wind energy potential is an essential criterion with a relative importance of 30.1%

Following by distance from natural environments, distance from the power grid and land use with 15.7 and 16.9% respectively, the lowest relative importance criteria in this study are the distance from road network and distance from urban areas with 8.7% and 6.7% respectively.

Table 8.The relative importance of criteria.

Criterion	**Relative importance [%]**
Wind energy potential	30.1%
Distance from natural environments	15.7%
Distance from power grid	16.9%
Land use	22.6%
Distance from road network	8.7%
Distance from urban areas	6.7%

Table 9 describes the suitability index corresponding to the evaluation of the study area, with a value score between 0 and 5, where zero represents the excluded areas and five areas with very high suitability potential.

Table 9. The suitability index.

Suitability	Value Score
Excluded	0
Low	1
Medium	3
High	4
Very high	5

3.6.2 Suitability model

The suitability model is the combination of the restriction model and the rated potential model; this model is created in order to find the optimal sites for developing a wind farm in the study area, in ArcMap with the tool *TIMES*, the exclusion model and the rated potential model are combined as a result of the combination the suitability model is created.

In order to obtained the suitability wind energy potential area for each department of the study area, the *Zonal Geometric As Table (Spatial Analysis)* tool is used, the Zonal tool calculates for each zone(suitability index) in a data set the geometry measures such as area, perimeter, thickness or the characteristics of the ellipse, after performance the calculation the tool reports the results as a table such as Table 10.

The suitability model results are divided into five categories(suitability index), from excluded to very high, Figure 18. Illustrates the wind energy suitability in the study area, as well as the suitability model flow is shown in Appendix D.

Table 10. Suitability index according to the study area's department.

Value Score	Suitability index	La Guajira [km^2]	The Magdalena [km^2]	The Atlántico [km^2]
0	Excluded	8.7302	10.3	2.043
1-2	Low	-	0.000484	-
3	Medium	2.952	0.07115	0.046
4	High	5.677	5.1062	1.56
5	Very high	0.0484	1.9301	-

The suitability model results determined, that almost the 55.24% of the study area is excluded, 1% of the study area has a low suitability for developing wind farms, the 2% has a medium-suitability category, as well as, the 37.73% of the study are own a high suitability, and the 3.1% of the study is has a very high suitability.

It means that nearly the 43.83% of the study area is suitable for onshore wind energy, In addition, as exposed in Figure 18, it can be clear, observe that the "*Jepirachi"* wind farm, in La Guajira is located at this model in an estimated area classify as high.

Although for a potential investor or shareholder is very impressive that the 55.7 % of the study area is excluded, this percentage is due to two mainly constraints, first deficiencies of technical factors (distance from power grid) and second the outstanding presence of the natural environment in the study area including natural parks, bird reserve and hydrographic resources.

However, is remarkably the high potential present in the study area with almost 40% of high suitability for developing onshore wind farms and obviously, the potential will increase if the evaluation is a performance for an offshore project due to the study area strategic position surrounded by the Caribbean Sea.

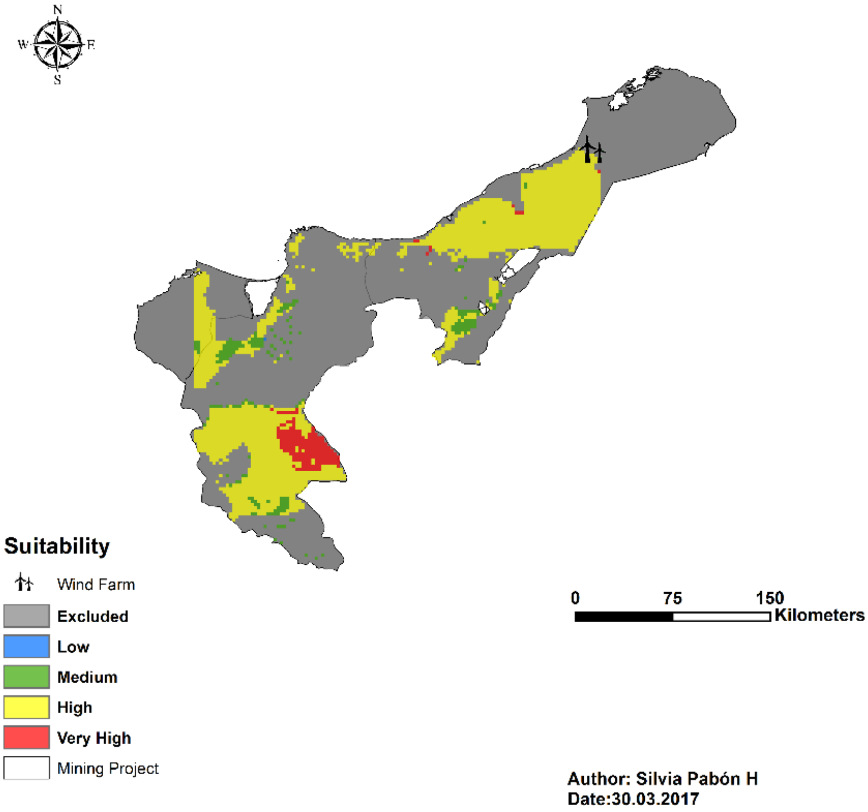


Figure 18.Wind energy suitability of study area, author´s map.

4. Wind farm project

The process of developing a wind farm project is complex, with several steps to be coordinated simultaneously, many of the tasks which are concurrent rather than sequential. Therefore developer must perform different tasks on the same project (Busby, 2012).

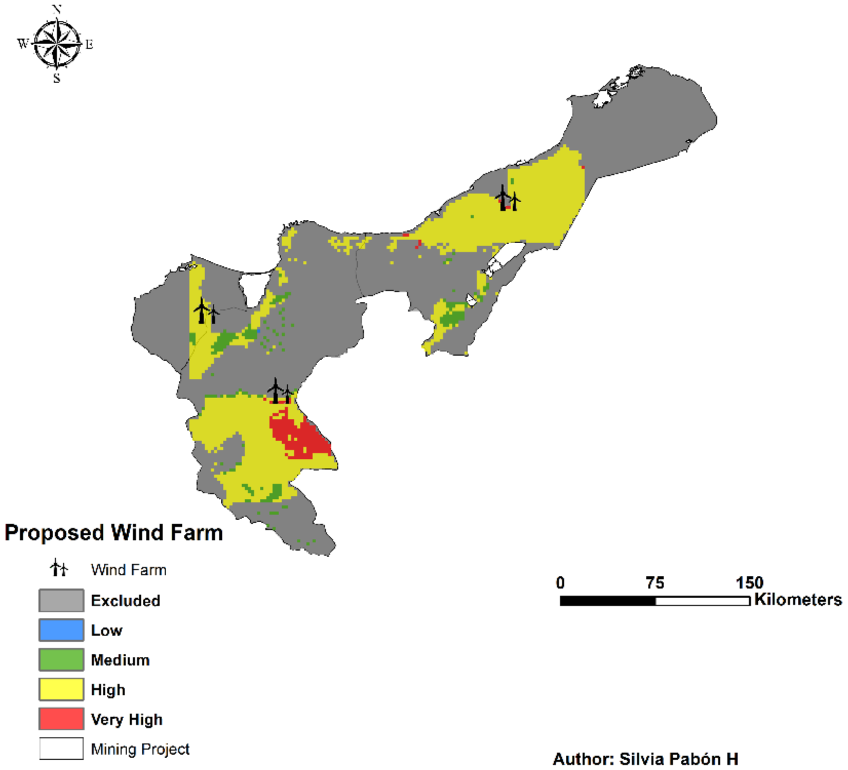
The following is a wind farm development project review that describes the steps that a developer may apply to develop an onshore wind farm.

Five typical phases of developing an onshore wind farm are considered: Selecting the optimal site, wind assessment, turbine selection, turbine output and turbine siting issues.

4.1 Selecting the optimal site

As described in chapter three, the selected study area owns a noteworthy wind potential, in Figure 19 shows the proposed wind farm sites in three different locations in the study area: La Guajira (Latitude: **11° 13' 47.28'' N,** Longitude: **72° 57' 11.16'' W**), in Magdalena (Latitude: **9° 43' 21.335'' N,** Longitude: **73° 56' 22.69'' W**) and in Atlántico (Latitude: **10° 45' 29.124'' N,** Longitude: **74° 50' 33.899'' W**).

The proposed wind farms are sited in areas with a very high suitability category, except for the wind farm located in the Atlántico department, which is being sited with a high wind suitability category.



Author: Silvia Pabón H
Date:30.03.2017

Figure 19. A proposed wind farm in the study area, author´s map.

4.2 Wind assessment

The following section will discuss the different issues related to wind power generation as well as characteristics of the wind properties with a focus on the proposed wind farm project in the La Guajira Department.

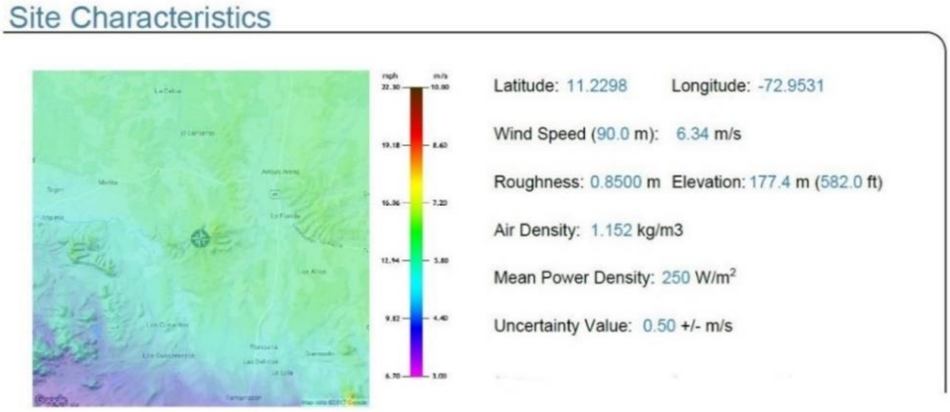
4.2.1 Selected site characteristics

The proposed wind farm is located at Latitude: 11° 13’ 47.28’’ N, Longitude: 72° 57’ 11.16’’ W, with an annual average wind speed of 7[m/s] and a monthly average temperature of 35°C.Table 11 describes the monthly wind speed of the selected site according to (IDEAM, 2002).

Likewise, in Figure 20 and Figure 21 describes the site characteristics calculated with the help of the *software AWS Truepower, Windnavigator® dashboard*.

Table 11. Monthly wind distribution of selected site.

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Average
Wind Speed [m/s]	7	8	7	8	7	7	9	6	6.	6	7	6.5	7



Site Characteristics

Latitude: 11.2298 Longitude: -72.9531

Wind Speed (90.0 m): 6.34 m/s

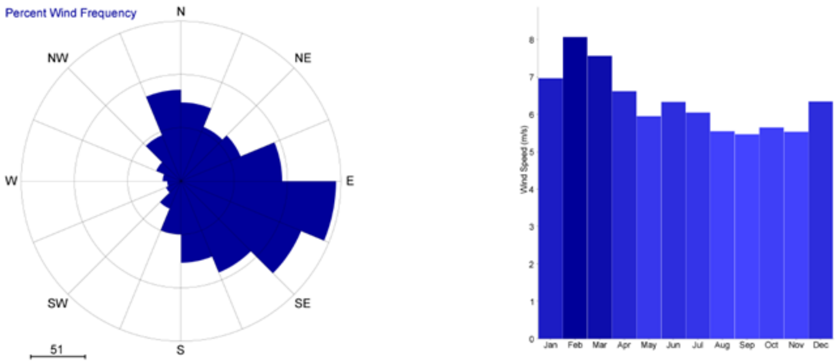
Roughness: 0.8500 m Elevation: 177.4 m (582.0 ft)

Air Density: 1.152 kg/m3

Mean Power Density: 250 W/m^2

Uncertainty Value: 0.50 +/- m/s

Figure 20. Site characteristics at hub height 90[m], based on Windnavigator software.



Wind Rose

Monthly Distribution

Figure 21. The wind rose and monthly distribution at hub height [90m], based on Wind navigator software.

4.2.2 Roughness and shear

Wind speed will increase with the height because the friction of the earth's surface is significant; The rather of the increase of wind speed that often used to characterise the impact of the roughness of the earth´s surface on wind speed (Jain, 2011) is given as:

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$ *Equation (5)*

Equation (5) shall be used to compute the unknown V, where *V* is the wind speed at height *H* (often referred to the Hub Height), and V_0 is the wind speed at height H_0 (often a reference height of 10 m), and α is the friction coefficient.

The friction coefficient *α* is a function of the terrain over which the wind blows. Table 12 gives some typical values for rather loosely defined terrain types.

Table 12. Friction coefficient for various terrains.

