Modeling the Colombian electricity sector using *urbs*

Master's Thesis

In partial fulfilment of the requirements for the degree
Master of Science Power Engineering
At the TUM Department of Electrical and Computer Engineering
of the Technical University of Munich.

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Chair of Renewable and Sustainable Energy Systems

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Abstract

Colombia's electricity generation matrix is mainly based in Hydropower technologies with 67% of the installed capacity due to the great resources of the country; such large hydro capacity is greatly influenced by changes in the rainfall due to phenomena like El Niño and La Niña and climate change. Taking into account the effects of such phenomena, a plausible electricity system and generation matrix that is both resilient, reliable, and sustainable will be sought after. The Colombian electricity system will be modeled in "*urbs".* This linear programing optimization program models the operation of the power plant fleet by optimizing the cost of electricity, and according to the availability of the different resources and under different scenarios. For this the current state of the Colombian electrical system is studied, how it is composed, the different technologies that are present and the potentials for the different renewable energies. It is observed how the different hydrology levels have great influence in the electricity matrix and how the non-conventional Renewable energies will play an important role in all of the scenarios. In regions where water is not available, wind energy is the path to follow. PV still is an expensive technology comparatively to wind and large RoR, so it is only implemented in the regions and scenarios where the other options are thermal plants; or when wind and hydro are not balancing each other.

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Contents

1. Introduction

The Republic of Colombia is a country located in the north of South America, with a terrestrial area of 1,141,748 km^2 and a water area of 928,660 km^2. Colombia is largely diverse country, with territories such as rainforests, highlands, grasslands, deserts, islands and coastlines. It´s neighboring countries are Venezuela, Brazil, Peru, Ecuador and Panamá:

Figure 1 Location and mains cities of Colombia. Credits: OCHA

The country has an estimated population of 48'258,494[1], which are mainly located in the Andean areas and the Caribbean coast, with the most important cities being shown in Figure 1. The five main cities are: the capital, Bogotá, is the most populated city with 8 million people, Medellín is next with 2.5 million, Cali with 2.4 million, Barranquilla and Cartagena with 1.2 and 1 million respectively. The country is divided in 32 "Departamentos" which are what the local administrative regions are called.

Since most of the population is located in the central area of the country, the electrical system is divided in 2 areas, the first one is the National Interconnected System ("Sistema Interconectado Nacional", SIN), where about 97% of the population is covered, but it only represents 33% of the national territory [2], the rest of the area and population are covered or on the way of being covered by different Non Interconnected Zones ("Zonas No Interconectadas", ZNI) where the electricity supply is usually intermittent, or for some hours of the day, mostly generated by diesel power plants, being the cost for diesel in these areas much higher and dependent on government subsidies. In this thesis only the SIN with its current coverage area will be considered.

The SIN is administrated and operated by the company XM, through the National Dispatch Center ("Centro Nacional de Despacho, CND)", but it is regulated and controlled through different entities in the national government: the direction is done by the Mining and Energy Ministry, the planning through the Mining and Energetics Planning Unit ("Unidad de Planeación Minero Energética", UPME) , the regulation by the Commission for Energy and Gas Regulation ("Comisión de Regulación de Energía y Gas", CREG), among others.

The SIN as any other electrical system is divided in four different sectors, first there is the generation sector, that has an installed capacity of 17 326 MW, distributed among 77 companies but remains being an oligopoly market with just three companies - EPM, EMGESA, ISAGEN - having over 59% of the market share. Then there is the transmission sector, that even if there are multiple companies operating in the country, they are monopolies in each of the regions they operate; the 17 companies in charge of the transmission count with more than 26.000 km of electricity grids, that are divided in the National Transmission System ("Sistema de Transmisión Nacional", STN), which are the high voltage grids, with an operating tension over 220 kV, which connect neighboring regions, and then there is the Regional Transmission System ("Sistema de Transmisión Regional", STR) which operates between 110 KV and 220 kV [3] both of these are just for the transmission. For the distribution sector, there are 40 companies and they also operate as local monopolies, finally there is the commercialization sector and there are 118 companies [4]. In 2018 the SIN as a whole had an energy demand of 69 TWh and a maximum power demand of 10 700 MW.

1.1. Electricity demand by sectors

Colombia is a country with a relatively low electricity consumption, with a per capita consumption in 2017 of 1.5 MWh according to International Energy Agency (IEA) [5], which compared with industrialized countries in Europe like Germany with 7.25 MWh, in North America like United States of America with 13.66 MWh and with neighbors like Brazil with 2.52 MWh which almost doubles our consumption. This can be understood when looking deeper into the demand distribution across the economic sectors.

As seen in the Figure 2 the sector that demands the most electricity is the manufacture sector, followed by the mining and quarrying industries, showing that Colombia is industrialized but the services sector is not very developed. Also because of the privileged weather conditions Colombia has, large energy demand for heating and/or cooling is not necessary; compared with countries like Germany where the energy demand for heating can be up to one third of the total primary energy demand, in Colombia this percentage is only 1.85% from the electricity demand.

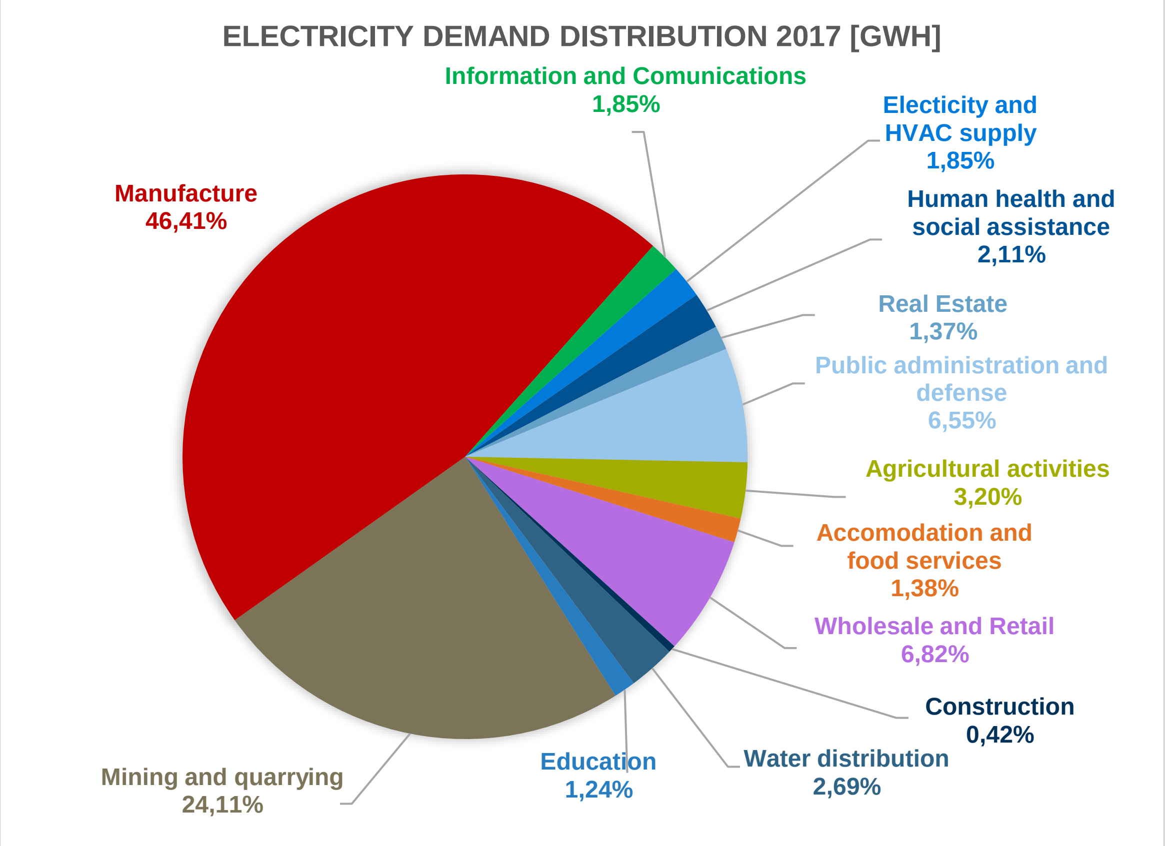

Figure 2 Demand distribution across the economic sectors [6]

1.2. Current generation system and its challenges

Colombia's electricity generation matrix is mainly based in Hydropower technologies, 59% of the installed power consist of conventional hydropower plants with dams, 3% of large run of river plants (> 20 MW), and 5% of small run of river plants (<20 MW) and this is because of the great resources of the country; in the Hydro energetic potential atlas [7], the experts estimated a potential of 56 GW only for run of river plants.

Colombia's large hydro capacity is greatly influenced by changes in the rainfall which is mainly governed by the Intertropical Convergence Zone (ITCZ), the trade winds and Colombia's Orography [8] there is phenomena of climate variability like el Niño and la Niña that also affect it and others of climate change due to global warming. It is an issue because in dry seasons, hydro generation is greatly reduced, going from 76% in a normal year to 63% in a El Niño year [9], and the dammed reserves start hitting low levels, making shortage a constant threat and threatening Colombia's energy security. In these instances, Colombia starts relying more heavily on thermal power plants, but further diversification of energy sources would also be in the country´s interest, this means installing different types of technologies that do not depend on water, for example wind turbines and solar photovoltaics.

1.2.1. El Niño Southern Oscillation - ENSO

El Niño is a phenomenon of climate variability, not of climate change, this means that is an abnormal climate behavior that is been happening throughout history, happens every so often, it is temporal and transitory [10]. El Niño Southern Oscillation (ENSO) is a phenomenon where, the temperatures, pressure, winds and other oceanic and atmospheric variables present some differences from the historic averages.

In the normal or neutral times, the trade winds blow from east to west, moving the waters from South America to Southeast Asia, causing warm waters to accumulate there as seen in the Figure 3 [11]. Since warm waters are moved away from the South American coast, there is an upwelling from the deeper, cold waters to replace this water. This deeper water is rich in nutrients, this is why the South American coasts of Ecuador, Peru and Chile are important fishing places. The atmospheric convection is where the warm and moist air ascends in the atmosphere and clouds form, causing a wet and tropical weather in the western pacific; the Walker circulation causes the remaining dry air to be pushed across to the eastern Pacific and descend in South America adding to the cold and dry weather.

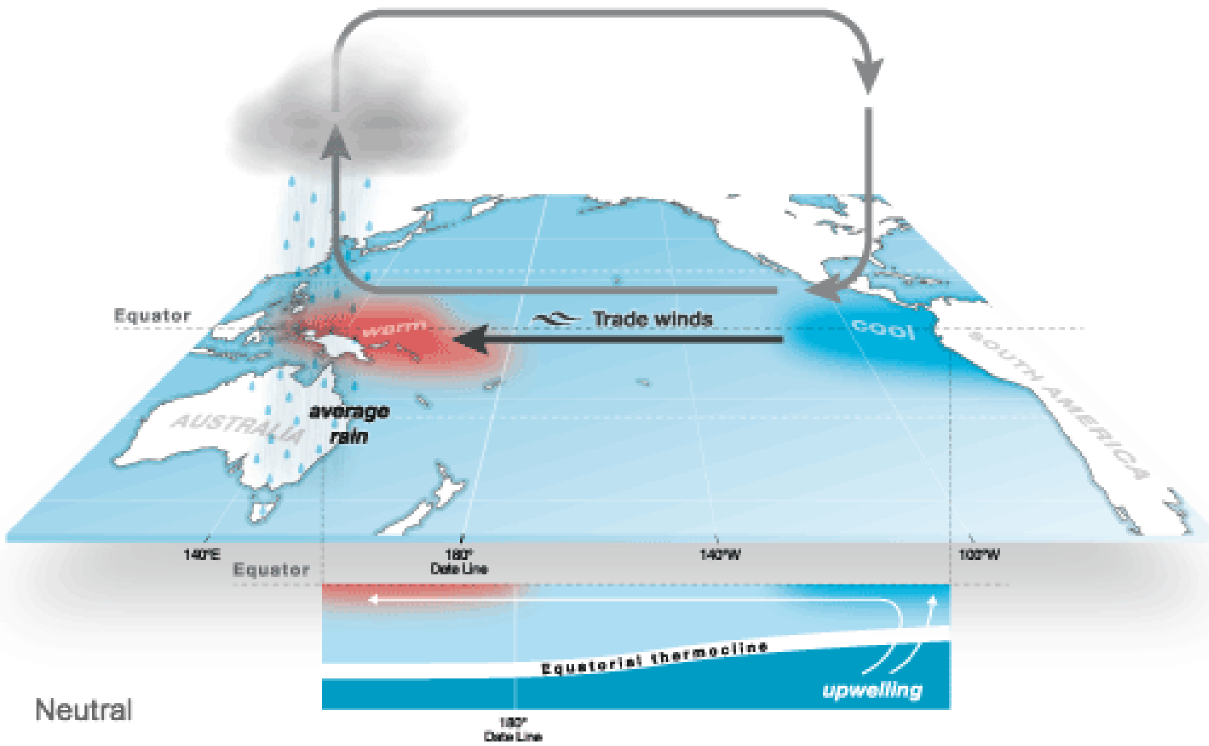

Figure 3 Neutral behavior of the El Niño –Southern Oscillation phenomenon.[11]

In El Niño behavior, the trade winds loose strength and the warm waters move farther east, staying in the central and eastern pacific. There is also a decrease in the upwelling, further helping in the warming of the South American sea surface temperature. This combination increases the atmospheric convection in the eastern pacific, affecting the walker circulation and causing a more wet and hot weather in South America and a dry and cooler weather in the western pacific. Such atmospheric variation can be better observed in Figure 4. El Niño is characterized by a raise in the surface temperature of the pacific ocean of at least 0.5 °C according to the simplest definition; there are several governmental and international organizations who observe this phenomena and others include variables like the air surface pressure and the wind speeds.

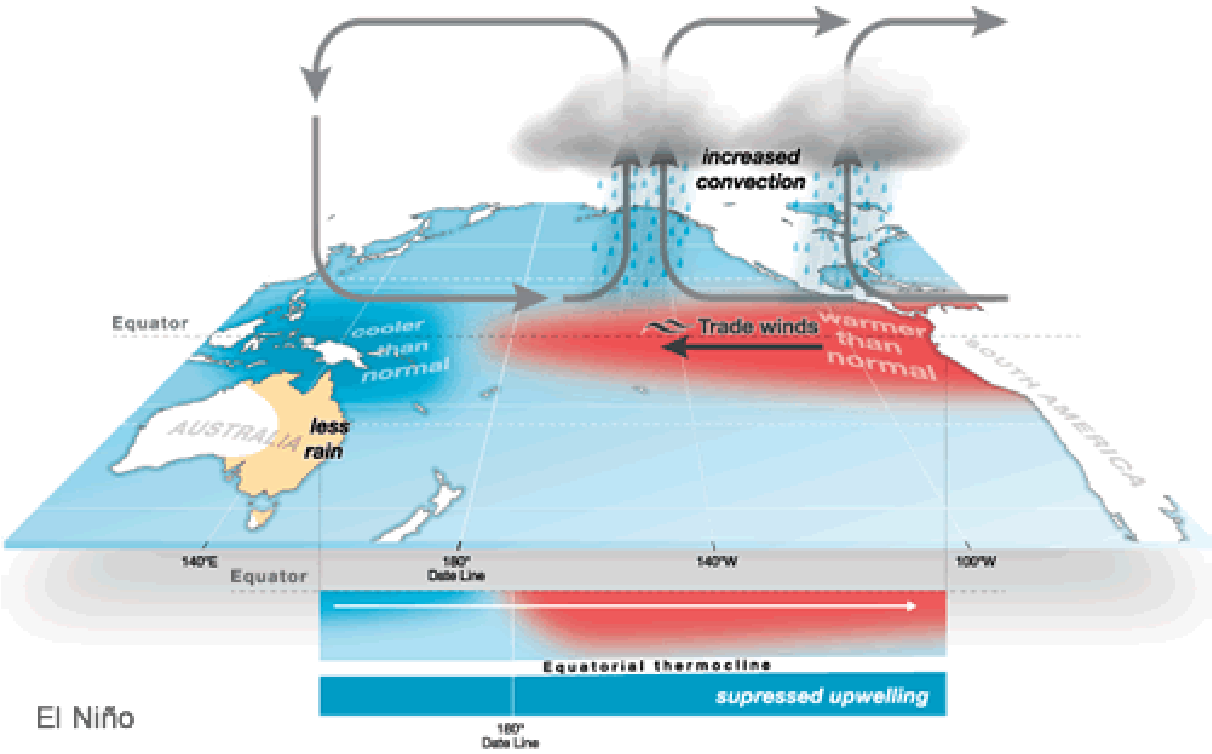

Figure 4 El Niño behavior in the El Niño – Southern Oscillation [11]

On the opposite case, La Niña, the trade winds increase their strength what causes the warm waters to accumulate north of Australia, increasing the convection, the walker circulation and upwelling effects, causing a greater than average rainfall and temperature increase in the west and a cooler and dryer weather in the eastern pacific. This can be better observed in the Figure 5. The simplest definition of La Niña effect consists in the cooling of at least 0.5ºC of the sea surface temperature. This phenomenon happens around every 2 to 7 years and happens less often than El Niño.

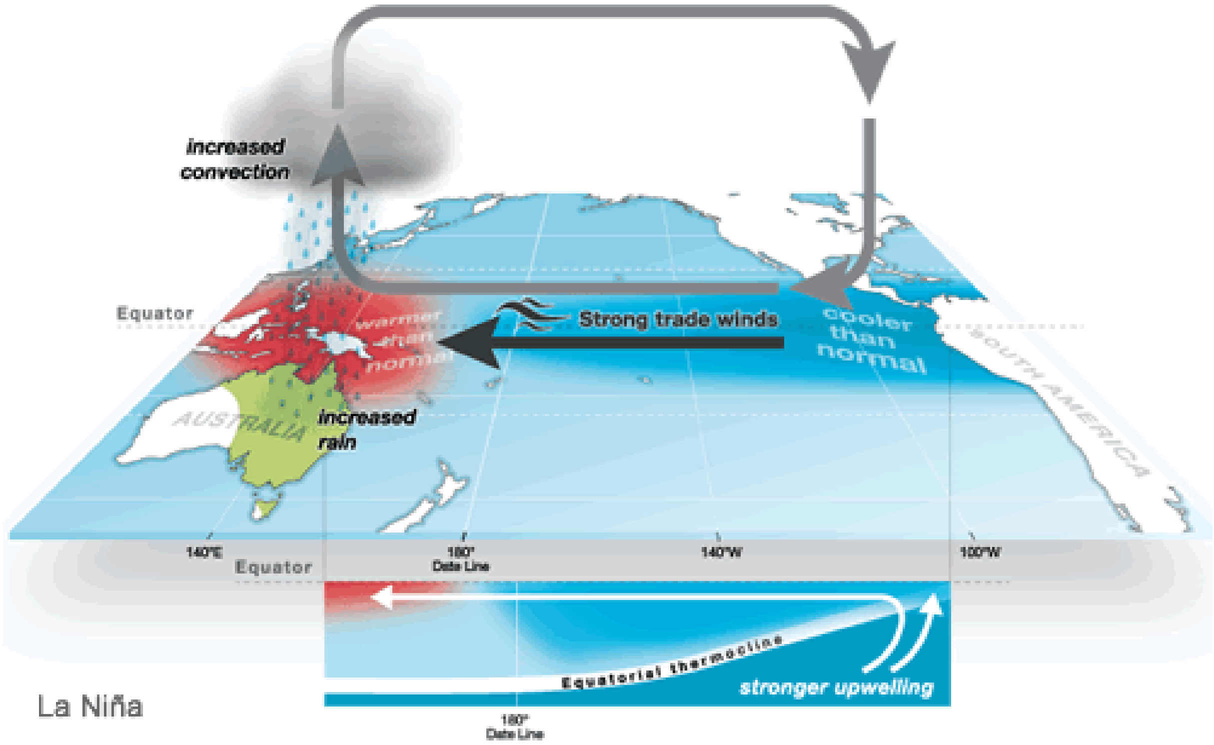

Figure 5 La Niña behavior in the El Niño - Southern Oscillation [11]

El Niño in Colombia

In Colombia this phenomenon has different effects that the rest of the continent, this is because of our tropical climate and the lack of seasons, with just some seasons of more or less rain. In the country El Niño causes a change in the wind circulation causing the cloudiness to disperse and a reduction in the rainfall probability, especially in the Caribbean and Andean regions. Since this phenomenon represents a reduction in the rains it is critical when it happens during the dry seasons of the end and beginning of the year, making drought a threat. The rain diminution causes the rivers to decrease their mass flow, affecting human consumption and in sectors like agriculture; there is an increment in the fire threats and it is an optimal environment for viruses like Chikungunya and Dengue to spread [10].

The Institute of Hydrology, Meteorology and Environmental Studies ("Instituto de Hidrología, Meteorología y Estudios Ambientales", IDEAM), organization in charge of getting the data, making studies and generate scientific and technical data for helping the communities and sectors, identifies an El Niño episode when this sea surface temperature is over 0.5ºC from the historic values for at least 5 consecutive months.

La Niña in Colombia

La Niña has different effects in Colombia and this depends of its intensity, and how it might interact with other phenomena in the Caribbean and Atlantic Sea affecting the country's climate. Nevertheless La Niña usually represents a considerable increase in the rainfall and a reduction in the temperature in the North, Andean and Pacific regions. This represents a threat of sudden river flow rate increases, floods and landslides [12].

Similarly as for El Niño, IDEAM identifies a La Niña episode when the temperature of the sea Surface is -0.5ºC from the historic average for five consecutive months.

1.2.2. The requirement for diversification of the electricity mix

Colombia is conscious about the need to diversify its generation matrix, this started back in 1992, when Colombia suffered one of its strongest droughts, caused by El Niño phenomenon, this episode caused the country to go under a blackout starting officially in May 2 1993 until February 7 1993, during this period there where programmed blackouts for 9-10 hours during the day [13]; back then, the problem was not only the lack of water but also a structural problem of the energy sector and corruption scandals where some new generation plants where not ready to come into operation, which accelerated the rationing. Then the government decided to implement a time change in order to have a better use of day light which was called "Hora Gaviria" named after the then president, Colombia changed from UTC -5:00 to UTC -4:00 this hour change lasted for a period of 13 months [14], even if the black outs lasted a shorter time.

All of this caused the Energy sector to undergo a structural change which was implemented in 1994, with the creation of the generation market, and the energy and gas sector regulation commission (CREG) [15] overall with a positive outcome; also in 2006 they created a mechanism called "Cargo por Confiabilidad" (Reliability charge) which is a Power Market, where they ensure the supply of energy during periods of water scarcity [16]. This system awards firm energy obligations in which generators are obliged to provide reliable and stable energy when needed, therefore they are payed directly a fixed price for their available power capacity. This is done through auctions and until 2019 most of the generators were thermal power plants and some conventional hydro plants. This guaranteed that the country overcame another 3 to 4 Niño phenomena until 2016, where rationing and a blackout was again a threat, this time because a failure in one of the largest conventional hydro plants and one of the thermal power plants [17], plus all the water shortage due to a rather severe el Niño, that affected the communities, vegetation and caused fires throughout the country [18].

