Politecnico di Milano
SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING
Master of Science – Energy Engineering

Colombian projected power generation system and CO_2 emissions for the most energy consuming sectors until 2050, using MARKAL standard model

Supervisor
Prof. Mister Massimo Tavoni

Candidate
Angela Dubois Camacho – 872535

Academic Year 2019 – 2020

Acknowledgments

As first instance, I would like to thank to Prof. Tavoni and Dr. Marcucci for the guidance material for the development of this work.
Thanks to Politecnico di Milano and all the people involved in my formation in the last couple of years, and more precisely a lot of thanks to Las Chicas, Alicia, Karlita, and Lau, and to Frida, who shared with me the whole spectrum of the master experience and became my biggest support here.
I would also like to thank my families, Dubois-Camacho and Guglielmotti, who from the far and the close fully followed this life experience.
Bunch of thanks to Pamela Choo team, Tesy and Paola, and to my current working group at ESE, who had become essential in the last phase of this work.

Vale, Sofi, Emmita, thanks for being the reasons for me for trying to give always the best I can.

Table of Contents

List of Tables

List of Figures

Abstract

Policies and decision making at any level is never an easy task: many factors and details have to be considered, projections have to be made and lot of figures have to be assessed. Nevertheless, it is hard to be ready for the future without projections of what could happen and of how to possibly avoid negative situations.

Currently the world is placed in a turning point and this is the moment to act against climate change. Colombia is a country which contributes in average with less than 0.5% of the total global emissions, but it still is a country that got compromises after Paris agreement and it is necessary to understand how the national energy matrix works in order to accomplish its emission reduction set goals.

To do the latter needs a very detailed description of the system, this is why Colombian government historical data and National Energy department library are taken as sources for this analysis. The details of Colombian energy system are inputs in a model called MARKAL. In this model the drivers are the demands of energy in Industrial, Residential, Commercial and Transportation sectors, projected until year 2050. MARKAL model also allows to set as input the cost of producing each energy unit, taking into account every step of the process, from the mine to the end-use demand. After the model is well detailed, some possible future scenarios are chosen to be evaluated: a variation on ±10%, ±30% and ±50% on demand projections, scenarios with low Hydropower availability and at last a set of scenarios combining low Hydropower availability plus an emission cap.

Different scenarios are evaluated in order to see how the cost effective reaction to the countries to different possible futures is and to determine if there are common factors which could be avoid in order to enhance the energy system.

At the end it is possible to see how the lack of proper policies which incentive the use of more efficient technologies lead to the same results in all scenarios: growth of industrial and transportation sector emission level without any restriction, zero investment on non-conventional power generation technologies and dependency on international electricity market if global temperature increases.

That is why, starting from government level, it has to be taken action to favor and incentivize the use of renewable technologies at population and industrial level. Also laws must be stronger when it has to do with emission limits for old vehicle fleets and with low efficient industrial machinery.

Sommario

Le politiche e il processo decisionale a qualsiasi livello non sono mai un compito facile: molti fattori e dettagli devono essere considerati, le proiezioni devono essere fatte e molte cifre devono essere valutate. Tuttavia, è difficile essere pronti per il futuro senza proiezioni di ciò che potrebbe accadere e di come eventualmente evitare situazioni negative.

Attualmente il mondo è in una svolta e questo è il momento di agire contro i cambiamenti climatici. La Colombia è un paese che contribuisce in media con meno dello 0,5% delle emissioni globali totali, ma è ancora un paese che ha ottenuto compromessi dopo l'accordo di Parigi ed è necessario capire come funziona la matrice energetica nazionale per realizzare la sua riduzione delle emissioni obiettivi stabiliti.

Per fare questo ha bisogno di una descrizione molto dettagliata del sistema, ecco perché i dati storici del governo colombiano e la biblioteca del dipartimento di energia nazionale sono presi come fonti per questa analisi. I dettagli del sistema energetico colombiano sono input in un modello chiamato MARKAL. In questo modello i driver sono le richieste di energia nei settori industriale, residenziale, commerciale e dei trasporti, proiettate fino all'anno 2050. Il modello MARKAL consente inoltre di impostare come input il costo di produzione di ciascuna unità energetica, tenendo conto di ogni fase del processo, dalla miniera alla domanda di uso finale. Dopo che il modello è ben dettagliato, vengono scelti alcuni possibili scenari futuri da valutare: una variazione su ± 10%, ± 30% e ± 50% su proiezioni su richiesta, scenari con bassa disponibilità di energia idroelettrica e infine una serie di scenari che combinano bassa energia idroelettrica disponibilità più un limite di emissione.

Vengono valutati diversi scenari al fine di vedere come sia la reazione economica ai paesi verso diversi possibili futuri e per determinare se ci sono fattori comuni che potrebbero essere evitati al fine di migliorare il sistema energetico.

Alla fine è possibile vedere come la mancanza di politiche adeguate che incentivano l'uso di tecnologie più efficienti porti agli stessi risultati in tutti gli scenari: crescita del livello di emissioni del settore industriale e dei trasporti senza alcuna restrizione, zero investimenti in energia non convenzionale tecnologie di generazione e dipendenza dal mercato internazionale dell'elettricità se la temperatura globale aumenta.

Questo è il motivo per cui, a partire dal livello governativo, è necessario agire per favorire e incentivare l'uso delle tecnologie rinnovabili a livello di popolazione e industriale. Inoltre, le leggi devono essere più rigorose quando hanno a che fare con limiti di emissione per le flotte di veicoli vecchi e con macchinari industriali a bassa efficienza.

1 INTRODUCTION

Nowadays' industrialized countries had the opportunity of growing by many means, including hard and cheap human work and almost unlimited usage of natural resources. Back then, during their growing period, they had no strong boundaries imposed by environment issues, global warming and all damages that have been lately discovered and have been directly linked to the industrial activity, to transportation emissions and other quotidian activities. Therefore, they could establish a production basis and they could develop economies, economies which even if sometimes have not been very stable, at least have given some wellness and live standards to these countries.

On the other hand, nowadays' developing countries, which have had a lower share in the worldwide overall environmental damage, have to take into account and adopt these recently placed environmental boundaries, in order to contribute to the worldwide overall solution. Even if the measures that have to be taken by developing countries are less radical than the ones that have to be adopted by the already developed ones, it still means a change in the way of doing things for everybody: adopting new technologies, adapting to new economy flows and adopting cultural behaviors at a higher rate than usual.

The annual Conference of Parties, COP, was born as a tool to review and assess the implementation of the above named measures. The COP is the supreme decision maker of the United Nations Framework Convention on Climate Change (UNFCCC), which has as objective the stabilization of emissions to a level in which the anthropogenic interference does not have dangerous effects on the climate system. All of this guaranteeing at the same time not to stop the worldwide development, which means, guaranteeing a sustainable development.

COP21, which is the 21st annual Conference held in Paris, was the first Conference in which all the parties agreed to work together for a common global goal: keep the rise of the temperature under 2 °C, and even under 1.5 °C, with relation to the Temperature in the pre-industrial time. This event is known as the Paris Agreement. As result of this agreement, all involved parties have to take domestic measures, which will contribute to their Nationally Determined Contributions (NDC), being the latter the post- 2020 climate actions taken by each Party [1].

Colombia counts as a developing country, also known as Non-Annex I party. The latter means it is highly affected by the adverse impact of climate change, making it more vulnerable. The Convention, by means of its structure, assures extra incentives, support and technology transfer to these developing countries.

With a share of 0.46% of the global greenhouse emissions in 2010, Colombia is among the 50 most contaminating countries. This value could not be representative, but if no measure is taken, then the total emissions could increase 50% by 2030 [1].
As a first compromise, Colombia decided to decrease by 20% the emissions in 2030, in respect of the expected emissions resulting from following the scenario of BAU. In addition, if there is enough international support, Colombia compromises to reduce by 30% the greenhouse emissions in 2030 [2].

However, Colombia cannot slow down its developing rhythm, because as a country, it lies still far behind of developed countries' rights and laws. Following aspects are an example of the latter: a share of population does not have access to the interconnected grid leading to a poor education and health system in these zones, main urban areas are full of polluting spots leading to severe respiratory issues, illegal (and sometimes legal) land exploitation which ends up in uncontrolled deforestation and water pollution, among many others.

In order to achieve the COP21 emissions goals without slowing down the economy and hence on-the-way developing dynamics, it is necessary to implement energy efficient processes and unbound as much as possible the Gross Domestic Product GDP growth from the emissions growth, which means, among others, to decrease the energy intensity, to find new economy activities and to stop deforestation.

According to the country energy efficient development action plan for the years 2017 to 2022 (Plan de Acción Indicativo de Eficiencia Energética), there is an average yearly loss of 52% out of the total consumed Energy [3], which means that less than half of the consumed resources end up in useful energy. The sector with the highest losses is the transport one; it contributes with 64% of the total loss, followed by the industrial and residential sector, with a share of 16% and 15%, respectively.

The latter is due to the age of the vehicle fleet. Almost 40% of the vehicle fleet has more than 20 years in circulation [4]. Unfortunately, the taxes for the old vehicles and the incentives for the new ones are not enough to decrease the share of these old vehicles. An old vehicle fleet also implies high levels of pollution in the main urban areas [5]. Regarding the industrial and residential sectors, the reason for the high losses is similar to the one in the transport sector: old and low efficient home appliances and industrial equipment. Income ranges for most families in Colombia do not allow them to renew these home appliances.

Everything what was mentioned above start having full sense when it can be showed numerically, not only because this thesis is made for an engineer audience, but also because what moves companies and therefore the economy systems nowadays are figures. In the past, studies have been made on Greenhouse Gases mitigation measurements in Colombia [6], because climate change is not a new issue.
In order to envisage some possible scenarios and its emissions, its power generation levels and in short, its numbers, MARKAL Model is going to be used.
Therefore, the scope of this thesis goes from the energy offer/demand in Colombia, through its characteristics and costs, and through the demand type segregated by sector until the possible scenarios in the period horizon from 2010 to 2050. Then, emissions of all possible scenarios are calculated together with the power generation levels, and then the resulting figures are assessed to understand which the cost effective solutions distribution are and which policies/incentives/recommendations could be made in order to support positively the global warming issue.

2 COLOMBIA

Transportation, Commercial, Industrial and Residential sectors are the ones with the largest share in the energetic final use, in total they add up 85% of the total consumption [3]. They also contribute together, in yearly average, to approximately 45% of the total Colombian GDP, which gives us a first look on how economy is linked to energetics [7]. Additionally, more than 95% of the total energy losses in the country are contributed by these sectors [3], which means there are many things that can still be done to make them use energy in a more efficient way.

The main goal of this chapter is to clarify the Colombian energy matrix, in the sectors where the largest losses are centered and to give a first assessment of where energy saving measures could be made against bad future scenarios.

2.1 COLOMBIAN ENERGETIC USE

On 2010 and 2015 Colombia had a total consumption of 1150 PJ and 1320 PJ, respectively [8]. Compared to industrialized countries like Italy and Germany, which consume at least 5 and 9 times more primary energy, one might say that developing countries have it easy on emission reductions and on being less energy intensive. Truth is that economic develop is still strongly linked to energy use, as in almost every single country, and industrial plus transportation sector have a share of more than 50% of the total energy consumption. Residential sector has a share almost as high as the industrial one on the total energy consumption; the latter is due to inefficient cooking activities and inefficient house appliances. Wood is still used in rural areas for feeding stoves and old air conditioning plus old ventilation appliances makes the energy consumption to raise up.

Figure 1. and 2. Shows how is distributed the share on energy consumption by each sector on years 2010 and 2015. Agricultural sector has the smallest share, this is why from now on it will not be included in further energy demand details and neither on possible future scenarios. Additionally, from now on, the analysis is focused on emissions and on energy efficiency from the point of view of energy consumption, and agricultural sector, even if it has the biggest contributions to the total country emissions level, it is due mainly to cattle and deforestation for giving space to new plantations [9].