Terrain Characteristics	**Friction Coefficient (α)**
Smooth, hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Largest city with tall buildings	0.40

From the proposed wind farm the following data are obtained, V_0=7 [m/s], H_0= 10 [m] and H = 90 (Approx. Hub height) substituting the values in the Equation (5),

$$V = V_0.\left(\frac{H}{H_0}\right) = 7[m/s].\left(\frac{90}{10}\right)^{0,1} = 8{,}72\ [m/s]$$

The next step is to calculate the Weibull parameters as well as the power production of the selected wind turbine in the chosen site.

4.2.3 Weibull distribution of wind speed

When the wind speed frequency(distribution) is unknown, the Weibull distribution can be used to estimate the wind speed distribution for a site by putting in the shape parameter(k) and the scale parameter(c) (Zobaa, Bansal, 2011).

For wind speed is a stochastic quantity, the most common density function used to represent wind speed is the Weibull distribution, whose probability density function p (ʋ) is given by Equation (6):

$$p(\upsilon) = \left(\frac{k}{c}\right).\left(\frac{V}{c}\right)^{(k-1)} \exp\left[-\left(\frac{V}{c}\right)^{(k)}\right]$$ *Equation(6)*

The Equation (6) may be used to calculate the probability of occurrence of wind speed between certain intervals, where *V* is the wind speed, *k* is the shape factor, and *c* is the scale factor.

There are several methods by Weibull shape factor “k” and Weibull scale of the factor of “c” can be determined. According to (Justus et al., 1977), it is possible to calculate the parameter k using the average wind speed by applying the formulae in Table 13.

Table 13.The k factor calculation.

Variance	**Velocity**	***k***
Low	V>4 m/s (Coastline)	$1{,}05\sqrt{\tilde{V}}$
Medium	V>4 m/s	$0{,}94\sqrt{\tilde{V}}$
High	V<4 m/s	$0{,}93\sqrt{\tilde{V}}$

Since the wind speed in the proposed wind farm is greater than 4 [m/s], the k factor is calculated with k= 0, 94$\sqrt{\tilde{V}}$ as following:

$k = 0{,}94\sqrt{8{,}618}$ =2, 77

The Weibull scale of factor *c* is a characteristic speed related to the average wind speed at the site (Burton, 2011) by:

$$c = \left(\frac{\tilde{V}}{\Gamma(1+\frac{1}{k})}\right) \qquad \textit{Equation(7)}$$

The Equation (7) may be used to calculate the Weibull scale factor, where Γ is the gamma function, $\tilde{V}$ is the Average wind speed, and *k* is the Weibull shape factor. Applying the Equation (7) the scale factor is calculated as follows:

$$c = \left(\frac{\tilde{V}}{\Gamma(1+\frac{1}{k})}\right) = \frac{8{,}72}{\Gamma(1+\frac{1}{k})} = \frac{8{,}72}{\Gamma(1{,}361)} = \frac{8{,}72}{0{,}9354} = 9{,}31\ [m/s]$$

Applying the Equation (6), the probability density function is calculated, and the results are shown in Appendix E and Figure 22 Weibull distribution of wind speed in the selected site.

$$p(v) = \left(\frac{2{,}77}{9{,}31}\right).\left(\frac{V}{9{,}31}\right)^{(2{,}77-1)} exp\left[-\left(\frac{V}{9{,}31}\right)^{(2{,}77)}\right]$$

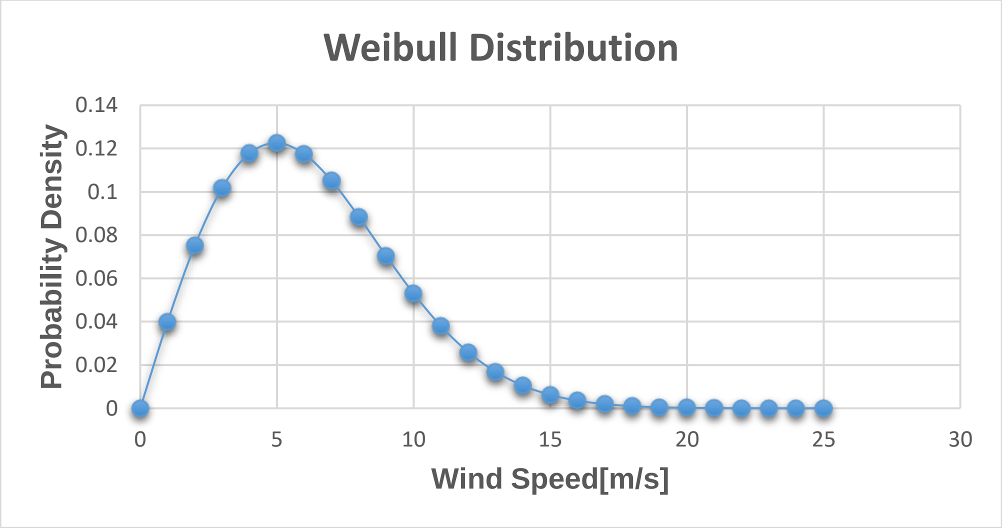


Figure 22.Weibull distribution of wind speed at the selected site, author´s diagram

4.3 Turbine selection

Potential site conditions never match perfectly to the parameters specified in the catalogue of the turbine; Wind developers shall ensure that the machine will perform as specified over a 20-year life.

Hence normally wind developers get performance curves and other specifications from at least two wind turbines with the aim of making performance comparisons.

For the proposed wind farm in La Guajira Department, the Gamesa G128- 5.0 MW **(**Appendix H contain the description of the characteristics of the wind turbine) wind turbine is selected for the following reasons:

- The G-128 5.0 MW wind turbine has a higher power production with a limited space; besides large turbines are expensive that small turbines the amount of manpower involved in building a small machine is not very different from what is required to build a large machine, e.g. the safety features, and some electronics needed to run a small or a large machine are roughly the same (Wizelius, 2007).

- Gamesa nowadays is focused on the Latin American market, with projects in Brazil, Mexico, Honduras and Costa Rica making uncomplicated the benchmarking between similars projects and knowledge transfer.

- Gamesa is a Spanish company, which reduces the communication problems considering that the official language of Colombia is Spanish.

An important factor in the selection of the wind turbine is the power curve, which shows how much power the rotor produces at different wind speeds.

Typically the wind turbine catalogue specifications are expressed with reference to a standard air density, which is given as 1.2256 [kg/m^3] at a standard temperature of 15 °C.

Since these characters are not the conditions of the selected site, it is necessary to adjust the air density by altitude and temperature according to (Park, 1981).

For instance, the density correction formula is given as follow:

$$\rho = \mathrm{C_A} \times \mathrm{C_T} \times 1{,}2256 \, \frac{\mathrm{kg}}{\mathrm{m}^3} \qquad \textit{Equation(8)}$$

The Equation(8) proposed for (Park, 1981) may be used to calculate the density of the air at the selected site, where C_A is the altitude correction factor in meters, and temperature correction factor and C_T is the temperature correction factor in °C.

In Table 14 the adjusted power value of the turbine with the combination of the factors of C_A and C_T are described.

Table 14. Altitude and temperature correction based on (Park, 1981).

Altitude[m]	**C_A**	**Temperature[°C]**	**C_T**
0	1	-18	1.13
762	0.912	-6	1
1524	0.832	4	1.04
2286	0.756	16	1
3048	0.687	27	0.963
		38	9.929

Nevertheless, the proposed site is located at 10 meters above sea level, with an average temperature of 35°C. Moreover, interpolation is necessary to for intermediate values. The correction air density by height is shown in Figure 23, and the correction air density by temperature is shown in Figure 24.

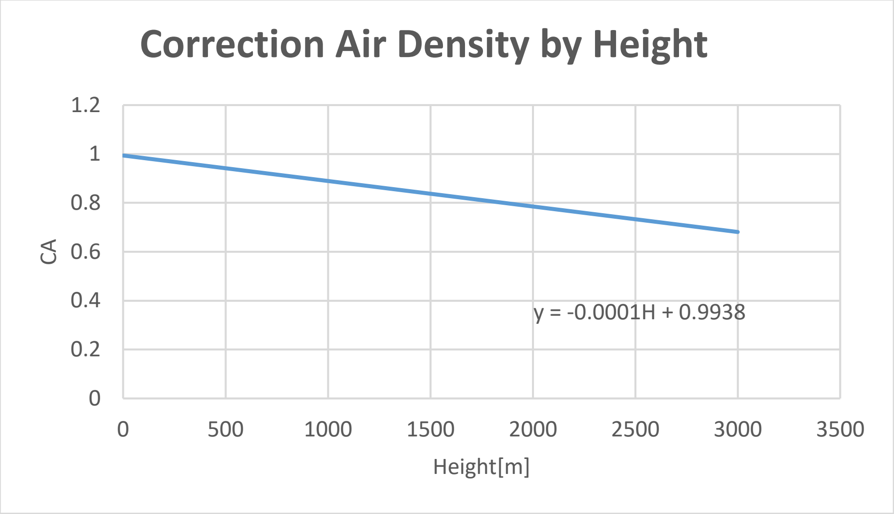


Figure 23. Correction air density by height, author´s diagram.

Where C_A Altitude correction factor equation is equal to:

$$C_A = -0.001H + 0.9938 \qquad \text{Equation(9)}$$

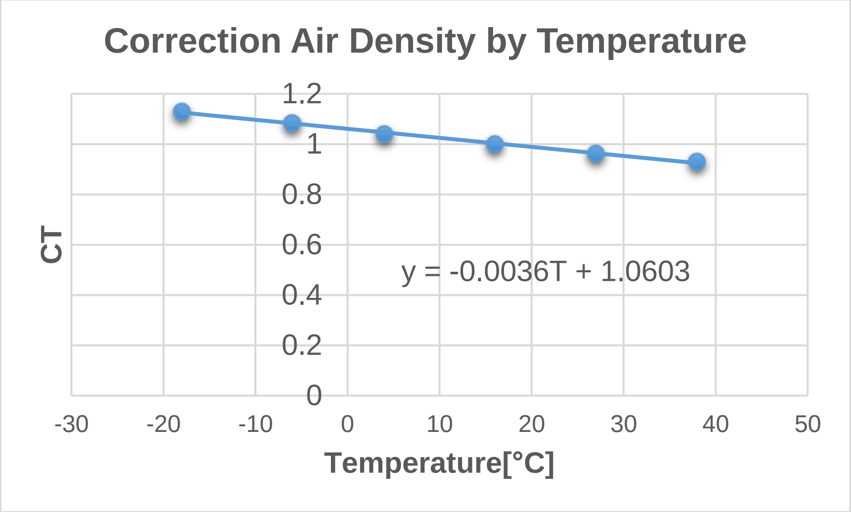


Figure 24. Correction air density by temperature, author´s diagram.

Where C_T Temperature correction factor is equal to:

$$C_T = -0.0036T + 1.0603 \qquad \text{Equation(10)}$$

Substituting the site characteristics values in the Equation (9) and Equation (10) for obtaining the altitude and temperature corrections factors,

$C_A = -0.001(10m) + 0.9938 = 1.0038$ and $C_T = -0.0036(35°C) + 1.0603 = 0.9343$

From Equation (8), (9) and (10) the value of the density at the selected site is obtained as follows:

$$\boldsymbol{\rho} = \mathbf{C_A \times C_T \times 1{,}2256 \frac{kg}{m^3}} = 1.0038 * 0.9343 * 1{,}2256 \frac{\mathrm{kg}}{\mathrm{m}^3} = 1.1494 \frac{\mathrm{kg}}{\mathrm{m}^3}$$

The value of density is in close accordance with the value estimated by the Windnavigator® (1.152 kg/m^3).

To adjust the wind turbine power curve, the wind turbine power shall be multiplied by the relation of the correction factors $\mathbf{C_A \times C_T}$ = 1.0038 x 0.9343= 0.9378

Figure 25 shows the power curve and the adjusted power curve of the Gamesa 5.0 MW wind turbine at the altitude and temperature of the site the maximum power of the turbine is 4.689 MW instead of 5.0 MW.