The Reliability Charge auctions done on 2019 year, for the 2022-2023 period have for the first time, new participants like the 1170 MW of wind plants and 173,2 MW photovoltaics [19]. Furthermore they recently developed a new mechanism to improve the participation of renewable energies [20], they designed an auction system where they created special type of contracts between the generators and the retailers, this causing a cost reduction for the final consumer and guarantying the participation of the renewables in the market, the auction assigned generation responsibilities to eight projects, 5 wind projects with an installed capacity of 851 MW, and 3 solar PV projects with a capacity of 289 MW and the buyers are a total of 22 retailers [21].

1.3. Motivation and objectives

The importance of the hydroelectric plants for Colombia is evident, this implies that any issue regarding its operation causes large uncertainty in the electricity supply. My motivation relies in the need for Colombia to have a more resilient and sustainable electricity matrix, because with the threat to the hydro resources, Colombia will need other sources to supply the missing energy. This leads to the research question:

"How can Colombia achieve a more resilient and sustainable electricity system in the future?"

In order to find a plausible electricity system and generation matrix, that is both resilient, reliable, and sustainable, I will model the Colombian electricity system in a program called "*urbs*" [22]. This is a linear programing optimization program that models the operation of the power plant fleet by optimizing the cost of electricity, and according to the availability of the different resources. For this the current state of the Colombian electrical system is studied, how it is composed, the different technologies that are present and the potentials for the different renewable energies.

The objective is finding the possible participation of technologies that help achieve an even cleaner and more sustainable matrix, by reducing the sole dependence on hydro plants and decreasing the participation of thermal power plants. Another objective is being able to simulate dammed hydro plants correctly, because of their participation they have an enormous effect in the model, and doing it correctly, which is representing the reality through the *urbs* model is an essential part of this thesis and is one of the main objectives.

2. Methodology

This work is based in the implementation and application of the *urbs* model for the Colombian Electrical System. *urbs* is a program developed in the Chair of Renewable and Sustainable Energy Systems at the Technical University of Munich [23, 24]. This model has multiple inputs, it can be analyzed under different scenarios and the result is the generation matrix and how it operates during the analyzed timeframe, better visualized in Figure 6.

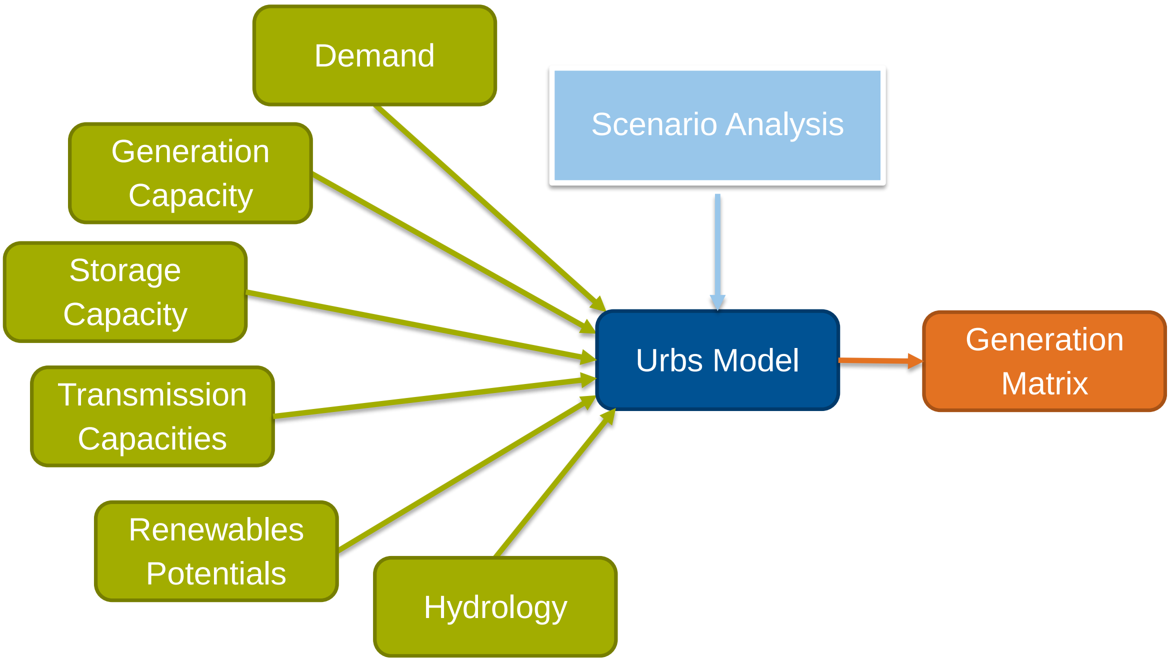

Figure 6 Structure of the *urbs* model

The first input is the electricity demand, since the operation is going to be evaluated, the hourly demand is necessary, and the model will find the way to operate the power plant fleet every hour so that the demand is supplied.

The second input is the technologies to be considered, each with its current installed capacities, this represents the installed power plant fleet, here the amount of each technology to be installed can be limited, as well as forced, this is a way to feed the information on the expected growth and upcoming projects for the future years; Part of the information on the technologies are the necessary investment costs, fixed costs, operating costs, and fuel costs, these are very important because they help the model decide which plants should be installed in the future to keep electricity prices at a minimum.

Information on the Storage capacity, is another input, in this case the storage is the water storage in the Conventional hydro plants, because the water comes in but it only flows when the plants needs to generate. The availability of the water gets separated in time from the generation. The storage is considered to be like a battery, only that you charge and discharge water from it: the charging process is due to rain and the water that comes in the rivers, and you discharge it once you let the water flow through the turbines and generate electricity. Understanding the operation of the dams is critical, so the simulation can work likewise.

Additionally there is another input which is the installed transmission capacities because the modeled nodes are not isolated from each other, they have transmission capacities to transport and receive energy from/to another node with some associated losses. The model does not consider distribution losses inside the node.

When considering renewable energies, it is important to remember that they generation depends on the availability of the specific resource, for that reason, the capacity factors for each place to be considered for installation is so important. This capacity factor quantifies the amount of energy you could get by installing your plant in this determined place. Therefore renewables are only installed were the capacity factors are as high as possible and in this way the electricity costs are reduced because of a better utilization of the plants. The information regarding this availability and the location is what is called the renewable potential, and it is also one of the main inputs to the model. The possible participation of these other technologies is what I seek to find with the developed model.

For determining the operation of hydro power plants, we have to input the information of the water potential, this is fed as a hydrology series, meaning how much water was available for generation at each time step of the simulation. In this model, I will create multiple scenarios and seeing how significant various alterations can be in the results of the model.

2.1. Model nodes

Colombia is a big country which historically, geographically, and ethnologically has been subdivided in different regions, this happens as well when dividing the electrical grid in sub regions for the power generation and supply. The governmental institution divides the country in Units for the Prognostic Control ("Unidades de Control de Pronóstico", UCP), the National Interconnected System is divided in 33 of these, but bigger groups of these small ones make up for eight stablished areas. In order to reduce the complexity of the model, it will analyze five nodes which are built based on this eight UCPs. This joining can be done since the areas are similar in geography, in some extent in hydrology and they are closely meshed. The determination of the area of the UCP is usually closely related to the geographical division of the municipalities and departments, but it is not necessarily exact. It is decided to move some UCPs from East to Center because of the proximity of the large generation plants to the demand centers.

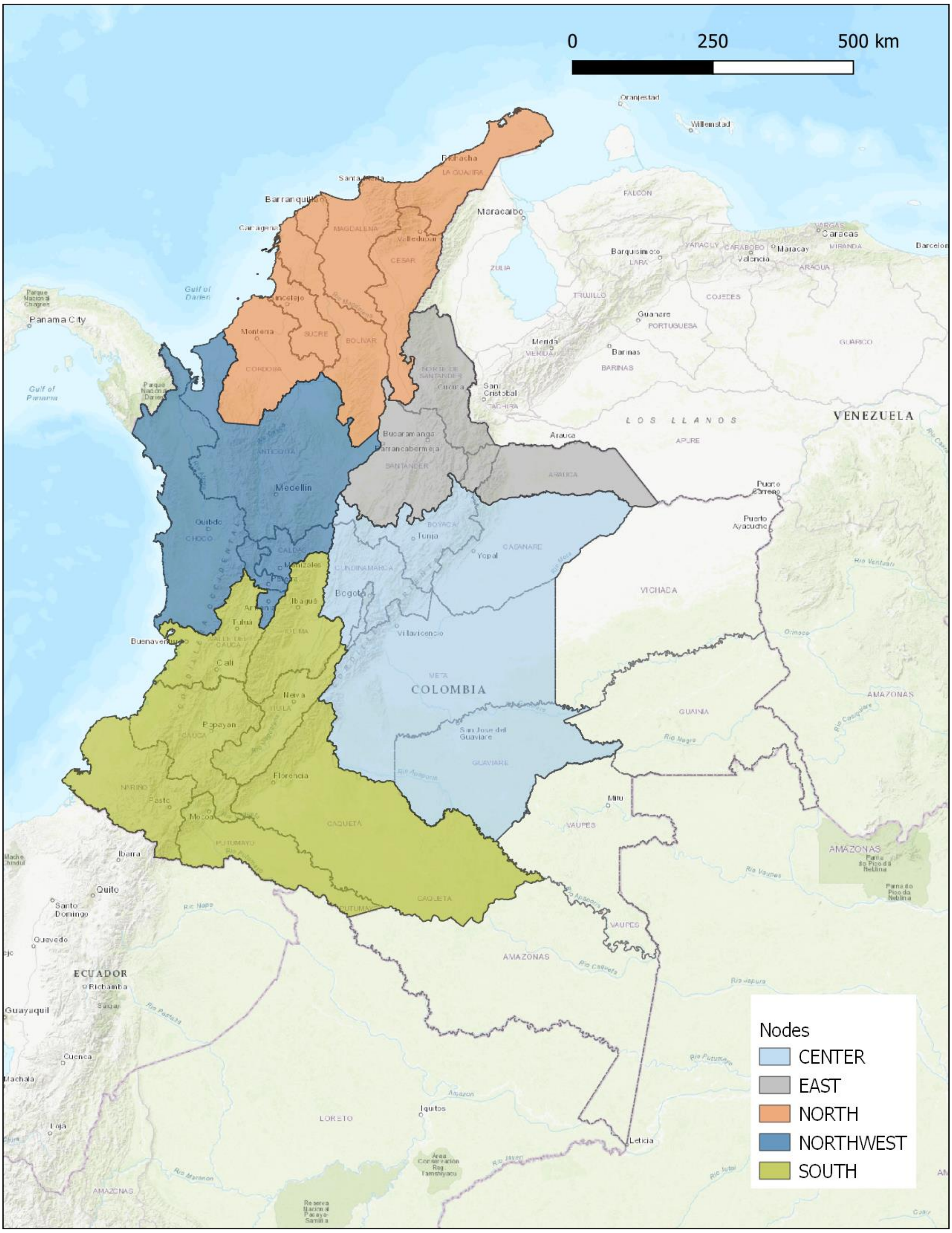

Figure 7 Considered nodes for the model

Each node has a determined demand, power plant fleet, renewable energy potentials, associated available area, and transmission capacities.

The final distribution is shown in the Figure 7. It is important to note that the areas from Colombia which are not covered with this nodes do not belong to the National grid, they belong to the Not Interconnected Zones.

2.2. Scenarios creation

To look into the future it is necessary to consider various possible scenarios, because variations in the considered factors may lead to totally different outcomes. That is why the model will be looking into the influence that different factors have in the results. On Table 1 a short explanation on which are the scenarios to be modeled.

Table 1 Explanation of the scenarios to be considered

Scenario	**Variables to Change**	**Objective**
Base	None	This is a business as usual scenario, where the model will install what can supply the demand with the lowest costs and without any restrictions.
Demand Max	Demand	Business as usual but with the high demand projection
FNCE	None	Constraint on non-conventional renewable energies production
Thermal Phase Out	None	Constraint on renewable energies production
Niño	Hydrology series, Wind and PV series	Simulate the hydrology, wind and solar irradiation of a El Niño year
Niña	Hydrology series, Wind and PV series	Simulate the hydrology, wind and solar irradiation of a La Niña year
Climate Change	Hydrology series	Simulate the hydrology on the expected effects of climate change.
Strong Drought	Hydrology series, Demand	Simulate the effect of El Niño additional to the effect of climate change and the high demand projection.
Worst Case	Hydrology series, Wind and PV series, Demand	Simulate the effect of El Niño plus the climate change effect and the high demand projection, additionally there is a constraint on the generation of renewable energies.

In the beginning it was also considered to include scenarios like a demand reduction because of Energy Efficiency, but in the consulted documents they estimated a reduction of only 1.71% for the industrial sector, which is not representative [25, 26]. Other scenario that was initially considered is a demand increase due to electrification of the transport sector, this scenario was left out because even if there are numbers on how much the demand would increase, there are no studies on how this would change the demand curve for Colombia, and it is a fact that electrical vehicles integration redistributes the demand.

3. Input data collection and modeling

3.1. Electricity demand expected growth and changes

The demand curves have a characteristic shape, with a peak demand around 7pm and another smaller peak around 12m, this can be seen in the Figure 8, where the demand for the first week of 2018 can be seen. The region with the largest demand is Center which includes the capital, then it is North, Northwest, South and lastly East. In this figure it can also be seen that the regions North and East have somehow flatter curves, this could be explained with the higher temperatures present in these regions and the requirement for air conditioning around the hour, both in industry and households so this demand is not just limited to the peak hours.

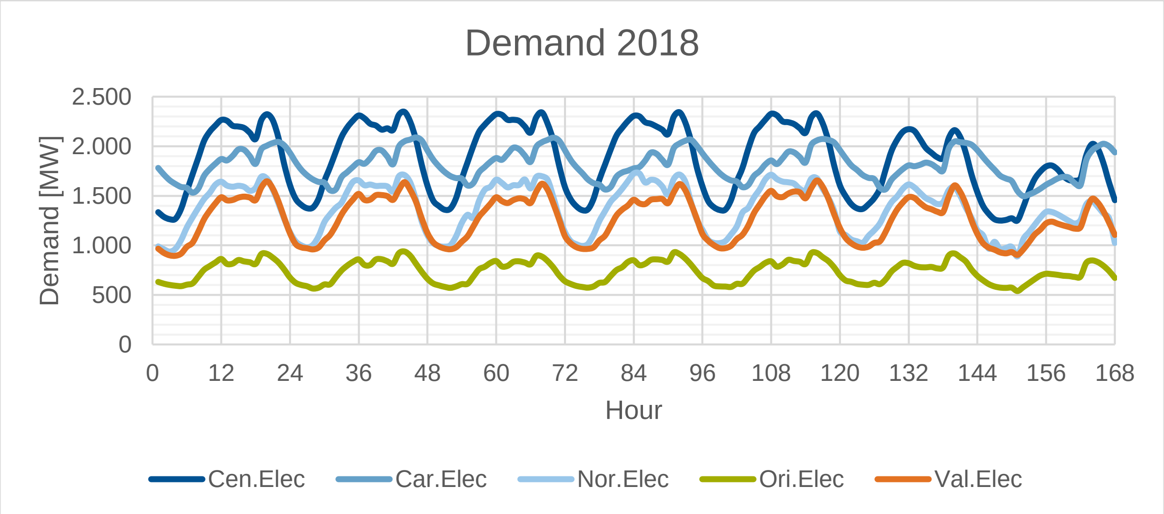

Figure 8 Demand curves for each of the nodes on 3rd week of January 2018.

Even if the Colombian demand is not large comparatively, it still is expected to grow through the analyzed time frame. Some regions with a more accelerated behavior than the others. The expected demand was estimated using the information found in the Regional demand projection [27], where they have different scenarios - a reference, a low, and a high projections - for each of the UCPs, this study does not include projections for the industrial UCPs, for which I decided to use a growth rate equal to the expected GDP growth for Colombia until 2050 [28] as the reference value and in the high and low projections I just added or subtracted the average difference from the other UCPs in the same node with the reference case. In this way the average yearly growth for each region can be seen in Table 2.

Table 2 Average yearly demand growth for each region

	North	Center	Northwest	East	South
Low	3,42%	3,21%	1,29%	3,04%	1,66%
Reference	3,64%	3,38%	1,39%	3,25%	1,84%
High	3,85%	3,54%	1,49%	3,47%	2,02%

Visualizing the demand growth is easier by considering the annual energy demand, which is depicted in Figure 9, for the reference projections. It can be seen that Regions like North and Center almost triple their demand form 2018 until 2050, in the other regions the growth is not so accelerated.

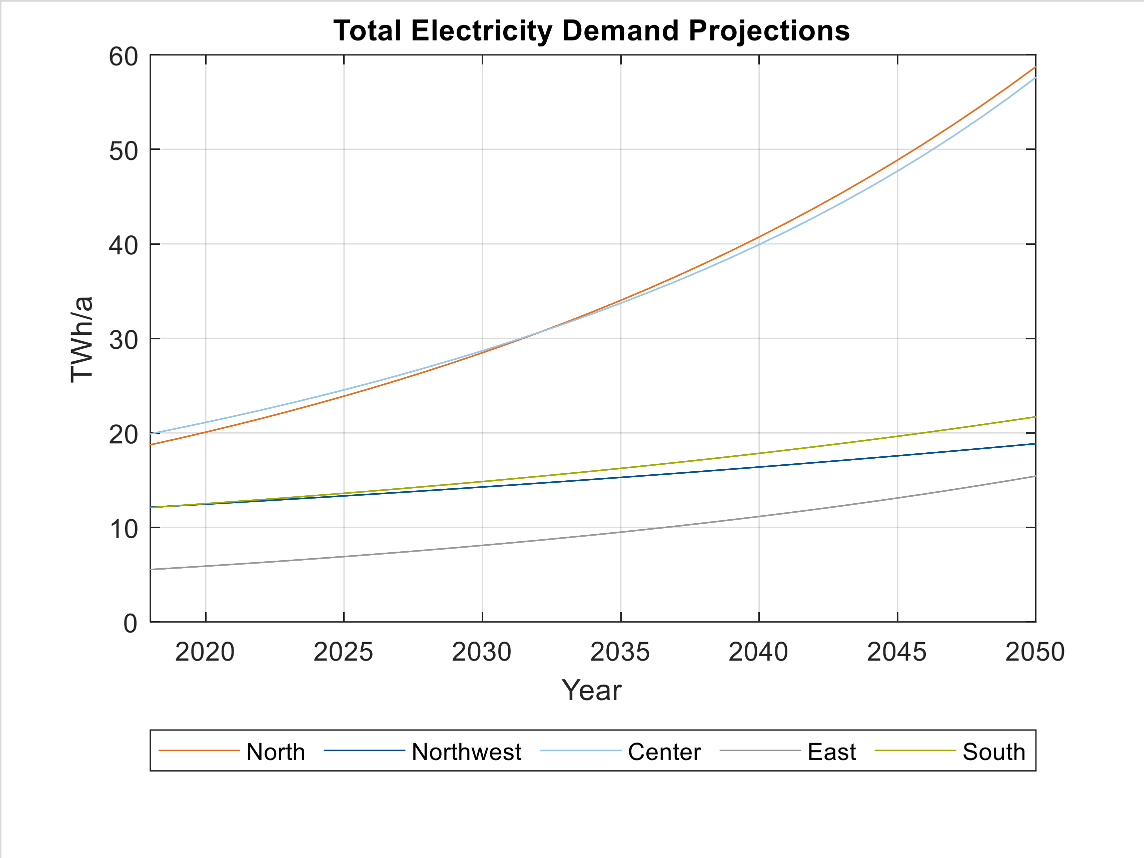

Figure 9 Electricity demand growth reference projections by region

3.2. Transmission capacities

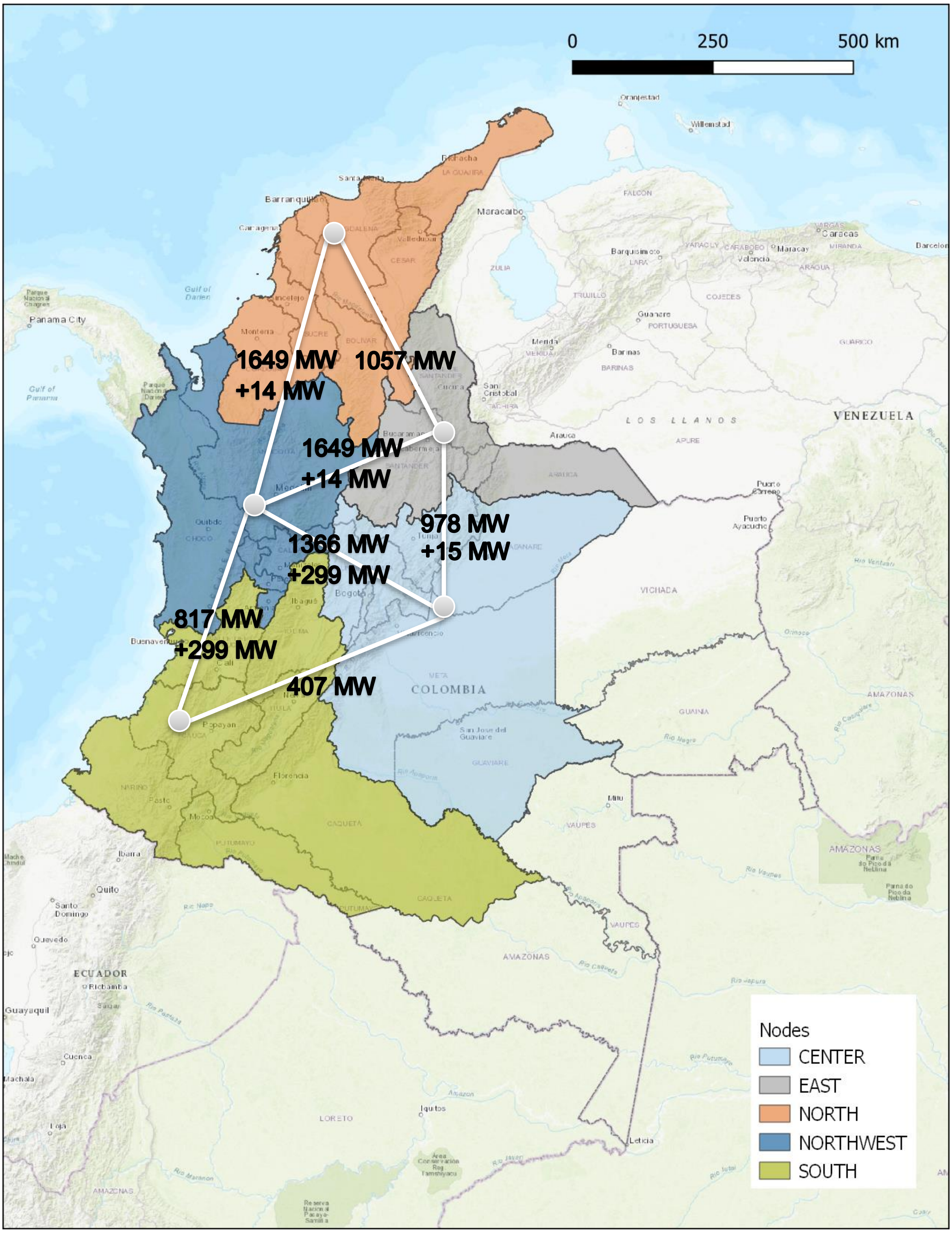

Figure 10 Transmission lines with capacities and expansion plans

The nodes forming the Colombian electrical grid are interconnected between them, this transmission lines connect all the generation plants and distribution centers. For the analysis it is necessary to do the simplification of considering each area as a node, and all the transmission lines that might connect some of the areas, are considered as one singular transmission line. The model uses the installed power transmission capacities stablished in the National Generation and Transmission Expansion Plan [29] The resulting transmission capacities that will be used for the 2018 model, and the corresponding expansion plans for 2022 can be seen in Figure 10.