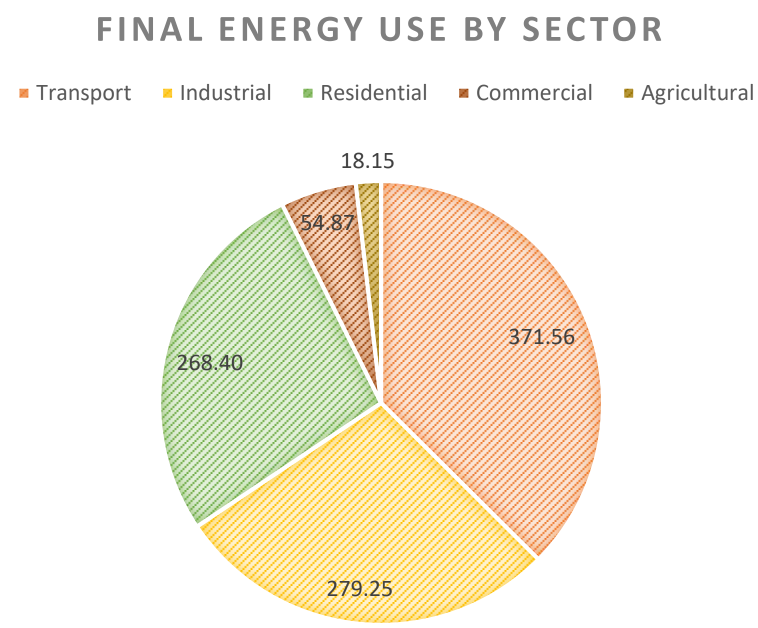


Figure 1 Final Use by Sector in PJ

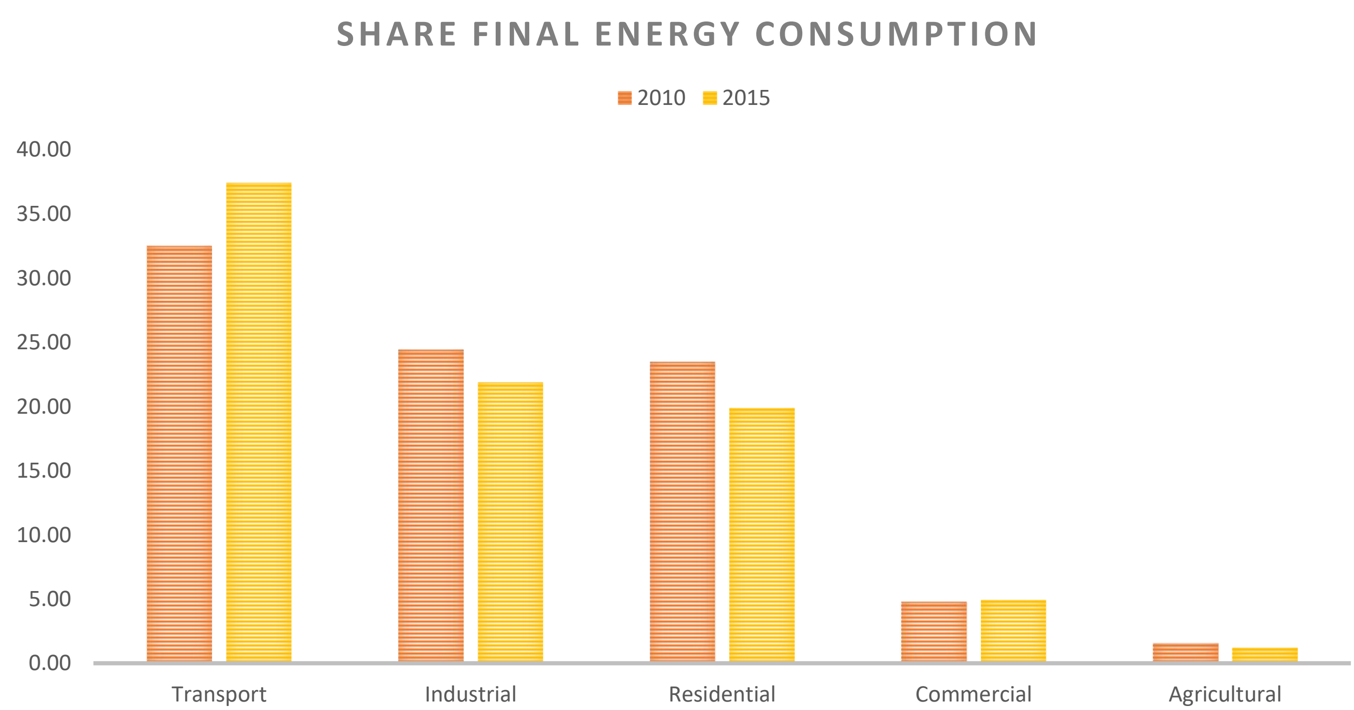


Figure 2 Share Final Energy Consumption by Sector

2.1.1 Transport Sector

As it is shown in Figures 1 and 2, transportation sector is the one that consume the most energy. Old vehicle fleet and lack of regulation are the main reason for the low efficiency, resulting in higher fuel consumption.

Approximately 45% of load transportation vehicles fleet, which are mostly Diesel vehicles as shown in Figure 3, have more than 20 years of use, and even 20% has more than 40 years of use [10]. The latter trigger the PM detection alarms, because in cities like Bogotá and Medellin the limit concentration values have been passed in a quantity of times more than the recommended by World Health Organization.

Unfortunately, greenhouse emissions are not the only air pollution problem present in Colombia. Main cities like Bogotá, Medellin and Santa Marta show high levels of Particulate Matter, crossing sometimes, the World Health Organization concentration limits for PM10 and PM2.5 [11].

All across the country there are measuring stations, which continuously send the data of the concentration levels to the information center. In some cases, the data reliability is doubtful; it is due to the age of the measurement equipment, to the damages made by people on the stations and to the improper equipment handling and calibration. Then, in total, only 75% out of the ca 200 measuring stations send reliable data [12].

In 2017, levels of Total Suspended Particles (TSP) almost totally did not cross neither the national daily nor the national yearly limit, 300µg/m3 and 100µg/m3 respectively. Only 2 stations, one located in Bogotá and the other one located near a coal mine, crossed the yearly average limit.
However, PM10 and PM2.5 exceeded the maximal limit in 10% and 25% of the measuring stations, respectively. These particles are directly related to some respiratory diseases, affecting mostly children and elderly population. The excess on the concentration levels ends up in increasing health issues for the population surrounding the contaminated areas, because according the Colombian quality of air report for 2017, all stations with high concentration levels are located in populated areas. The high levels are due mainly to mobile sources (80%) and to industrial activity in a couple of areas (20%). In 2015 the cost of respiratory diseases caused by P10 and P2.5 Particles was 12.2 billion COP, which equals 1.5% GDP of the same year.
Starting in 2018, Colombian government has establish new maximum allowed levels. From 2018 on: there is no limit to TSP levels, there is a reduction in the limit for SO2 and CO, and PM10 together with PM2.5 keep on with their previous daily and yearly limit values [11].

In order to stop the increasing levels of pollutants in the air without making big restrictions to the mobility services, there is the alternative of giving incentives for the acquisition of electric vehicles and also to implement taxes for cars which are older than a certain age and that therefore do not comply with the emissions limits.

Penetration of hybrid and electric vehicles is still on a “pilot” scale, some electric taxis have been placed in two main cities, Bogotá and Medellin, and there are around 170 hybrid private vehicles and circa 80 electric private vehicles circulating in the country. The lack of incentives by the government side is what holds back the number of environmental friendly vehicles, nowadays, year 2019, there is still no law nor decree that favors the purchase of hybrid/electric vehicles.
Gasoline, Diesel Oil and Natural Gas are default fuels, as shown below, and there is still no share on any of the categories for hybrid nor for electric vehicles

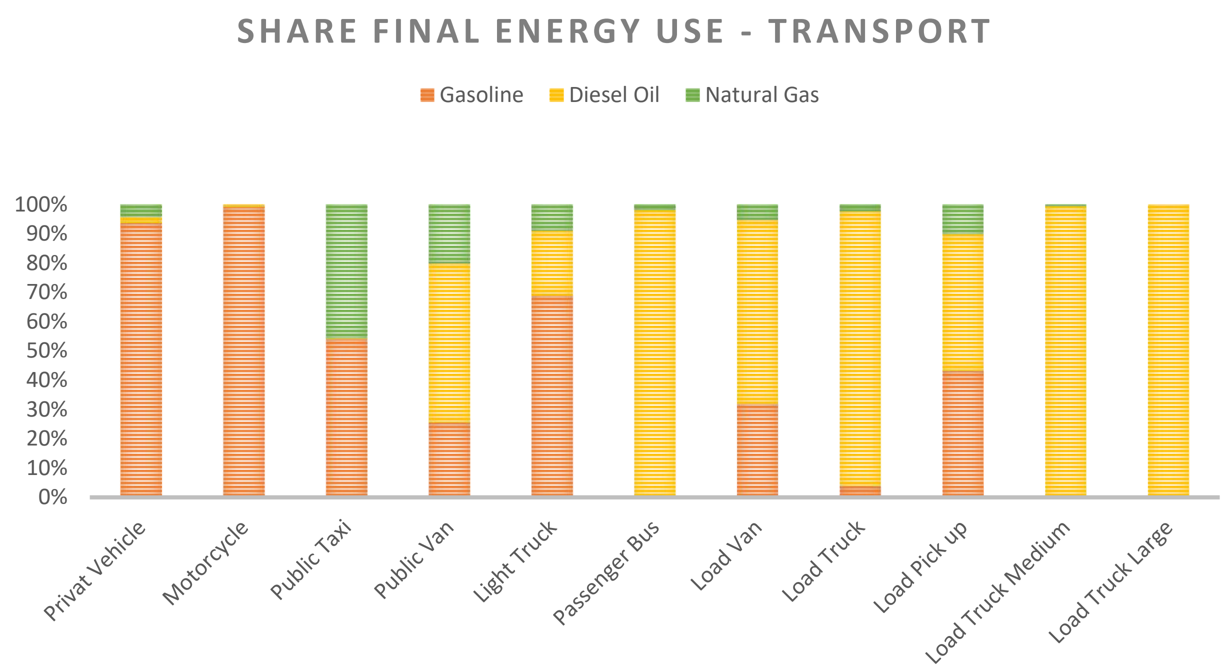


Figure 3 Share Final Energy Use – Transport

Following, it is shown how behind Colombian legislation is regarding the emissions limits for purchased cars, which leads to a further increase on emissions per vehicle in comparison to European countries for example.

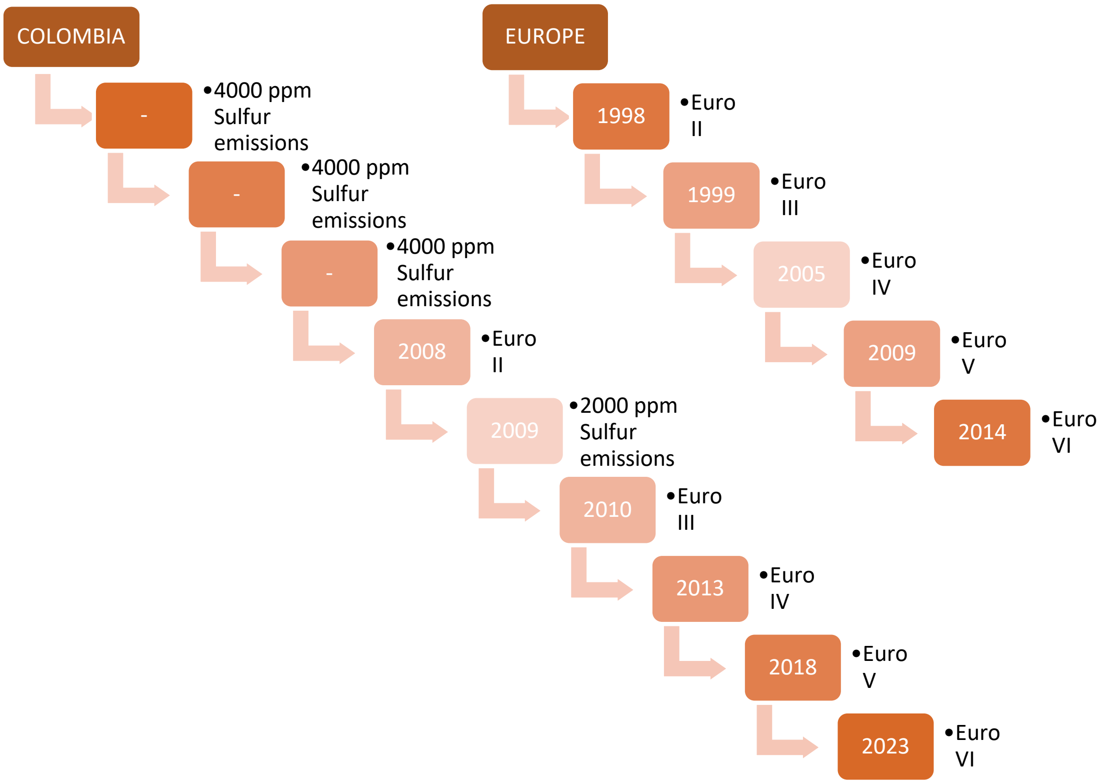


Figure 4 Emissions standards/limits in Colombia and Europe [4]

Old fleet and the lag on proper government incentives and legislation end up in a higher fuel consumption and hence in larger GHG emissions. Possible future scenarios include a minimum share of hybrid/electric vehicles in the whole total (at least for private vehicles and Taxis), reduction of diesel vehicles fleet hence increasing GDP by some points due to the lower expenses in health services and stronger emissions standards policies, lowering the remaining share of old vehicles that do not comply with these norms.

2.1.2 Industrial Sector

Since direct heat and vapor generation have the largest share in the total energy use in the industrial sector, boilers and heaters are the appliances that have the biggest impact on the sector efficiency and on the sector total emissions.
Motors are mainly fueled by electricity, which comes primarily from hydro power plants, as it will be discussed further in this text. Hence, driving force is not to be considered as a final use that affects significantly the total sector emissions. Office supplies, Air conditioning, refrigeration and lightning sum up less than 5% of the total energy use, and every of them are fed by electricity, so this is similar case as the one of driving force, since electricity in average years (No Niño nor Niña phenomenon year) is produced by hydro power plants. Nevertheless, this is a good introduction point for the low efficient appliances: even if only 5% of final energy in industrial sector goes to “household supplies” (lightning, air conditioning, etc.), the same supplies and its low efficiency have bigger impacts in other sectors, such as commercial and residential, since the number of these devices is larger. More on this will be discussed in commercial and residential sector sections.

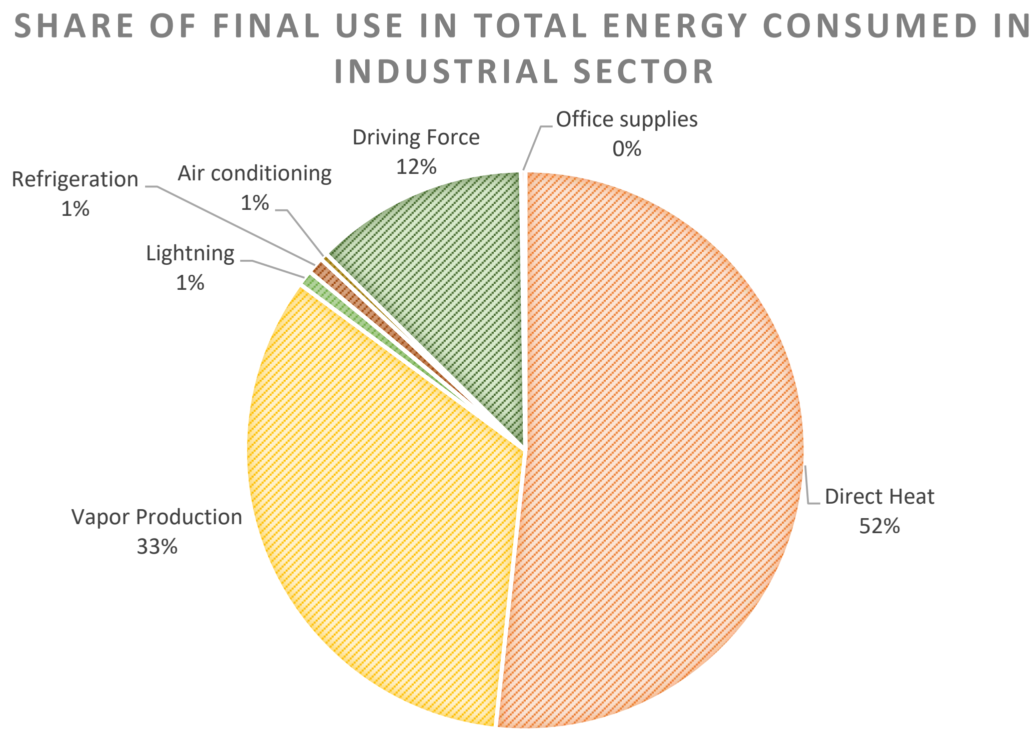


Figure 5 Share of Final Use in Total Energy Consumed in Industrial Sector

As shown in the Figure 7, Coal is the most used fuel in Colombian Industry. Here is to be said, that Colombia exported in 2017 a record of 105 million tons of Coal and in average it exports 85 million tons yearly [13]. From all the Coal that Colombia extracts, it exports 95%, only 5% goes to internal use [14]. Nevertheless, one of the main goals set in the United Nations Framework Convention on Climate Change held in Paris is to leave the fossil fuels under the earth, and more specifically, many countries agreed on reduce by 50% their current coal consumption on 2030 and to totally suppress its use by 2050 [15]. This decision, which in one hand is good for the environment, in the other hand affects the economy (GDP) of Colombia, since the countries that agreed on reduce its coal consumption have a share of more than 80% on the total Colombian coal exportation.