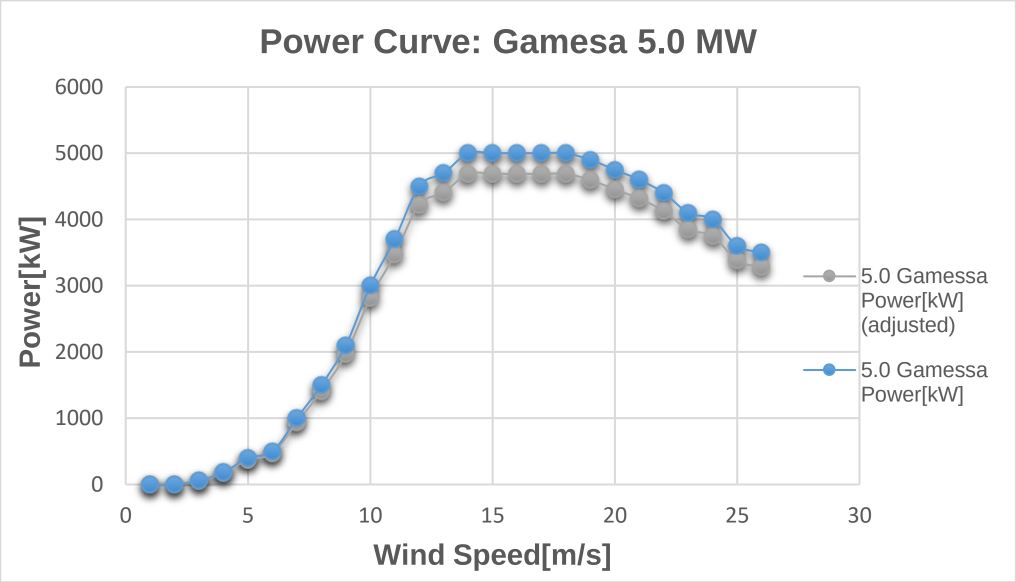


Figure 25. Power curve Gamesa 5.0 MW (adjusted at site characteristics), author´s diagram.

4.4 Estimated power production

How much power the wind turbine at the selected site will produce, is the most significant input to the economic calculations as well as the final decision to go through with the project or not.

The estimated power production helps the developer to show an overview of project regarding the possible revenues for the project investors and shareholders

To calculate the electrical output of a wind turbine at a given site, two things must be known-firstly, the power curve of the wind turbine and secondly, the frequency distribution of the wind speed at the hub height at the site (Wizelius, 2007).

4.4.1 Energy yield (E)

The energy yield generates from the turbine over a period can be computed by adding up the power corresponding to all possible wind speeds in the related conditions at which the system is operational defining by (Stiebler, 2008) as follows:

$$E = \sum_{i} P_r(V_i) \, . \, t_i \qquad \text{Equation(11)}$$

Equation (11) may be used to calculate the energy yield (E), one of the most important data developer project as well as shareholders and decisions takers. t_i is the time during which the (V_i) wind speed occurs, and $P_r(V_i)$ is the power for $V = V_i$ based on the wind turbine power curve. The result of applying this formula is shown in Appendix E.

After having the information about the power production of a single turbine at the selected site, it is necessary to calculate the total power generation of the 15 turbines of the wind farm; Including the possible power losses that should be considered for a real calculation of the total power output of a wind farm.

4.4.2 Energy losses

When a wind farm developer undertakes a project, they will initially look at the wind climate and the power. However, the power generation will be reduced by some factors, including:

- *Array losses*, or park effects, which occur due to wind turbines shadowing one another in a wind farm, leaving less energy in the wind downstream of each wind turbine.
- *Rotor blade soiling* losses, soiled blades are less efficient than clean ones.
- *Grid losses* due to electrical (heat) losses in transformers and cabling within the collection grid inside the wind farm (EWEA, 2009).

The percent of losses is divided into two categories, losses from the wind turbine and losses corresponding to wind farm project sited, as is described in Table 15.

Table 15.Losses per kWh/year of a wind farm, based on (EWEA, 2009) and (Hau, 2013).

Component / Parameter	%Losses	kWh/year
Wind Turbine		
Gear Box	1%	3,026,034
Rotor blade soiling losses	1%	3,026,034
Transformer	1%	3,026,034
Yawing	2%	6,052,067
Sited Project		
Technical losses	1%	3,026,034
Technical availability	1%	3,026,034
Array losses	4%	12,104,134
Overall Safety deduction	2%	6,052,067
Grid losses	2%	6,052,067
Total losses	15%	45,390,503

Table 16.A 75 MW Wind farm power output.

Wind Farm (15 turbines)	kWh
Total Power Output	302,603,354
Losses (15% of the power output)	45,390,503
Total Power Output	257,212,851

The total wind farm power output of 257,213 MW describes in Table 16 is enough to supply 76,711 Colombian households, assuming a capacity factor of 30% and 3.353 MW annual average amount of energy used in Colombia households (WEC, 2014).

Once the energy yield is known, the capacity factor is calculated assessing the performance of the wind turbine, this is a percentage defined as the actual amount of energy produced by a wind turbine or farm over a given period divided by how much energy it should have generated during that time if running at maximum output (Busby, 2012).

The annual value of capacity factor can be calculated with the formula given below:

$$Cp = \frac{Total\ amount\ MWh\ produced}{rated\ MW\ x\ hours} \qquad \text{Equation(12)}$$

Equation (12) may be is used to calculate the performance of the wind turbine over a year, where the total amount of MWh produced by the turbine is the sum of the Power output in the case of study is 20,174 MWh.

The rated MW which is the maximum power output that can be extracted from the turbine in a year in the proposed wind farm is used the adjusted power output at the site characteristics (4.718 MW instead of 5.0 MW) by 8760 hours/year.

Substituting the values from the Equation (12) for getting the value of the Cp:

$$Cp = \frac{257{,}213}{619{,}910} = 41{,}4\%$$

Today´s utility-scale wind turbines typically operate 65%-90% of the time, but often at less than full capacity (lower than the maximum power rating). So, when actual output is accounted for, capacity factors of 25% - 40% are common, and 33%-35% is about average (Busby, 2012).

4.5 Turbine siting

Siting a turbine within a wind project involves careful considerations of an array of factors relating to the terrain such as Hills and obstacles, sound propagation, shadows, wake effect and impact in the landscape.

In order to maximise the energy production, careful attention must be paid to the prevailing wind direction, proper spacing of wind turbines is critical to obtaining the maximum energy output of a wind farm.

For turbines that are erected side-by-side, perpendicular to the site´s prevailing wind, the turbines ideally should be spaced at least three rotor diameters apart or up to five diameters, if enough space is available.

Turbines that face into the prevailing wind arranged front to back, should be a least five rotor diameters apart or up to ten diameters (Busby, 2012).

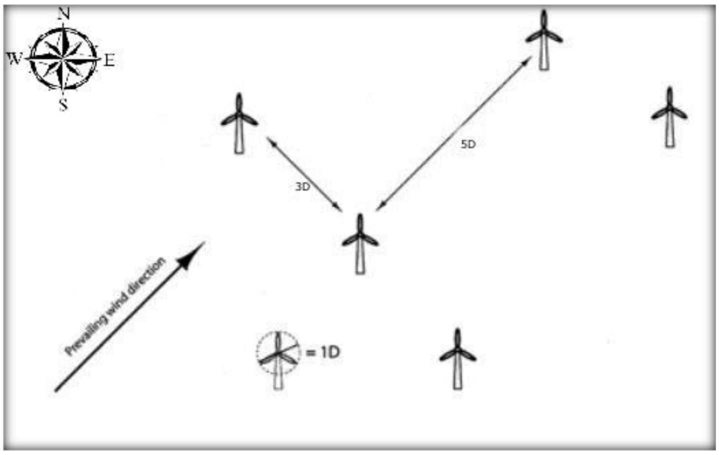


Figure 26. Wind turbines spacing distance, author´s diagram based on (Busby, 2012).

The proposed wind farm spacing distance is shown in Figure 26, the predominant wind direction in the selected site is described as East(E) predominant wind direction from January to December except in April with predominant wind direction North-North-East(NNE).

Likewise, the lower wind speed occurs between August and October with an average wind speed of 6 [m/s] due it the rows are situated perpendicular to those prevailing winds.

Appendix I showed the wind farm layout for developing 15 turbines wind farm in the selected sited in the Guajira department.

For the generation of the design of the proposed wind farm in ArcMap was necessary added a Base map (topographic) from ArcGIS online, finding the selected site according to the suitability category, for this wind farm the very high suitability category was selected.

The diameter of the turbine’s rotor was created with the *BUFFER’S* tool in ArcMap, which generates a buffer of 128 m around every turbine in order to visualised the distance that shall be present between every turbine.

Likewise, the prevailing wind of the selected site (coordinates and wind direction information) was obtained from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, acronym in Spanish).

4.5.1 Noise

The sound emission from a wind turbine is about 100dB, varying from 95 to 108dB. The noise from modern wind turbines originates from the rotors blades. Sound-absorbing materials, better precision in the manufactured components and damping. Have eliminated the mechanical noise in the nacelle.

Figure 27 shows the propagation of sound propagation from a wind turbine. Table 17 shows the noise level from a wind turbine related to distance in meters and Appendix J shows the noise propagation of the wind farm in the selected site.

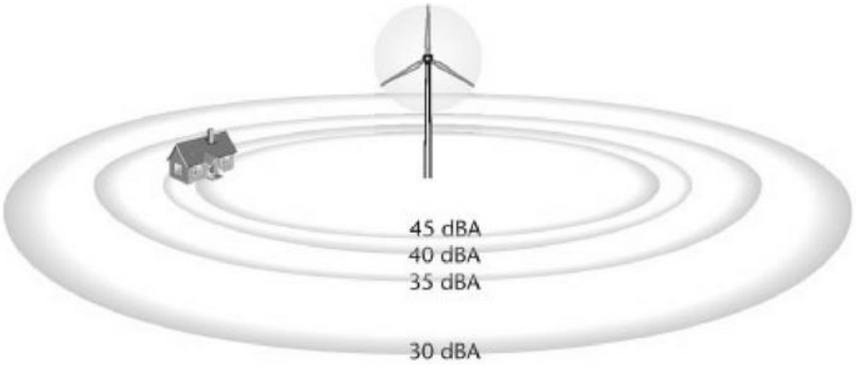


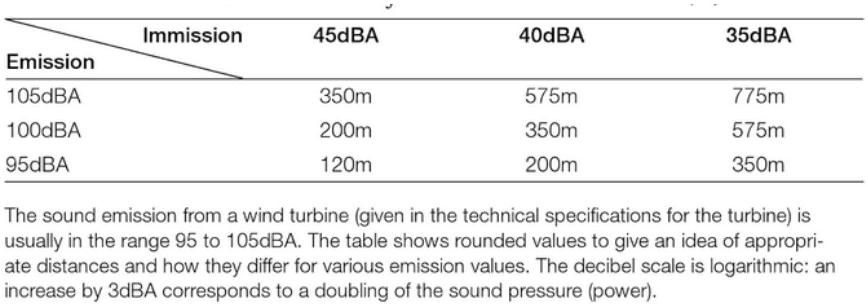
Figure 27. Wind turbine sound propagation, based on (Wizelius, 2007).

For the generation of the sound propagation of the wind farm in ArcMap was necessary added a Base map (topographic) from ArcGIS online and generated three different buffer with the *BUFFER* tool of ArcMap.

The wind turbine sound propagation was divided into three categories 35 dBA (775 m), 40 dBA (575 m),45 dBA (350 m) generating three buffers around every wind turbine of the wind farm based on (Wizelius, 2007).

Nevertheless, the result of the sound propagation in the selected wind farm shows that the nearest population centre is at 1.95 km.

Table 17.The sound level from a wind turbines/distance[m] based on (Wizelius, 2007).



Immission Emission	45dBA	40dBA	35dBA
105dBA	350m	575m	775m
100dBA	200m	350m	575m
95dBA	120m	200m	350m

The sound emission from a wind turbine (given in the technical specifications for the turbine) is usually in the range 95 to 105dBA. The table shows rounded values to give an idea of appropriate distances and how they differ for various emission values. The decibel scale is logarithmic: an increase by 3dBA corresponds to a doubling of the sound pressure (power).

4.5.2 Visual impact

Visual impact is assessed based on visual context and project characteristics. Visual context is determined based on the followings factors: Distance of viewers from the project, view duration, angle of view and visibility among others.

Project characteristics that have a visual impact are the scale of the project relative surroundings, the number of the turbine in view, noise and lighting (Jain, 2011).

For the generation of the layout of the proposed wind farm in ArcMap was necessary added a Base map (open street map) from ArcGIS online, in order to visualise the terrain of the selected site or the nearest population

The diameter of the turbine's rotor was created with the *BUFFER'S* tool in ArcMap, which generates a buffer of 128 m around every turbine in order to visualised the distance that shall be present between every turbine.

An approximation assessment of the visual impact of the project is visualised in the Appendix K.

5. Wind energy economics

Colombia is trying to attract national and foreign investment in the field of renewable energy. In 2014, the law 1715, that aims to incentivize private capital investment in renewable energy integration, was passed. The law 1715 provides fiscal incentives and establishes dedicated fund and creates the legal basis for the development of renewables support initiatives (Colombia National Congress, 2014).

Fiscal incentives are also provided by the law, including, income tax deduction of 50% of investment value for up to 50% of taxable income for up to 5 years.