3.3. Hydrology

3.3.1. Hydrology natural regions and hydrology nodes

Colombia has five main hydrologic regions, which are named based to the main rivers or the seas where all of the rivers in that hydrologic region flow into, they can be observed in Figure 11. These Hydrologic regions do not comply entirely with the nodes used in the model, besides this nodes refer to where the power plant is actually located and into what distribution grid it is delivering the generated electricity, so it is possible that one node has more than one hydrology present in their territory; but it is also true that the data for the hydrology is given in regions that are somewhat more similar to the nodes division that we have. So in order to be clear I will explain the hydrology assigned for each node to which natural hydrologic region they belong to.

- North: corresponds to the hydrology of the Sinú River, which belongs to the Caribe hydrology region, and is the only river with a power plant in the region.
- Northwest: corresponds to the hydrology of the tributaries of the Cauca and Magdalena Rivers on this node territory.
- Center: corresponds to the Magdalena River and its tributaries located in the South, Center and East nodes.
- East: corresponds to the Orinoco Basin and it covers the nodes of East and Center.
- South: corresponds to the Pacífico area that is present in the South node.

Since one of the main goals was the correct modeling of the Conventional hydro plants it was necessary to include the different hydrology that have influence in the nodes, this is relevant for the Center and East hydrology, which are present in different operation nodes, in the

Table 3 this can be seen in more detail:

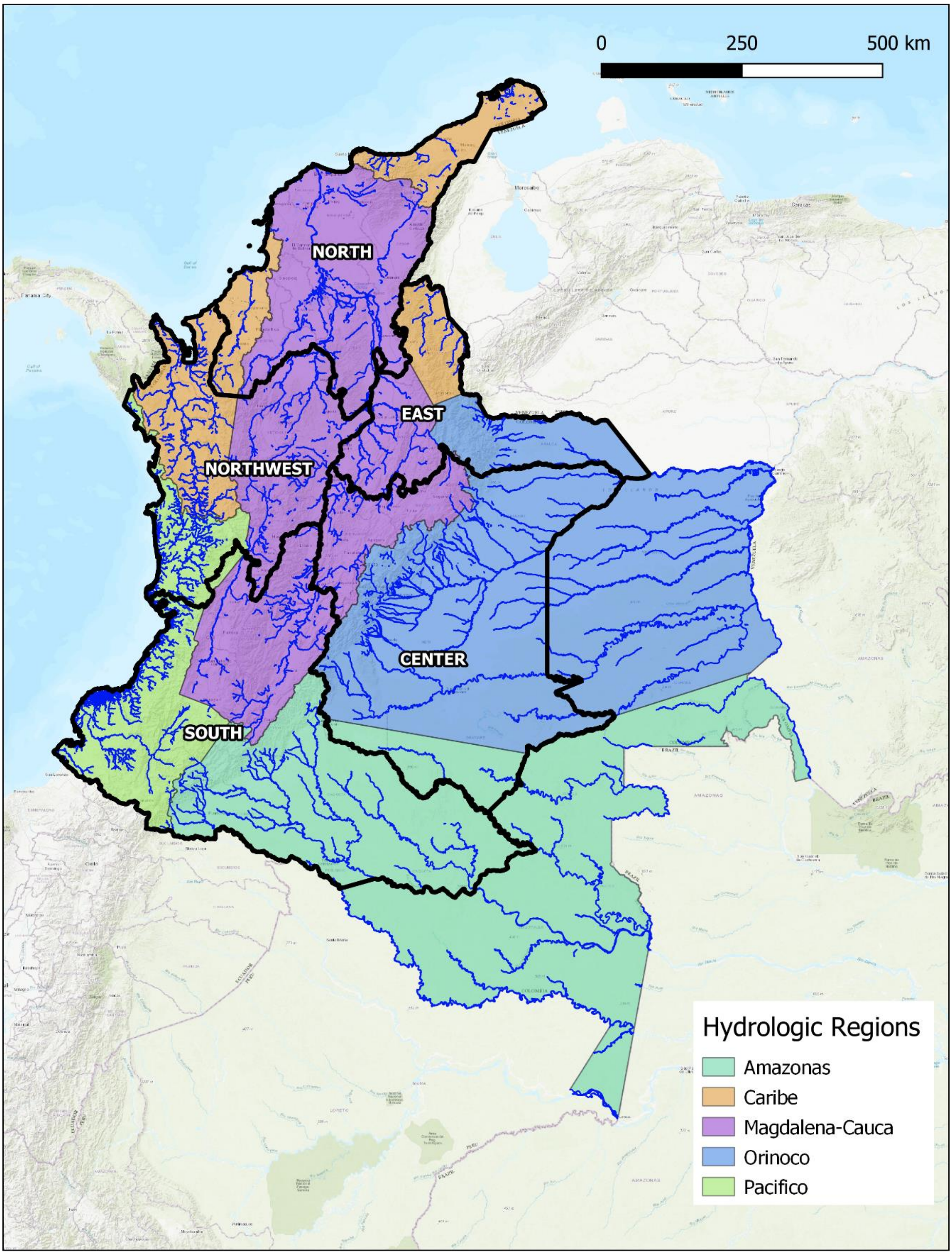

Figure 11 Natural Hydrologic Regions

Table 3 Hydrology distribution for conventional hydro plants

Hydrology	Operation	Hydrology distribution for Conventional Hydro
Center	South	51%
Center	Center	3%
Center	East	47%
East	Center	100%
East	East	0%

3.3.2. Creating the Hydrology series

The information that is available for the hydrology is based on the historical records. XM in its BI Portal [9], has information on the daily and monthly average mass flows for the rivers related to the conventional hydro plants and some large run of river plants. One of the information they have is the monthly historical and real mean mass flow values. The different hydrology series are created based the on this monthly mean values.

But for being able to say what a El Niño, La Niña and Neutral year look like, first it was necessary to determine which years to consider in each scenario and how to quantify this phenomena, this was done with the ONI index is considered [30]. The Figure 12 illustrates this index, values in Red represent an El Niño behavior, values in Blue a La Niña behavior, this index value is a 3 month running mean measurement of the temperature difference between the recorded temperature and the historic average. For analyzing on how to change the hydrology series in order to represent the effects of El Niño and La Niña phenomena, the 5 strongest episodes for each phenomenon are considered from 2000 until 2018 , which are the years with recorded data [9], but also it was analyzed 3 years that the effects of the ENSO where not significant for creating the neutral series, this years were 2005, 2006 and 2018. The analyzed years for El Niño are 2002, 2004, 2009, 2015 and 2016 and for La Niña they are 2000, 2007, 2008, 2010 and 2011.

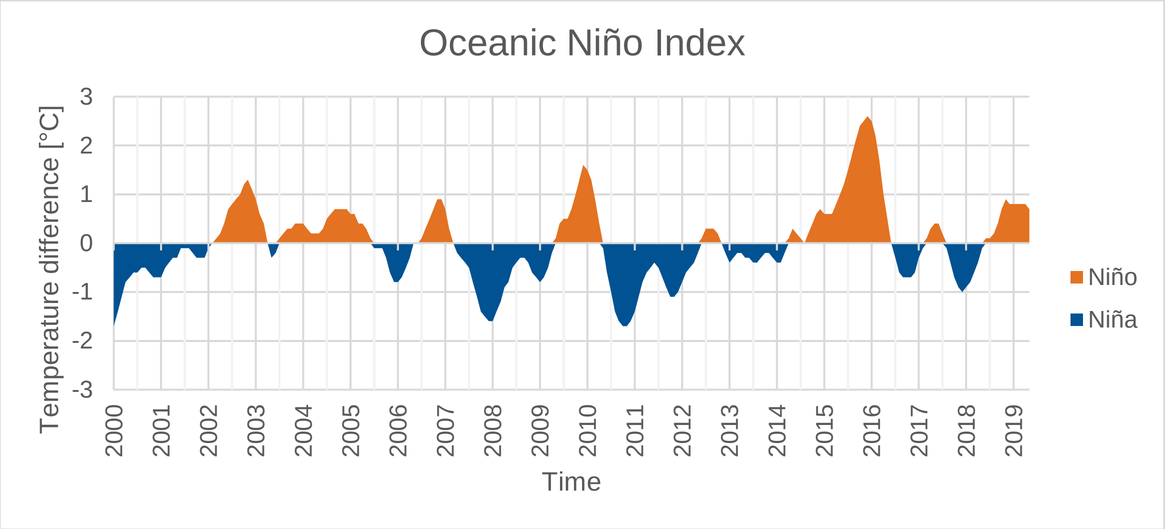

Figure 12 ONI Index for quantifying the El Niño Southern Oscillation phenomena [30]

The issue is that the information available for the water mass flows is related to the installed power plants. Since there were power plants that did not exist in some of these years, I analyzed the monthly flows in relation to the yearly historic average with the following formula:

$$q_m = \frac{Q_m}{\bar{Q}_h} \qquad (1)$$

With:

q_m: The monthly average mass flow in relation to the yearly average [-]

Q_m: The monthly average mass flow for the analyzed year [m^3/s]

$\bar{Q}_h$: The average mass flow for the analyzed year [m^3/s]

In the end monthly average values for each of the scenarios were created and they can be observed in Figure 13, It is important to remark that the East region sees no effect of such phenomena mainly because it is separated from the oceanic interactions by the Andes and it has a more continental climate, and as some of the consulted resources had already noted [31].

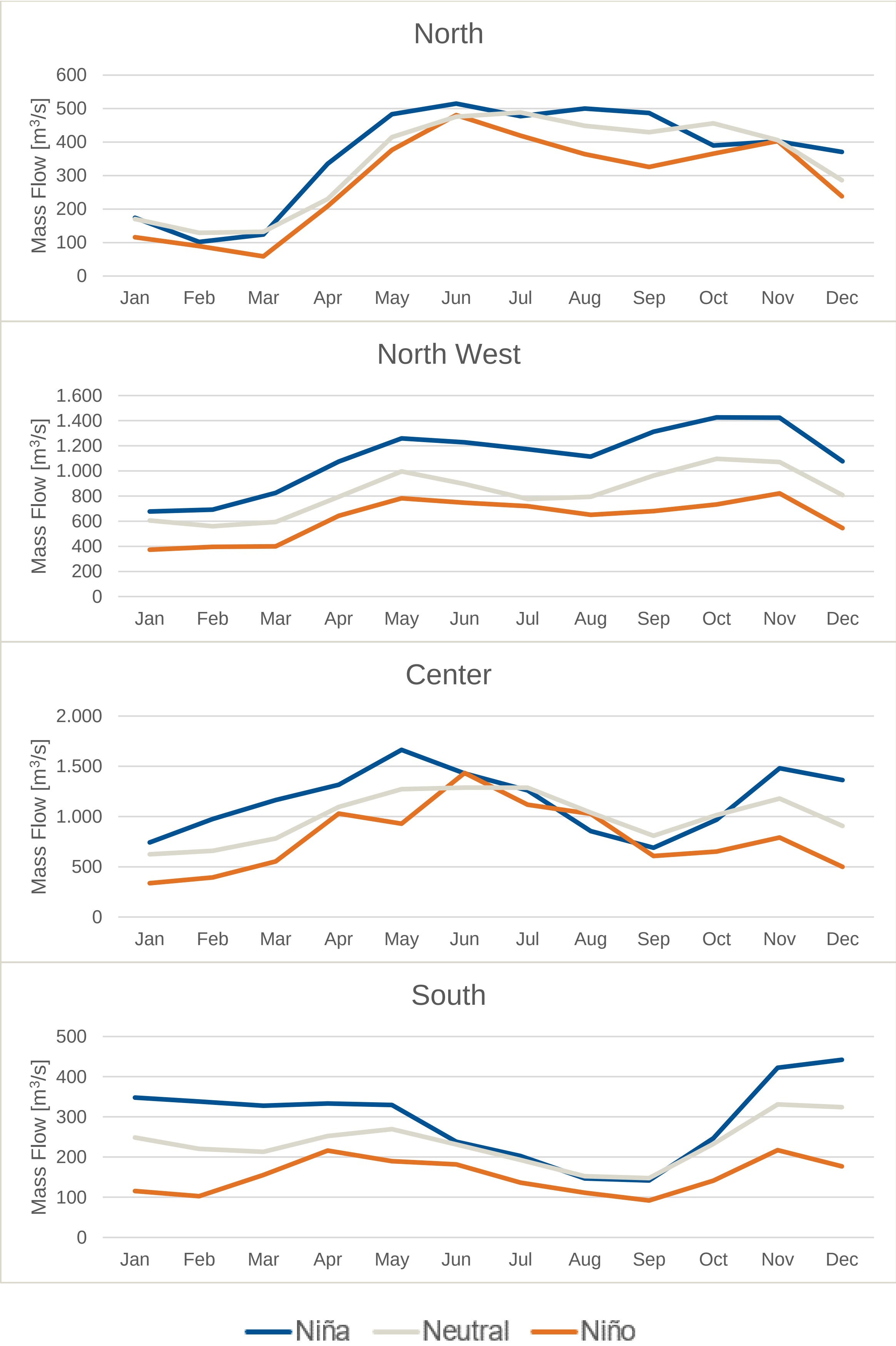

Figure 13 Monthly average mass flow variations for the regions North, North West, Center and South with effects of Niño and Niña.

Generating the hourly series is done based on a model for the generation of synthetic mass flow series created in 1962 by Thomas and Fiering [32]. The model takes into account statistical characteristics of the historical series and the formula is the following:

$$\boldsymbol{X_{t+1} = \hat{\mu}_x + \hat{\rho}(X_t - \hat{\mu}_x) + \hat{\sigma}_x(1 - \hat{\rho}^2)^{1/2}\varphi} \quad \textbf{(2)}$$

Where:

X_{t+1}: is the calculated mass flow, for the current hour in the time series

$\hat{\mu}_x$: is the mean of the historical series; the historic monthly averages are considered

$\hat{\rho}$: is the correlation factor, a correlation factor of 0.45 is used. This value was chosen arbitrarily so that it would give the series some intermittency, but still held a significant correlation with the historical values.

X_t: is the mass flow for the previous hour.

$\hat{\sigma}_x$: is the standard deviation of the historic series. Corresponds to the standard deviation when considering the monthly averages.

φ: is normal aleatory noise.

3.3.3. Modeling Run of River plants in *urbs*

Run of river plants, since they have no storage function are modeled as normal renewable energy plants, as explained in the Figure 14.

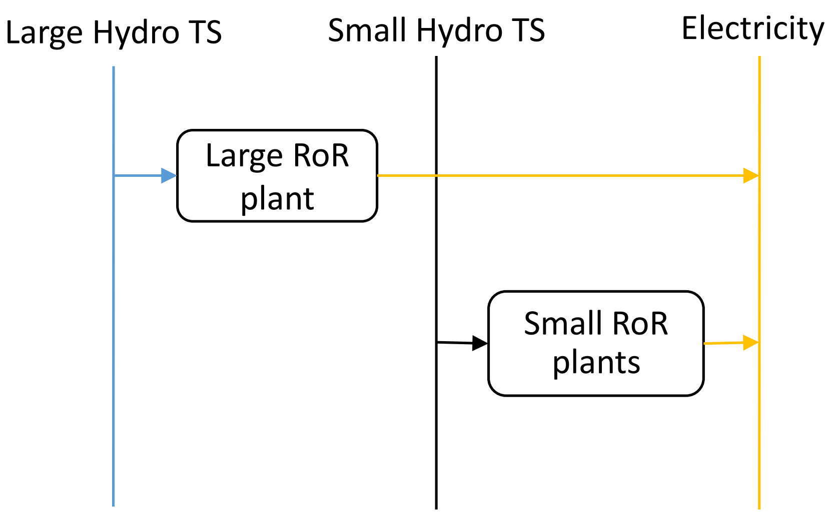

Figure 14 Processes and commodities involved in the run of river hydro generation

It is important to notice that in this model each of the technologies has its own time series, and these change as well for representing El Niño, La Niña, and climate change phenomena, these time series have the same shape as the time series for conventional power plants, but are escalated according to the utilization factor for each technologies in each node.

3.3.4. Modeling Conventional Hydro plants in *urbs*

In order to be able to supply the information regarding the hydrology series in *urbs* and to analyze how the water interacts with the generation plants and storages, it was necessary to create several processes and intermediate commodities to simulate the generation process for the conventional hydro plants, it is explained in the following diagram, Figure 15.

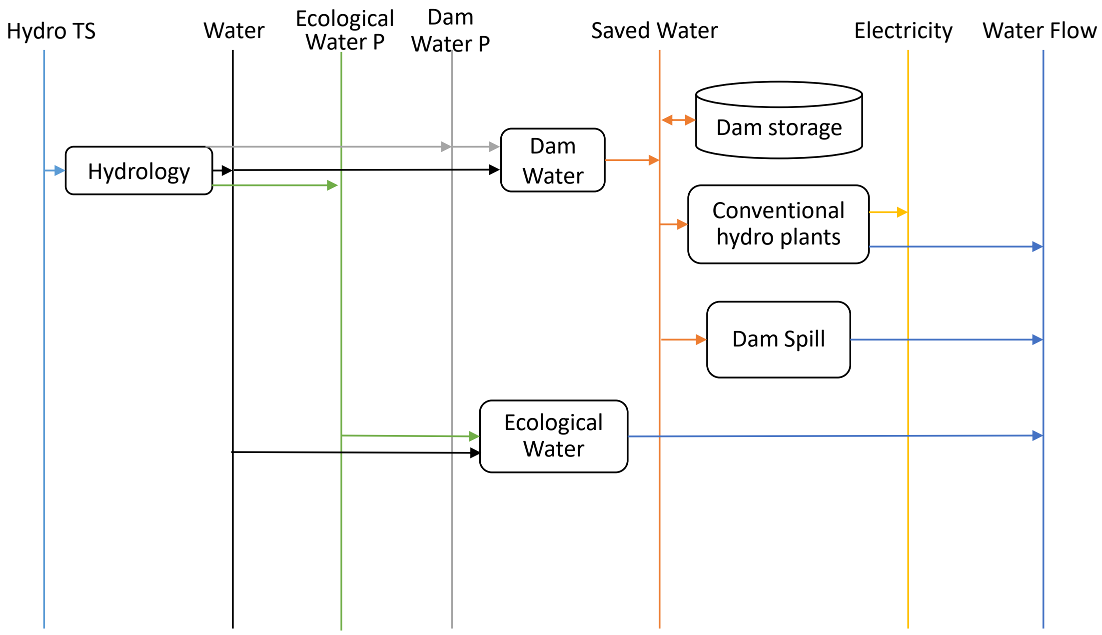

Figure 15 Processes and commodities involved in the conventional hydro generation

The *urbs* models has general a structure where you define commodities, processes and how they interact between each other. The process starts with a commodity called “Hydro”, which contains the hydrology series in the form of a capacity factor series, then there is a process “Hydrology”, which transforms this capacity factor series into instant available water “Water” and the commodities “Ecological Water P” and “Dam Water P”, in a 0.25 and 0.75 ratio, which are created to limit the amount of water that gets transformed into the other types of water instantly. The “Dam Water P” and “Water” are used as inputs in the process “Dam Water” for creating “Saved Water” this commodity is then stored in the dams, spilled, or used directly by the conventional hydro plants for generating electricity. The

“Ecological Water P” is used for creating water which cannot be used that corresponds to the ecological mass flow, just in Colombia there are multiple ways to define it, so it is decided to set it in 25% of the mass flow for being conservative and according to the studies from Ocampo et al. [33].

3.4. Installed technologies

Electricity generation is distributed not so equally among the different regions, with two main regions for hydroelectric generation, which are the Northwest and Center regions and the others with mixes from the available technologies. The North region is especially problematic because it has only a small conventional hydro power plant and a large demand, so this region relies mainly in fossil fuels. Since there are different technologies which are characteristic for the different regions, I will analyze the installed capacities in the following categories: hydroelectric plants, fossil fuel plants and renewable energies.

3.4.1. Hydroelectric plants installed capacity

When considering this type of power plants there is one region that predominates in installed capacity, it is the Northwest region, it has an installed capacity of 4 496 MW in just conventional hydro power plants, which is much larger than the region´s demand. Overall the installed capacity is mainly conventional hydro plants, with some regions without run of river plants like North, and East which only has small run of river plants, the installed capacities for each technology and region can be seen in Figure 16 .