A possible future scenario includes the reduction on GDP due to the unpurchased coal, which exportation sales contributes with approximately 1.5% of the total GDP.

Natural Gas has also a large portion on the final use in industrial sector, and this fact has a drawback: natural gas reserves in Colombia will not last long. After years of exploration the number of unmined fields is not growing, it fact it has been said that it will be over by 2025. Nothing depending fully or high-partially on natural gas will be economically beneficial.

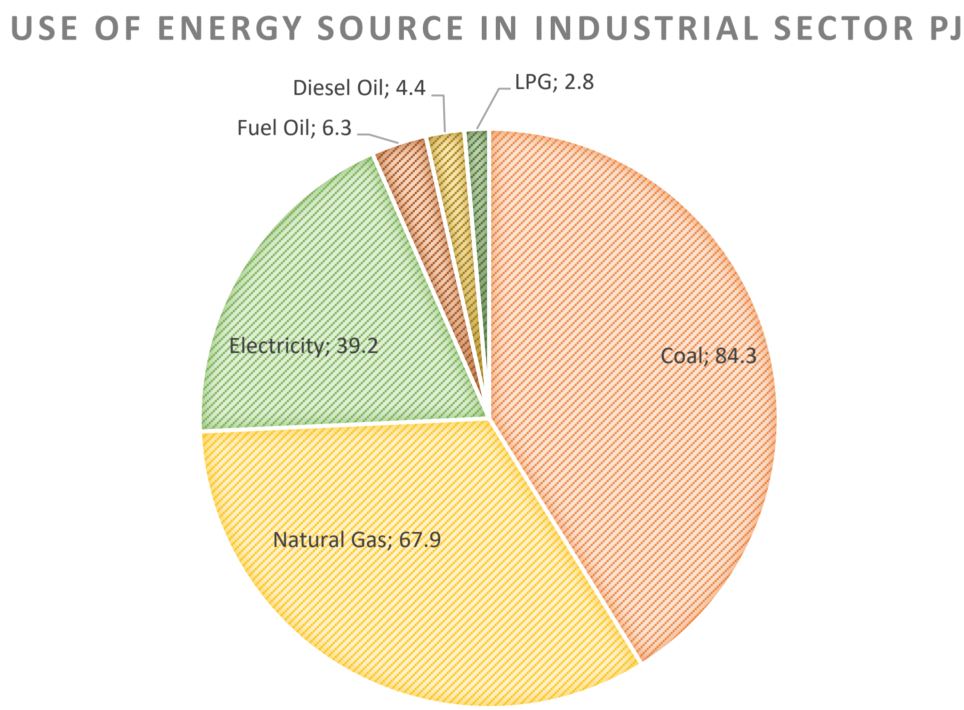


Figure 7 Use of Energy Source in Industrial Sector in Petajuoles

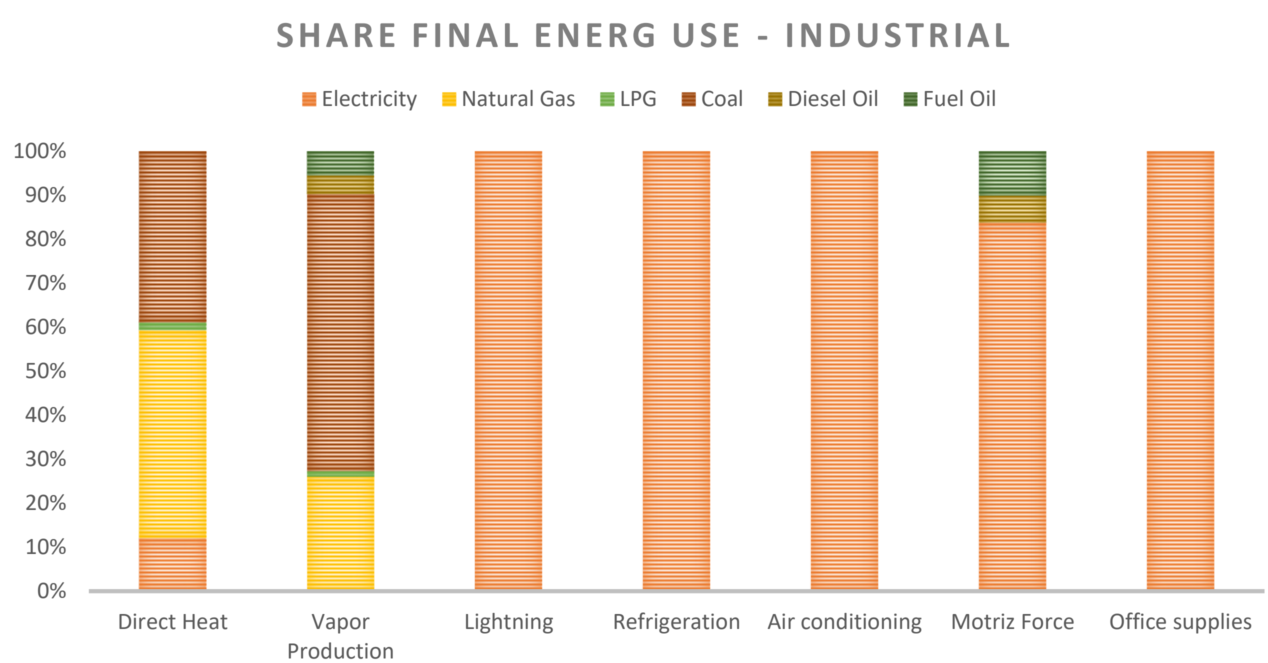


Figure 6 Share Final Energy Use - Industrial

2.1.3 RESIDENTIAL SECTOR

Most of rural areas in Colombia are difficult to access. Mountains, deep jungles and dangerous rivers cross from north to south this country, making any social venture and development hard to achieve. As a first example, natural gas pipe lines have not reached the whole territory, and neither has electricity grid. That is why wood has still the largest percentage in the fuel uses, it is mainly used as heat source in rural areas.

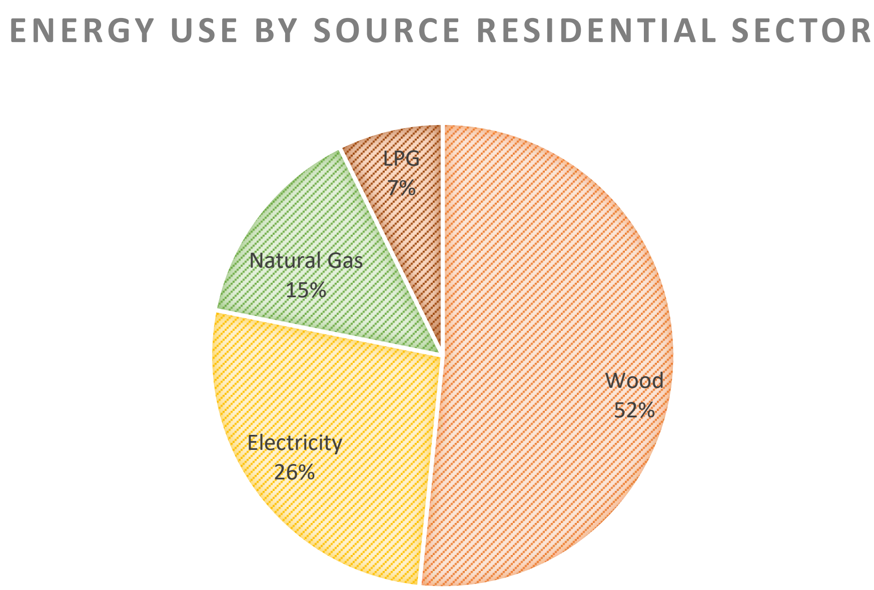


Figure 9Energy Use by Source, Residential Sector

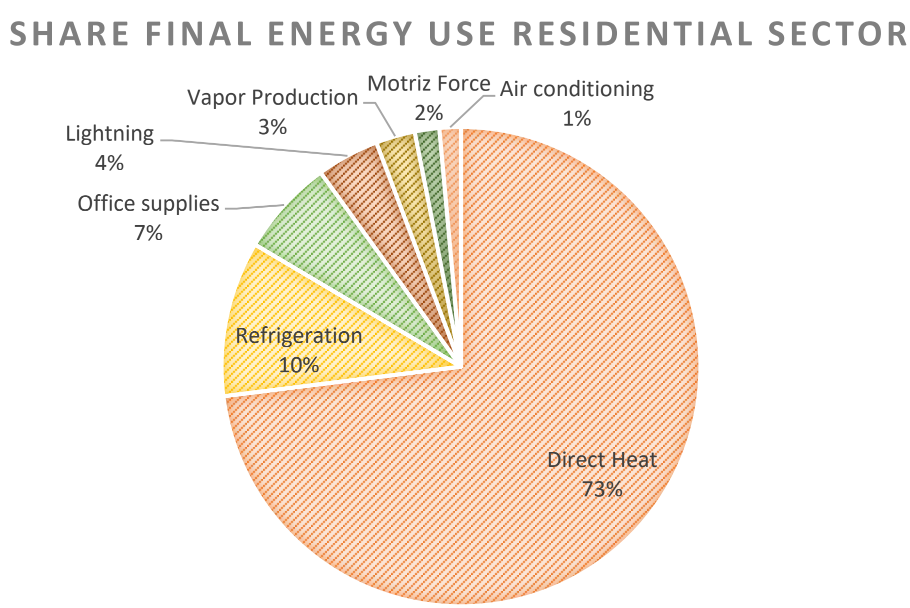


Figure 8 Share Final Energy Use Residential Sector

In Urban areas, home appliances have a higher share in the final energy use. The current existing house appliances are old and inefficient, increasing then the energy consumption by household [16]. Colombia has no heating systems, in cold cities people are used to wear warm clothes and cover themselves instead of using interconnected heating pipelines. Some old houses have chimneys, but that is not the rule. On the other hand, what is mostly found in every Colombian household is a ventilator and/or air conditioning device, this is due to the fact that most places with access to electricity have an average yearly temperature above 25°C. Colombia is on the equator, therefore, there are no seasons and the temperature tends to be constant along the year.
Possible future scenarios for this sector will include following: if world average temperature raises, the air conditioning and refrigeration system will demand more energy, which will be mostly supplied by thermoelectric plants or renewable sources as soon and/or wind since the water availability decreases when temperature increases so hydro power plants cannot be fully utilized.

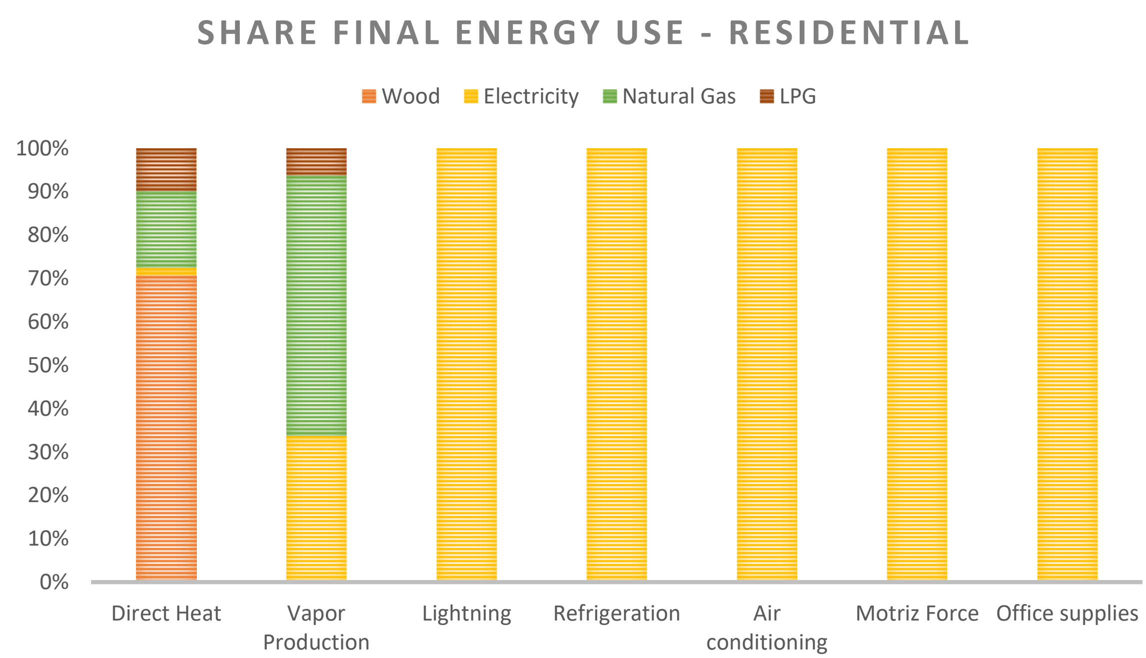


Figure 10 Share Final Energy Use - Residential

2.1.4 COMMERCIAL SECTOR

This sector has the lowest energy use of this analysis. However, it contributes to almost 9% of the total GDP, which means this sector is not very energy intensive.
As expected, commercial sector does not involve many activities that require direct heat or water vapor, offices appliances and refrigeration have the largest share in energy use of this sector. Air conditioners, fridges, ventilators and light bulbs efficiencies are the ones that affects the total energy use, which has as main source the electricity.