VAT exemption for renewable energy equipment and services, import duty exemption for renewable energy equipment not produced locally as well as accelerated depreciation of up to 20% per year for renewable energy investments (Colombia National Congress, 2014).

It aims for the substitution of diesel generation in isolated areas with renewable energy, either through exclusive concessions or other incentives. It creates a dedicated fund for renewable energy and energy efficiency (FENOGE) to provide soft loans and other forms of support for energy access and productive activities, mainly with renewable energy.

However, the country does not have an implemented feed-in tariff mechanisms either renewable energies auction.

5.1 Wind energy breakdown structure

The approximate breakdown structure of an onshore wind project is shown in Figure 28, the cost of the turbine is the most significant cost of a project with almost the 64% of the first investment is followed by the foundation with 16%, grid connection 11% and planning & miscellaneous with 9%.

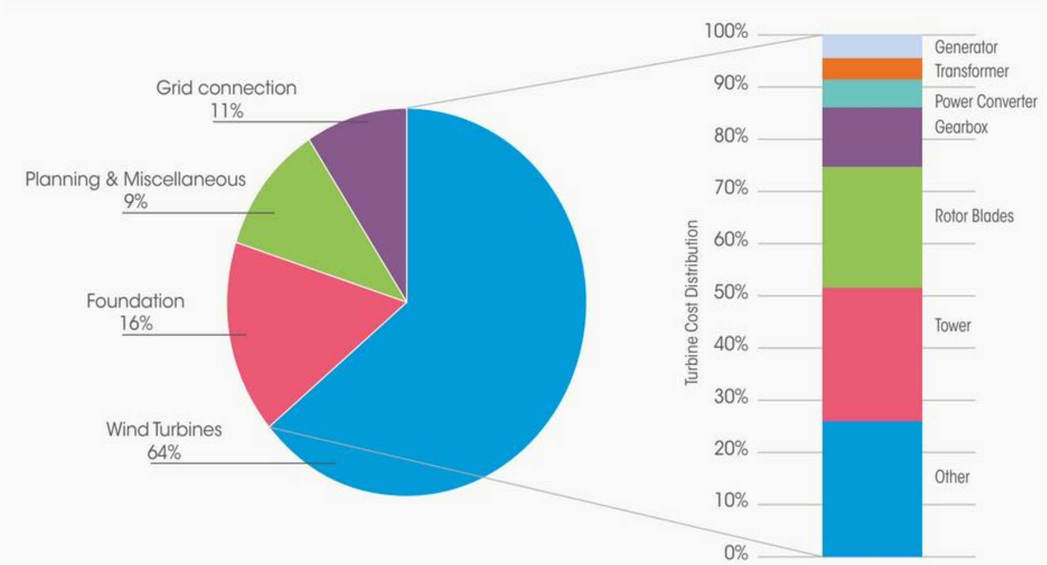


Figure 28. General breakdown structure of a wind farm, based on (IRENA, 2012).

Wind turbine costs can vary significantly in generalised economic studies. Wind turbine installation costs are often normalised to cost per rated kilowatt.

The cost of a wind farm increases with its hub height as well as the performance class. Table 18 describes the different costs of a wind turbine according to the hub height (HH) and its power output.

For the proposed wind farm in La Guajira, the selected wind turbine has a hub height of 90 m and a power performance class of 5.0 MW, cost approximately 1,108 $/kW equal to $5,540,000.

Table 18.Turbine cost according to hub height and power performance, based on (Lüers et al., 2015).

Hub Height	**Power Performance Class**	
	2 MW < P ≤ 3 MW	3 MW < P ≤ 4 MW
HH ≤ 100 m	1,096 $/kW	1,108 $/kW
100 m < HH ≤ 120 m	1,298 $/kW	1,252 $/kW
120 m< HH≤ 140 m	1,432 $/kW	1,320 $/kW
140 m < HH	1,544 $/kW	1,376 $/kW

5.2 Economic analysis

To be economically viable, the cost of generating the electrical energy has to be less than its selling price. It is known that the cost of energy will be low if the site has a high wind speed.

There are several different methods to calculate the returns on an investment such as the annuity method, the present value and the pay-back method.

All these calculations are however fairly approximate since they are based on assumptions on future power production (while winds vary), the power prices, interest rates and so forth that cannot always be accurately foreseen (Wizelius, 2007).

5.2.1 General cost of a wind farm

- Investment Costs, any price from the start of the idea until the date of operation which includes land preparation, site, equipment, transport, consultancy, project management.

- Financing Costs, wind energy projects need investment up front to meet the purchase and installation costs. For this reason, the developer or purchaser will pay a limited down payment of 10-20% and borrow the rest. The source of capital may be a bank or investors where the lenders will expect a return. For the proposed wind farm, a financing cost of 20% is assumed.

- Operation and Maintenance Costs(O&M), according to Danish Wind Industry Association, O&M cost are very low when the turbines are brand new but increase as the turbine gets old.

  The O&M annual cost range from 1.5% to 3% of the original turbine cost. For the proposed wind farm, an operation and maintenance cost of 3% is assumed.

5.2.2 Present value of cost (PVC)

The method of the present value of cost (PVC) is employed, to estimate the cost of a kilowatt-hour produced by the chosen wind energy conversion system. Similar procedure and assumptions have been used for many authors (Ahmed, 2012) and (Belabes et al., 2015).

$$PVC = I + C_{\text{omr}} \left[\frac{1+i}{r-i}\right] x \left[1 - \left(\frac{1+i}{1+r}\right)^{n} - S\left(\frac{1+i}{1+r}\right)^{n}\right] \qquad \text{Equation(13)}$$

Equation(13) from (Ahmed, 2012),where, the initial investment (I), is the cost of the wind turbine plus its 20% for the civil work and other connections, the cost of the wind turbine according to (Lüers et al., 2015) is the relation between hub height the power performance class, the lifetime of the wind turbine (n) is 20 years.

The real interest rate(r) is the sum of the interest rate and the inflation rate, in Colombia the interest rate depends on the change of the Fix-term Deposit (Depósito a Término Fijo, DTF acronym in Spanish), the fix-term deposit is similar to the Prime Rate in USA and Libor rate in the UK, this fix- term usually vary every year in 2016 the rate is 6.05% plus the 4.95% the interest rate (r)

Additionally, an inflation rate (i) of 7% is assumed. In negotiated labour markets, inflation is a way to make up for labour cost increases considered too high by industry.

However, people and institutions dealing with money cannot simply correct their interest rate for inflation but have to estimate the likely inflation over an entire investment depreciation time in order, for example, to offer a loan on fixed interest terms (Sørensen, 2011). The real interest rate for the project is 18%.

Likewise, operation, maintenance and repair cost (C_{omr}) is the 3% of the annual cost of the turbine (machine price/lifetime), and the saved value (S) is 10% of the turbine price and civil works.

5.2.3 Levelized cost of energy (LCOE)

LCOE is all the costs are added during a selected time which is divided into units of energy. A net present value calculation is performed and solved in such a way that for the value of the LCOE chosen, the projects NPV becomes zero; it means that the LCOE is the minimum price at which energy must be sold for an energy project to break even (Zobaa, Bansal, 2011).

The LCOE of typical new onshore wind farms in 2010 assuming a cost of capital of 10% was between $0.06 to USD $0.14/kWh (IRENA, 2012).

$$LCOE = \sum \frac{\frac{Costs}{n}}{Annual\ yield\ (kWh)} \qquad \text{Equation(14)}$$

Equation 14 from (Zobaa, Bansal, 2011), where the *Costs* are the annual costs of operations, maintenance and others, the *Annual yield* is the annual energy production for the lifetime of the project and *n* is the life of the project.

The breakdown of the structure in Figure 28 is used to calculate the different parameters cost of a wind farm. Likewise, the project in La Guajira generated an LCOE =$0.02/kWh or = 2 cents/kWh. It means that this is the lowest selling price of electricity to break even at the end of the project life time of 20 years.

The result of the Equation (13) and Equation (14) are shown in Table 19 investment and cost of a 75 MW wind farm. The cost of planning and miscellaneous, foundation, grid connection are based on the relation of the general breakdown structure Figure 28.

5.3 Income

The basic revenue for a wind farm is the revenue generated from the sale of electric power. To calculate the economic result, it is necessary to assume about a price per kWh for the coming 20 years.

In Colombia, a feed-in tariff for renewables does not exist yet. Also, the electricity price varies substantially between the type of user and the electricity supplier company.

Three electricity supplier companies are chosen for the analysis: **EPM, Electricaribe** and **Codensa** with the same user type (middle class =3), the price of the kilowatt-hour varies from company to company, EPM ($0.130 kWh), Electricaribe ($0.100 kWh) and Codensa ($0.120 kWh), the average price for the project is ($0.124 kWh).

Table 19.Investment and cost of a 75 MW wind farm.

ID	*Parameter*	*Unity*	*Value*
[1]	Annual Energy Power Output	Kwh/a	257,212,851
[2]	Turbine Life Time	a	20
[3]	Turbine Price Gamesa 128G-5.0MW	$	99,720,000.00
[4]	Planning and Miscellaneous= **(9/64)** *[3]	$	14,023,125.00
[5]	Foundation= **(16/64)** *[3]	$	24,930,000.00
[6]	Grid Connection = **(11/64)** *[3]	$	17,139,375.00
[7]	Total Investment= [3] + [4] + [5] + [6]	$	155,812,500.00
[8]	Financing Bank [80%]	$	124,650,000.00
[9]	Own Capital [20%]	$	31,162,500.00
[10]	Annual Turbine Cost= [3]/ [2]	$	4,986,000.00
[11]	Energy Produce during life time= [1] *[2]	kWh	5,144,257,018
[12]	Cost of Operation & Maintenance =3%*[3]	$	149,580.00
[13]	Interest Rate (r)	%	18
[14]	Inflation Rate (i)	%	7
[15]	Save Value (S)=10%*[7]	$	15,581,250.00
[16]	Present Value of Costs(PVC)	$	99,720,000.00
[17]	LCOE	$kWh	0.02

5.3.1 Annual Profit

$$P_{\mathrm{a}} = I_{\mathrm{a}} - C_{\mathrm{a}} - OM_{\mathrm{a}} \qquad \text{Equation(15)}$$

P_{a} = annual profit, I_{a} = annual income, C_{a} = annual cost of capital and OM_{a} = annual cost of O&M

$$C_{\mathrm{a}} = a \times C_{\mathrm{i}} \qquad \text{Equation(16)} \qquad a = \frac{rq^n}{q^n - 1} \qquad \text{Equation(17)}$$

Where *a*=annuity, *Ci* = investment cost, *r*= interest rate, q= 1+ r, *n*=depreciation time in years (20 years).

5.3.2 Simple payback method (SPB)

The Simple Payback Method is one of the most common ways of finding the economic value of a wind energy project. Payback considers the initial investment costs and the resulting annual cash flow, the payback time (Period) is the length of time needed before an investment makes enough to recoup the initial investment (Zobaa, Bansal, 2011).

$$SPB = \frac{Investment}{Annual\ net\ income} \qquad \text{Equation(18)}$$

Where *Investment* is the total inversion of the wind farm and *Annual net income* is the annual income (I_{a}) minus the annual cost of O&M(OM_{a}); The time required to recoup, the funds expected in the proposed project in La Guajira is five years.

5.3.3 Cost of energy

The cost of energy produced by the wind farm is possible to calculate with the Equation (19), this energy cost is equal to the annual capital cost plus the annual O&M cost divided by the annual production in kWh.

$$E_{\mathrm{cost}} = \frac{C_{\mathrm{a}} + OM_{\mathrm{a}}}{kWh/year} \qquad \text{Equation(19)}$$

The result of the calculation of the equations 15,16, 17,18 and Equation 19 from (Wizelius, 2007) are shown in Table 20 revenue and profit of a 75 MW wind farm.

Table 20.Revenue and profit of a 75MW Wind Farm.

ID	Parameter	Unity	Value
[18]	Annual Income(I_{a})	$	31,894,393.48
[19]	Annual Net Income	$	30,647,893.48
[20]	Annuity(a)		0.18681
[21]	Annual Capital Cost (C_{a})	$	29,107,333.13
[22]	Annual Profit(P_{a})	$	1,540,560.36
[23]	Capitalization Factor		5.35
[24]	Net Present Value (NPV)	$	163,966,230.14
[25]	P_{20}	$	8,153,730.14
[26]	Simple Payback(SPB)	years	5.1
[27]	Cost for Energy(E_{cost})	$	0.12

5.3.4 Internal rate of return (IRR)

The IRR acts as a minimum threshold indicator for the investment, If the internal rate of return is below this minimum threshold, there is no need to proceed with the investment. Following this rule where the internal rate of return shall be greater than the minimum interest rate (IRR>IR).