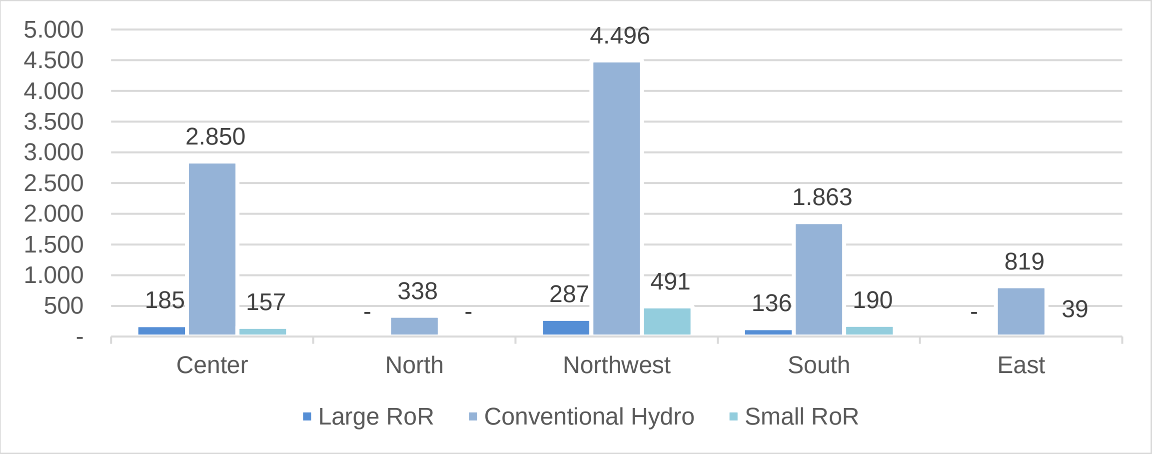

Figure 16 Installed Hydroelectric Capacities

Also the utilization factors for the type of plants varies between regions, but overall it can be said that hydro power is used largely and efficiently in Colombia, with capacity factors around 50%, this is especially significant for the run of river plants. For the conventional dammed plants, this value is just representative because they control their operation according to a plan that takes into account the predicted hydrology series for the following 2 years, the electricity price, the contract responsibilities and other market behaviors, and since they can store water for long times, if in the current year there is a lot of available water and in the upcoming year they expect a drought they will store it so they can use it then. The capacity factor for this technologies according to their operation node in 2018 can be found in Table 4.

Table 4 Hydroelectric capacity factors for 2018

	Center	North	Northwest	South	East
Mean CF Large RoR	47%	-	61%	59%	-
Max CF Large RoR	55%	-	82%	64%	-
Mean CF Conventional Hydro	54%	49%	59%	42%	63%
Max CF Conventional Hydro	61%	49%	75%	59%	63%
Mean CF Small RoR	50%	-	56%	57%	55%
Max CF Small RoR	78%	-	93%	90%	86%

For the storage itself, the capacity is given by the volume of useful water that could really generate electricity, so it is the maximum level minus the minimum technical level - the lowest level at which you can still generate. The storage capacity today in Colombia is around 16953 GWh or 13.306 Million m^3[19]. In Table 5 there is the information on the conventional power plants that have dams, the information on the associated Dam, such as the Useful Volume and the information on which hydrology and where the plant is located.

Right now there is a project under construction which is the largest conventional hydro plant to be built in the country, with a total installed power of 2400 MW and a useful dam capacity of 980 million m^3, this project called Hidroituango, to originally start operation on 2019 had an emergency which pushed the delivery date indefinitely and brought a lot of uncertainty to the project [34–36]. This episode has now the country divided in whether they support this kind of projects or not, due to the effect they have in the communities and ecosystems. Therefore this project will be considered as the only addition to the current conventional hydro plants and that it will be operating in 2024.

Table 5 Conventional power plants and information on their associated dams

Generation Plant	Installed Capacity [MW]	Associated Dam	Useful Volume [thous. m^3]	Operation Node	Hydrology Node	Conversion factor [$MW/m^3/s$]
Albán	429	Altoanchicaya	27 460	South	South	4.5098
Betania	540	Betania	755 980	South	Center	0.5974
Calima	132	Calima 1	417 360	South	South	1.8322
Chivor	1000	Esmeralda	587 590	Center	East	6.9035
El Quimbo	396	El Quimbo	2 360 260	South	Center	1.1048
Guatapé	560	Peñol	1 044 020	Northwest	Northwest	6.9915
Guatrón	512	Miraflores	96 580	Northwest	Northwest	8.45
Guavio	1250	Guavio	764 340	Center	East	9.8098
Jaguas	170	San Lorenzo	161 860	Northwest	Northwest	2.3302
La Tasajera	306	Riogrande 2	137 060	Northwest	Northwest	8.0813
Miel I	396	Amani	441 380	Northwest	Northwest	2.0373
Pagua	419	Muna, Agregado Bogotá	841 170	Center	Center	11.46
Pagua	181	Chuza	220 370	Center	East	4.94
Playas	207	Playas	49 220	Northwest	Northwest	1.7193
Porce II	405	Porce II	88 820	Northwest	Northwest	2.0166
Porce III	700	Porce III	130 870	Northwest	Northwest	3.2028
Prado	51	Prado	420 660	South	Center	0.4783
Salvajina	315	Salvajina	696 880	South	South	0.8483
San Carlos	1240	Punchiná	48 390	Northwest	Northwest	5.3318
Sogamoso	819	Topocoro	2 756 310	East	Center	1.2372
Urra	338	Urra1	1 237 910	North	North	0.4587

3.4.2. Thermal power plants installed capacity

In the Colombian electricity mix there are several types of fossil fuels present, not only the traditional ones like natural gas and hard coal, but also others like Diesel, Fuel Oil and Jet-A1, which are also used in the Gas turbines, all of the Gas plants in Colombia have a main fuel depending on the availability, but they can also operate with a second or even third fuel. In the model only the main fuel was assigned and considered this plant as this certain "technology". Now when talking about the installed capacities there is mainly Combined Cycle plants, followed by Gas turbines and Coal, as mentioned before the North region has a large thermal fleet, this can be understood not only because of the lack of hydroelectric power plants in this region but also because most of the import and export of fuels in Colombia is done in the Caribbean coast, and the largest coal mine I located in this region as well. Installed capacities in Figure 17.

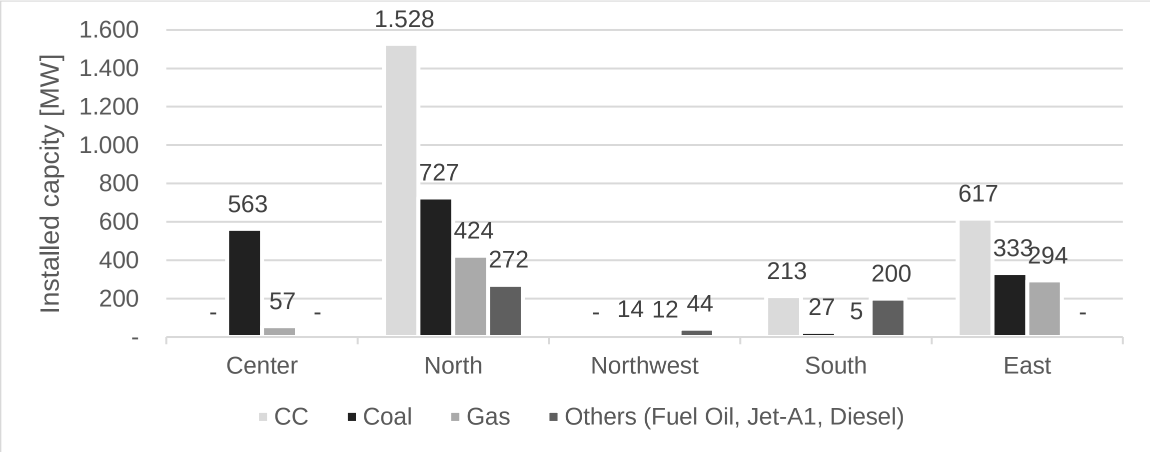

Figure 17 Installed capacities for thermal power plants per region

In all the other regions there are thermal plants which mainly work as back up for the hydroelectric plants and as peak plants. The thermal plants that are smaller than 20 MW are not centrally dispatched which means that they operate as long as they want, usually being on the whole year and just stopping for maintenance. The capacity factors in Table 6.

Table 6 Capacity factor for the thermal power capacity per region

	Center	North	Northwest	South	East
Mean CF Gas	46%	31%	2%	1%	66%
Max CF Gas	96%	79%	2%	1%	95%
Mean CF Coal	18%	28%	7%	5%	28%
Max CF Coal	35%	58%	8%	10%	29%
Mean CF CC	-	25%	-	1%	0%
Max CF CC	-	58%	-	1%	0%
Mean CF Others (Fuel Oil, Jet-A1, Diesel)	-	6%	0%	5%	-
Max CF Others (Fuel Oil, Jet-A1, Diesel)	-	12%	0%	5%	-

3.4.3. Renewable Energies installed capacity

Renewable energies in Colombia have seen a slow development, this is mainly because of the high costs due to the immature market, which is more evident in a market dominated by hydroelectric plants. That is why when considering the large potential Colombia has for renewables, the installed capacities are extremely low. The renewable energy has been most largely exploited are Bagasse plants, these are cogeneration plants that belong to the Sugar cane industries, here they burn the bagasse which is the rest of the sugar cane once the juices are extracted, this plants generate heat and electricity for the own plant's use, but also they can inject electricity to the grid, they decide whether to inject or auto consume according to the markets behavior.

Wind energy is present with great potential in one specific region, the North region in La Guajira, the only installed plant is there and it works as a pilot plant, which is why its capacity factor is so low, but there are several projects on the way.

Photovoltaic plants are new in the grid but every day there are new installations for self-consumption and new plant large plants are coming to the grid. The installed capacities for renewables are in Figure 18 .

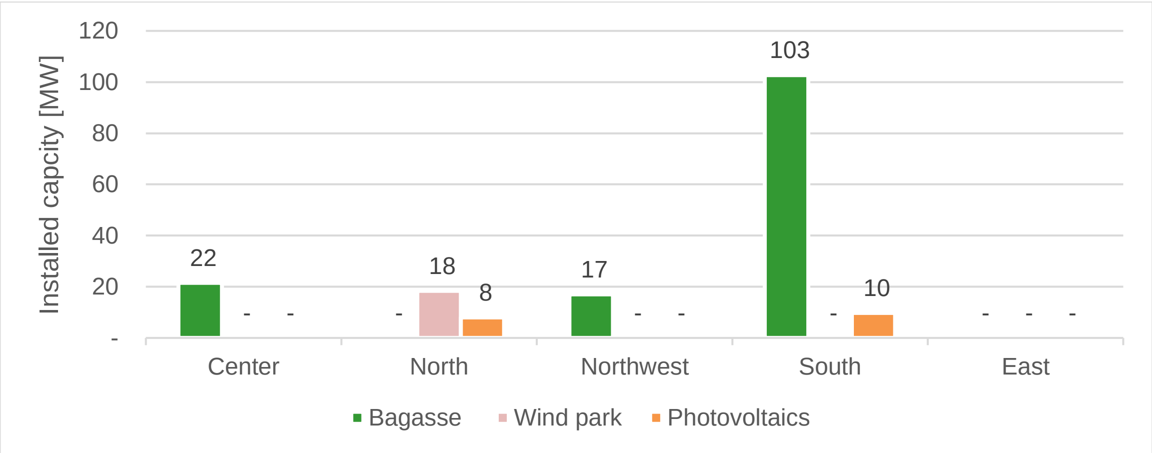

Figure 18 Renewable Energies Installed Capacity

3.5. Technology Inversion and Operation costs

The implemented model is a cost optimization tool, so the results depend directly on the costs that are given to each of the different technologies to be considered. Each technology needs to be assigned the CAPEX [USD/MW], which are the inversion costs, the Fixed Operation Costs [USD/MW-y] which do not depend on the actual generation of the plant and the Variable Operation Costs [USD/MWh] that are related directly with the electricity generation. It is important to state that since the results depend entirely on this associated costs, they are only applicable for this costs behavior. The Table 7 indicates the used costs and the source for each of the technologies, the source choice was based in that the CAPEX was the most similar to the costs reported in the Generation-Transmission Expansion plan 2017-2031 for Colombia [37], which has a summary of the inversion costs reported to the authorities by all the subscribed projects.

Table 7 Inversion, fixed and variable operational costs for each technology

	CAPEX [USD/MW]	**Fixed O&M [USD/MW-y]**	**Variable O&M [USD/MWh]**	**Source**
Large RoR plant	1.801.530	33.480	0,0	GeoLCOE [1] [38]
Conventional Hydro plant	2.036.060	14.370	0,0	GeoLCOE [38]
Small RoR plant	2.204.310	34.740	0,0	GeoLCOE [38]
Combined Cycle plant	1.393.530	14.480	3,3	GeoLCOE [38]
Coal plant	1.779.720	46.290	7,3	GeoLCOE [38]
Gas plant	1.151.000	6.440	13,5	GeoLCOE [38]
Wind park	1.582.585	43.205	0,0	NREL 2019 Annual Technology Baseline[41]
Photovoltaics	1.114.755	13.803	0,0	NREL 2019 Annual Technology Baseline[41]
Diesel plant	1.151.000	6.440	13,5	GeoLCOE [38]
Fuel oil plant	1.151.000	6.440	13,5	GeoLCOE [38]
Bagasse plant	1.346.000	21.000	11,5	Integracíon energías Renovables [42]
Jet-A1 plant	1.151.000	6.440	13,5	GeoLCOE [38]

[1] This is a Colombian specific online tool that allows you to calculate the costs for different technologies and projects, the tool is accessed in [38], further explained in [39], and the documentation can be found in [40].

It is also important to establish the lifetime of the different technologies, in this model, the economic lifetime is the same as the operational lifetime, so only the depreciation period is used, for the model the following times were utilized:

- 50 years for all of the hydro technologies (Large RoR plant, Conventional Hydro plant and Small RoR plant)
- 35 years for all the thermal power plants (Combined Cycle plant, Coal plant, Gas plant, Diesel plant, Fuel oil plant and Jet-A1 plant)
- 25 years for renewables like Wind parks and Photovoltaics
- 30 years for the Bagasse plants

Furthermore for technologies like Wind parks, Photovoltaics and Bagasse plants it is considered that this technologies will decrease their costs over time due to the R&D and the more availability in the market, in Table 8 the future costs can be observed.

Table 8 Discounted inversion and operation costs for renewables in the future

	Wind park		**Photovoltaics**		**Bagasse plant**	
	CAPEX [USD/MW]	Fixed O&M [USD/MW-y]	CAPEX [USD/MW]	Fixed O&M [USD/MW-y]	CAPEX [USD/MW]	Fixed O&M [USD/MW-y]
2024	1.417.446	41.078	990.069	11.720	1.277.347	19.929
2030	1.252.307	38.950	861.664	10.200	1.212.196	18.912
2040	1.157.868	36.029	766.136	9.069	1.110.912	17.332
2050	1.052.089	33.108	683.310	8.089	1.018.090	15.884

Additionally for 2040 and 2050 batteries were considered as an alternative for energy storage, the costs and variables for such technology can be observed in Table 9 and where taken from [41].

Table 9 Costs for battery storage

Year	**Roundtrip eff [-]**	**Inv. Cost P [USD/MW]**	**Inv. Cost C [USD/MWh]**	**Fixed O&M [USD/MW-y]**	**Depreciation [years]**
2040	0,85	667.969	151.463	31.846	15
2050	0,85	667.969	141.365	30.836	15

3.6. Fuel costs

The cost of fuels is also one of the most important variables in the cost optimization tool. In Colombia there are several fuels which are used for electricity generation, the importance of each changes from region to region especially because Colombia produces some of them, the prices used the simulation are based on the projections done by UPME [43], in their document they analyze different factors that could influence the price of the fuel for electric generation in Colombia, for example the WTI and Brent oil prices, Henry hub gas prices, market assumptions, price assumptions, but also the associated costs that are required to get the fuel to the generation plants, for example the liquefaction, maritime transport and regasification processes, needed for the LNG.

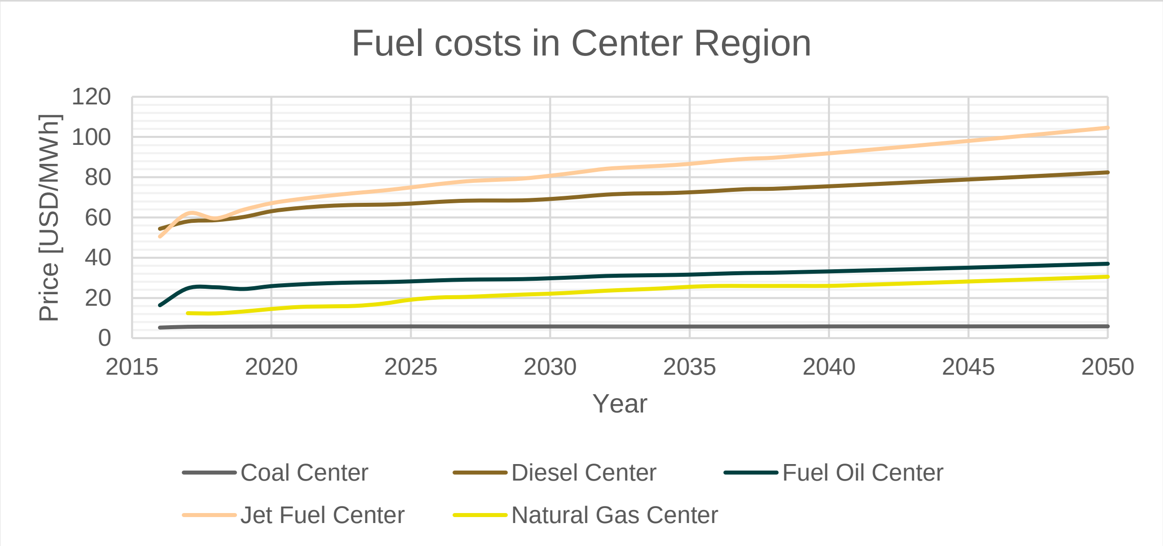

Figure 19 Reference fuel cost projections for the Center Region

Natural Gas is analyzed deeper than the other fuels, primarily because Colombia is a natural gas producer. Unfortunately the availability is reducing over time when considering the demand, therefore the authorities are looking for alternatives and the most promising is to start importing LNG that is why a storage and regasification plant was built in Cartagena on the Caribbean cost, and another one is under planning in the pacific coast, in order to have certainty in the supply of natural gas. The other fuel costs are calculated according to the different laws and regulations defined in the country for the price calculation. In the document they do three different projections: a low, reference and high price scenarios, in this study the reference scenario is going to be used. This projections go until 2040 and since they are needed until 2050, I used the growth rate of the last 10 years of the projection, 2030-2040, and obtained the expected values for 2041-2050.The different projections are available for different power plants around the country, where they include the cost of transporting the fuel to the specific regions, for some it was necessary to complete this transportation cost in which the values found in the GeoLCOE online tool [38] were used, in the Annexed Excel File all the projections per Fuel are summarized, in Figure 19 the reference prices of the different fuels for just the Center region are shown.

3.7. Renewable Energy Potentials

Renewable energies have the particularity hat they are intermittent, and the power output depends on the availability of such energy source; the availability in a determined site determines how good it is for installing the specific technology. For this reason renewable energies are only installed in good sites and the amount of good sides determines the potential for this technology in each region.

3.7.1. Run of River Potential

As mentioned in the introduction experts estimate the country's potential for Run of river plants as 56GW [7] but this estimation includes all of the territory and is more as a resource and technical potential but not exactly a economic potential, that is why a further analysis of the potential is performed to establish the potentials for each region and technology.

In the Potential Atlas they divide the potential for each hydrologic region (remember Figure 11) and type of power plant, between Pico (0.5- 5 kW), Micro (5- 50 kW), Mini (50- 500 kW), and Small (500- 19 000 kW), which would represent Small RoR plants, and then there are the Large (20- 40 MW) and the >40 MW power plants, which constitute the Large RoR plants, the potentials are presented in Table 10:

Table 10 Resource potential for Run of River plants [7]

Hydrologic region	Total <20 MW [GW]	Total Large RoR [GW]
Amazonas	933	11 041
Caribe	455	3 671
Magdalena Cauca	1 700	20 522
Orinoco	1 271	12 432
Pacífico	586	3 576

Afterwards I took some data they have on the distribution of these potentials between the sub regions, and the information of the current distribution of installed power in the general regions because the potential in the Magdalena Cauca needs to be distributed between the Northwest, Center, South and East regions which I did according to the following percentages, Table 11 :

Table 11 Distribution of the Magdalena -Cauca potential among the analysis regions

Region	Magdalena - Cauca Distribution [%]
Center	18%
Northwest	44%
South	27%
East	11%

Then for determining the actual economic potential, because some regions are definitely better than other for these technologies, an estimated percentage was applied to the potentials in Table 10 that will limit the economic potential (EP) for the technologies in the different regions:

Table 12 Economic RoR potentials for the different analysis regions

Region	EP Small RoR [%]	Small RoR [MW]	EP Large RoR [%]	Large RoR [MW]
Center	1	304	0.3	1 102
Northwest	1	755	0.3	2 737
South	1	458	0.3	1 658
East	1	182	0.2	439
North	0.5	228	0.15	551

3.7.2. Biomass Potential

In the National Residual Biomass Potential Atlas [44], there are some estimates on the potential for the biomass residues for different agricultural industries in the country, such as Rice, Banana, Coffee, Corn, Oil Palm, Plantain, and Sugar Cane for both Sugar and Panela (unrefined whole cane sugar). In the developed model the only type of biomass that was considered is Bagasse plants, so they process the residue for both sugar and panela industries, which potential locations are shown in Figure 20 and Figure 21 respectively.

For determining the potential, the calculations were made based on the energetic potential [44], the average capacity factor and the electrical efficiency [40], because these plants are used as cogeneration plants where the main product is the heat they require for the production process, the resulting potential for sugar and panela industries is shown in Table 13 and Table 14 respectively.

Finally there was a correction factor to increase the potentials, around 20%, in order to somehow include some of the biomass from other industries that could also have cogeneration plants with participation in the national market.

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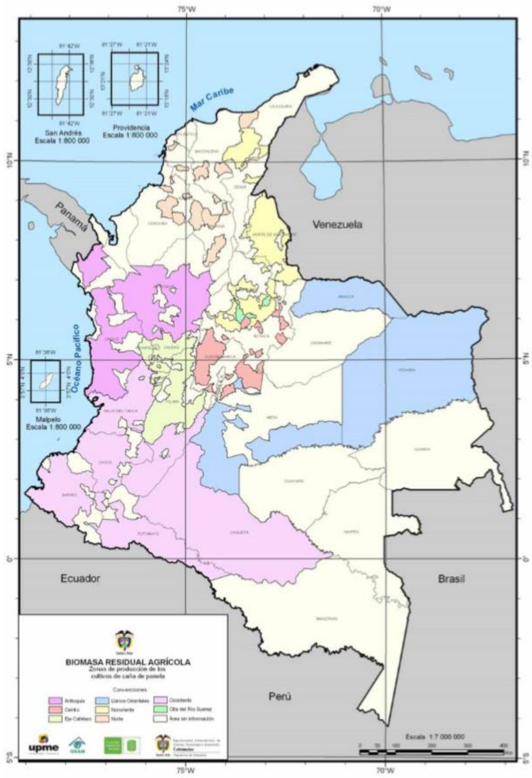

Figure 20 Location of Sugar industries [40].

Figure 21 Location of Panela industries [40].