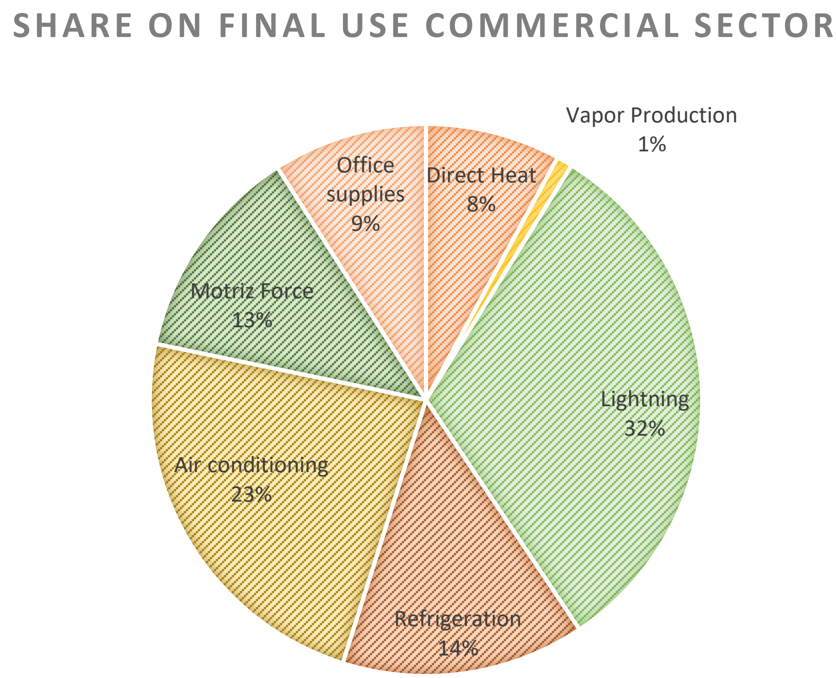


Figure 11 Share on Final Use Commercial Sector

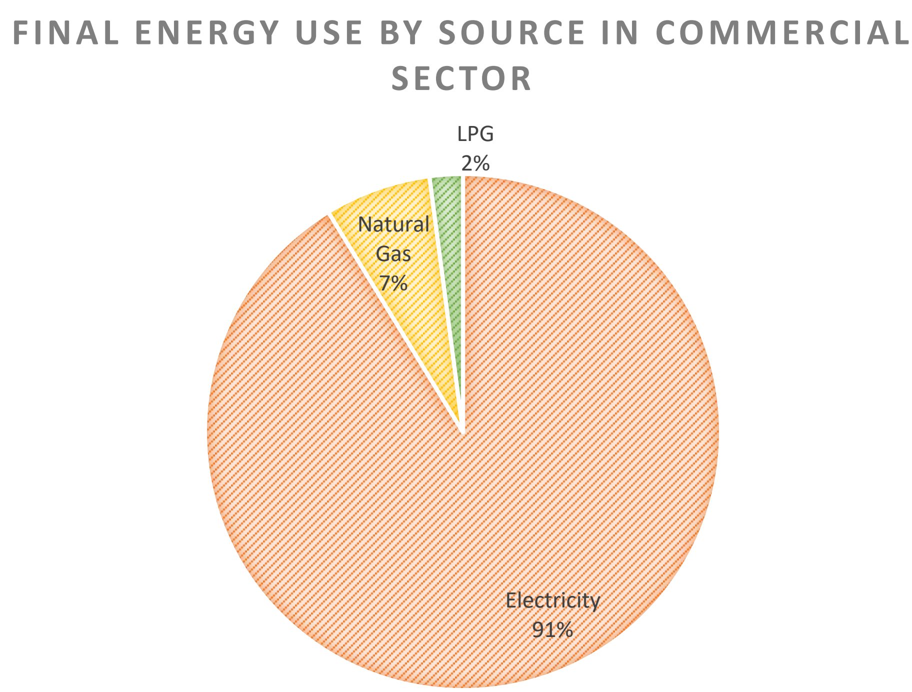


Figure 12 Final Energy Use by Source in Commercial Sector

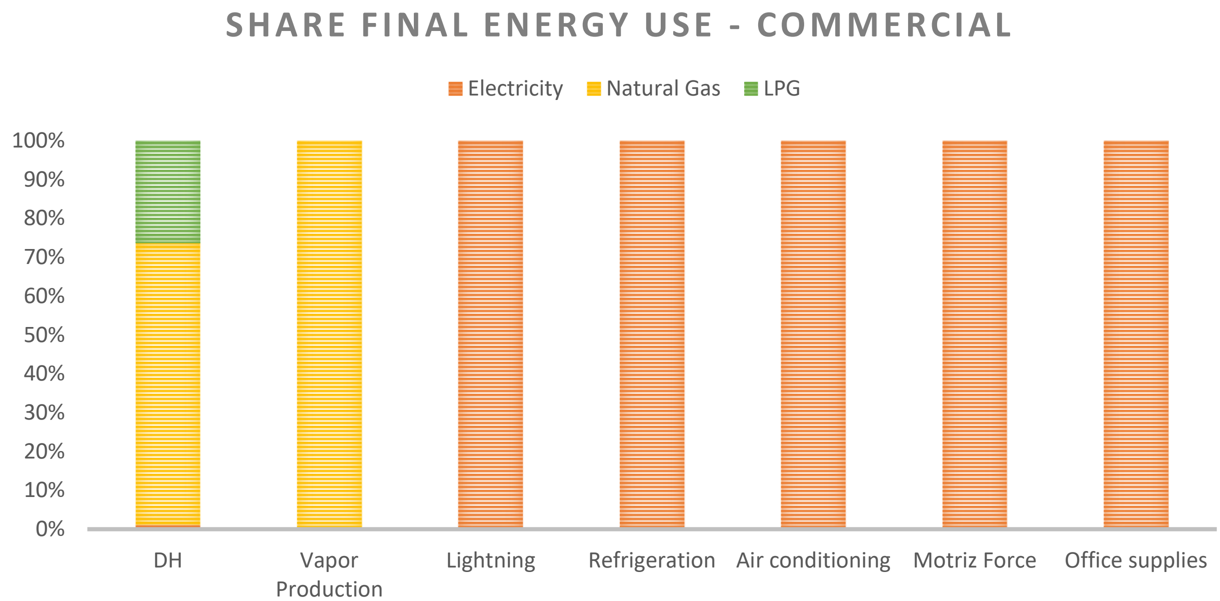


Figure 13 Share Final Energy Use - Commercial

2.2 COLOMBIAN POWER GENERATION

Thanks to the privileged number of river basins present in Colombia the power generation matrix has a big portion of hydro power plants. Almost 70% of installed power, which supplies the national grid, comes from hydro power plants placed all around the country [8]. Power plants have not reached just a few areas; these areas are by coincidence the poorest zones in Colombia, such as La Guajira, in the deserted north part of the country.
Coalmines are also a good source of fuel for thermoelectric plants. Coal is mainly used to feed power plants near the coalmines, as it happens in the Atlantic Zone and in Boyacá [17] [14].
Thermoelectric plants are mainly fed with natural gas, which could become a problem in the future since there have not been found outstanding natural gas reservoirs, and according to expert's opinions, it might be over by 2025, which means the fuel cost will increase and hence the total operation plant costs will increase.

Future scenarios in Colombian power consider that when global temperature increases, the level of water deposits decreases and hence the power coming from hydro power plants also decreases. But the latter triggers a chain reaction, because in countries like Colombia, where the power comes weather from hydro sources or from burning fossil fuels, if the first is not available then more fuels will be used, increasing then the total emissions and contributing to the global damage caused by greenhouse gases.

Incentives for installation of renewable energy plants are still doing baby steps in Colombia, with a wind park of 18 MW and total solar power installed of 100 MW circa to the date, the country is still far behind on the renewable field. Truth is, hydro power plants work well under normal climate conditions, however, after all the expected changes due to global warming, and a minimum share of renewable energy must be encouraged in order to guarantee electricity supply. Moreover, renewable energy sources are the best solution for remote rural areas, because nowadays still more than 3% of total population (approximately 1.700.000 people) have no access to the national grid, which means their electricity comes mainly from diesel motors, which work less than 12 hours a day, or they simply have no electricity.
Zones with no electricity have an economy which lags behind if the national average, and their social situation is very vulnerable (no electricity leads to no hospitals/schools, no refrigeration for provisions of any kind and almost no way to make industry nearby).
Therefore, it is necessary to consider in future scenarios the penetration of solar, wind and biomass as energy sources to supply and bring stability to the non-interconnected areas.

As mentioned before, hydro power plants have the largest share in the total power generation system; however, this does not mean that they dispatch as much energy as they were designed to. In El Niño phenomenon years, the availability of some plants reaches levels of less than 30% their installed capacity, and there is when thermoelectric plants reach more than 95% of their installed capacity. Following it is shown the dispatching orders in year 2010 of the generation plants connected to the national grid.

Table 1 Power plants on a year of El Niño phenomenon (2010)

Name	*Type*	*Fuel*	*Capacity MW*	*Energy Dispatched in 2010 GWh*	*Total availability*
Betania	Hydro	--	540	1336.8	28%
Bquilla 3	Thermal	NG	64	450.4	80%
Bquilla 4	Thermal	NG	63	409.5	74%
Calima	Hydro	--	132	93.8	8%
Candelaria 1	Thermal	NG	157	1325.6	96%
Candelaria 2	Thermal	NG	157	1245.0	91%
Cgena 1	Thermal	NG	61	441.2	83%
Cgena 2	Thermal	NG	60	409.5	78%
Cgena 3	Thermal	NG	66	477.8	83%
Chivor	Hydro	--	1000	2848.8	33%
Esmeralda	Hydro	--	30	154.0	59%
Flores 1	Thermal	NG	160	1252.4	89%
Flores 4	Thermal	NG	450	3744.9	95%
Guajira 1	Thermal	CM	151	1097.7	83%
Guajira 2	Thermal	CM	145	989.6	78%
Guatape	Hydro	--	560	1947.2	40%
Guatron	Hydro	--	512	2247.1	50%
Guavio	Hydro	--	1200	4433.6	42%

Jaguas	Hydro	--	170	387.3	26%
La Tasajera	Hydro	--	306	1288.9	48%
Merilectrica	Thermal	NG	169	1367.2	92%
Miel I	Hydro	--	396	604.2	17%
Pagua	Hydro	--	600	4376.2	83%
Paipa 1	Thermal	CM	31	214.4	79%
Paipa 2	Thermal	CM	70	553.1	90%
Paipa 3	Thermal	CM	70	503.5	82%
Paipa 4	Thermal	CM	150	1255.5	96%
Playas	Hydro	--	201	1166.2	66%
Porce II	Hydro	--	405	1294.5	36%
Prado	Hydro	--	46	66.0	16%
Salvajina	Hydro	--	285	592.6	24%
San Carlos	Hydro	--	1240	4735.2	44%
San Francisco	Hydro	--	135	196.9	17%
Tasajero 1	Thermal	CM	151	1313.8	99%
Tebsab	Thermal	NG	791	6220.9	90%
Termocentro	Thermal	NG	278	2266.2	93%
TermoDorada	Thermal	NG	51	316.5	71%
TermoEmcali	Thermal	NG	229	1707.0	85%
TermoSierra	Thermal	NG	460	3208.4	80%
TermoValle	Thermal	NG	205	1612.0	90%
Urra	Hydro	--	338	697.1	24%
Yopal2	Thermal	NG	30	221.5	84%
Zipa5	Thermal	CM	64	476.8	85%
Zipa2	Thermal	CM	34	283.6	95%
Zipa3	Thermal	CM	63	531.0	96%
Zipa4	Thermal	CM	64	540.0	96%

3 MARKAL MODEL

MARKAL, an acronym for MARKal ALlocation, is a demand driven linear programming model. It works in a horizon period, where all the exogenous end-use demands are satisfied (as the ones presented in chapter 2.1). In the present analysis a standard MARKAL model will be used, which means that the demand will be a fully exogenous input and it will not respond to price changes [18].

Bottom-up models such as the Standard MARKAL are very detailed models, they are focus on the technologies related to the energy sector of a region, as part of an economy branch of it. . Very detailed inputs, outputs, unit costs and several other technical and economic characteristics of every energy using technology are part of this kind of models. All technologies are logically linked together by means of their “resources” and “products”, which could be energy carriers, materials emissions and/or energy services, all of them constitute the bottom-up model. In the MARKAL model, the production of one unit (it could be a billion vehicle kilometers of motorcycle service or a Petajoule of industrial direct heat service) is possible by using a mix of individual technologies' outputs (e.g. industrial direct heat produced by coal or natural gas). Therefore, the production function of a sector is implicitly, rather than explicitly built as in more aggregated models (Top-down models). Such implicit production functions may be quite complex, depending on how detailed the energy system is described, and in the case of MARKAL, it has to be pointed that the level of details is very high.

When the types of energy demand are defined per year, i.e. annual steam production, residential lightning, kilometers travelled by a single taxi, etc., it is possible to set the technologies that are going to meet the demand. These technologies are at all levels of an energy system, from mining of primary energies to transformation technologies (as refineries and power plants), from secondary fuels to technologies which will actually meet the demand such as diesel fueled taxis or incandescent light bulbs, just for giving some examples. In this case, the demand on years 2010 and 2015 are known, and the ones until year 2050 are developed taking as basis the economic and demographic projections, such as the GDP projections found on the OECD Database.

The more details given in the technology part, the better the model determines the group of technologies and fuels with the less cost over the forecast period. This is a cost effective model.

More on MARKAL model, the code behind and how its structure works (variables, objective functions and constraints) can be found on Annex A.

4 MARKAL INPUTS

4.1 DEMAND DRIVERS

This model is a demand driven one, which means that the demand projections are as important as the details given for each energy-use technology, the model will carry out a good optimization and results can be well assessed only if the future periods' demand represent in the most accurate way the Colombian economy-population dynamics.

The Organization for Economic Co-operation and Development, OECD, has available for public use Real Gross Domestic Product (GDP) forecasts. The available forecasts go from global level, going through regions level, until reaching the country level.

The entity in Colombia in charge of economy statistics and population projections is the DANE (Departamento Administrativo Nacional de Estadística, National Administrative Department of Statistics). Everything related to the economy sector in numbers can be found in DANE Data bases, data and lists of such records as imported/exported quantities, gross domestic product by economy activity (industrial, commercial, transportation, etc.) and population historic data and forecast, are only few examples of the wide spectrum made available by DANE.

On the other hand, the Mines and Energy planning department of the Colombian government, UPME by its initials in Spanish (Unidad de Planeación Minero Energética), has the record of the energy use by type of energy source and by type of end-use sector and it is updated until year 2016 [8]. For example, it is possible to know how many energy units of coal were consumed by the industrial sector in year 2010.

In order to determine and to detail which is the final use of each energy carrier (fuels and electricity for example) different studies and publications made by UPME were used. The aim of these studies is to find out which are the hot points of the whole energetic matrix in which some changes can be made in order to reduce consumption. These studies were very useful for the analysis carried out in this thesis, since they have detailed data about end-use demands of Industrial, Commercial and Residential sectors and also gave some hints of which could be the improvement in the appliances efficiency in the near future. All this data is included in the different energy-use technologies of MARKAL, since efficiencies, residual capacity and past years energy use records are part of the Energy System items. Plus, as mentioned before, the more detailed the model, the better the assessment of future scenarios.