An adequate initial rate of return for the proposed wind farm is 18%, which generated the energy price of $0.124 and an IRR of 20%.

In Table 21 are compare different electricity prices in Colombia and their internal rate of return, although the price is chosen for the project is an average of the different price in Colombia, it generated a close net present value, and the same initial interest rate wherewith makes a price attractive in the electricity market.

Table 21.The comparative of the initial rate of return varying the electricity price.

Energy Supplier	(E_{cost}) (COP/kWh)	(E_{cost}) (USD/kWh)	NPV ($)	SPB(years)	IRR (%)
EPM	358.69	0.13	$ 178,091,284.50	4.7	20%
Codensa	371.46	0.12	$ 164,330,397.13	5.1	20%
Electricaribe	319.36	0.11	$ 150,569,509.62	5.5	18%
Average	358.83	0.124	$ 169,834,752.14	4.9	20%

5.4 Financing

The process of financing a wind power project depends on its owner. Large companies may have the capital needed for the investment available within the company this is called *Corporate Financing* or the wind power project is treated as an independent economic entity, usually have to take out loans from a bank or other institution this is called *Project Financing (Wizelius, 2007)*.

For the proposed wind farm, it is decided to chose the Project Financing option, where the conventional financing structured for a wind farm project is divided into Owner (Equity Investors, Owner corporation) and Lender usually represents for Banks.

Onshore wind farms usually rely on project financing, where the lender or underwriter focuses on the credit of the project rather than the credit of the borrower, the opportunity for repayment is confined to the wind farm´s performance and its values as collateral.

The project financing for the proposed wind farm in La Guajira is assumed as 20% of the total inversion is financing by the owner with a purchase and sale agreement and 80% a funding agreement with the banks, is assumed a period of one year for the completion of work and 20 years for fixed assets amortisation and three years of grace period given by the government.

5.4.1 Amortisation

After deciding the financing method of the project, it is necessary to know the amount of money that needs to be repaid annually to the bank.

The amortisation is the paying-off of debt with a fixed repayment schedule in regular instalments over a period of 20 years in this case.

Appendix M describes the amortisation calculation of the 75 MW wind farm, with a normal straight line depreciation and a grace period of 3 years (during this period, no taxes are charged. Table 22 describes the data necessary for performing the amortisation of the proposed wind farm.

Table 22.Amortisation loan wind farm.

Parameter	Value
Total Loan (80% of the Initial Investment)	$ 124,650,000.00
Loan Terms	20
Interest Rate	18%
Payment	$ 24,145,961.96
Grace Period	3

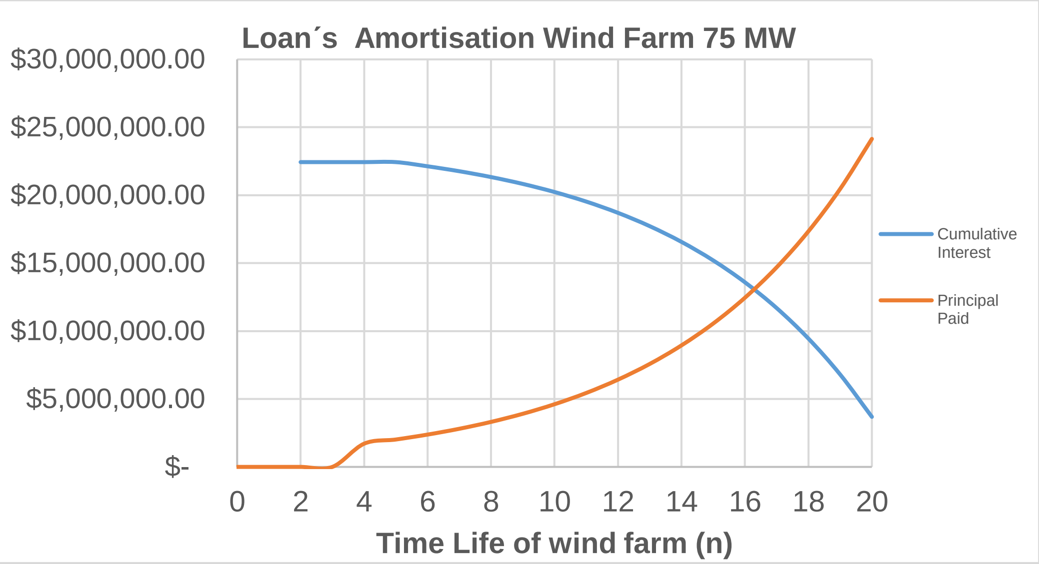


Figure 29. Amortisation of a 75 MW wind farm, author´s diagram.

5.4.2 Cash flow analysis

The cash-flow analysis is a useful method to calculate the economic result by year. It shows the cash flow during the economic lifetime of the project; this technique easily accounts for complicating factors such as fuel escalation, tax-deductible interest, depreciation, periodic maintenance costs and disposal or salvage value of the equipment at the end of its lifetime (Zobaa, Bansal, 2011).

Information on the calculated power production, power price, loans, interest rates and others factors that have an impact on the project economics are included in the analysis, as well as inflation rates and increases in the power purchase price.

Applying the Equation (20) enable detailed information to be computed for each year along the wind farm, the cash flow should always be positive.

$$\sum Cash\ flow_n = \sum Benefits_n - \sum costs_n \qquad \text{Equation (20)}$$

Where Benefits= the annual profit, *Costs* = O&M cost, *n*= life time of the project (20 years).

In the analysis, the outcome year by year, the annual revenues, capital cost, O&M cost and remaining surplus are calculated. Figure 30 shows the cash-flow of the proposed wind farm in La Guajira, as well as Appendix N, describes the calculation of the cash-flow analysis.

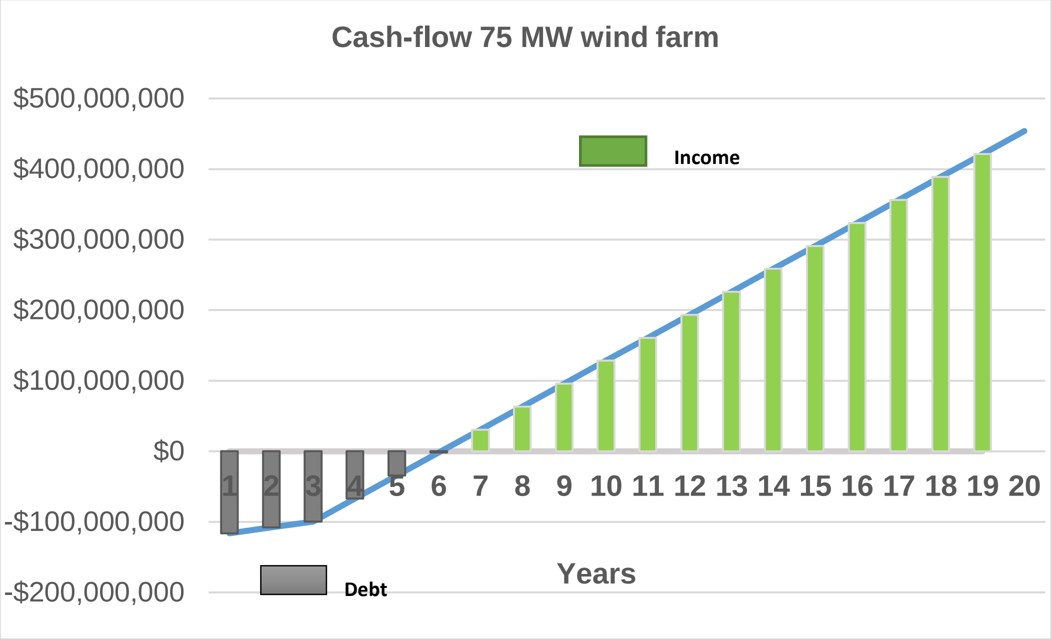


Figure 30.The cash flow of a wind farm (75 MW), author´s diagram.

The proposed wind farm in the La Guajira has a surplus and positive cash asset and that the pay-back time will be 5.1 years (where the debts/assets graph crosses the x-axis), as described in Table 20 revenue and profit of a 75 MW wind farm.

The interest rate has a great impact on the economics result, the higher the interest rate is, the longer it will take to pay back the loans. Nevertheless, the uncertainty over the energy content of the wind should be considered, for a specific 20-25 years that the wind turbine will operate, the energy content in the wind can be considerably different, in some of this years the turbine could produce 20 per cent less than average, others 20 per cent more (Wizelius, 2007).

6. Discussion of results

The framework developed in this thesis successfully identified areas suitable for wind energy development based on a thorough analysis of a set of eight criteria and the application of a multi criteria decision making combining with an analytical hierarchy approach.

The results of the thesis based on the suitability model reveal that the majority of the areas with high suitability are located in the La Guajira department.

Likewise, with the result of the suitability model, the location of the wind farm “Jepirachi” in the La Guajira department was entirely overlapping with the areas identified as suitable which confirm the robustness of the results obtained.

6.1 Results

La Guajira department has 8.678 km^2 of wind energy suitability area from a total of 17.408 km^2 which makes it 49.85% of the department territory. From the total area, 50.15% excluded due to the fact that the department has low access to the national power grid as well as its outstanding natural reserve, which shall be protected.

The Magdalena department, on the other hand, holds 7.108 km^2 , 40.8% of suitability area from a total of 17.408 km^2. Nearly 59.2% of the total territory is excluded from the study area, which makes the department with the largest excluded area in proportion.

This excluded area represents 10.3 km^2 of the department territory and is due to the low wind speed (<5 m/s) in the southern part of the department.

An area of 1.569 km^2 (42%) of the total 3.649 km^2 in the Atlántico department is found to be suitable for wind energy development. Although the Atlántico department is one of the population densest departments in Colombia, it has an excellent suitability for onshore wind energy

Interestingly, the Atlántico department wind energy potential increases significantly if the assessment is considered for offshore wind projects on the strategic position of the department, the surroundings of the Magdalena River and the Caribbean Sea.

Altogether, 3.1% of the total study area is characterized by very high suitability (value score 5), 37.73% by high suitability (value score 4), 2% medium suitability (value score 3), low suitability (value score 2), and the rest 55.24% is excluded area (value score 0).

Based on these findings, there is sufficient space available for developing a wind farm in the north Caribbean region, especially in the selected study area.

The restriction model generated a significant percent of excluded areas due to three sound reasons: Natural environment, power grid access, and proximity to urban areas.

1. The study area own notable natural resources, including nature and bird reserves, regional and natural parks. These all make the logistics tasks especially transporting components of the wind turbine, difficult as making new roads is not an option in such areas.

2. About 98 % of Colombia has access to electricity. However, there are zones in the country still without access to electricity, very particularly the case of La Guajira department where wind speed between of 10-15 m/s at 10 m above ground is prevalent.

   However, recently the National Energy Commission of Mining and Planning Unit (UPEM, acronym in Spanish) established in 2016 a power grid expansion plan, which includes La

Guajira department, the target of the expansion plan is increase the electricity access of the department up to70% (UPME, 2016).

3. Proximity to urban areas, Areas which are very remote from the public account for a significant proportion of the large excluded area. However, this constraint helps to create a major public support for wind farm projects within the proposed locations.

Furthermore, the three geospatial analysis models (restriction, rated and suitability) developed within this thesis framework proved to be effective at handling the various types of data necessary for the analysis, and they can be adapted to other situations (solar energy assessment, geothermal systems) or study areas.

Likewise, the geoinformation system set up in this thesis offers sufficient information about the suitability and restrictions of particular areas for wind energy development, and the analytic hierarchy process approach based on a robust, quantifiable and defendable multi criteria analysis methodology employed in this study.

Additionally, the importance of criteria selection and constraint determination in site suitability studies cannot be emphasised enough as these processes are arguably more important than the methodology itself.

The more comprehensive the set of criteria and constraints used in the preliminary analysis is, the more likely the project will avoid costly setbacks and additional resource allocations during the site selection process.

The economic assessment of wind energy potential for the proposed wind farms results in a leveled cost of energy (LCOE) of USD 0.02/kWh generation.

According to the International Renewable Energy Agency (IRENA), shifting to larger turbine sizes with taller towers and larger rotor blades has contributed to an increased output and a lower LCOE for wind ,this statement confirms that the selected wind turbine model for the wind farm was proposed guessed correctly instead of choosing a small wind turbine which could generate a low-priced inversion.

Furthermore, the cash flow of the proposed wind farm achieves a 5.1-year payback time due to the high-interest rate and the current selling price of the electricity produced by the wind farm, which increases the opportunity to investors for obtaining earliest utility of the wind farm project in the region.

In addition to inflation rates and increases in the power purchase price, information on the calculated power production, energy price and other factors that have an impact on the project economics are included in the economic analysis, generating a clear overview to possible investors and shareholders.