Table 13 Potential calculation for sugar industry residues

Sugar Industry	Energetic Potential TJ/a	Electricity Potential MWh/a (η=12.15%)	Potential [MW] (CF=0.64)
Northwest	3 226.9	108 863	19
Center	0	0	0
North	495.31	16 710	3
East	472.46	159 389	3
South	114 384.22	3 858 879	688

Table 14 Potential calculation for panela industry residues

Panela Industry	Energetic Potential TJ/a	Electricity Potential MWh/a (η=12.15%)	Potential [MW] (CF=0.64)
Northwest	16 794.62	566 585	101
Center	22 593.37	762 212	136
North	1 478.31	49 872	9
East	12 246.11	413 136	74
South	27 905.32	941 417	168

3.7.3. Wind Potential

Wind energy in Colombia is still in its initial stages, with just one wind park in operation and it is mainly a pilot plant, but there are several wind parks under construction, but all of them located in the same region, the North node, so identifying the potential for the other regions is somewhat difficult and even more considering that what is needed are the time series. Here is where the tool “Renewable - time series” developed by Siala and Houmy [45] comes in handy because it generates time series for user-defined regions, so it allows to find the best locations between the analyzed nodes and gives the time series for the particular years.

So the sites where chosen according to the data for 2015, which is a El Niño year, and then the program is run again to find the time series for the locations already chosen in 2018, the neutral year and for 2011 a La Niña year. What happened is that the program underestimated some regions and might have overestimated the others, since it takes into account a factor in which, if there are mountains present, there is an increase in the velocity, seen in Figure 22. So when comparing this results to the wind atlas created by IDEAM [46], Figure 23, the potential of the North region is cut short. Since North is the region with the highest recognized potential, for this particular region it was decided to use the online tool Renewable Ninjas [47], based on the works [48, 49], which gives the time series for different years for a specific location, for which the location of the existing wind park was given, the summary of the locations, and Capacity factors is shown in Table 15.

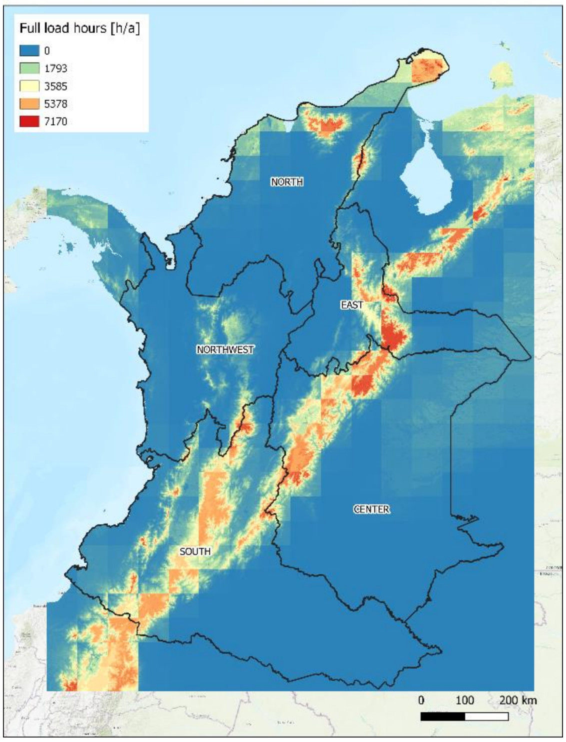

Figure 22 Full load hours according to the Renewable timeseries program

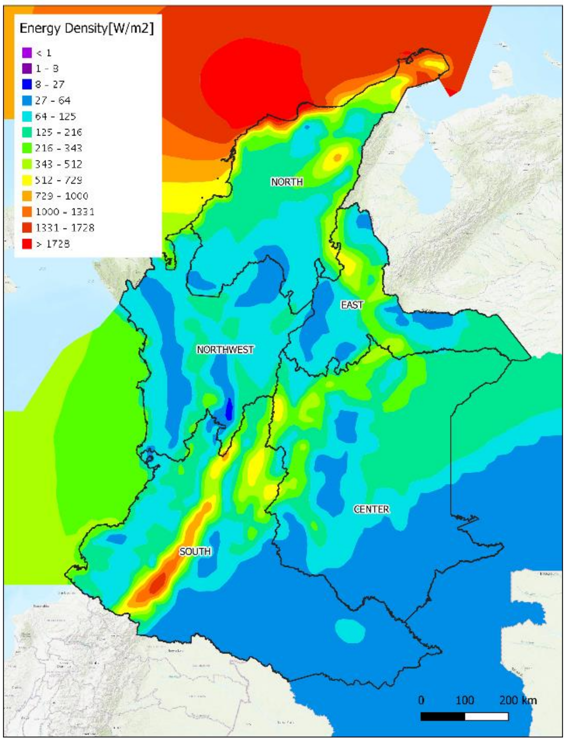

Figure 23 Wind Energy density according to the IDEAM wind atlas.

Table 15 Sites used for the wind time series

	North	Northwest	Center	East	South
Latitude	12,23	6,78	4,74	7,66	3,17
Longitude	-72,04	-75,62	-73,93	-72,92	-75,92
CP 2015 (Niño)	77,7%	19,5%	59,6%	63,0%	60,9%
CP 2011 (Niña)	55,1%	20,9%	44,5%	51,2%	44,5%
CP 2018 (Neutral)	74,3%	20,4%	51,5%	58,3%	53,7%
% variation Niña	-19,2%	0,5%	-7,0%	-7,1%	-9,2%
% variation Niño	3,4%	-0,9%	8,0%	4,8%	7,3%

Now that the time series were set, it is necessary to limit the potential for installing this type of technology, because this time series represent just the best places in each region, for this some studies by the Colombian government where used [42], in Table 16 the specific values are presented.

Table 16 Install Capacity potential for Wind parks per region

Region	North	Northwest	Center	East	South
Potential [MW]	20.000	1.000	2.500	5.000	3.500

3.7.4. Photovoltaic Potential

Colombia is a tropical country with relatively high levels of irradiation on all of its territory and with more or less constant levels thorough the year, but still photovoltaic plants are still not widely spread mainly because of their high costs. There are not a lot of reference plats for obtaining the time series for PV, therefore the tool by Siala and Houmy [45] was used again, to obtain some of the best locations and their time series for the years 2015, 2011 and 2018, see Table 17. The information obtained is shown in the map in Figure 24, which is somewhat similar to the information from IDEAM [50] shown in Figure 25.

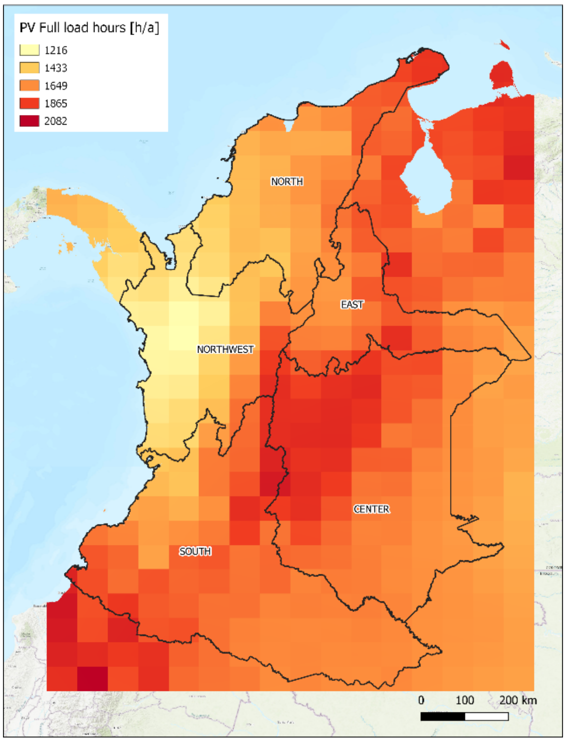

Figure 24 Full load hours for PV in 2015 using renewable timeseries tool.

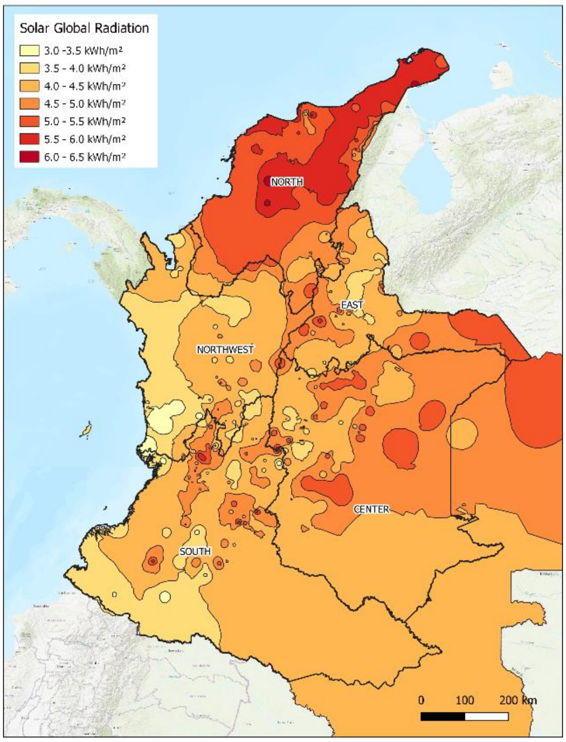

Figure 25 Solar Global Radiation according to IDEAM

Table 17 Sites and properties used for the photovoltaic time series

	North	Northwest	Center	East	South
Latitude	11,95	5,30	3,25	6,25	3,25
Longitude	-71,25	-75,00	-74,39	-71,88	-74,76
CP 2015 (Niño)	21,7%	21,9%	22,7%	20,3%	22,7%
CP 2011 (Niña)	19,6%	20,8%	21,4%	19,7%	21,5%
CP 2018 (Neutral)	21,7%	21,7%	22,2%	20,1%	22,2%
% variation Niña	-2,1%	-1,0%	-0,8%	-0,4%	-0,8%
% variation Niño	0,0%	0,2%	0,5%	0,2%	0,5%

3.8. Data for the Scenarios

3.8.1. Base Scenario

In the base scenario the model uses the neutral hydrology series for all the regions and technologies, except for the Northwest region and the Conventional hydro technology where the used hydrology series corresponds to La Niña.

3.8.2. El Niño and La Niña

In the Hydrologic analysis that I performed, and explained in Section 3.3.2, I got to the results that during El Niño and La Niña episodes, there is an average yearly mean mass flow reduction and increase respectively which can be observed in Table 18 for each region.

Table 18 Average yearly mass flow reduction for the different regions during El Niño

Conventional Hydro	Northwest	North	Center	East	South
Niño	-24,50%	-15,24%	-21,49%	-	-34,63%
Niña	33,81%	7,76%	16,54%	-	24,53%

As for the RoR plants the yearly average capacity factors for the different scenarios can be observed in Table 19, for Large RoR and in Table 20 for Small RoR.

Table 19 Average yearly capacity factor for Large RoR for Neutral, Niño and Niña scenarios.

Large RoR	Northwest	North	Center	East	South
Neutral	56,9%	40,2%	51,9%	41,6%	60,2%
Niño	42,8%	34,7%	40,7%	-	39,3%
Niña	75,9%	43,4%	60,4%	-	74,5%

Table 20 Average yearly capacity factor for Small RoR for Neutral, Niño and Niña scenarios.

Small RoR	Northwest	North	Center	East	South
Neutral	62,6%	43,2%	52,3%	58,2%	58,9%
Niño	47%	35%	41%	-	38%
Niña	82,8%	59,3%	60,9%	-	73,1%

3.8.3. Climate change

Global warming and climate change is causing disasters and catastrophes all around the world, and Colombia is not alien to this this increment of extreme conditions that translates into droughts, heat waves and floods [51]. Not only is water important for electricity generation but very vulnerable communities are constantly under threat because the lack of water resources. Sadly like the most vulnerable countries all over the world, the GHG emissions, as a country in the way of industrialization, are not representative or decisive in the global atmosphere, but still it is one of the areas globally that are more threatened by its effects, especially the Colombian Andean region [52].

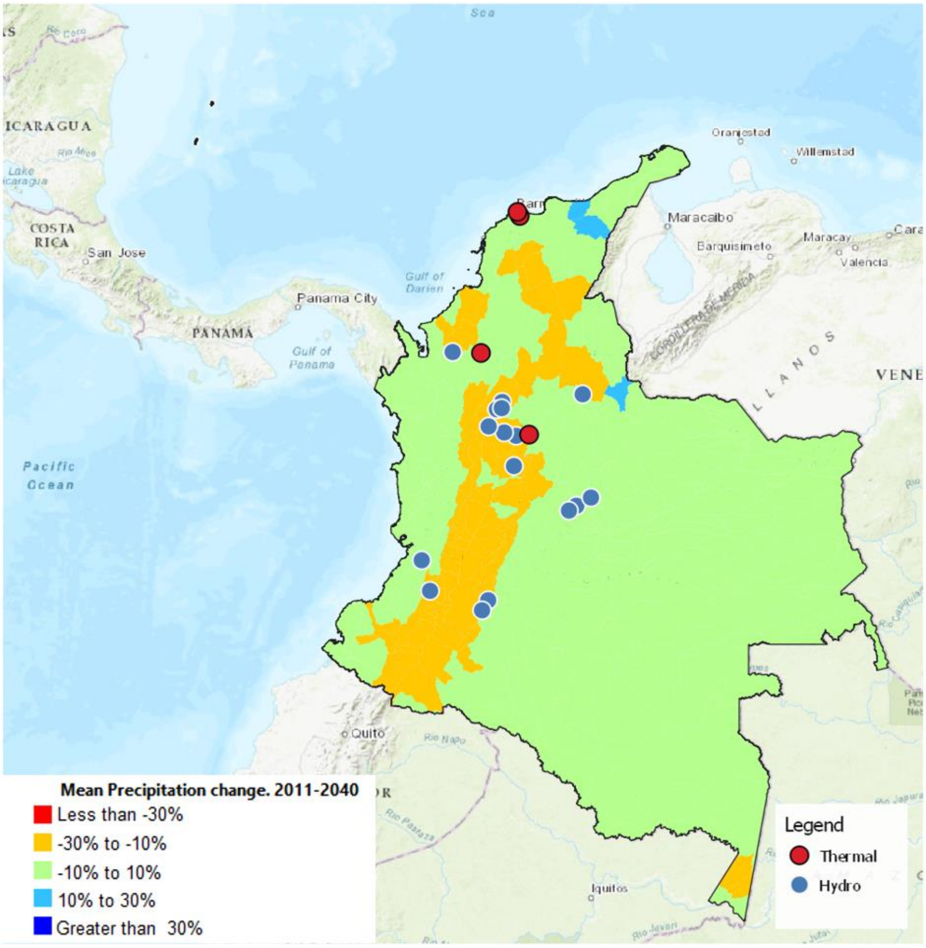

Figure 26 Mean precipitation change for the period 2011-2040. Data: [53]. Map: Own elaboration.

The Colombian institutions worry about this topic greatly and that is why there are different studies on the possible effects of climate change in our country, especially in the water availability and the temperature. There is a study [8], where researches took a look in the time period of 2011-2100 and defined that there will a decrease in the rainfall for most of the part of the Andean and North regions, while in regions like the Pacific and Amazonia there is a little increase, other regions like East won't have any significant change. This is done when comparing the prognosis with the historic data, the records from 1971-2000. From the analyzed regions they estimated anomalies to the historic values from -70% to -%10. Looking further into their studies the authors stablished different GHG emission scenarios, so the rainfall reduction changed for reach of these scenarios and they also calculated an intermediate scenarios where they found an average emissions and precipitation reduction, which equals to a reduction of 30% for the hydrologic regions of North, Center, Northwest and South, as mentioned before East won´t have any significant change. On

Figure 26 the mean precipitation change can be observed for the whole country and the 2011-2040 time period, in this map the 20 largest power plants are also pinpointed, and as it can be seen most of them are located in the affected areas, only the ones located in the East hydrologic region will stay unaffected.

IDEAM is the organization in charge of studying and analyzing this information, one of their studies arrived to similar conclusions with a minimum reduction of 15% and maximum 36% [54]. Taking into account all this information, the reduction of the hydrologic flow is set to 25% for the mentioned regions, both for the conventional hydro plants, and both large and small run of river plants. As Macías Parra explains in her study of the effects of climate change on the electricity generation in Colombia [55], this hydrology reductions can be analyzed since it is considered that rainfall is the main source of the mass flow for the rivers in each region and that it is considered as a reduction in magnitude but not in behavior or seasonality so a direct percentage reduction in the mass flows is a close approximation.

3.8.4. High Demand Forecast

The institute in charge of doing the demand forecast for Colombia [27], as any other forecast has different scenarios: a reference a high and low estimate; this scenario will consider the demand to be the one with the high expected growth, to see how more robust the electrical system has to be to supply this extra demand.

3.8.5. FNCE - Non-conventional renewable energies participation

This scenario forces the participation of non-conventional renewable energies ("Fuentes no convencionales de energía renovable", FNCE), under this name in Colombia we understand small RoR plants (<20 MW), bagasse plants, PV and wind plants, this concept pretends to include technologies like wind and PV which are just starting in Colombia and to have a more distributed generation in the country. This scenario will force to increment the generation of these technologies as a percentage of the demand, the Colombian government has some conservative goals, for example stablishing that for 2030-2050 they should be 20% of the generation [56], or in the national development plan 2018-2022 which they expect to have an installed power of 1500 MW at the end of the term [57]. I will set up a somehow higher goal, forcing more percentage in the years after that, following the following values:

Table 21 Participation of Non-conventional Renewable energies in the demand

	2018	2024	2030	2040	2050
RE%	-	12%	20%	25%	30%

3.8.6. Thermal Phase out

This scenario will force to increment the renewable generation until it is equal to the demand, for this there will be an incremental participation on the generation. The technologies considered as renewable are: conventional hydro, large RoR, small RoR, bagasse, wind and PV; the participation of this technologies over the demand in 2018 is calculated, which is 67% and did an incremental participation until they would become the 100% of the demand in 2050, obtaining the following values for each of the analyzed years:

Table 22 Participation of Renewable energies in the demand

	2018	2024	2030	2040	2050
RE%	67%	73%	79%	89%	100%

3.8.7. Strong drought

The scenario combines the effect of El Niño that means using the time series for El Niño but additional to that a reduction of 25% in the instant available water flow because of climate change, including the conventional dammed hydro plants and the large and small run of river plants, but also considering the high forecast for the electricity demand.

3.8.8. Worst case

This scenario combines what would put the Colombian Electricity sector at the most risk. This consist of combining El Niño, the reduction caused by climate change, eliminating the fossil fuels which are the backup electricity nowadays and additional using the high forecast for the electricity demand.

4. Results and Evaluation

For presenting the results, the scenarios are divided into four categories, each category will be analyzed by its own and in different levels of detail; first comes the analysis for the different hydrology levels, then the effect of the demand prognosis, afterwards the renewable energies participation and last the resilience analysis which is the scenarios that are combination of other scenarios and taste the resilience of the system.

4.1. Effect of El Niño, La Niña and Climate change hydrology levels

One of the main objectives of this thesis was analysing phenomena like El Niño, La Niña and climate change and see what effect this hydrology levels might have in the electrical system of Colombia. When analyzing each of these escenarios the results are the optimal electricity mix to face this environmental conditions, as if the simulated scenario was the constant state from now until 2050, off course this wont be the real case, but this analysis indicates a path on the right direction on what technologies might help mitigate the impacts of hydrology changes.

In Figure 27 the national installed capacities for each of the scenarions can be observed.

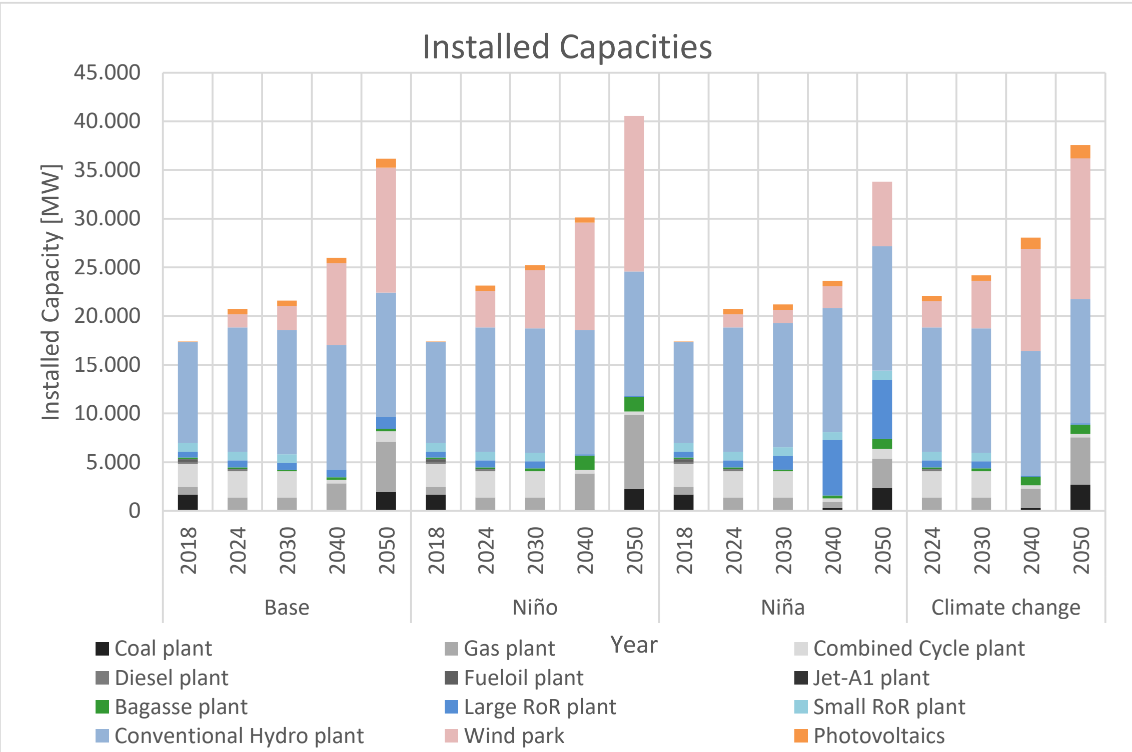

Figure 27 Installed capacities for the scenarios analyzing the different hydrology levels

From Figure 27, it is observable that in scenarios like Niño and Niña, the hydro and wind technologies balance each other, so when either of them has the extra boost, the other is no loger needed, neither other technologies, see Figure 28 where in El Niño scenario the wind capacity has by 2050 extra 3000 MW, but the PV capacity is no longer needed.