Transportation sector has a different set of reports used to determine its end-use demands. These reports are still made by the UPME but referred to urban and interurban transportation. The first report is used to find the share of each transportation type that uses a certain fuel, i.e. for example how many private vehicles use gasoline and how many use natural gas in the urban area [19]. A second report is used to calculate the average of kilometers by energy unit which belong to each vehicle category and fuel category [20] [21]. This is done because unlike the other sectors, which use energy units in MARKAL (Petajoules), the transportation sector uses billion of kilometers per year made by the whole vehicle type fleet in order to assess its total demand. Both quantities, petajoules and billions of kilometers per year, are equally valid at the moment of assessing an energy system, everything relays in how many details and how good and valid are these details to represent the real scenarios.

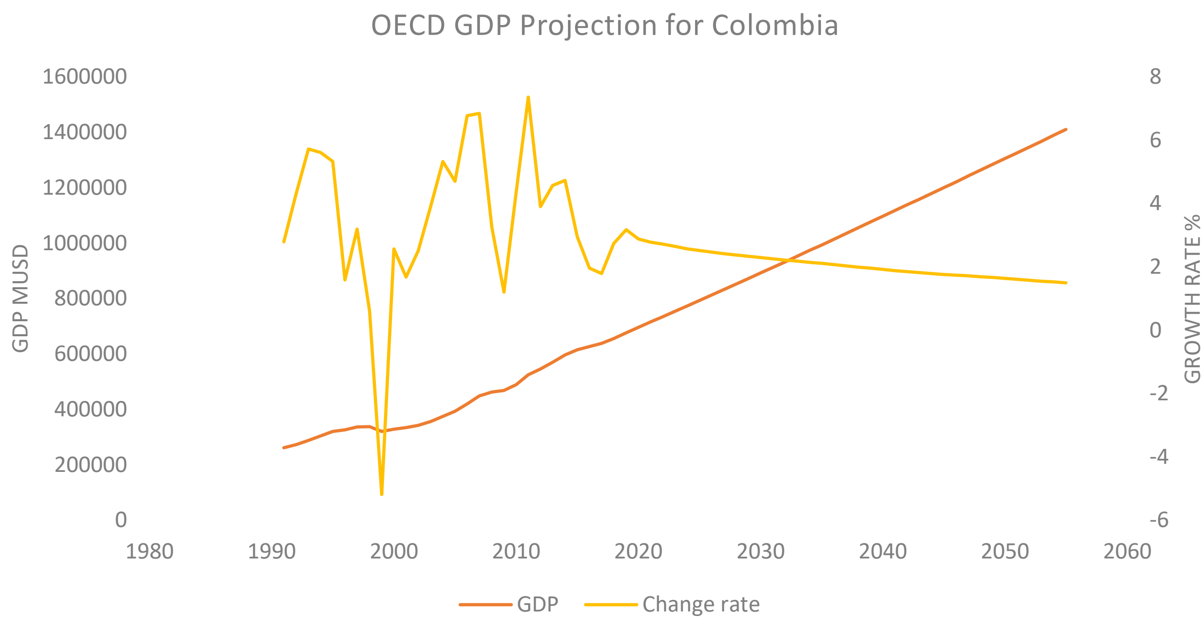
The results of the asses of the different studies, reports and records made available by UPME have been already shown in a succinct way in chapter 2, where Colombian energy system was described. All end-use quantities are calculated for both year 2010 and year 2015, and these will be the learning base for the MARKAL model.

Now, as the model already has reported data for the "past", it is needed to determine which will be the drivers for the "future". OECD GDP forecast, which was mentioned at the beginning of this chapter, is the one used to determine the grow rate of the demand on each sector, excluding only residential sector, which use a forecast base for the population projections made by DANE and United Nations UN, more details on this will come later on this document.

Industrial, commercial and transportation activities have a big share in Colombian Gross Domestic Product. Nevertheless, even if all of these economic activities follow a similar behavior as the whole, the fraction or elasticity at which they relate to the GDP might differ by some points. Following it is shown how the projections of Demand for each sector is calculated, taking as base GDP and UN projections.

4.1.1 *Growth rate and Elasticity*

In the figure below it is shown the OECD forecast for Colombian GDP [22]. It shows how bad economy went at the end of last century due to a stock market bubble. People back then got more credit than what they could pay for. In terms of growth rate, 1999 internal crisis was worse than 2009 world crisis for Colombian Economy.



The following is taken textually from OECD source: "Forecast is based on an assessment of the economic climate in individual countries and the world economy, using a combination of model-based analyses and expert judgment."

In general terms, OECD forecast show a worldwide slowdown in economy growth, only few countries, such as India, will have positive slope in the growth rate.

General GDP values are the first step on projecting the end-use demands for MARKAL until year 2050. As base principle, the main assumption is that end-use energy demands of each economy sector are proportional to the economic growth thereof.

In order to assess how each sector behaves with respect to the total GDP, it is calculated the relationship between growth rates of each one for the past ten years. This relation shows in how many units each sector changes with regard to a unit change in the total GDP, it will be called from now on as elasticity.

Industrial sector contributes with 15% of the total GDP, in average, which means that growth behaviors of both have a similar shape. The elasticity of industrial sector is showed in the figure below.

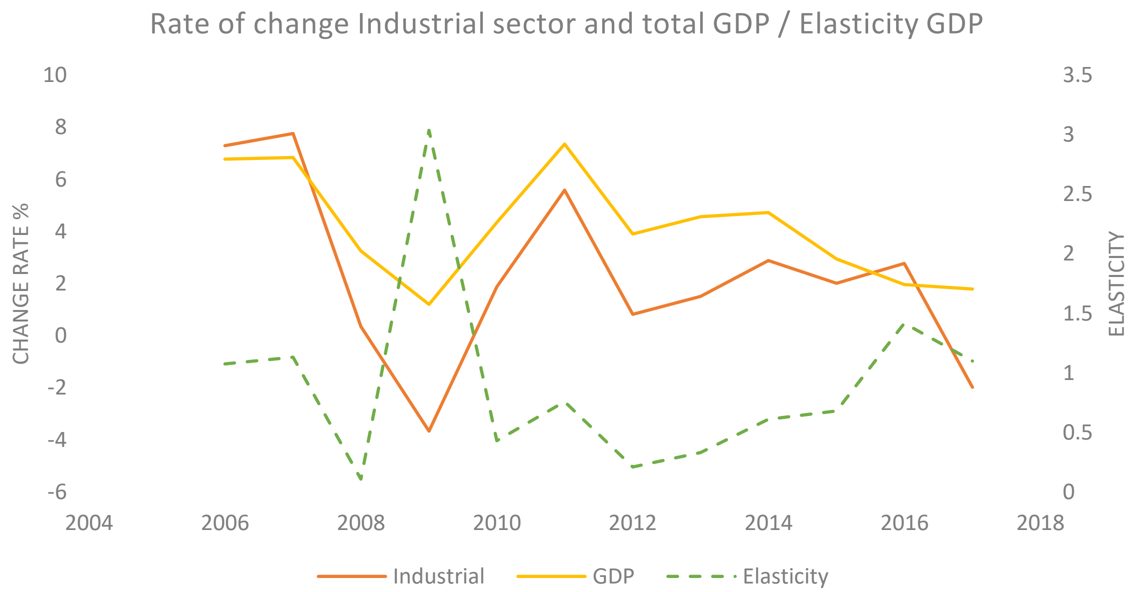


Figure 14Industrial Sector Economy Rate of Change

Commercial sector grows almost proportionally to the total GDP. It has a share of circa 9% on the total Colombian economy activity, and even if it's a low energy-intensive sector, its contributions are still of high value in future scenarios projections. Below it is shown its elasticity and its change rate for the past ten years. This sector is closer than industrial one to the total GDP change rate shape.

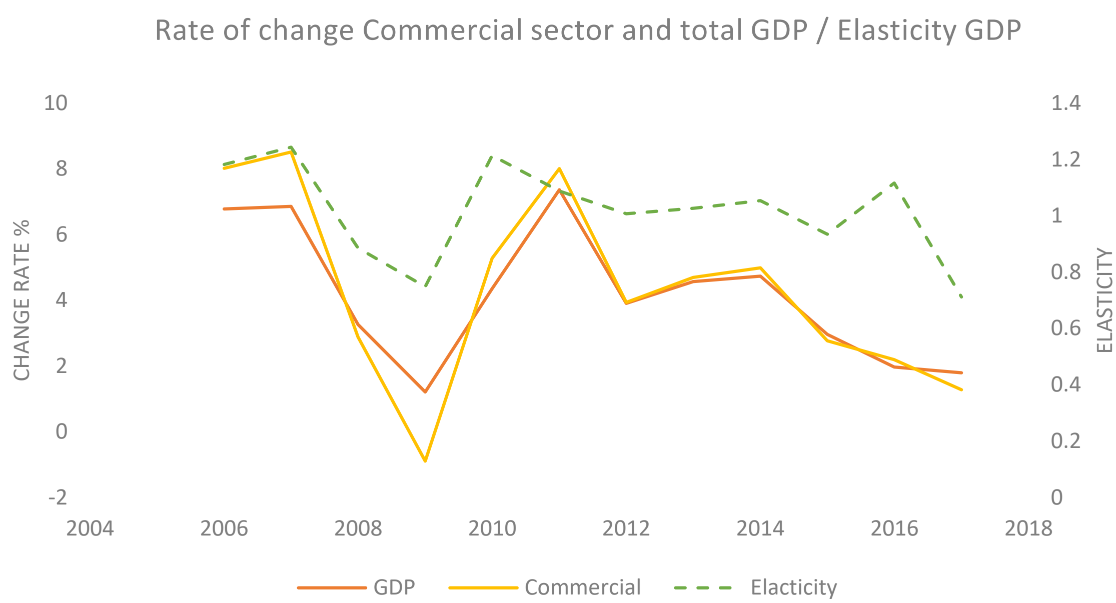


Figure 15 Commercial Sector Economy Rate of Change

The last of the economic sectors which demand drivers are based on GDP projection is the transportation one. Its contribution to total emissions and its energy consumption are the

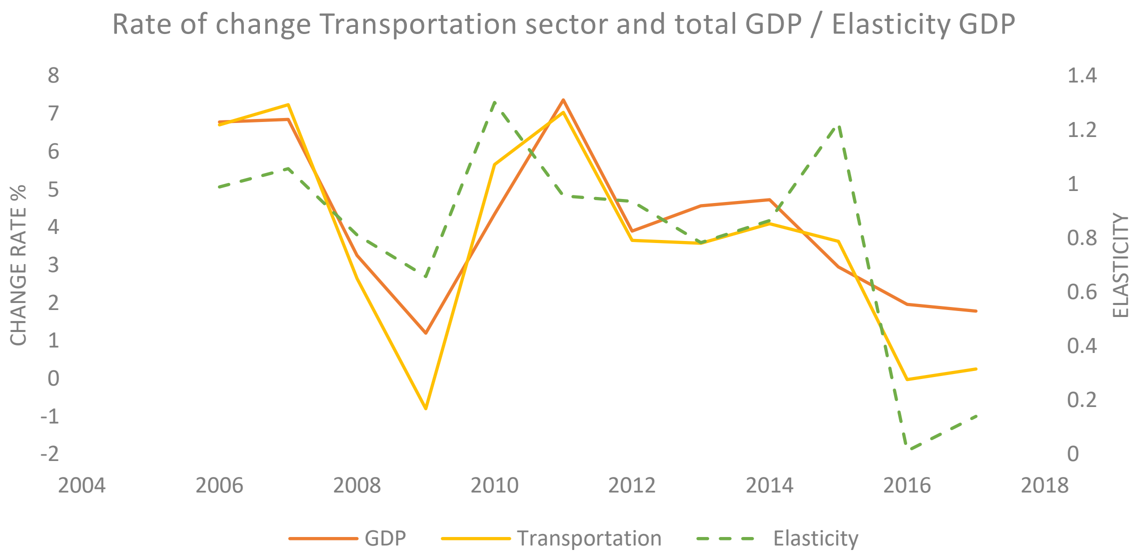


Figure 16 Transportation Sector Economy Rate of Change

largest compared to the commercial and industrial sectors, which makes any demand change to have a large impact in the whole energy system. The change rate of this sector does not follow the shape of the total GDP as acute as commercial sector does, but its behavior still does follow the general Colombian development.

As a result of the elasticity analysis it is possible to relate the data already available, which is the OECD GDP projection, with the economy of each single sector. Table 2. shows the average elasticity value, this value is used to calculate the growth rate of each sector in the time horizon of MARKAL, which is from year 2020 to year 2050.

Table 2 Sectors Elasticity with respect to Total GDP

Sector	*Elasticity*
Industrial	0.676
Commercial	1.042
Transportation	0.823

Residential Sector growth forecast is not related to GDP, but to population projections. The United Nations published on 2017 the last of their population estimates and projections, which is called "World Population Prospects 2017" [23]. These projections have been made by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, and their methodology is as taken from UN Webpage: "The method takes into account the past experience of each country, while also reflecting uncertainty about future changes based on the past experience of other countries under similar condition".

The median of the UN projections for Colombian population foresees a decrease in population starting around year 2040, as shown in Figure 17. The same phenomena is foreseen for South-America and Europe, which population starts decreasing by the mid of the century. North America and Northern Europe have a constant growth, according to UN projections their growth rate has no negative values along this century.

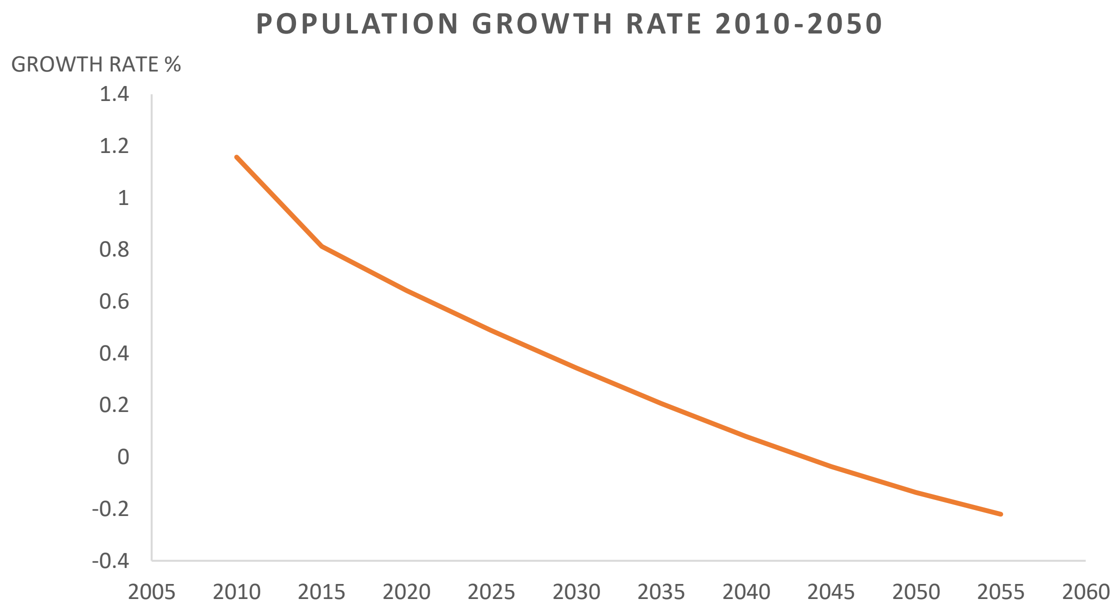


Figure 17 Population Growth Rate 2010-2050

Above shown elasticity and growth rates lead to a proper projection of demands for MARKAL model. The latter together with historic data (years 2010 and 2015) are taken as base to assess the forecast of drivers.