The performance of the result obtained in this study contributes to increasing the wind energy potential research in Colombia from its current low status. Likewise, it helps wind energy planners to identify the most suitable sites for wind energy development in the country.

The suitability model can be considered as a comprehensive pre-assessment wind energy tool, reducing the assessment phase time significantly from one or two years to 3 months when all the necessary data and criteria are available.

6.2 Future work

This research can have an extraordinary impact on the public through the production of interactive web-based maps, promoting wind energy planners and renewable energies students to develop wind farms with different constraint and criteria, in a visualised manner recognising how a criterion can affect the assessment of an onshore wind project.

Additionally, the publication of interactive web-based map in different interfaces such as through the ArcGIS Online interface can generate a free access to the wind suitability of the region, supporting the process of urban and regional planning of the departments in Colombia.

The interactive web-based maps provide a heightened level of access to students, politician and universities increasing the impact on possible investors, shareholders and wind energy companies such as Gamesa.

Moreover, for a better planning of wind farm in a location such the La Guajira department, it will improve the performance of the wind energy resource if the selected wind turbine for the wind farm has a power capacity of (2-3 MW) considering that the wind velocity varies from season to season and occasionally the maximum wind velocity does not reach the 7 m/s as required in the proposed wind farm.

Nevertheless, based on the economic assessment a wind farm with (2-3 MW) wind turbine capacity will increase the numbers of wind turbines shall increase from 15 to 25 in order to achieve the proposed wind power generated in with the selected wind turbine model, increasing the total cost of the project.

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Appendices

Appendix A: Pairwise comparisons.

Item Number	**Item Number**	**1**	**2**	**3**	**4**	**5**	**6**
	Item Description	**Wind Energy Potential**	**Land Use**	**Distance from power grid**	**Distance from natural environments**	**Distance from road network**	**Distance from urban areas**
1	**Wind Energy Potential**	**1.00**	**3.00000**	**3.00000**	**1.00000**	**3.00000**	**3.00000**
2	**Land Use**	**0.33**	**1.00**	**1.00000**	**1.00000**	**2.00000**	**3.00000**
3	**Distance from power grid**	**0.33**	**1.00**	**1.00**	**1.00000**	**3.00000**	**3.00000**
4	**Distance from natural environments**	**1.00**	**1.00**	**1.00**	**1.00**	**5.00000**	**3.00000**
5	**Distance from road network**	**0.33**	**0.50**	**0.33**	**0.20**	**1.00**	**3.00000**
6	**Distance from urban areas**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**1.00**
	Sum	**3.33**	**6.83**	**6.67**	**4.53**	**14.33**	**16.00**

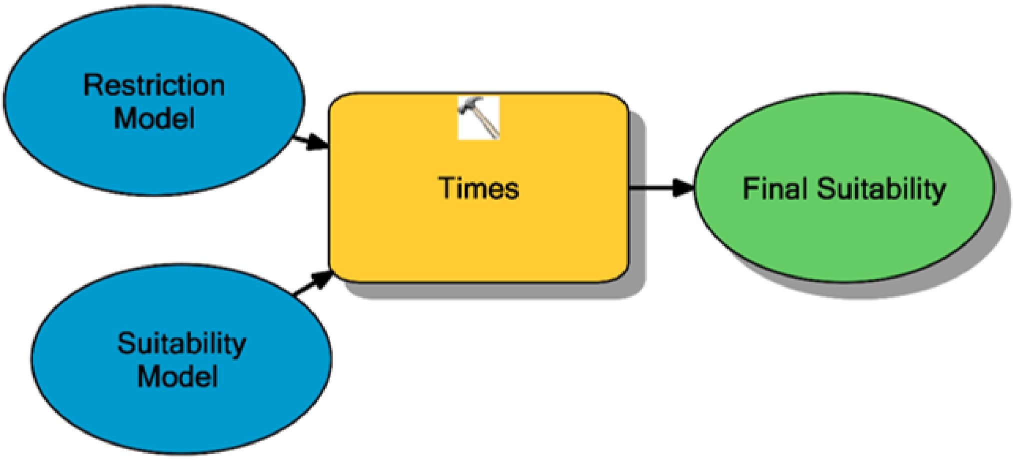
Appendix B: Standardised matrix.

		Wind Energy Potential	Land Use	Distance from power grid	Distance from natural environments	Distance from road network	Distance from urban areas	Weight
1	Wind Energy Potential	0.30	0.44	0.45	0.22	0.21	0.19	30.1%
2	Land Use	0.10	0.15	0.15	0.22	0.14	0.19	15.7%
3	Distance from power grid	0.10	0.15	0.15	0.22	0.21	0.19	16.9%
4	Distance from natural environments	0.30	0.15	0.15	0.22	0.35	0.19	22.6%
5	Distance from road network	0.10	0.07	0.05	0.04	0.07	0.19	8.7%
6	Distance from urban areas	0.10	0.05	0.05	0.07	0.02	0.06	6.7%

Appendix C: Priority vector and consistency of matrix

		Wind Energy Potential	Land Use	Distance from power grid	Distance from natural environments	Distance from road network	Distance from urban areas	SUM	SUM/ Weight
1	Wind Energy Potential	0.30	0.47	0.51	0.23	0.26	0.18	1.95	6.47
2	Land Use	0.10	0.16	0.17	0.23	0.17	0.18	1.021	6.523
3	Distance from power grid	0.10	0.16	0.17	0.23	0.26	0.18	1.108	6.588
4	Distance from natural environments	0.30	0.16	0.17	0.23	0.44	0.18	1.480	6.633
5	Distance from road network	0.10	0.08	0.06	0.05	0.09	0.18	0.566	6.529
6	Distance from urban areas	0.10	0.05	0.06	0.08	0.03	0.06	0.332	4.968
n		6.00							
λ_{max}		6.144							
CI		0.029							
CR		0.02							
RI		1.24							

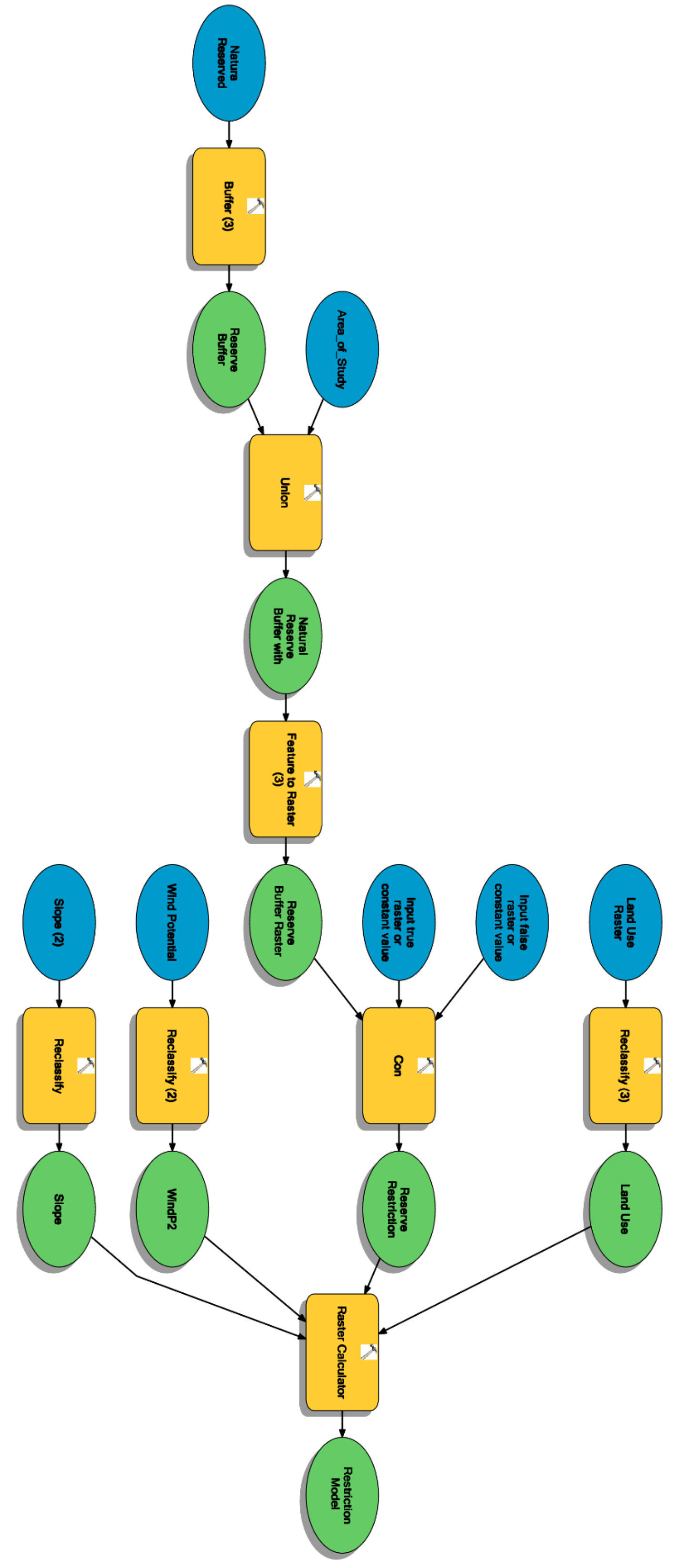
Appendix D: Suitability model



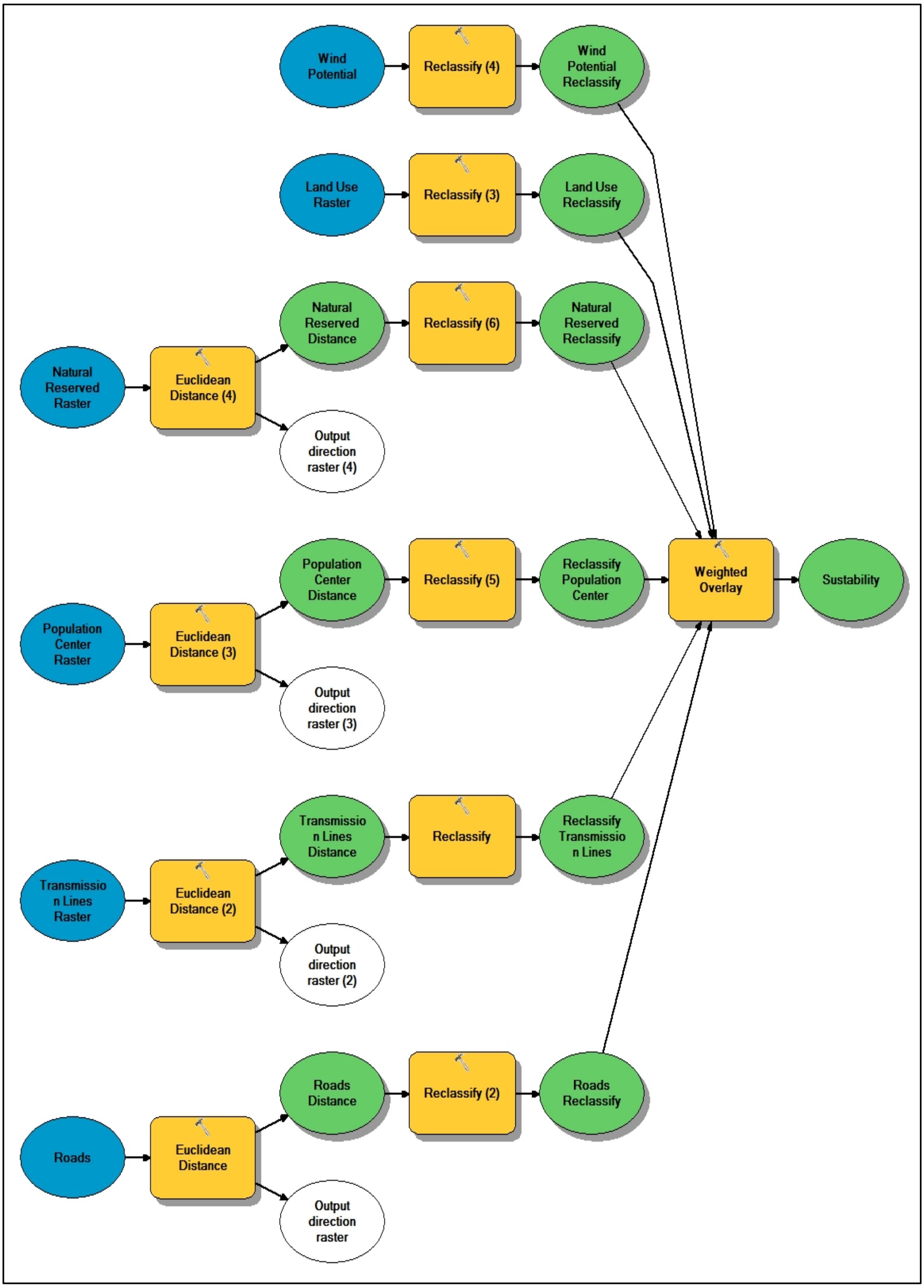
Appendix E.Power output Gamesa 5.0 MW.