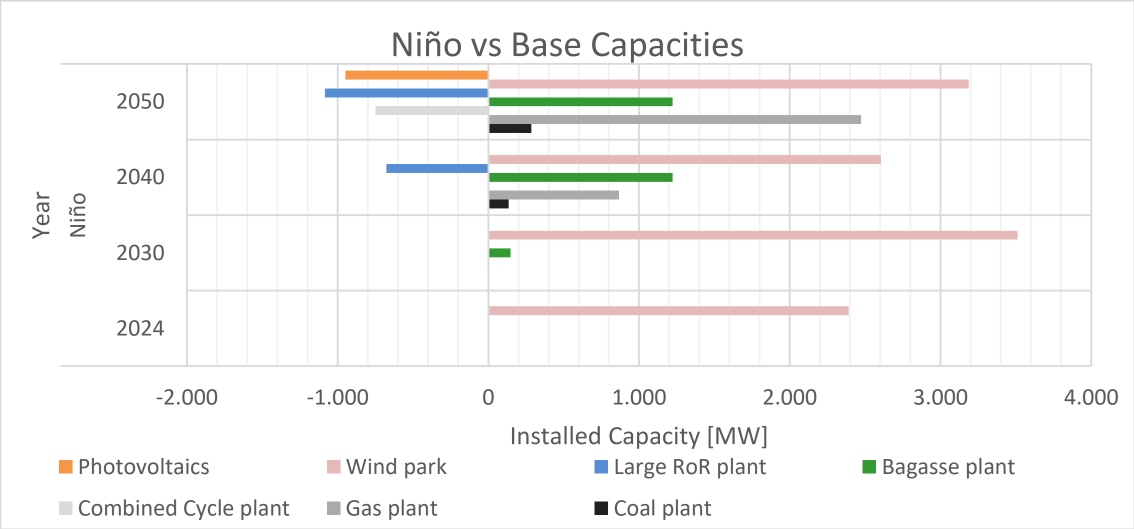

Figure 28 Comparison of Installed Capacities for Base and Niño scenario

And in Figure 29 when compared to La Niña, the RoR capacities are much higher, and wind greatly decreses its participation in the installed capacity.

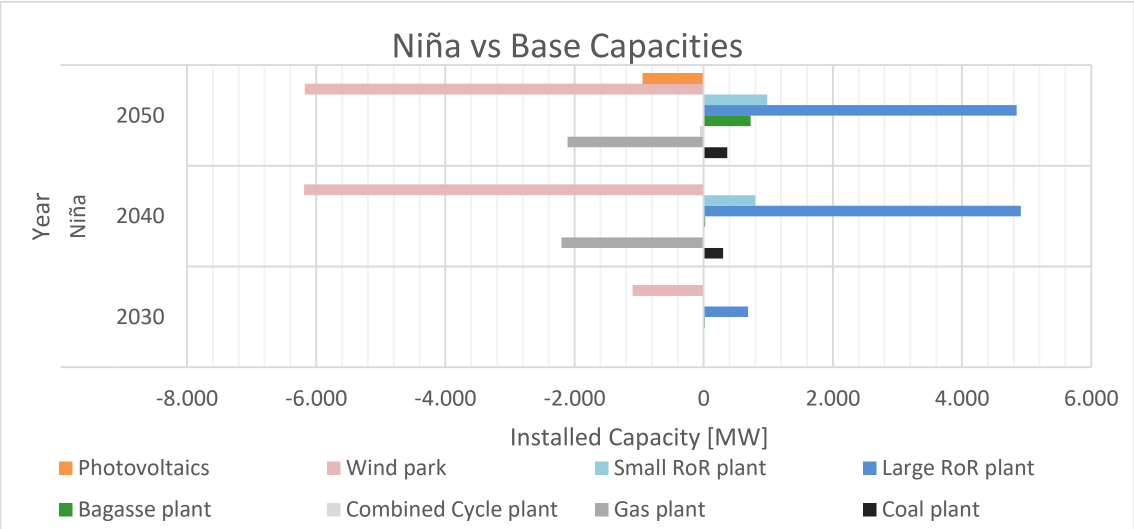

Figure 29 Comparison of Installed Capacities for Base and Niña scenario

In the Climate change scenario, where both hydro and wind technologies stay more or less neutral, technologies that normally would be more expensive become competitive, such as Photovoltaics, see Figure 30.

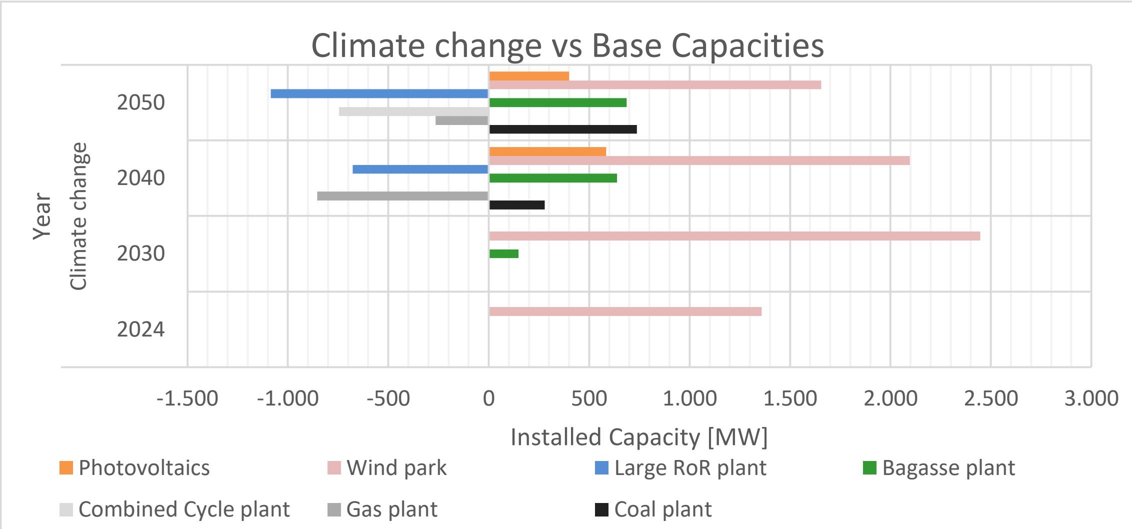

Figure 30 Comparison of Installed Capacities for Base and Climate change scenario

In the regional generation, it can be seen how the North West region, Figure 31, supplies most of the regions, so they are able to cover their demand; this region, very strong in Hydro generation, gets affected by the hydro variability, but still exports electricity under the toughest conditions, so it is then, where the other regions need to cover the missing energy they receive from this region.

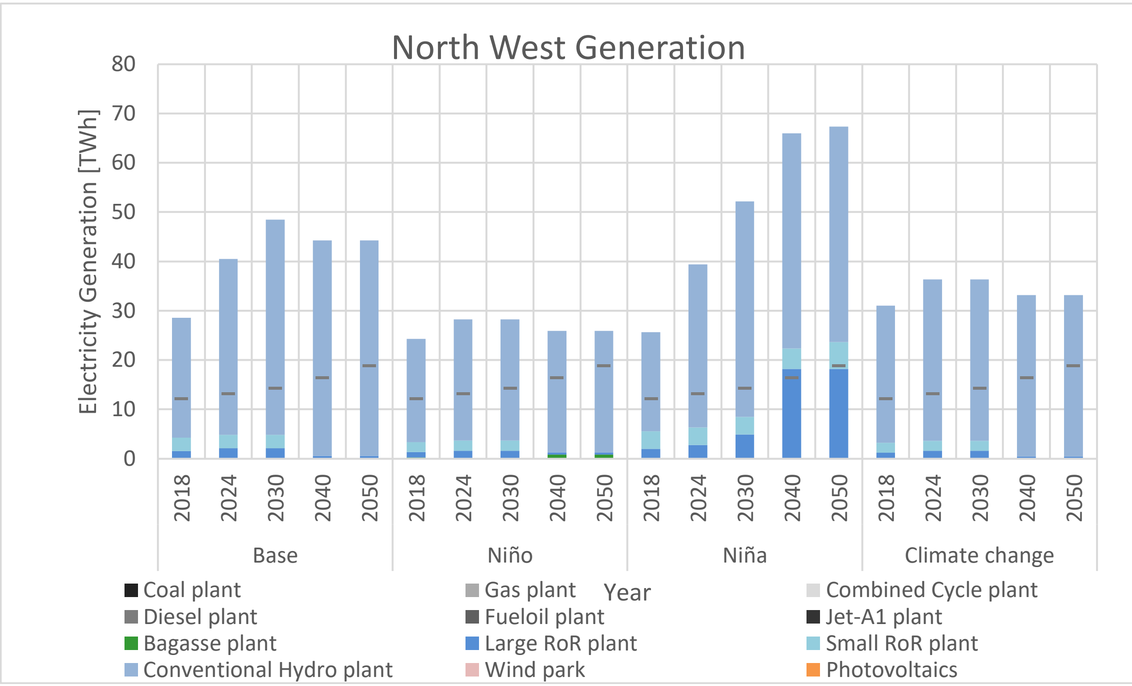

Figure 31 Electricity generation in North West region under different hydrology scenarios.

The North region, Figure 32, a place optimal for Wind power abandons the thermal power plants and starts covering as much of its demand with wind power as it can, even becoming a net exporter by the end of the model timeframe for all the scenarios except for the Niña scenario where the wind time series has a lower capacity factor.

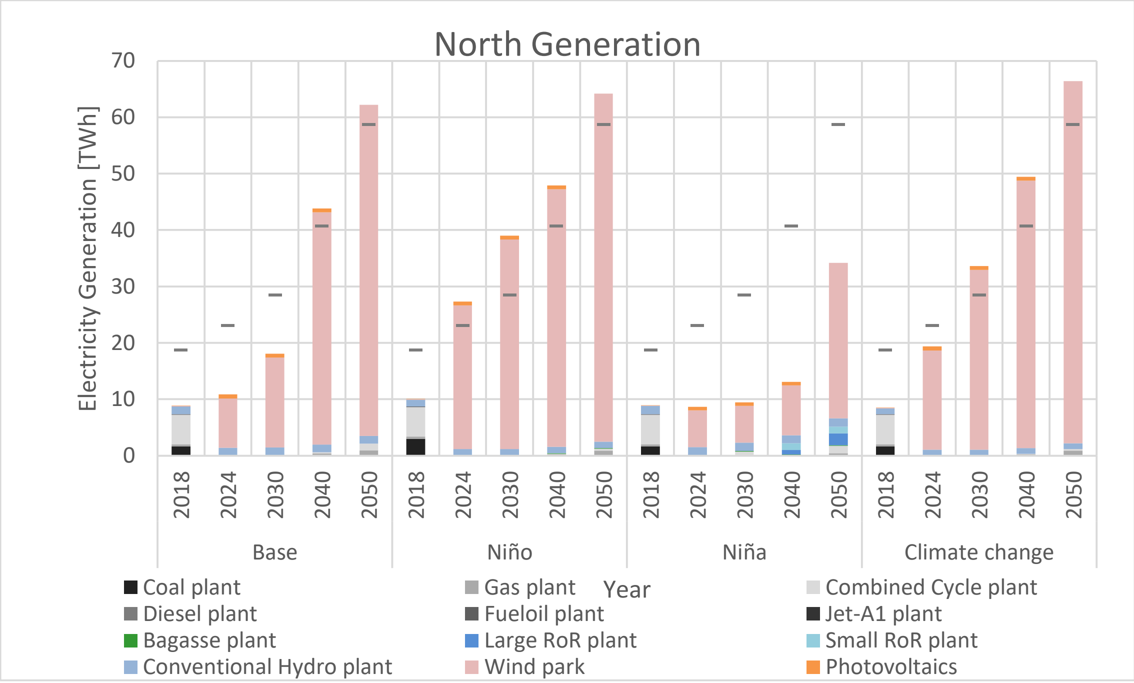

Figure 32 Electricity generation in North region under different hydrology scenarios.

The Center region, Figure 33, manages with hydro technologies and even install some wind power, but from 2040 it is inevitable to have coal generate a large part of their energy, still being a net importer region.

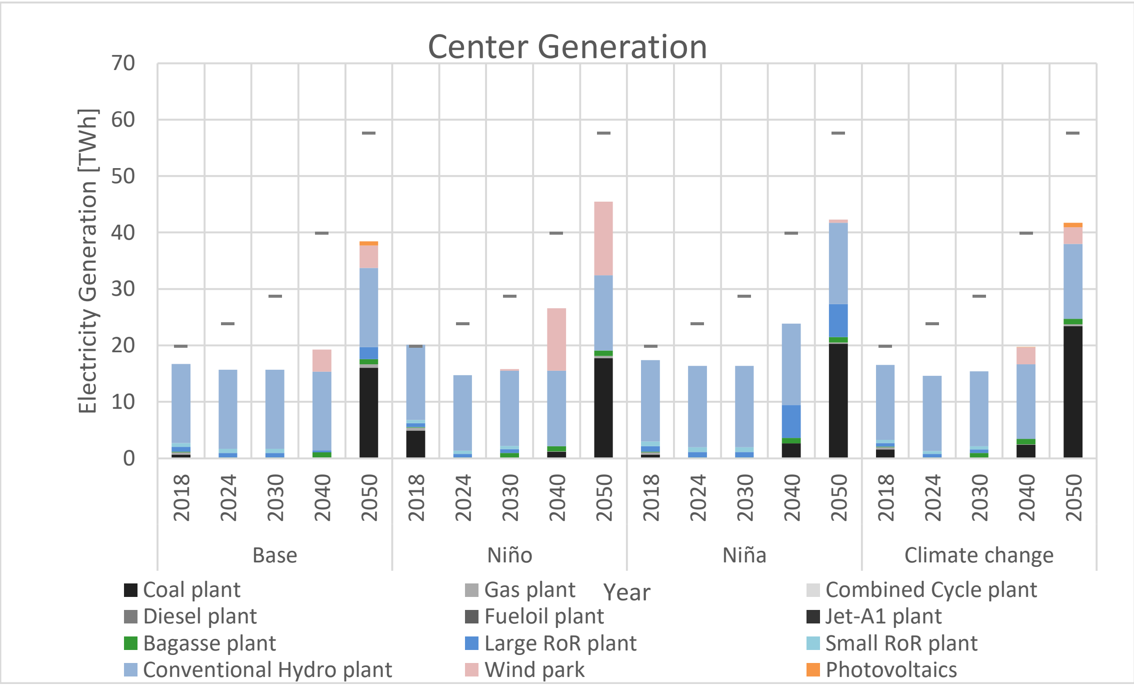

Figure 33 Electricity generation in Center region under different hydrology scenarios.

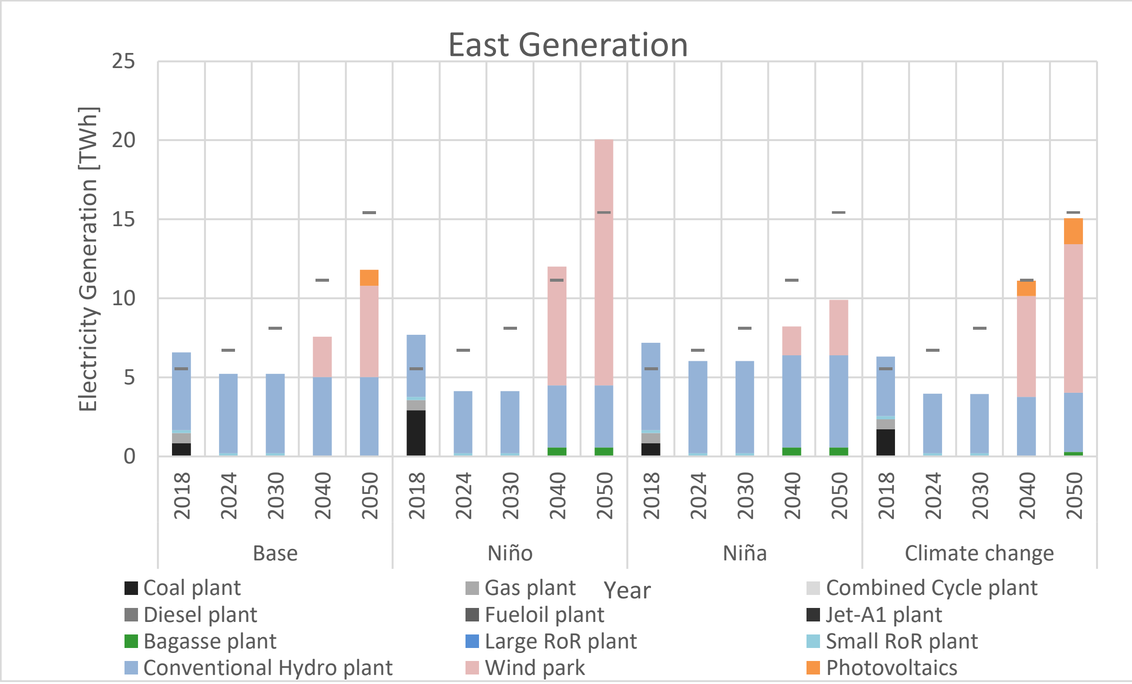

Figure 34 Electricity generation in East region under different hydrology scenarios.

The East region, Figure 34, sees a development for wind power by the end of the analysis time, and even some development of bagasse plants; PV only develops in the scenarios where neither wind nor hydro get the extra capacity factor, but when it is installed it plays an important role.

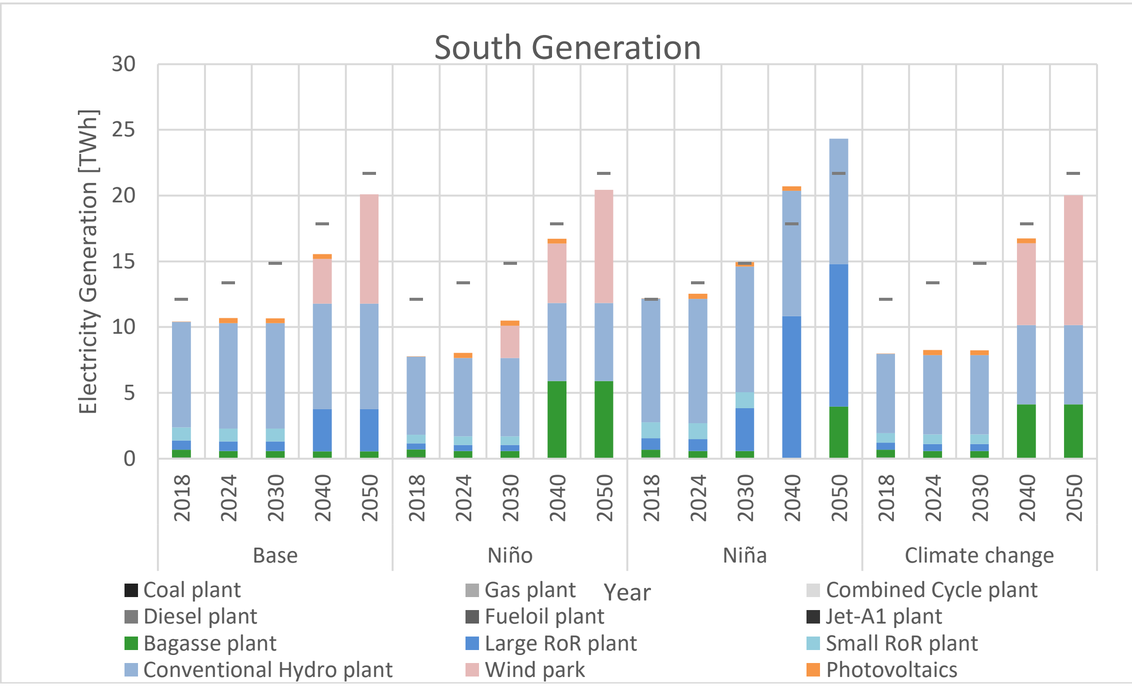

Figure 35 Electricity generation in South region under different hydrology scenarios.

In the South region, Figure 35, the large RoR plants play a role when their hydrology is not negatively affected, but when it does, technologies like bagasse plants and wind parks replace their participation and play an important role. PV only operate because of the forced capacity for 2024.

4.2. Demand prognosis effect

This section compares the results for the base and maximal demand scenarios, where the only difference between them is the demand; both of them are the business as usual behavior, indicating what should be the investment path when only considering the lowest cost for electricity generation, without any restriction.

First the total national installed capacities are presented, with the max demand scenario having a higher total installed capacity, Figure 36.

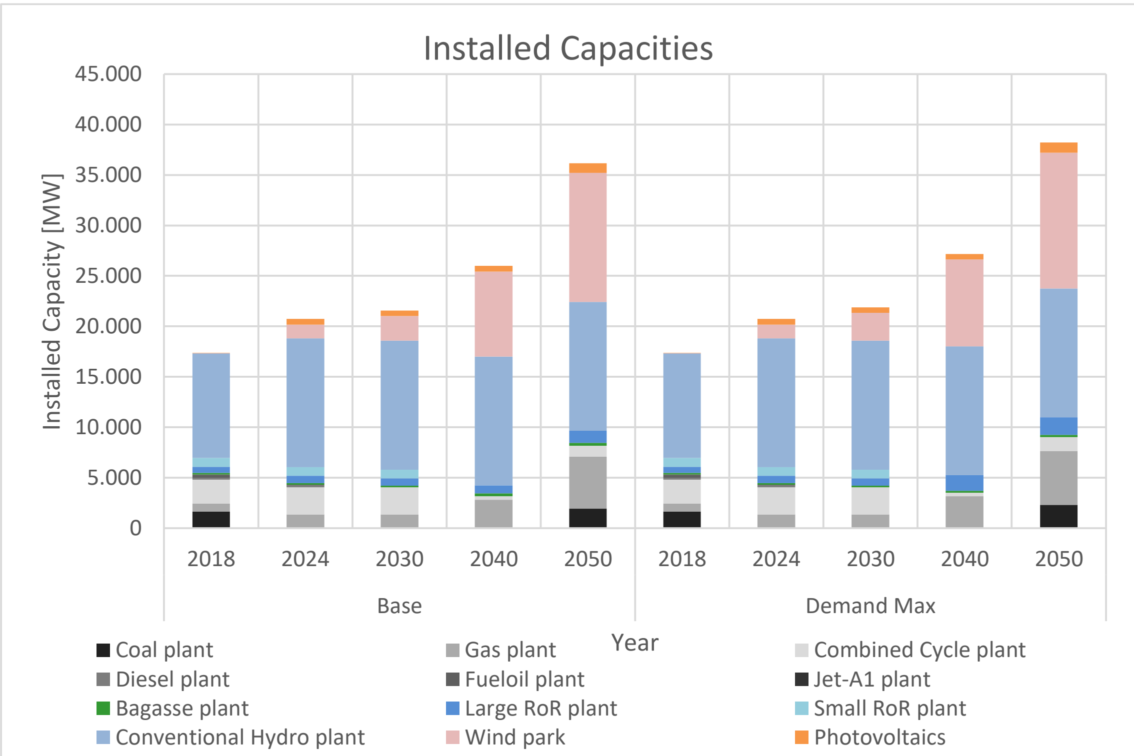

Figure 36 National installed capacities for Base and maximal Demand scenarios

In Figure 37, the comparison of installed capacities by technology can be observed, all participating technologies increase their participation but the bagasse plants, and this is because the South region now replaces the bagasse capacity for large RoR plants, presumably because they integrate and compensate better with the extra wind capacity installed in the North region.