4.1.2 Energy End-Use demands

Petajoules is the energy unit by default on MARKAL, it is not as common as GWh or as toe (Tone of oil equivalent). Industrial, commercial and residential sectors demands are measured in Petajoules per year, on the other hand transportation sector is measured in billions of kilometers per year.

Having as base the end-use energy consumption in year 2010 and in year 2015 plus elasticity and growth rate, it is possible to calculate the projected demands, which are also the drivers of MARKAL. Business as usual (BAU) MARKAL scenario has as inputs the demands showed in Figure 18, Figure 19, Figure 20 and Figure 21, for the Industrial, Commercial, Residential and Transportation sectors, respectively, which are based on the OECD and UN data bases for GDP projection and Population projection, correspondingly. The value equivalent to points at years 2010 and 2015 are historic values, they do not belong to the projections part, but they are taken from the studies made by UPME in the past years [8], as mentioned in previous sections, and hence these values are accurate with respect to the real situation going on in the Colombian energy system

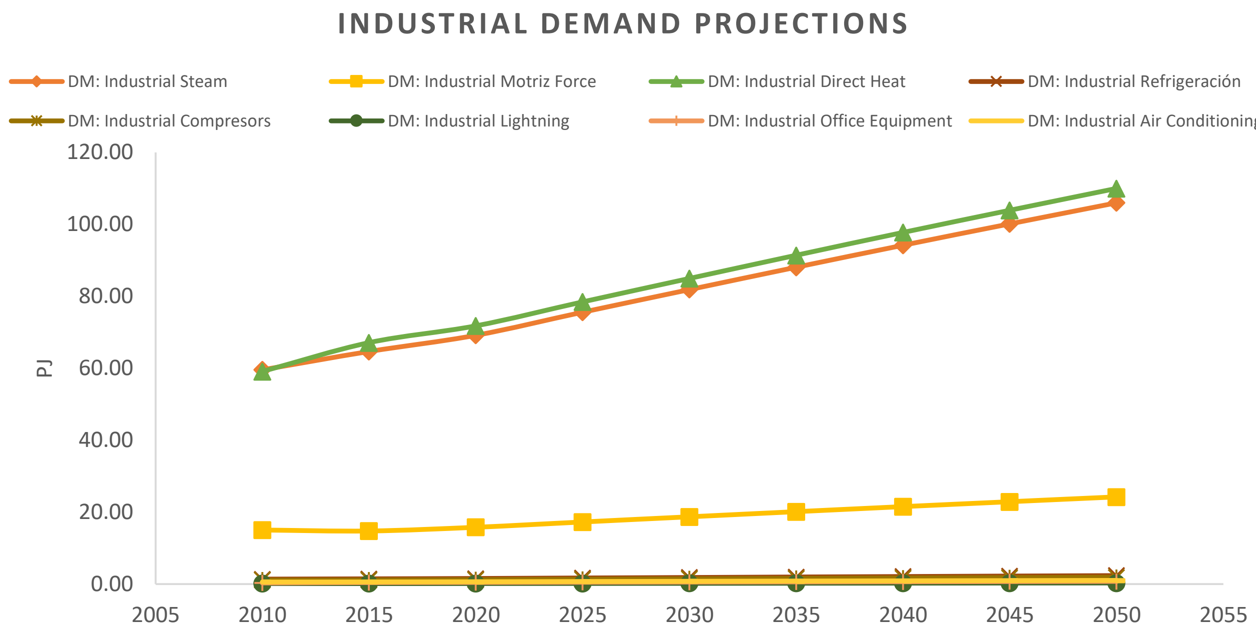


Figure 18 Industrial Demand Projections 2010-2015

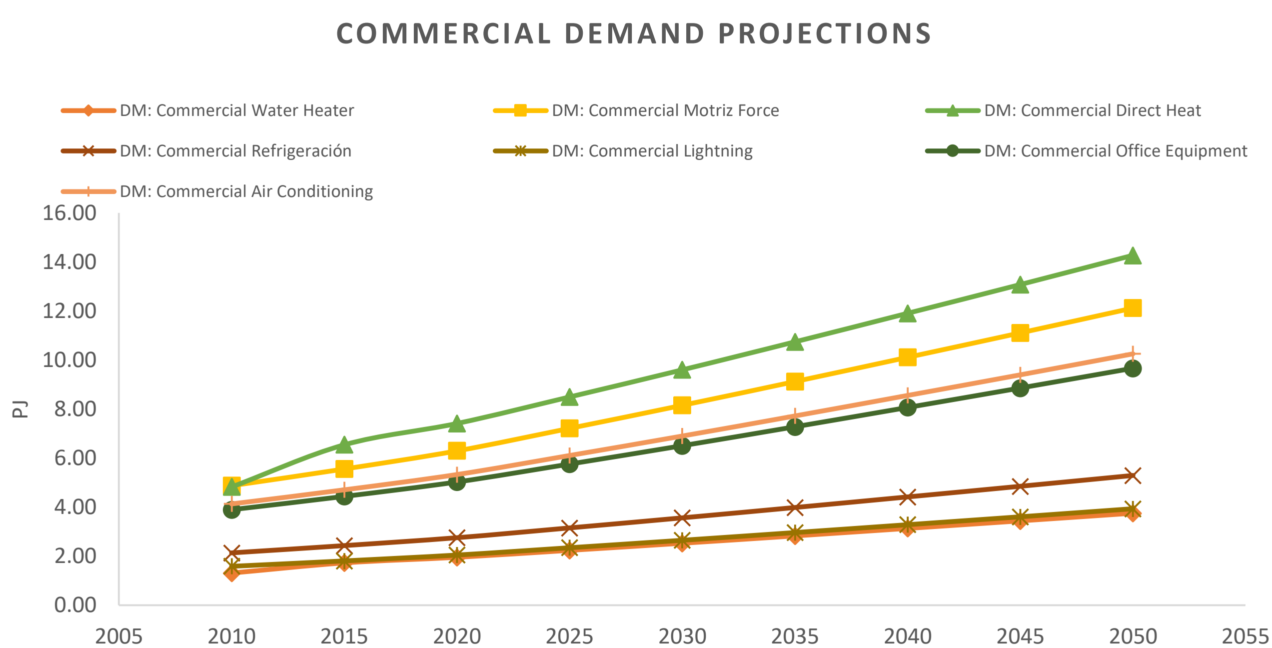


Figure 19 Commercial Demand Projections 2010-2050

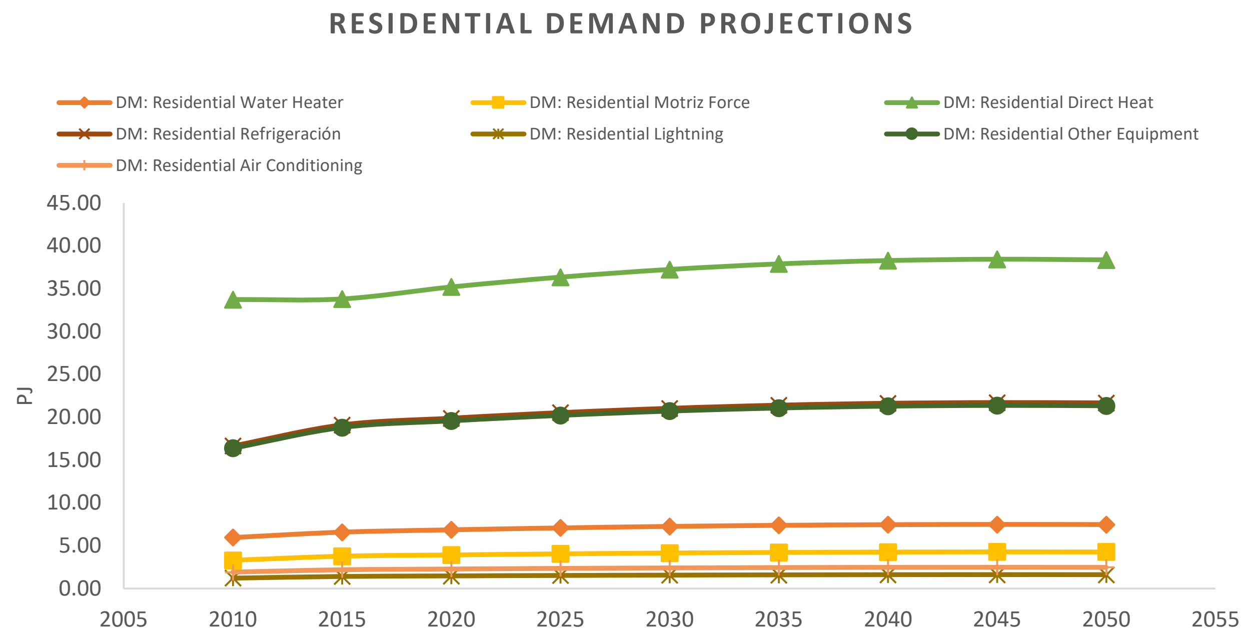


Figure 20 Residential Demand Projections 2010-2050

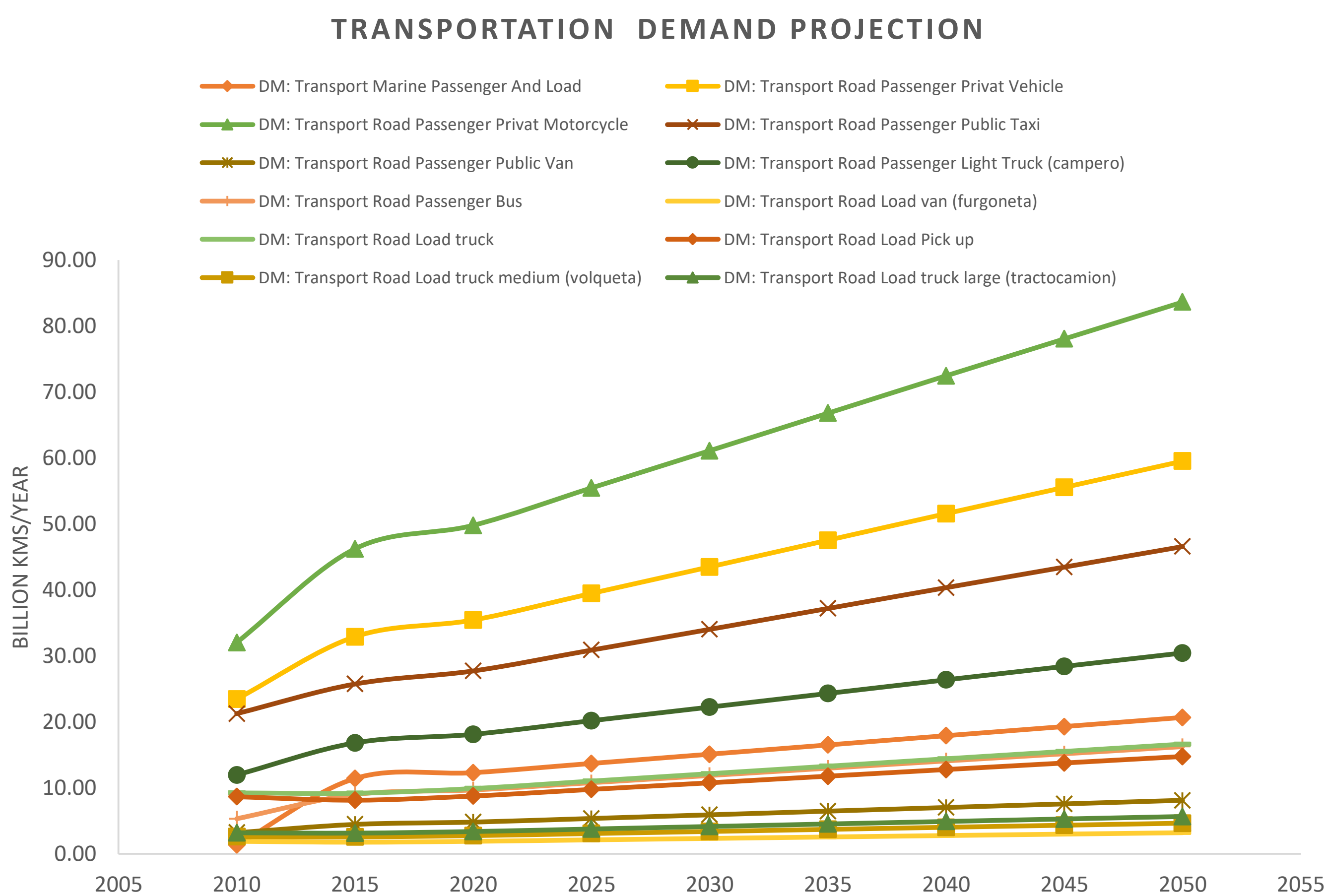


Figure 21 Transportation Demand Projection

As a last part of this section, it is shown in Figure 22 the growth rate for each sector demand. This is the base growth rate for the BAU scenario. As part of the analysis carried out in this thesis, variations of this growth rates will be assessed and compared among themselves. Variation such as ±10%, 30%, and 50% regarding the base complement the spectrum/range of the outputs of the model.