V[m/s]	**Time[hr]**	**Weibull**	**p(v)**	**5.0** Gamesa **Power[kW] (adjusted)**	**Output** (**kWh/yr)** Adjusted
0	0.000	0.000	0.000	0.000	0.000
1	58.700	0.040	0.006	0.000	0.000
2	187.400	0.075	0.019	54.392	10193.136
3	361.000	0.102	0.038	174.566	63018.326
4	555.700	0.118	0.060	377.440	209743.408
5	744.300	0.123	0.082	471.800	351160.740
6	898.300	0.117	0.101	943.600	847635.880
7	993.500	0.105	0.114	1415.400	1406199.900
8	1015.300	0.088	0.118	1981.560	2011877.868
9	962.700	0.070	0.113	2830.800	2725211.160
10	848.000	0.053	0.100	3491.320	2960639.360
11	694.100	0.038	0.082	4246.200	2947287.420
12	527.400	0.026	0.062	4434.920	2338976.808
13	371.500	0.017	0.043	4718.000	1752737.000
14	242.000	0.010	0.028	4718.000	1141756.000
15	145.600	0.006	0.016	4718.000	686940.800
16	80.600	0.004	0.009	4718.000	380270.800
17	41.000	0.002	0.004	4718.000	193438.000
18	19.100	0.000987	0.002	4623.640	88311.524
19	8.100	0.000490	0.001	4482.100	36305.010
20	3.200	0.000233	0.000	4340.560	13889.792
21	1.100	0.000106	0.000	4151.840	4567.024
22	0.400	0.000046	0.000	3868.760	1547.504
23	0.400	0.000019	0.000	3774.400	1509.760
24	0.100	0.000008	0.000	3396.960	339.696
25	0.000	0.000003	0.000	3302.600	0.000
Total hours	**8760**				
Total output 15 turbines					302,603,354
Max Output 15 turbines					619,909,815

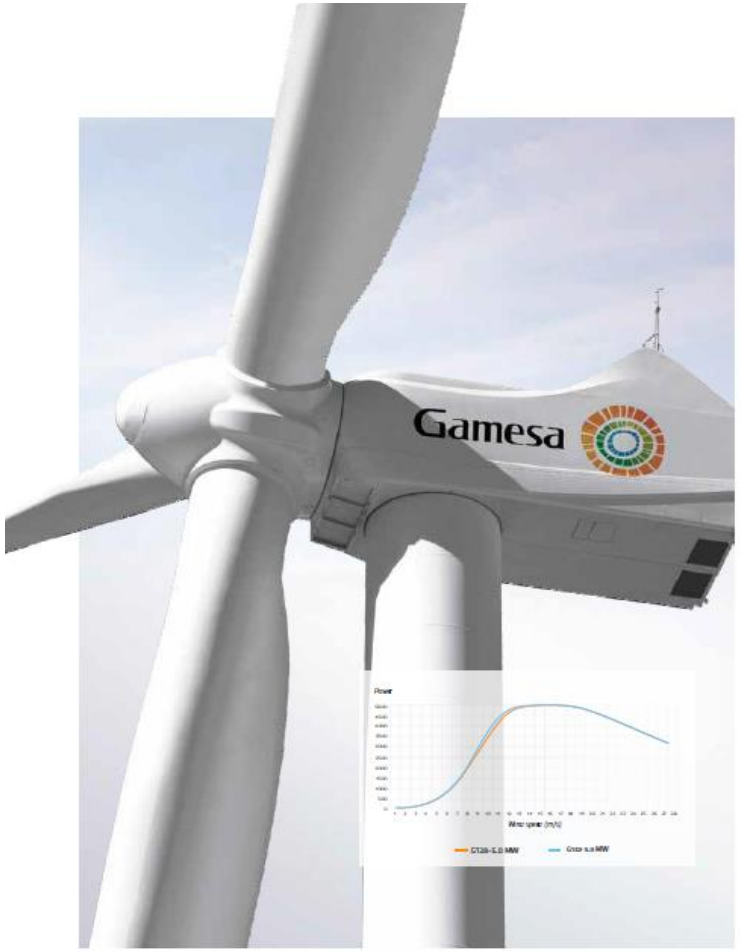
Appendix F: Restriction model flow.

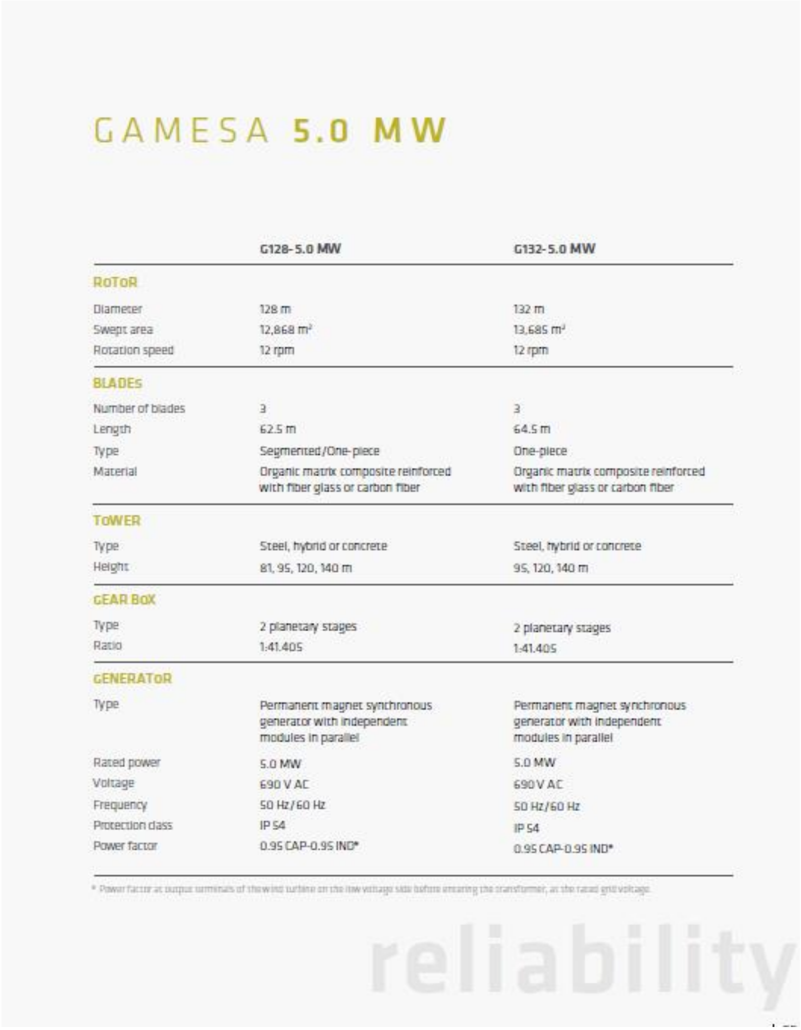


Appendix G: Rated area model flow.



Appendix H: Gamesa G-128 5.0 MW





GAMESA 5.0 MW

	G128-5.0 MW	G132-5.0 MW
RoToR		
Diameter	128 m	132 m
Swept area	12,868 m²	13,685 m²
Rotation speed	12 rpm	12 rpm
BLADEs		
Number of blades	3	3
Length	62.5 m	64.5 m
Type	Segmented/One-piece	One-piece
Material	Organic matrix composite reinforced with fiber glass or carbon fiber	Organic matrix composite reinforced with fiber glass or carbon fiber
ToWER		
Type	Steel, hybrid or concrete	Steel, hybrid or concrete
Height	81, 95, 120, 140 m	95, 120, 140 m
GEAR BoX		
Type	2 planetary stages	2 planetary stages
Ratio	1:41.405	1:41.405
GENERAToR		
Type	Permanent magnet synchronous generator with independent modules in parallel	Permanent magnet synchronous generator with independent modules in parallel
Rated power	5.0 MW	5.0 MW
Voltage	690 V AC	690 V AC
Frequency	50 Hz / 60 Hz	50 Hz / 60 Hz
Protection class	IP 54	IP 54
Power factor	0.95 CAP-0.95 IND*	0.95 CAP-0.95 IND*

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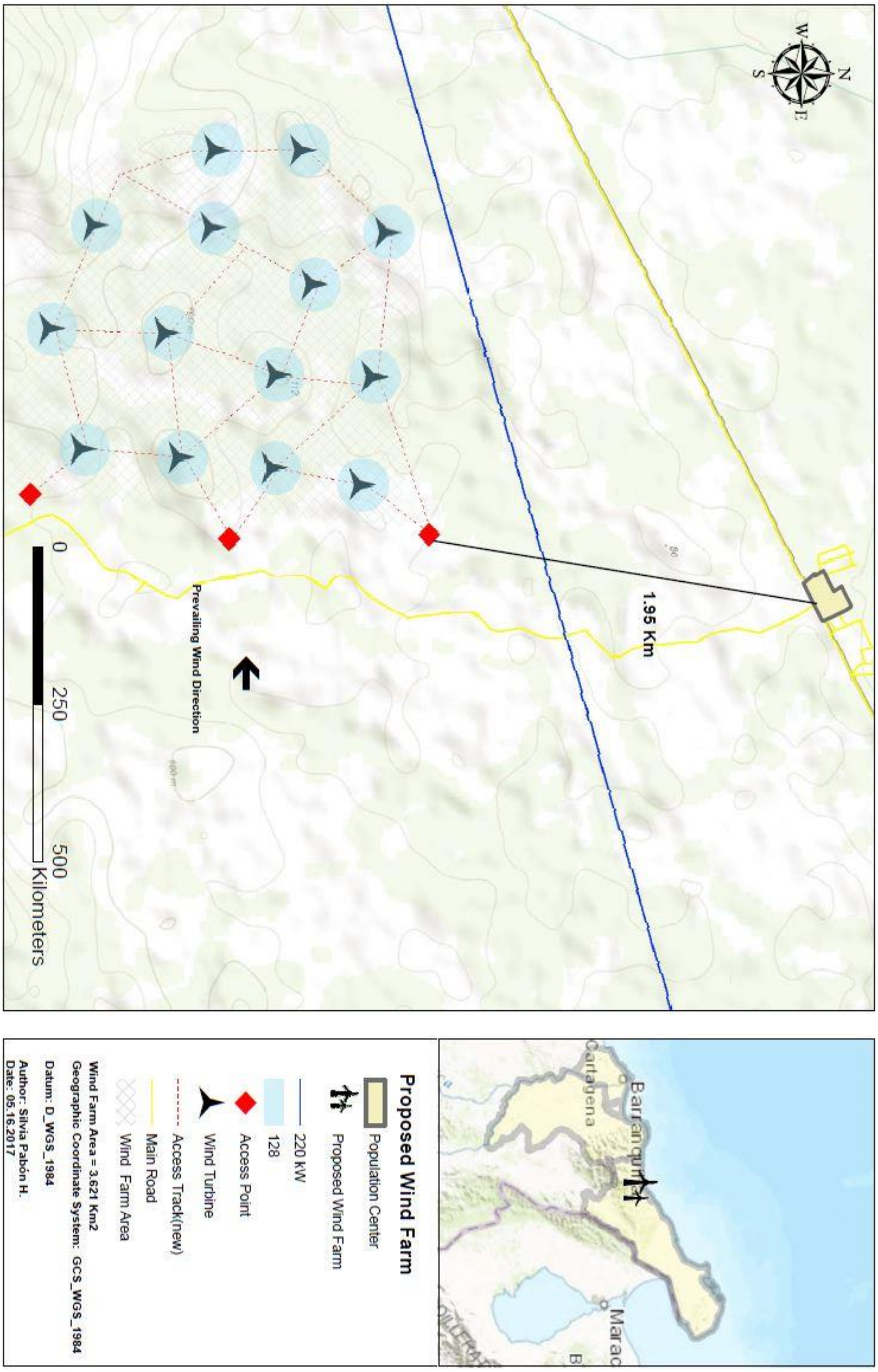
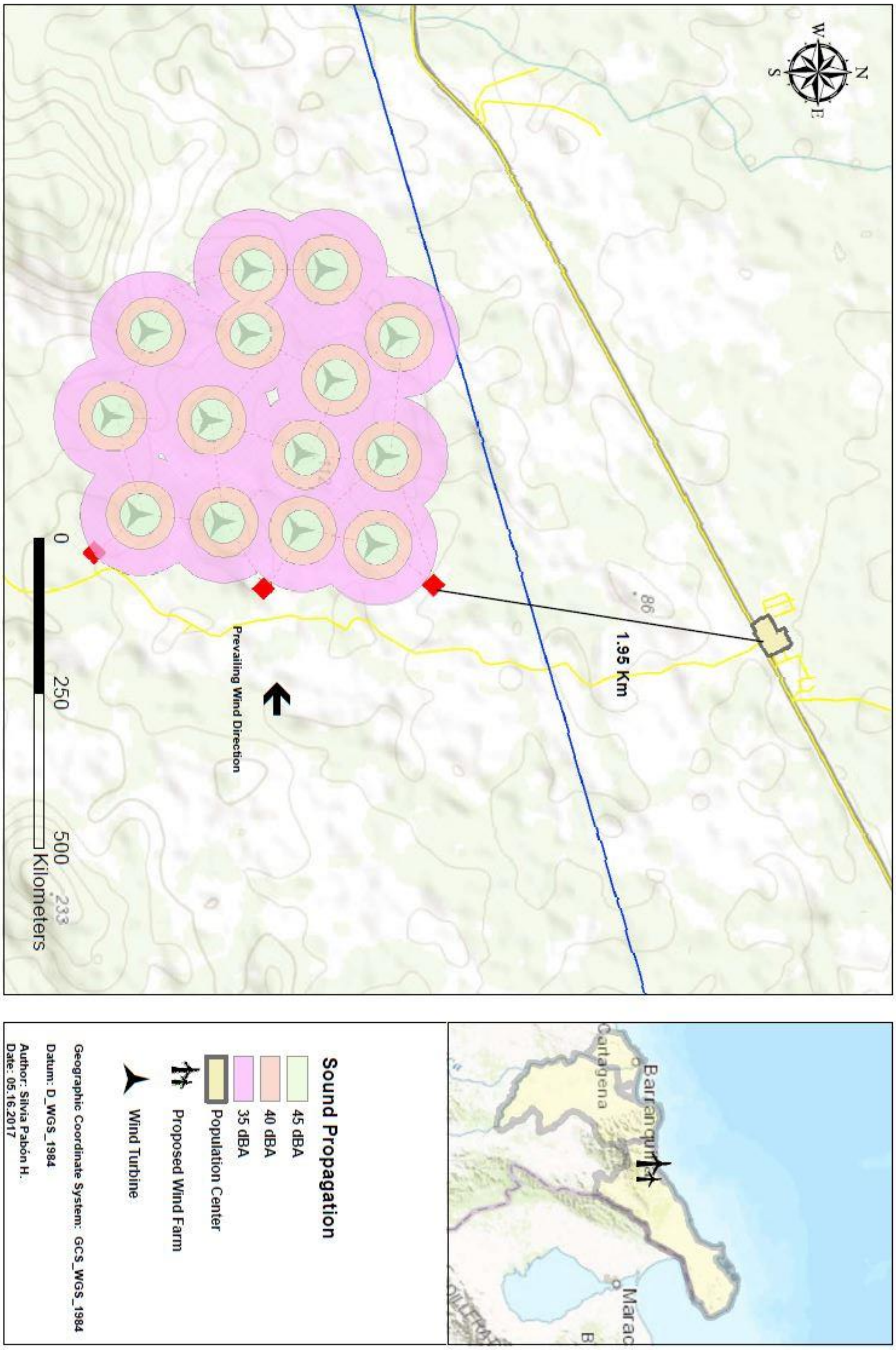
* Power factor at output terminals of the wind turbine on the low voltage side before entering the transformer, at the rated grid voltage.