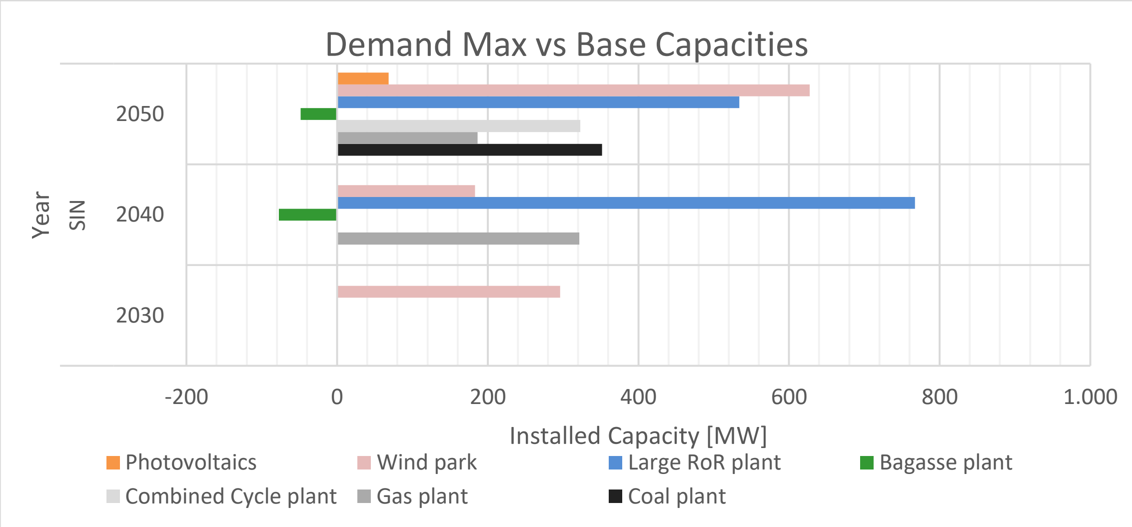

Figure 37 National installed capacities comparison for different demand levels

When looking into the national electricity generation the distribution doesn't change as much, Figure 38.

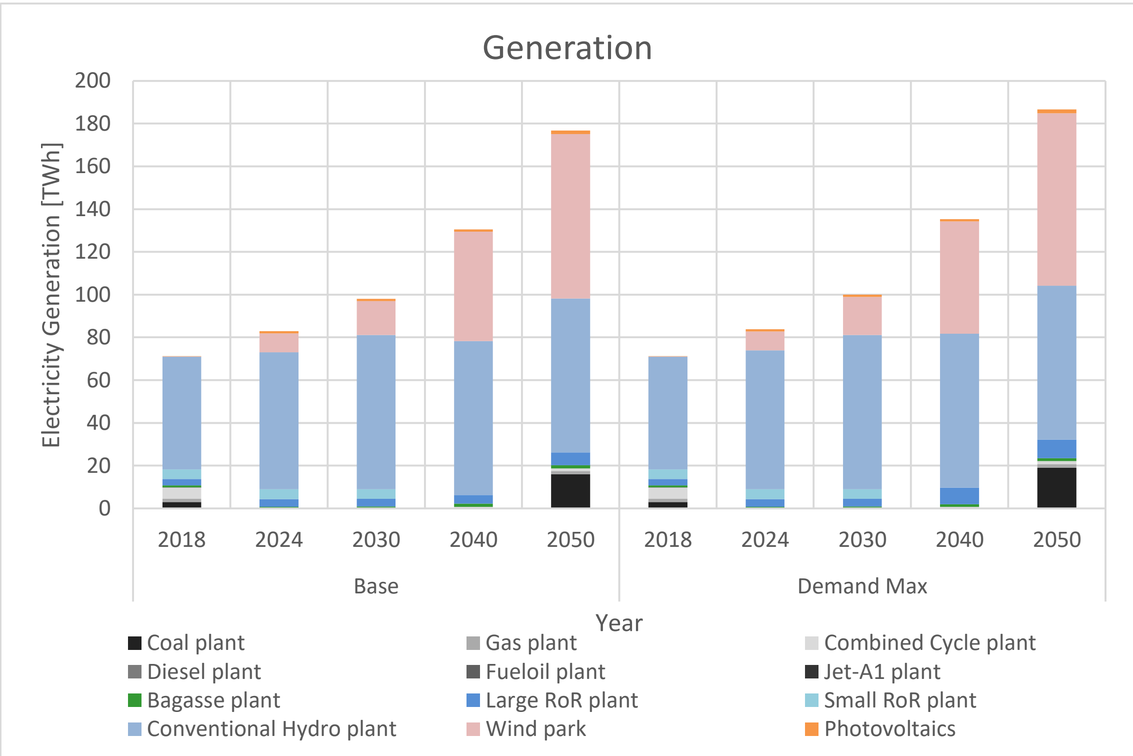

Figure 38 National Electricity generation for Base and Demand max scenarios.

On Figure 39 it can be observed that Coal, Large RoR, Wind and PV are the main contributors for supplying the extra demand.

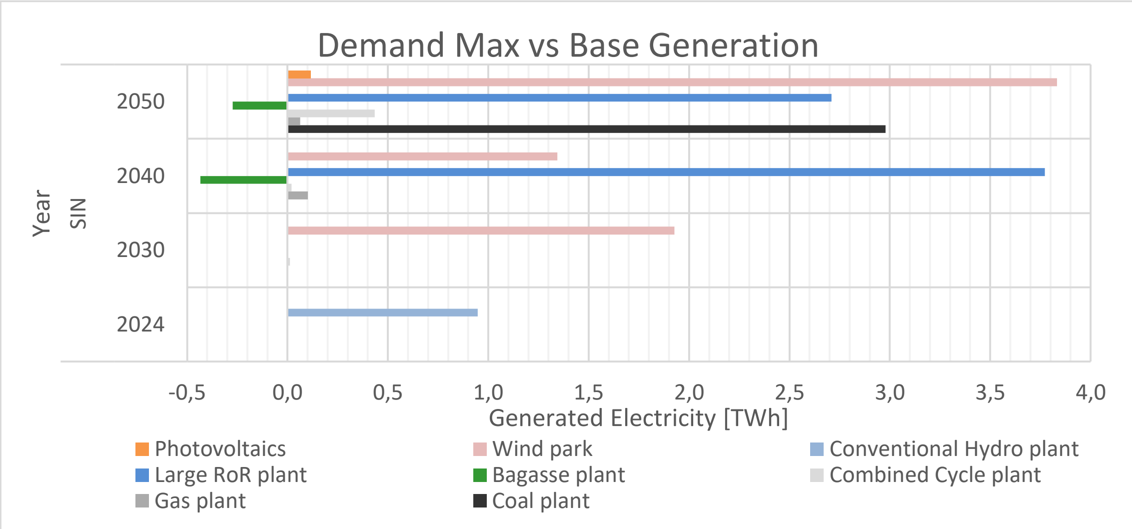

Figure 39 Electricity generation difference between Demand max and Base scenarios.

4.3. Participation of Renewable Energies effect

This section compares scenarios that expect to force the participation of renewable energies and Non-conventional renewable energies in the electricity participation. The base scenario is used as a comparison point. In Figure 40 it can be seen that the FNCE scenario has the same installed capacities as the Base scenario, which means that the base scenario complies with the constraints stablished for this scenario.

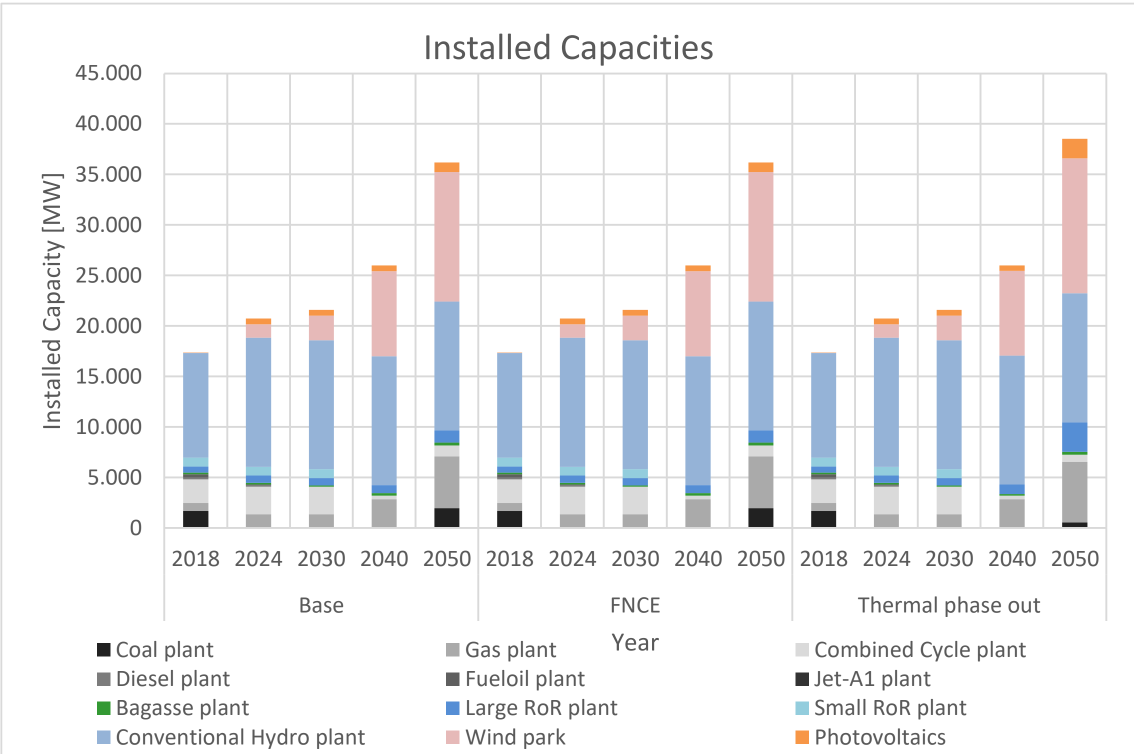

Figure 40 National installed capacities for FNCE and Thermal phase out scenarios

In the thermal phase out scenario as seen in Figure 41, the coal and combined cycle capacities are almost minimal but then they are replaced by gas turbines. Also PV, Wind, and Large RoR increase their capacities, but it is impossible to obtain a 100% renewable capacity.

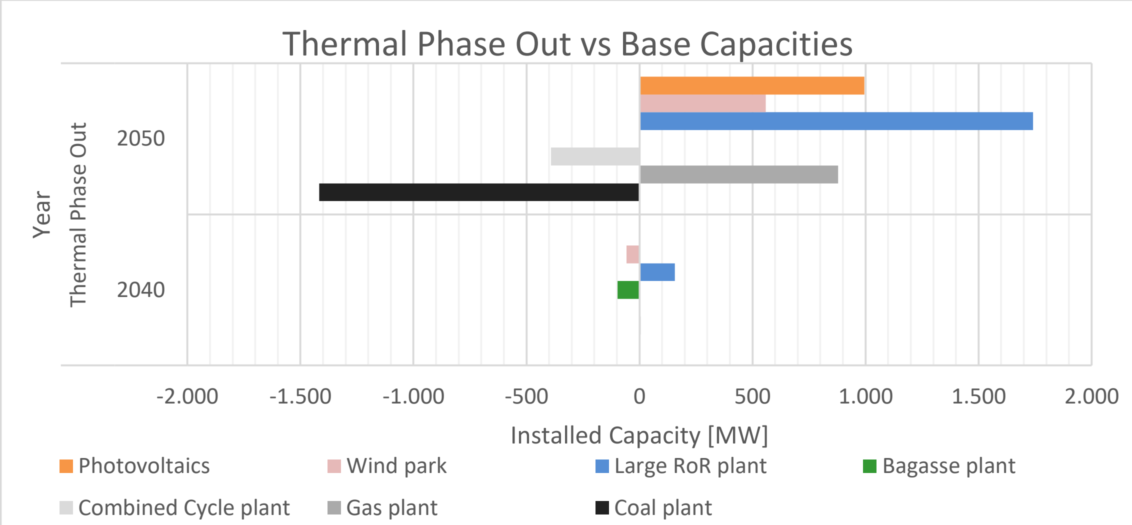

Figure 41 National installed capacities comparison of Thermal phase out vs Base scenario

For the generation, Figure 42, it is evident again that the FNCE scenario gives the same Base scenario which are good news for the sustainability of the Colombian electricity matrix, but still it is necessary to generate some electricity with fossil fuels when there are no renewable sources available.

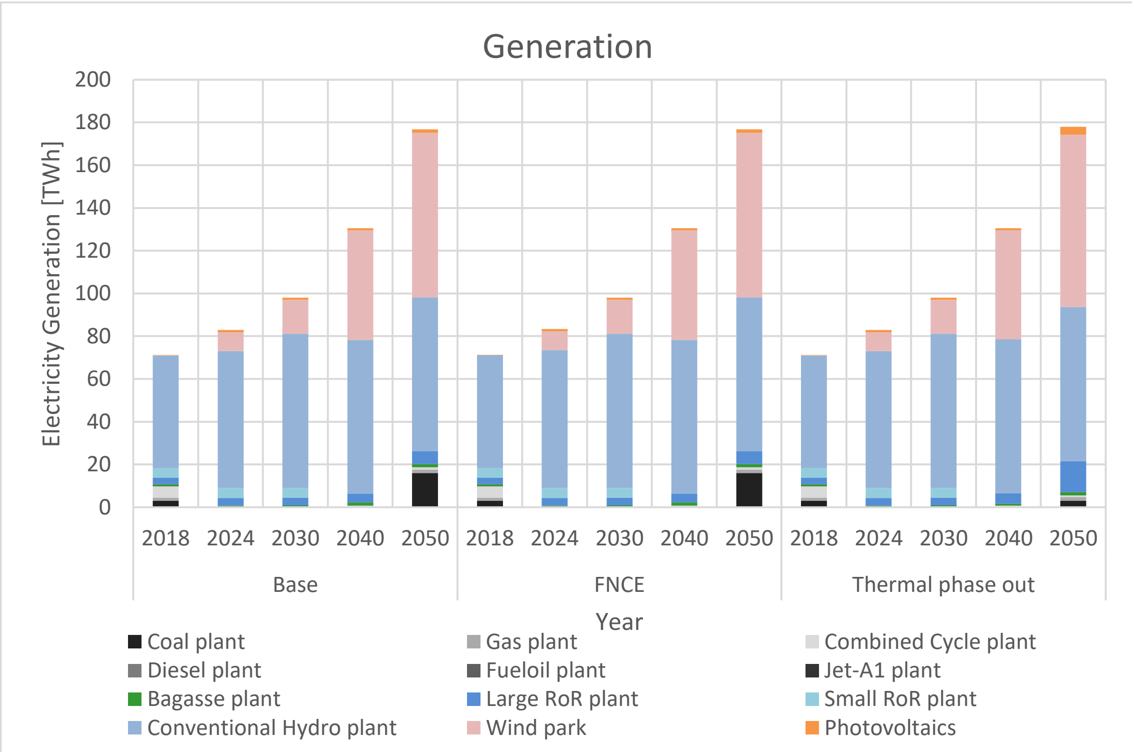

Figure 42 National electricity generation for FNCE and Thermal phase out scenarios

For the thermal phase out scenario, even if the coal generation is reduced greatly, it still participates, as well as the other thermal power plant technologies, this approach is not enough to be able to model a scenario with no thermal power plants.

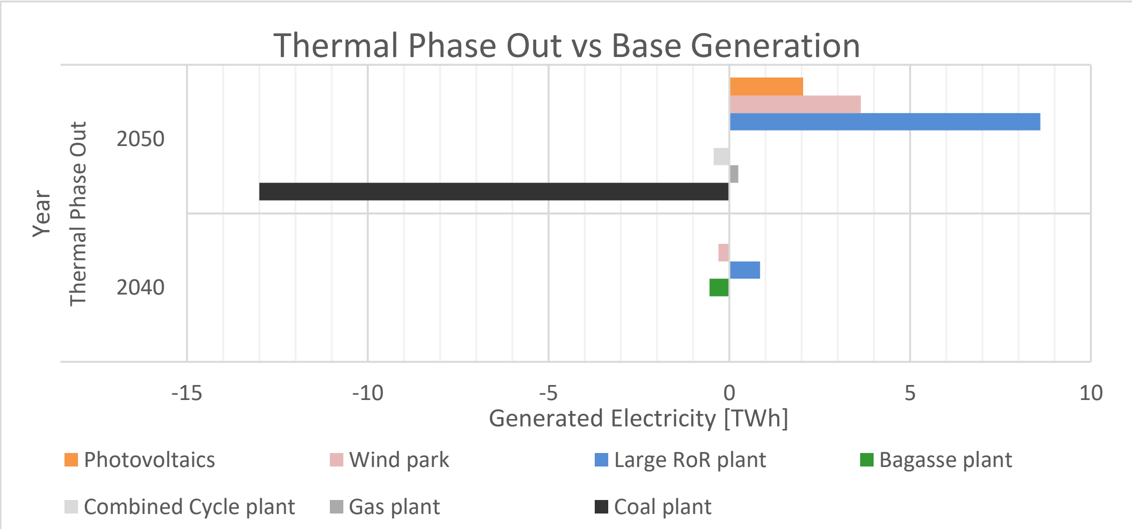

Figure 43 Electricity generation difference between Thermal Phase out and Base scenario

4.4. Resilience analysis

This section seeks to study what measurements the electricity mix has to take to be able to overcome situations where the current generation matrix has big difficulties, such as situations where the hydrology levels get reduced but also when the demand increases and the thermal power plants cannot be used.

In Figure 44, the different scenarios that are considered to belong to this section are presented. The new scenarios here are Strong drought and Worst case, both cover the maximal demand, but even then, they require a much higher installed capacity compared to the base scenario, and for example comparing Strong drought to Niño what grows is the coal and wind installation, no other technologies get as affected. The exact differences with the base scenario can be observed in Figure 45, where Wind, coal, gas, and bagasse grow, but combined cycle, large RoR and PV diminish.

The same comparison can be seen for the scenario Worst case in Figure 46, Wind grows even more, but PV is now present with even more capacity, and coal decreases its installed capacity.

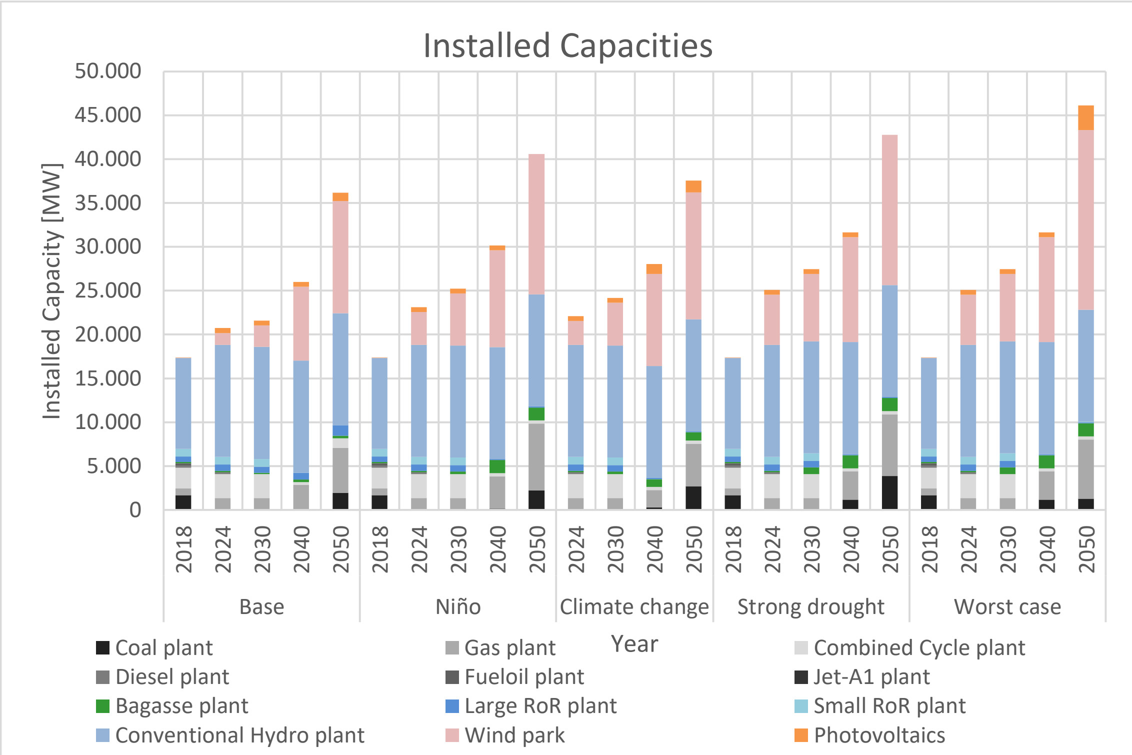

Figure 44 Installed capacities for scenarios where the resilience of the system is tested

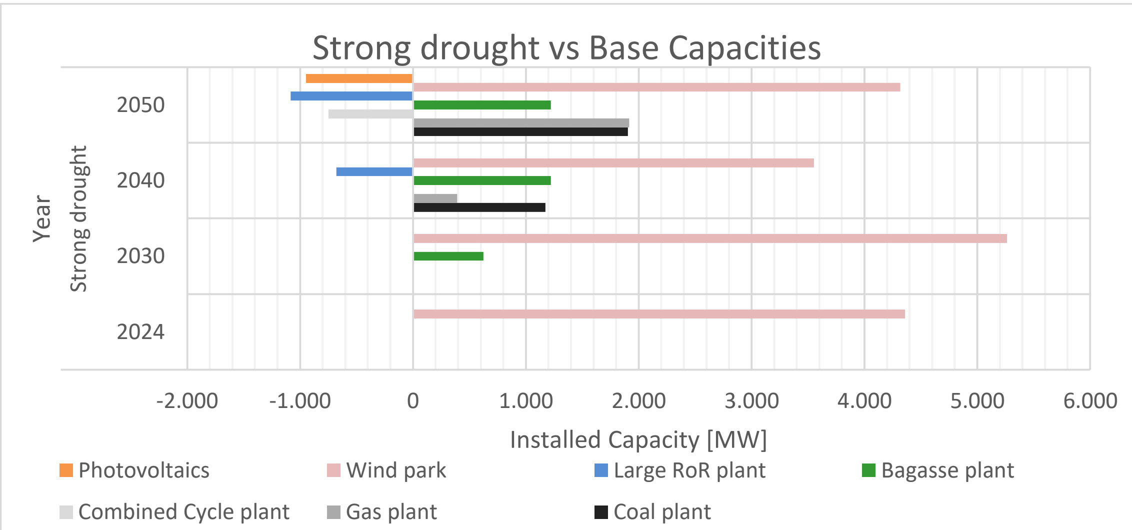

Figure 45 Installed capacities comparison between Strong drought and Base scenarios

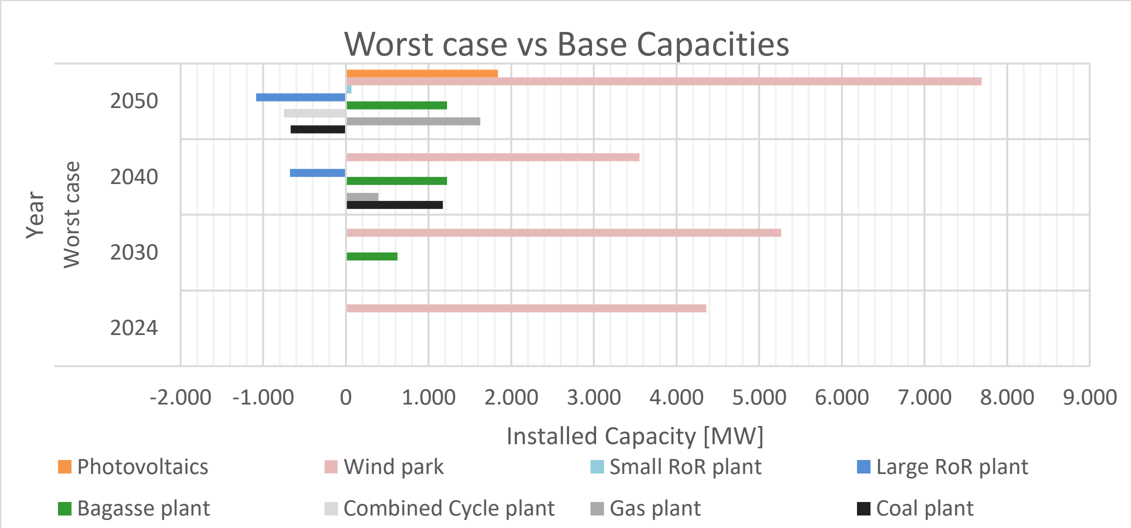

Figure 46 Installed capacities comparison between Worst case and Base scenarios

Looking into the national electricity generation, Figure 47, it is evident the hydro generation is even more reduced, and that wind and coal replace most of the generation.