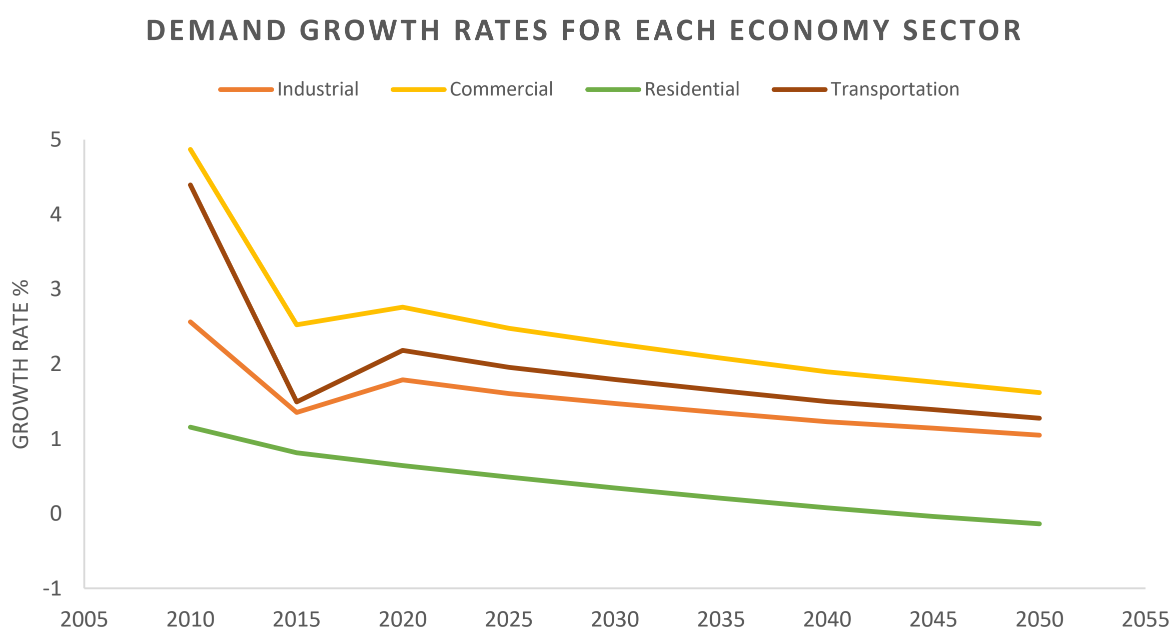


Figure 22 Demand Growth rates for each economy sector in Colombia 2010-2050

4.2 End-Use Technologies Efficiency

The energy system is made by different technologies that link the energy sources with the end-use demands. As an example, a technology is in charge of extracting the coal of a mine, another technology uses that coal to produce electricity and then an end-use technology uses that electricity to supply the residential lightning demand in a certain year.

As in every single conversion process, in the MARKAL energy system there are losses related to each technology. These losses depend on the exogenous efficiency set by the user. For this section it is taken as reference the study made by UPME [24], which is still under revision but a first copy was provided by the UPME administration department after being requested. This study includes the average efficiency of all the appliances related to final use of energy, from light bulbs to industrial boilers.

A summary of these efficiencies are shown in Table 3, Table 4, and Table 5 for Industrial, Commercial and Residential sector, respectively. As it is presented, there is an efficiency value by technology and by energy carrier (fuel).

Table 3 Industrial Energy End-Use Technologies Efficiency

Industrial Energy End-Use Technology	*Efficiency*
Industrial Steam Biomass	0.4100
Industrial Steam Petroleum	0.7600
Industrial Steam Carbon Mineral	0.6500
Industrial Steam Fuel Oil	0.5300
Industrial Steam Diesel Oil	0.5300
Industrial Steam Electricity	0.6900
Industrial Steam Kerosene	0.5300
Industrial Steam Liquified Petroleum Gas	0.6300
Industrial Steam Natural Gas	0.6900
Industrial Motriz Force Diesel Oil	0.4400
Industrial Motriz Force Fuel Oil	0.4000
Industrial Motriz Force Electricity	0.6300
Industrial Direct Heat Petroleum	0.4500
Industrial Direct Heat Carbon Mineral	0.4100
Industrial Direct Heat Fuel Oil	0.5900
Industrial Direct Heat Diesel Oil	0.6500
Industrial Direct Heat Liquified Petroleum Gas	0.6300
Industrial Direct Heat Electricity	0.7400
Industrial Direct Heat Natural Gas	0.6300
Ind. Other Electric Devices-ELC	0.6900
Ind. Other Processes - Fuel Share	1.0000
Industrial - Construction Fuel Share 1	0.9000
Industrial Lightning Electricity	0.1100
Industrial Lightning Electronic Bulb-ELC	0.0900
Industrial Lightning Fluorescent Bulb-ELC	0.1000
Industrial Lightning Incandescent Bulb-ELC	0.0200
Industrial Office Equipment Electricity	0.6900
Industrial Refrigeration Electricity	0.6900
Industrial Air Conditioning	0.6900
Industrial Compressors Electricity	0.6900

Table 4 Commercial Energy End-Use Technologies Efficiency

Commercial Energy End-Use Technology	*Efficiency*
Commercial Direct Heat Carbon Organic	0.5000
Commercial Direct Heat Electricity	0.9000
Commercial Direct Heat Liquified Petroleu Gas	0.4000
Commercial Direct Heat Natural Gas	0.4000
Commercial Lightning Electronic Bulb-ELC	0.1200
Commercial Lightning Fluorescent Bulb-ELC	0.1000
Commercial Lightning Incandescent Bulb-ELC	0.0200
Commercial Motriz Force Electricity	0.8500

Commercial Office Equipment Electricity	0.9500
Commercial Refrigeration Electricity	0.3300
Commercial Water Heater Electricity	0.9500
Commercial Water Heater LPG	0.8000
Commercial Water Heater Natural Gas	0.8000
Commercial Air Conditioning Electricity	0.3900

Table 5 Residential Energy End-Use Technologies Efficiency

Residential Energy End-Use Technology	*Efficiency*
Residential Direct Heat Carbon Organic	0.5000
Residential Direct Heat Electricity	0.8000
Residential Direct Heat LPG	0.3700
Residential Direct Heat Natural Gas	0.3500
Residential Direct Heat Wood	0.1000
Residential Lightning Electronic Bulb-ELC	0.0900
Residential Lightning Fluorescent Bulb-ELC	0.1000
Residential Lightning Incandescent Bulb-ELC	0.0200
Residential Other Equipment Electricity	0.9500
Residential Motriz Force Electricity	0.7500
Residential Refrigeration Electricity	0.6000
Residential Air Conditioning Electricity	0.5000
Residential Water Heater Electricity	0.9500
Residential Water Heater LPG	0.8000
Residential Water Heater Natutal Gas	0.8000

Regarding the transportation sector, as the energy demand is given in billion kilometers per year, it is necessary to use the vehicle average fuel efficiencies reported for the vehicle fleet in Colombia [21]. The Department of Transport has available for the public a series of reports and studies with historic data of Colombian vehicle fleet [21] [19]. A study about the kilometers per gallon of fuel is used as base of calculation for the MARKAL efficiencies inputs. Table 6 shows how many billion kilometers are covered by each vehicle type, when they consume one Petajoule of each energy carrier (fossil fuel). The previous mentioned study does not include electric vehicles, since its use share in Colombia is negligible, nevertheless, for projections of future years and scenarios with a larger use share of electric vehicles, it is taken a value of efficiency of 16,5kW/100 km is taken.

Table 6 Vehicles Efficiency by Fuel Type

Vehicle Type	*Fuel*	*Billion Kilometers / Petajoule*
Transport Road Passenger Private Vehicle	Gasoline	0.3214

Transport Road Passenger Private Vehicle	Diesel Oil	0.2879
Transport Road Passenger Private Vehicle	Natural Gas Comp.	1.1979
Transport Road Passenger Private Vehicle	Biodiesel 10%	0.3152
Transport Road Passenger Private Vehicle	Bioethanol 10%	0.3749
Transport Road Passenger Private Motorcycle	Gasoline	0.9965
Transport Road Passenger Public Taxi	Gasoline	0.3214
Transport Road Passenger Public Taxi	Bioethanol 10%	0.3749
Transport Road Passenger Public Taxi	Diesel Oil	0.2879
Transport Road Passenger Public Taxi	Natural Gas Comp.	1.1979
Transport Road Passenger Public Van	Gasoline	0.2813
Transport Road Passenger Public Van	Diesel Oil	0.2519
Transport Road Passenger Public Van	Natural Gas Comp.	1.0481
Transport Road Passenger Light Truck	Gasoline	0.2813
Transport Road Passenger Light Truck	Diesel Oil	0.2519
Transport Road Passenger Light Truck	Natural Gas Comp.	1.0481
Transport Road Passenger Bus	Diesel Oil	0.1295
Transport Road Passenger Bus	Natural Gas Comp.	0.5390
Transport Road Load van	Gasoline	0.2813
Transport Road Load van	Diesel Oil	0.2519
Transport Road Load van	Natural Gas Comp.	1.0481
Transport Road Load truck	Gasoline	0.1607
Transport Road Load truck	Diesel Oil	0.1799
Transport Road Load truck	Natural Gas Comp.	0.7487
Transport Road Load Pick up	Gasoline	0.2813
Transport Road Load Pick up	Diesel Oil	0.2519

Transport Road Load Pick up	Natural Gas Comp.	1.0481
Transport Road Load truck medium	Diesel Oil	0.1439
Transport Road Load truck medium	Natural Gas Comp.	0.5989
Transport Road Load truck large	Diesel Oil	0.0864

4.2.1 Technologies CAPEX [25] [26] [27] [28]

Cost of investment in new technology affect the model decisions, after calculating the present value of CAPEX and OPEX of each technology by energy unit, it is possible to optimize in a cost effective way the combination of technologies which will supply be linked together until end-use demands are fully covered. Following table shows the capital cost of each end-use technology. Also the Operation Cost of some technologies that are included in the model (such as boilers) are shown.

Table 7 CAPEX of End-use Demand Technologies

Technology	*Energy carrier*	*MUSD/PJ*
Aire Acondicionado ELC	Electricity	4.6663
DH Stove ELC	Electricity	0.9383
DH Stove NG	Natural Gas	1.2516
DH Stove LPG	LPG	1.3377
Lightning electronic	Electricity	1.8328
Lightning fluorescent	Electricity	0.5610
Lightning incandezcent	Electricity	0.2040
Motrix Force ELC	Electricity	11.1286
Commercial Office Equipment	Electricity	52.6850
Commercial Refrigeration	Electricity	6.9934
Commercial Water Heater ELC	Electricity	13.1288
commercial water heater NGA	Natural Gas	1.2600
commercial water heater LPG	LPG	1.5748
Motriz Force ELC	Electricity	2.8270
Motriz Force dso	Diesel Oil	3.2000
Motriz Force FO	Fuel Oild	3.4000
Steam Capital Coal/Biomass libras/kW 2010	Bagaze	2.5952
Steam O&M Coal/Biomass libras/kW 2010	Bagaze	0.1301
Steam Capital Coal/Biomass libras/kW 2020	Bagaze	2.1543
Steam O&M Coal/Biomass libras/kW 2020	Bagaze	0.1301

Steam Capital gas libras/kW 2010	Natural Gas	0.3398
Steam O&M gas libras/kW 2010	Natural Gas	0.1229
Steam Capital electric libras/kW 2010	Electricity	1.0916
Steam Capital oil fired million libras/TW 2010	Diesel Oil	0.2675
Steam O&M oil fired million libras/TW 2010	Diesel Oil	0.0217

4.2.2 Power Generation Technologies

Colombian government department in charge of electrical production has available for the public in detail the cost of new capacity of power generation technologies. A large spectrum of technologies that can be installed in Colombia are included. In order to do a more accurate analysis of the possible combination of generation technologies, all of the technologies, which are considered possible by the Colombian government, are included in the current MARKAL model. Below it is shown each technology, and some deatails such as capacity, capital cost, fixed annual cost and variable annual cost. The final combination of power generation technologies resulting at the end of the run of all scenarios is shown in the Results section.

Generation Technology	*Capacity MW*	*CAPEX MUSD/GW*	*FIXOM MUSD/GW-AÑO*	*VAROM MUSD/PJ*	*Plant factor*
Photovoltaic	20	3801.71	65.87		0.1642
Photovoltaic	85	2718.81	56.78		0.1642
Photovoltaic	150	2566.8	55.11		0.1642
Wind	10	7,965,265.10	78,886.43		0.1153
Wind	50	3,610,593.61	59,749.68		0.124
Wind	100	3,018,039.39	56,053.07		0.1268
Coal Thermoelectric	70	1,269.18	77.06	2.02	0.4382
Coal Thermoelectric	150	1,179.86	75.78	2.02	0.4382
Biomasa Bagazo	10	2,909.84	189.98	1.17	0.4171
Biomasa Bagazo	40	1,925.20	133.85	1.17	0.4171
Combined Cycle Natural Gas	200	1,495.65	43.89	0.91	0.5829
Combined Cycle Natural Gas	500	1,363.52	42.4	0.91	0.5829
Natura Gas Thermoelectric	10	2,185.86	51,201.23	3.76	0.5829
Natura Gas Thermoelectric	100	1,245.49	33,948.80	3.76	0.5829
Natura Gas Thermoelectric	1000	1,064.30	31,352.03	3.76	0.5829
Hydroelectric with reservoir	600	2,272.61	33.82		0.7
Hydroelectric with reservoir	1500	1,679.94	33.95		0.7
Hydroelectric with reservoir	3000	1,376.85	35.13		0.7

Small Hydroelectric	10	2,608.32	83.95	0.78
Small Hydroelectric	50	1,801.53	71.36	0.78
Geothermal flash	30	7,478.57	163.54	0.4027
Geothermal flash	100	6,993.32	157.96	0.4027
Thermosolar	50	8,475.48	151.06	0.3663
Thermosolar	200	8,022.81	143.72	0.3663
Photovoltaic small	0.01	2,404.35	370.01	0.1075
Photovoltaic Small	0.05	2,372.12	340	0.1075
Photovoltaic Small	0.1	2,227.73	285	0.1075
MiniHydro	0.5	985.19	145.9	0.0156
MicroHydro	0.04	2,563.53	485.03	0.2736

4.2.3 Fossil Fuels reservoirs

Resources are not unlimited, and that fact plays a primary roll when doing projections in a long term time horizon. Coal is the most abundant fossil fuel in Colombia, followed by Petroleum and Natural Gas. There are two big reservoirs of coal in Colombia, one situated in the Atlantic coast, and other in the center of the country [14]. Same for Natural gas, Atlantic coast and center “Los Llanos” part of Colombia has the largest reservoirs of Natural Gas in the country [29]. Figure 23 shows the quantity of each fossil fuel expected to be available in each reservoir, in energy units (Perajoules)

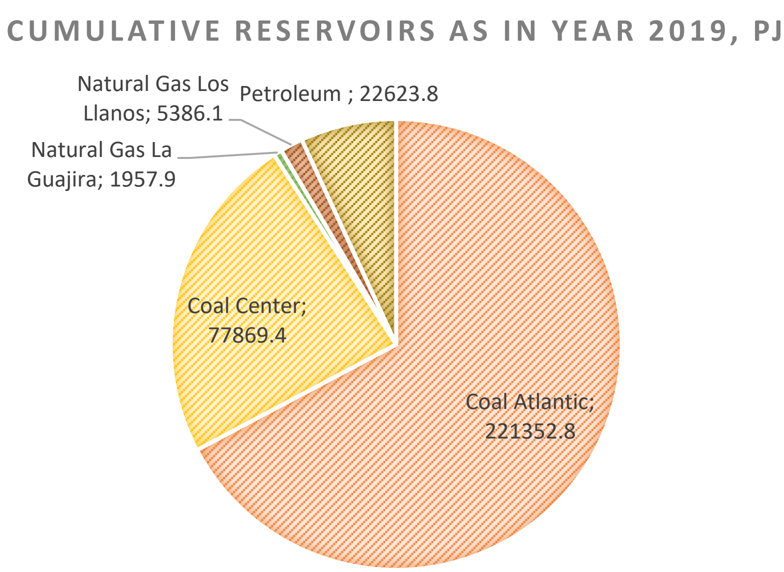


Figure 23 Cumulative Reservoirs as in Year 2019, Petajoules

4.3 Alternative scenarios to BAU

- In the scope of this analysis the demand drivers are taken in a range of ±10%, ±30% and ± 50% of what is originally projected by OECD and the United Nations for GDP and Population Growth, respectively. These variations from the original projected demands could represent the savings/extra expenses, which could affect Colombian economy/population in the long term, as the ones mentioned in chapter 2.