reliability

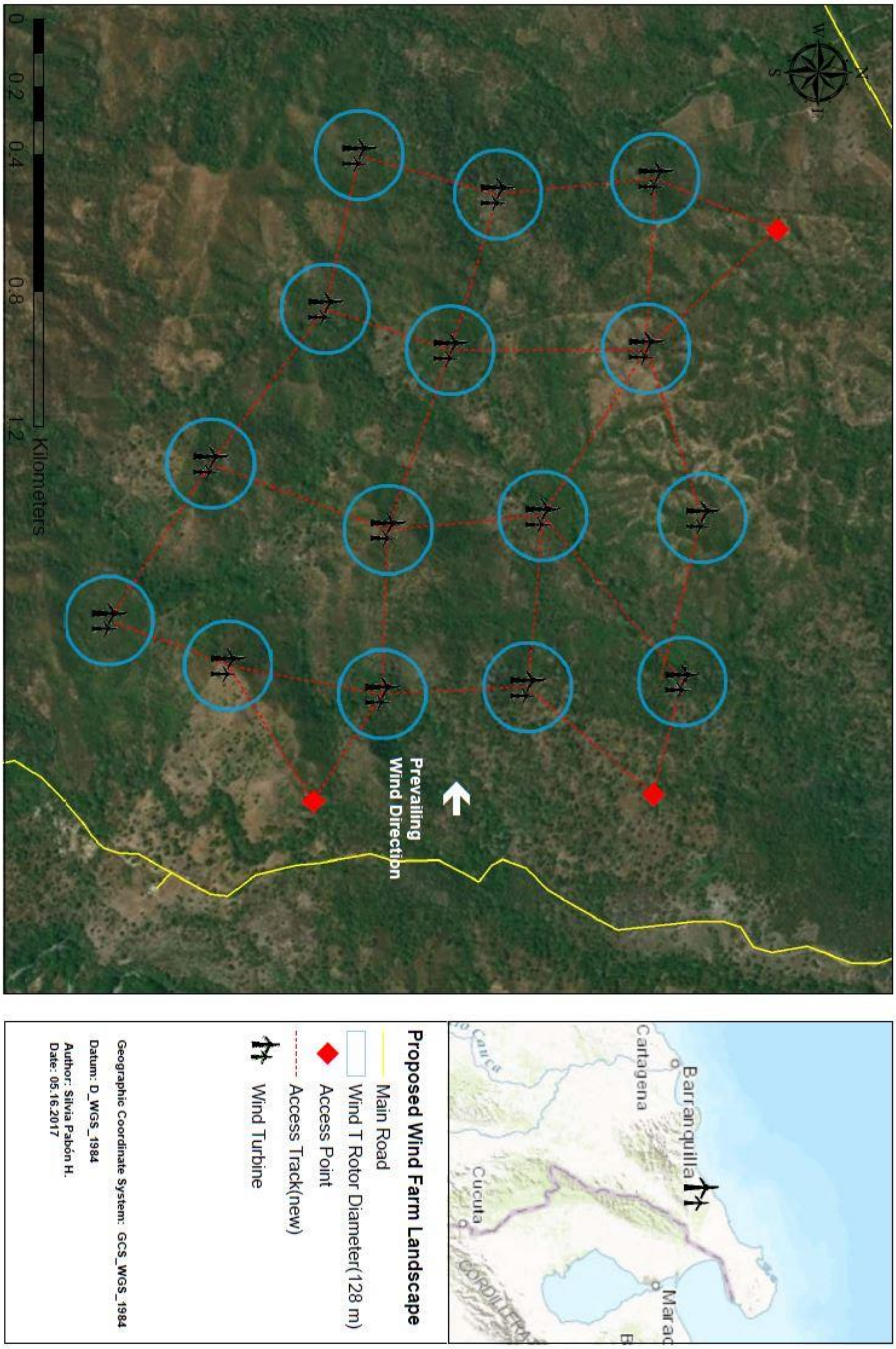
Appendix I. Layout of La Guajira wind farm.



Appendix J. Sound propagation La Guajira wind farm.



Appendix K. Landscape La Guajira wind farm.



Appendix L: Amortisation 75MW wind farm.

Amortisation Loan

Period(n)	Beginning Balance	Payment	Cumulative Interest	Principal Paid	Ending Balance
0	$ 124,650,000.00	$ -		$ -	$ 124,650,000.00
1	$ 124,650,000.00	$ -	$ 22,437,000.00	$ -	$ 124,650,000.00
2	$ 124,650,000.00	$ -	$ 22,437,000.00	$ -	$ 124,650,000.00
3	$ 124,650,000.00	$ -	$ 22,437,000.00	$ -	$ 124,650,000.00
4	$ 124,650,000.00	$ 24,145,961.96	$ 22,437,000.00	$ 1,708,961.96	$ 122,941,038.04
5	$ 122,941,038.04	$ 24,145,961.96	$ 22,129,386.85	$ 2,016,575.11	$ 120,924,462.93
6	$ 120,924,462.93	$ 24,145,961.96	$ 21,766,403.33	$ 2,379,558.63	$ 118,544,904.30
7	$ 118,544,904.30	$ 24,145,961.96	$ 21,338,082.77	$ 2,807,879.18	$ 115,737,025.12
8	$ 115,737,025.12	$ 24,145,961.96	$ 20,832,664.52	$ 3,313,297.44	$ 112,423,727.68
9	$ 112,423,727.68	$ 24,145,961.96	$ 20,236,270.98	$ 3,909,690.97	$ 108,514,036.71
10	$ 108,514,036.71	$ 24,145,961.96	$ 19,532,526.61	$ 4,613,435.35	$ 103,900,601.36
11	$ 103,900,601.36	$ 24,145,961.96	$ 18,702,108.24	$ 5,443,853.71	$ 98,456,747.65
12	$ 98,456,747.65	$ 24,145,961.96	$ 17,722,214.58	$ 6,423,747.38	$ 92,033,000.27
13	$ 92,033,000.27	$ 24,145,961.96	$ 16,565,940.05	$ 7,580,021.91	$ 84,452,978.36
14	$ 84,452,978.36	$ 24,145,961.96	$ 15,201,536.10	$ 8,944,425.85	$ 75,508,552.51
15	$ 75,508,552.51	$ 24,145,961.96	$ 13,591,539.45	$ 10,554,422.51	$ 64,954,130.00
16	$ 64,954,130.00	$ 24,145,961.96	$ 11,691,743.40	$ 12,454,218.56	$ 52,499,911.44
17	$ 52,499,911.44	$ 24,145,961.96	$ 9,449,984.06	$ 14,695,977.90	$ 37,803,933.54
18	$ 37,803,933.54	$ 24,145,961.96	$ 6,804,708.04	$ 17,341,253.92	$ 20,462,679.62
19	$ 20,462,679.62	$ 24,145,961.96	$ 3,683,282.33	$ 20,462,679.62	$ (0.00)
20	$ (0.00)	$ 24,145,961.96	$ (0.00)	$ 24,145,961.96	

Appendix M. Depreciation straight line model

Depreciation Straight Line Model

Investment	Safe Value	Lifetime
$ 155,812,500.00	$ 15,581,250.00	20

Years	Depreciation	Value
1	$ 7,011,562.50	$ 148,800,937.50
2	$ 7,011,562.50	$ 141,789,375.00
3	$ 7,011,562.50	$ 134,777,812.50
4	$ 7,011,562.50	$ 127,766,250.00
5	$ 7,011,562.50	$ 120,754,687.50
6	$ 7,011,562.50	$ 113,743,125.00
7	$ 7,011,562.50	$ 106,731,562.50
8	$ 7,011,562.50	$ 99,720,000.00
9	$ 7,011,562.50	$ 92,708,437.50
10	$ 7,011,562.50	$ 85,696,875.00
11	$ 7,011,562.50	$ 78,685,312.50
12	$ 7,011,562.50	$ 71,673,750.00
13	$ 7,011,562.50	$ 64,662,187.50
14	$ 7,011,562.50	$ 57,650,625.00
15	$ 7,011,562.50	$ 50,639,062.50
16	$ 7,011,562.50	$ 43,627,500.00
17	$ 7,011,562.50	$ 36,615,937.50
18	$ 7,011,562.50	$ 29,604,375.00
19	$ 7,011,562.50	$ 22,592,812.50
20	$ 7,011,562.50	$ 15,581,250.00

Appendix N. Annual cash flow model.

Annual Cash Flow Model

Year	Annual Profit	O&M Costs	Net Depreciation.	Net Loan Payments	Annual Cash Flow	Total Cash Flow
0					**($124,650,000)**	**($124,650,000)**
1	$1,540,560.36	**$149,580**	$ 7,011,562.50		**$8,701,703**	**($115,948,297)**
2	$1,540,560.36	**$149,580**	$ 7,011,562.50		**$8,701,703**	**($107,246,594)**
3	$1,540,560.36	**$149,580**	$ 7,011,562.50		**$8,701,703**	**($98,544,891)**
4	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**($65,697,227)**
5	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**($32,849,562)**
6	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**($1,897)**
7	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$32,845,768**
8	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$65,693,433**
9	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$98,541,097**
10	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$131,388,762**
11	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$164,236,427**
12	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$197,084,092**
13	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$229,931,757**
14	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$262,779,422**
15	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$295,627,086**
16	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$328,474,751**
17	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$361,322,416**
18	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$394,170,081**
19	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$427,017,746**
20	$1,540,560.36	**$149,580**	$ 7,011,562.50	$ 24,145,961.96	**$32,847,665**	**$459,865,410**