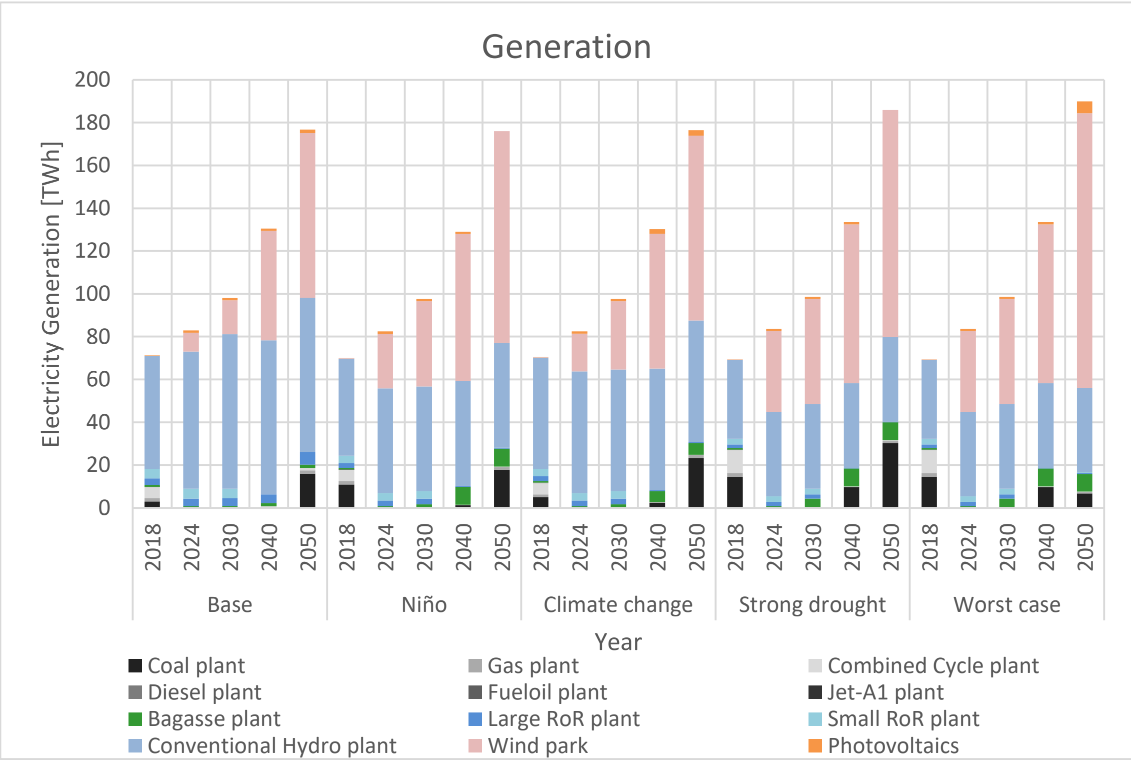

Figure 47 Electricity generation for scenarios testing the systems resilience

When looking into detail for each scenario, for the strong drought, Figure 48, the system has to cover for more than 32 TWh/y that are no longer generated with Conventional hydro plants, and the system generates it primarily with Wind, but also bagasse and coal play an important role. For the Worst case scenario, Figure 49, there is the same shortage in the conventional hydro plants, but the participation of thermal power plants is required to be reduced every year, that is why for 2050, most of the extra electricity is with wind, but it still is inevitable to have some thermal participation.

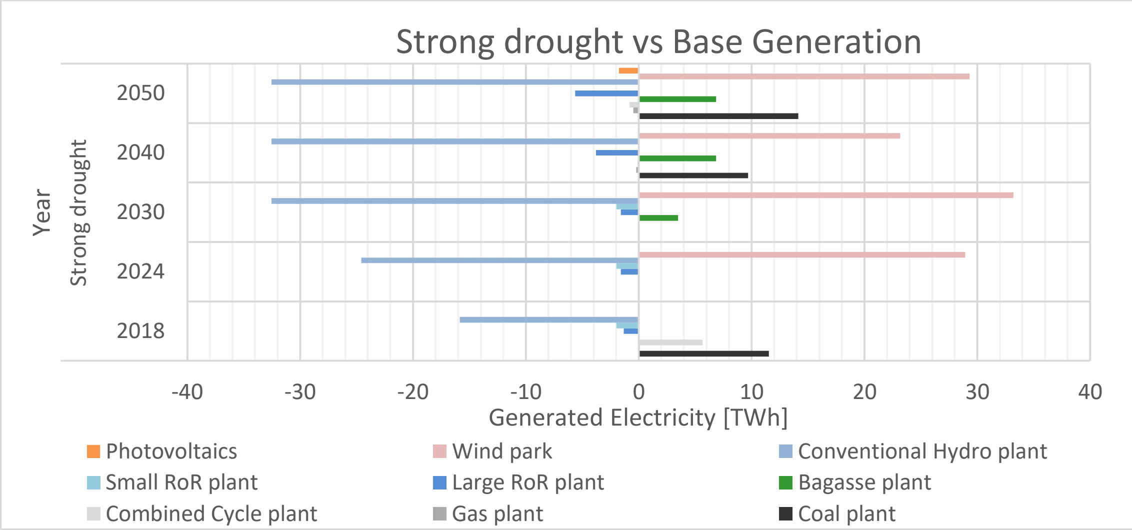

Figure 48 Electricity generation comparison between Strong drought and Base scenario

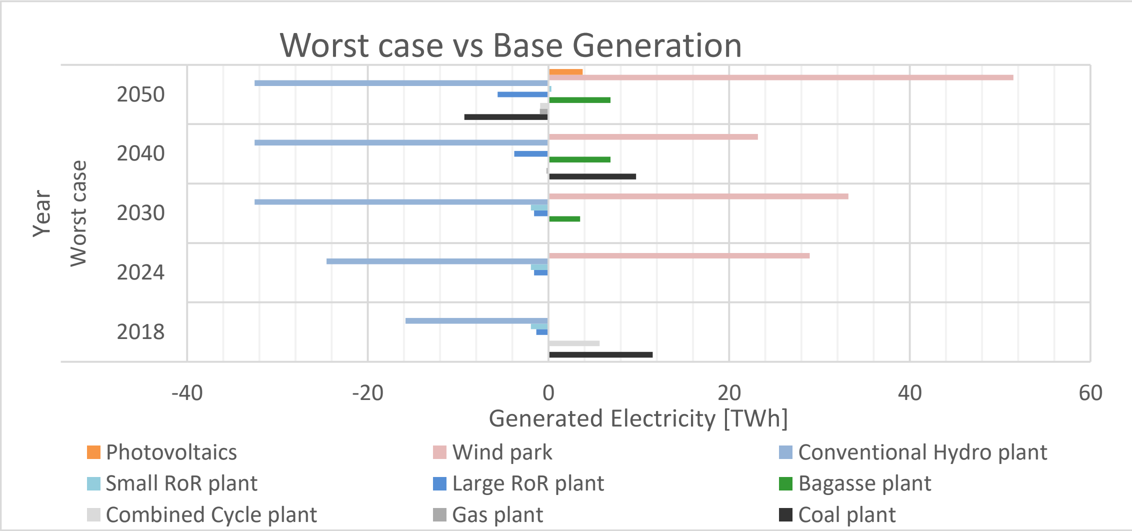

Figure 49 Electricity generation comparison between Worst case and Base scenario

4.5. Technology participation

This section of the results summarize all of the scenarios and shows the participation each technology has in the different scenarios, since what the model did was to use the scenario conditions for all of the modeled years, it is in understandable that the optimal solution is a combination and middle point of the different results. And that the most robust system would be to take the maximal installed capacities for each technology but this would lead to a result far from optimal.

In the first figure, Figure 50, the installed capacities for the different non-conventional renewable energies are compared, the technology with the highest participation is by far wind parks, and by 2050 they should at least have five times the installed capacity that is planned for 2024. Bagasse and PV also participate in different levels according to their comparison to other technologies like Large RoR.

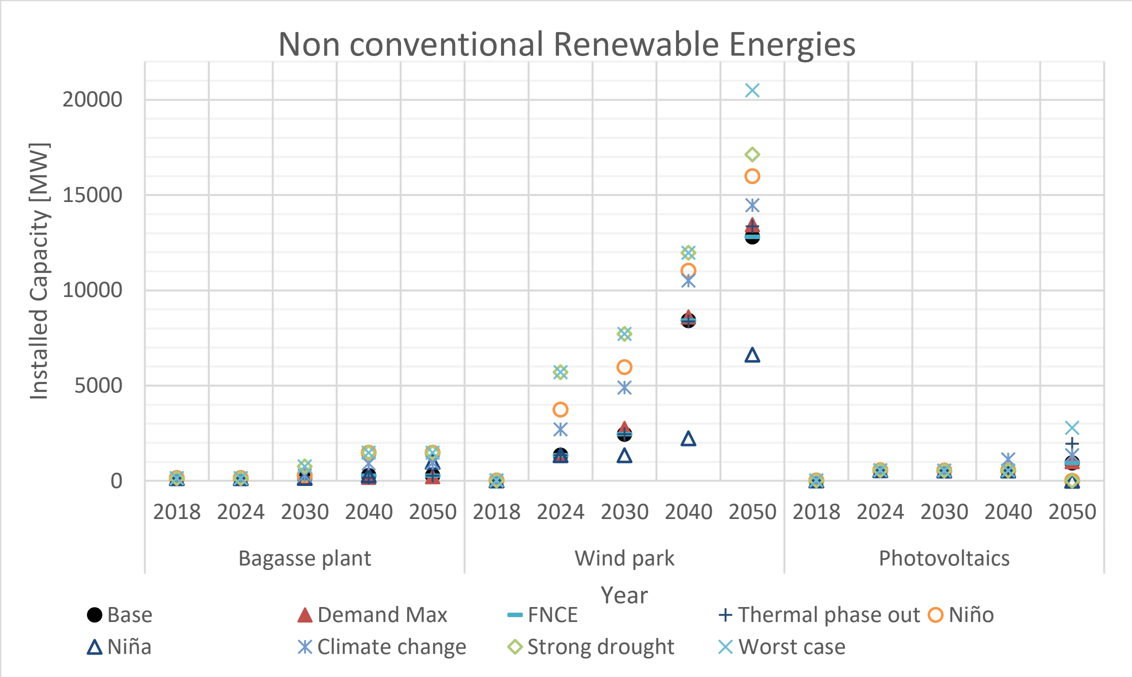

Figure 50 Installed capacities for Non-conventional Renewable energies

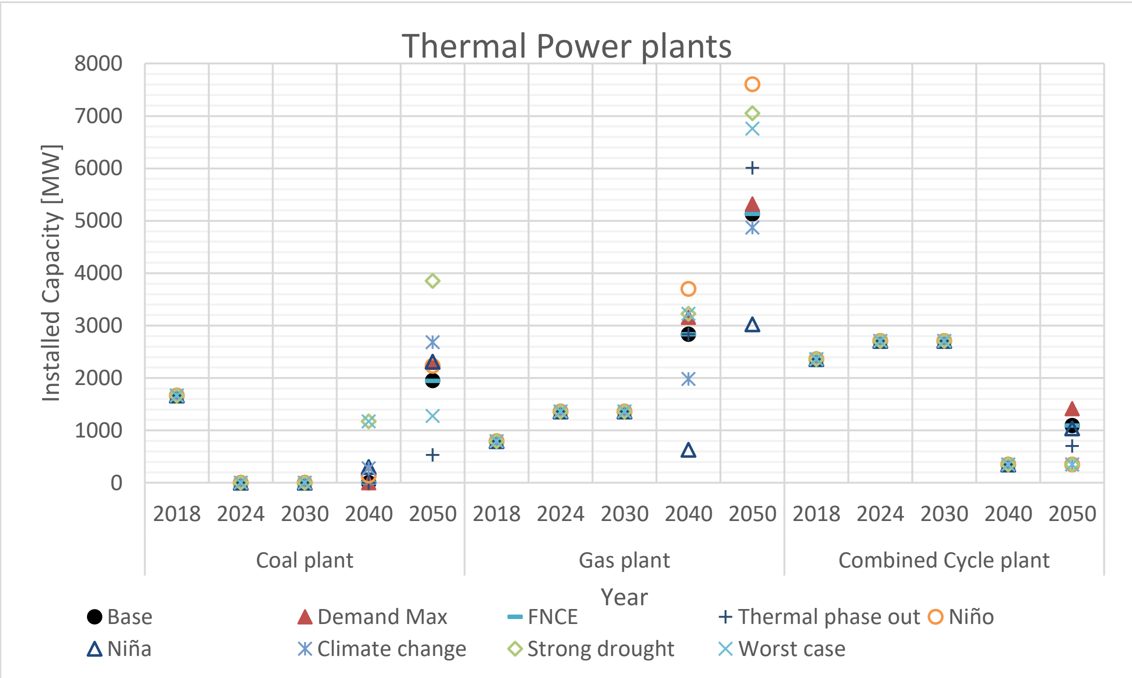

Figure 51 Installed capacities for principal Thermal power plants

The second figure, Figure 51, the comparison is done for the principal thermal power plants, it is evident that with the increasing participation of non-conventional renewable energies, the ideal back up plants are gas turbines, due to their lower installation costs, their fast ramping capability and their relatively low utilization factor; when a more constant generation is needed, in other words, when what is needed is a base load, then the coal participation increases.

The last figure, Figure 52, compares the capacities for the various hydro technologies, it is observed that the conventional hydro growth is limited to the project mentioned in section 3.4.1, also that due to the higher installation costs of small RoR, they are only renewed in the Niña scenario, and that large RoR plants are installed in all the scenarios where their hydrology is not affected negatively, which might indicate that their participation still is important.

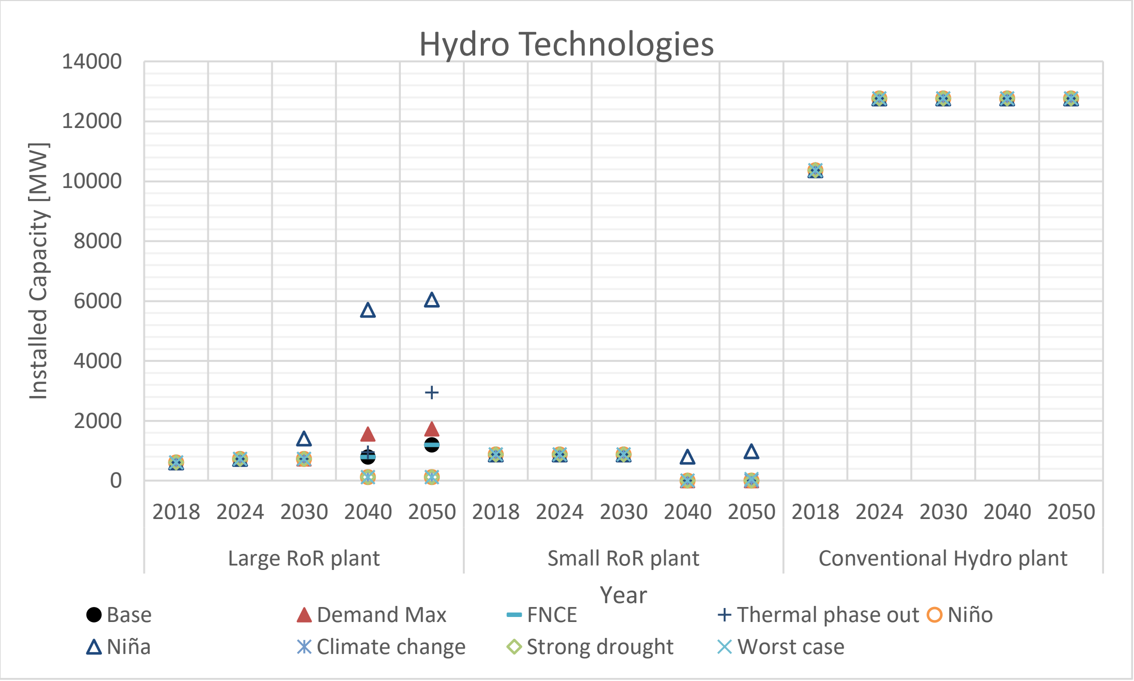

Figure 52 Installed capacities for Hydro technologies

Other results such as the costs, installed transmission lines, and storage capacities can be observed in the summary tables in the digital Annexes, as well as in the specific excel result files. In the *urbs* model, regions were called according of their actual name in Spanish, and not the coordinal names they received for the report, the clarification is done in Table 23.

Table 23 Report and *urbs* names clarification

Report name	*urbs* name
North	“Car” – Caribe
North West	“Nor” – Noroeste
Center	“Cen” – Centro
East	“Ori” – Oriente
South	“Val” – Valle

5. Summary and Outlook

It is evident that the different hydrology levels have great influence on how the electricity matrix might be in the future. One of the most important and exciting results is that Non-conventional Renewable energies play an important role in all of the scenarios. In regions where water is not available, wind energy is the path to follow, mainly due to the balancing effect it has with hydro. PV still is an expensive technology comparatively to wind and large RoR and is only implemented in the regions and scenarios where the other options are thermal plants or neither wind nor hydro technologies have the extra boost in the capacity factor. With the start of operation of the 1350 MW of wind plants in 2024, and hopefully normal hydro levels the generation can be mostly renewable up until 2040, because in principle Thermal power plants are just needed for situations where the water is not available. From 2040 the demand grows greatly and it makes the implementation of thermal power plants necessary even if their real generation is not high.

The model has various limitations that need to be considered when analyzing the results, for example that it doesn't allow the conventional hydro plants to further expand, also this method used for modeling conventional hydro plants summarized all of the plants of the same region under the same hydrology and assigned one unique conversion factor, the factor for going from mass flow to electrical power. All in all this method is an acceptable approximation to the actual operation plan for such plants, where the real deciding factors are the market price, contract responsibilities, individual conversion factors and climate predictions for the two following years. This solution is an approach for modeling hydro plants in countries where they play such an important role but for being able to implement it still requires an understanding of a lot of the variables that come into play, such as the location, tributaries, hydrological regions, hydrology seasonality and variability, and associated environmental phenomena that affect them.

Another limitation for the developed model is the exclusion of the Reliability charge costs (explained section 1.2.2) in the thermal power plants, such costs were not considered in this model and they would turn this technologies more expensive. Also forcing reducing installed capacities is not an option so the approach for modeling the thermal phase out did not achieve the expected installed capacities.

When looking into the future, Colombia will phase a turning point between 2040 and 2050, when technologies like Small RoR, Large RoR, Combined Cycle, and Gas turbines running on Diesel, Fuel Oil and Jet-A1 will reach the end of their operating life. So the gas turbines running on those more expensive fuels are coming out of the system definitely and the new installed capacities are conventional gas turbines. Also from 2050 seems inevitable to have coal power plants, considering Colombia is a coal producer seems like the obvious path to take, this makes the electrical system resilient to the variability of renewable energies but is not an environmentally friendly solution, further solutions and options should be studied in this area, for example repowering the RoR plants, or implementing carbon capture and storage technologies, or power-to-X, or any other technology that becomes economically available at such scale by then. Other option is increasing the conventional hydro capacities but as already mentioned before, it is a sensible subject for now, time will tell what solution the Colombian citizens are willing to implement. What it is evident is the importance of continuing supporting the implementation of renewable energy technologies in Colombia and generating and making available more information regarding the potentials and capacity factors for the different regions, for example wind in the North, East and South region and PV for all of the country.

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List of Abbreviations

CND	National Dispatch Center	“Centro Nacional de Despacho”
CREG	Commission for Energy and Gas Regulation	“Comisión de Regulación de Energía y Gas”
ENSO	El Niño Southern Oscillation	
FNCE	Non-Conventional Renewable Energies	“Fuentes no convencionales de energía renovable”
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies	“Instituto de Hidrología, Meteorología y Estudios Ambientales”
IEA	International Energy Agency	
ITCZ	Intertropical Convergence Zone	
ONI	Oceanic Niño Index	
PV	Photovoltaics	
RoR	Run of River	
SIN	National Interconnected System	“Sistema Interconectado Nacional”
STN	National Transmission System	“Sistema de Transmisión Nacional”
STR	Regional Transmission System	“Sistema de Transmisión Regional”
UCP	Units for the Prognostic Control	“Unidades de Control de Pronóstico”
UPME	Mining and Energetics Planning Unit	“Unidad de Planeación Minero Energética”
ZNI	Not Interconected Zones	Zonas No Interconectadas

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