  As a total, there is a combination of 36 scenarios. These 36 scenarios are the result of six different demand drivers that depend on GDP, which are the industrial, commercial and transportation ones, and of six different demand drivers that depend on population growth, which is the population one.

  A run of each of the above-mentioned 36 scenarios is made maintaining the remaining inputs constant, as the business as usual scenario; therefore, the main difference among these runs in the time horizon will be the final demand. As main goal from the latter, it is to assess how emissions and power generation plants share behave (how much power is generated from the different energy sources such as hydro, natural gas, biomass, etc.) under unexpected growing rates in the country. Furthermore, it is expected to assess which parameter between the economic and the population one has a larger weight on the total Colombian emissions and energy demand.

- As alternative scenario it is taken a definitive rise in the average temperature of Colombia which will lower the water reservoirs level, making the hydropower generation availability o have the same behavior as El Niño Phenomena years, it means, lower than 20% for some hydropower plants, as shown in Table 1. All above-mentioned 36 scenarios resulting from the combination of different demand drivers are run under this low Hydro availability condition. This exogenous condition for Hydro power plants forces the model to invest in diverse kinds of power generation plants, beside hydro plants.

- As a last overall set of scenarios, it is considered low hydro availability plus emissions cap plus net electricity imports equal to zero. Emissions cap might be a possible imposed solution in the long term due to the compromise the countries have to contribute to stop rising the temperature. The emission cap is set to be the 80% of the emissions expected from year 2030 in the BAU scenario. Just to make sure the power generation system complies with the emission cap, the imports of electricity are set to zero, because the energy source of the electricity imported is unknown, it could come from natural gas or coal fueled power plants placed either in Ecuador or in Venezuela. The only data available for imported electricity as input is the cost per Petajoules.

5 RESULTS AND ANALYSIS

All the above data mentioned in Section 4. is used as Business as Usual scenario. CAPEX, OPEX, Efficiencies and all values that do not correspond to Demands are kept as constant, at least there is indicated something else.

For alternative scenarios, demand values are evaluated in a range of ±10%, ±30% and ± 50% of GDP growth and Population Growth: all of the latter are variations of the BAU case. Nevertheless, there has not been any change besides the Demand Projection, i.e. no change on water reservoirs availability or emissions cap.

As a second set of alternative scenarios, there is the assessment of a future with low water level reservoirs, which means low hydroelectric power generation availability. The later could happen if average Colombian temperature keeps increasing and as it has been seen in the past, the hydroelectric power plants have in this case an availability lower than 20%. El Niño cyclic effect on Colombia Temperatures results also in low reservoirs levels, this phenomenon is expected at least every 5 years.

Another set of scenarios include a low Hydro availability plus an emission cap and Import of electricity set to be zero. Since the way in which the electric grid system in Colombia reacts to low Hydropower availability is by turning on thermoelectric power plants and by importing electricity, the latter increases the total emission levels hence it increases the country share on the worldwide emissions and hence it will contribute negatively to the already existing temperature rising issue. Moreover, the Imports of electricity starting on year 2025 is exogenously set to be equal to zero, because the main goal of this scenario is to reduce total emissions, and the primary energy from which imported electricity is produced is unknown for the model.

5.1 BAU Results

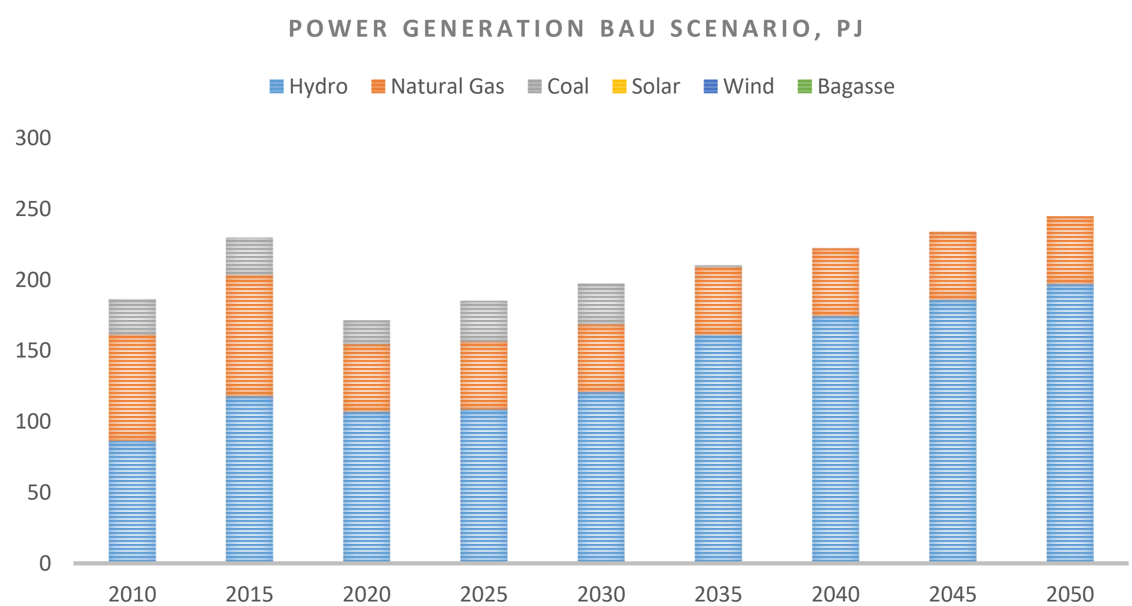
5.1.1 Power generation distribution

Economically speaking, the model itself results on an environmental friendly power generation system: in the time horizon the largest share corresponds always to hydro power generation. Natural gas and coal fueled power plants generated electricity decreases over time, but still no renewable source of energy has some relevancy on the power generation system. The lack of presence in photovoltaic fields, wind farms and even bagasse power generation, points out that none of this technology is economically competitive against the traditional ones, which is not something new to the people knowledge.

In BAU scenario, the model is not forced to invest in new capacity for renewable sources of electricity. Nevertheless, further in this analysis, alternative scenarios are proposed in which water availability has low levels and therefore, there should be found other ways to supply electricity demand in Colombia.

The model also complies with the fact that it is expected that coal is not going to be a main primary energy by year 2030, as many countries have already agreed [15]. No exogenous inputs are necessary for the model to show a time horizon with decreasing coal use, only with coal cost of production and prices projection it is enough for the model to lower its use in the future, since that is the cost effective result.

Electricity production on year 2020 seems to be slightly lower than the precedent years. The reason for this is that the model reacted to technology costs, and some of the demand that was covered by electricity on years 2010 and 2015 is covered starting on 2020 by other fuel sources (industrial direct heat and vapor production are now covered by natural gas, LPG and coal).



5.1.2 <u>Emissions results</u>

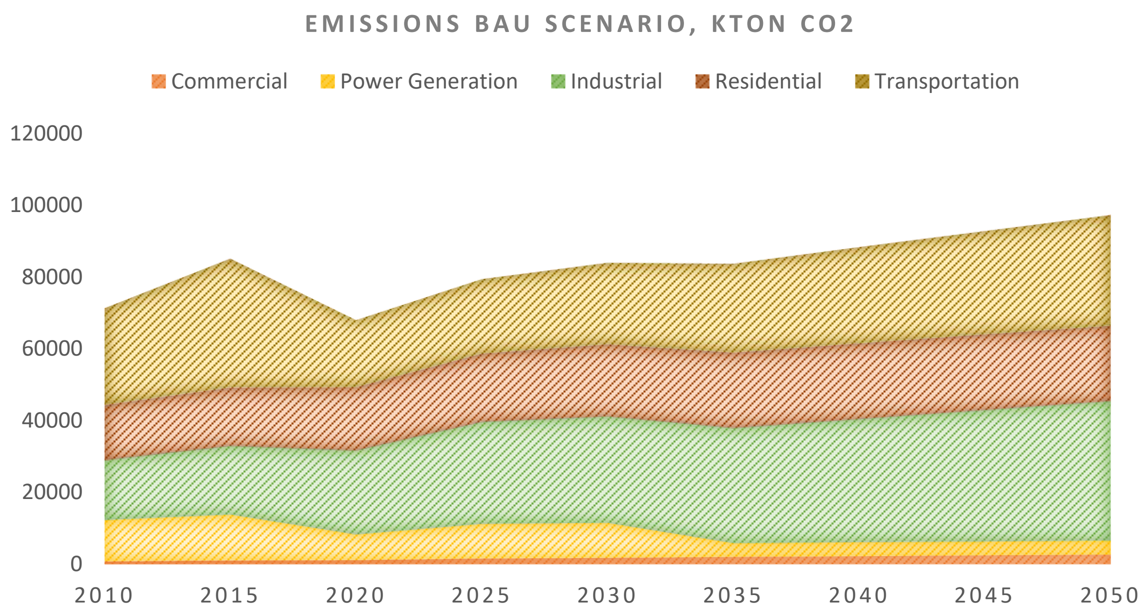
Starting from years 2010 and 2015, these are an example of how high temperatures affect the overall emissions level: as seen in the previous section, power generation system tends to increase its share on hydro power plants, this is why emissions are lower on year 2020 than on year 2015. Also, transportation demand starting on year 2020 tends to be supplied mainly by Natural Gas, hence emissions levels go lower due to the lower emission factor of natural gas in comparison to gasoline or diesel.

Emissions corresponding to residential activities keep a constant behavior in the long term. From the latter it is inferred that household might use less wood as fuel to cook and might start to use alternative technologies to cover cooking demand. The latter results in less respiratory diseases and less energy losses, since wood and the appliances that use it as heat source are not as efficient as the ones that use natural gas or electricity.

Emissions on years 2010 and 2015 comply with the ones reported on the National and Regional Greenhouse gases emission inventory [9] [2].

Industrial and transportation sector keep being the ones with the largest emissions share out of the five evaluated sectors. Which means that the cost effective solution to cover the energy demand in the considered time horizon does not choose technologies with higher efficiencies, this is why policies which incentive new appliances and/or taxes on emissions must be set by the government in order to reach the emissions target.

As a clarification point: laws might not be in Colombia as strong as they are in other parts of the world. The latter means, if a boiler or a vehicle fleet have to be changed after 20 years of use because its efficiency has decreased to a not allowed level, it could happen that from time to time, these regulations are ignored and people keep using the old appliances. As mentioned in chapter 2, 20% of the total Colombian vehicle fleet has more than 40 years on circulation. Then, even if the emissions showed below are the results from the cost effective optimization, the real behavior might tend to larger emission levels because people/companies do not want to invest in new vehicles/appliances.

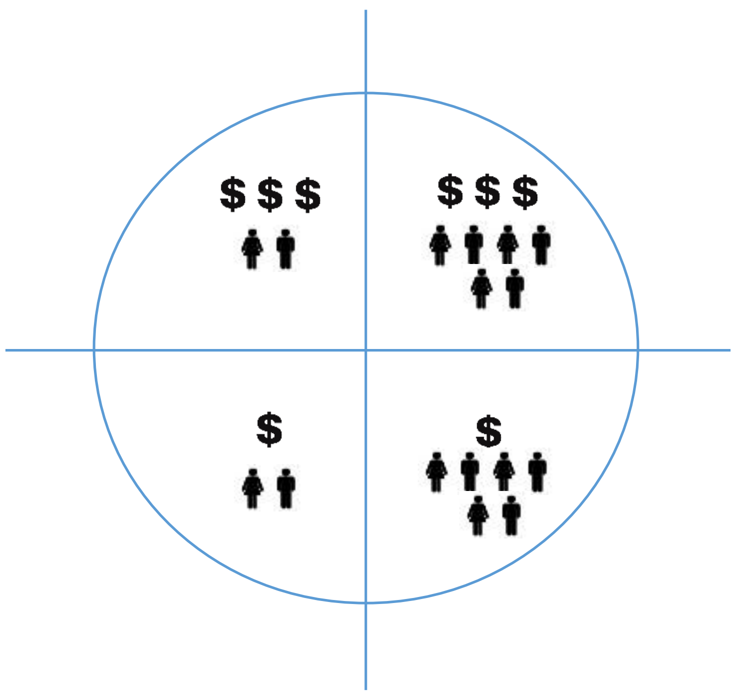


5.2 Alternative scenarios results

As mentioned in the input section of alternative scenarios in the previous chapter, there are in total 36 different combinations of scenarios resulting from the variation of the original demands drivers based on OECD and UN projections. These variations correspond to ±10%, ±30% and ±50% of the original projections. To represent such a high number of scenarios, which assess many variables itself, represents a challenge. Following it is explained how to read the figures representing the results of each set of scenarios.

First of all the kind of graph chosen is a radial one. From the center to the outer part there is a rise in the level of the variable, for example, if the graph represents the emissions level, near to the center are the results with the lower emissions and the further the results are from the center, the larger is the emissions level.

All 36 scenarios are represented in each graph. Projected population increases from left to right and GDP change rate grows from the bottom to the top.



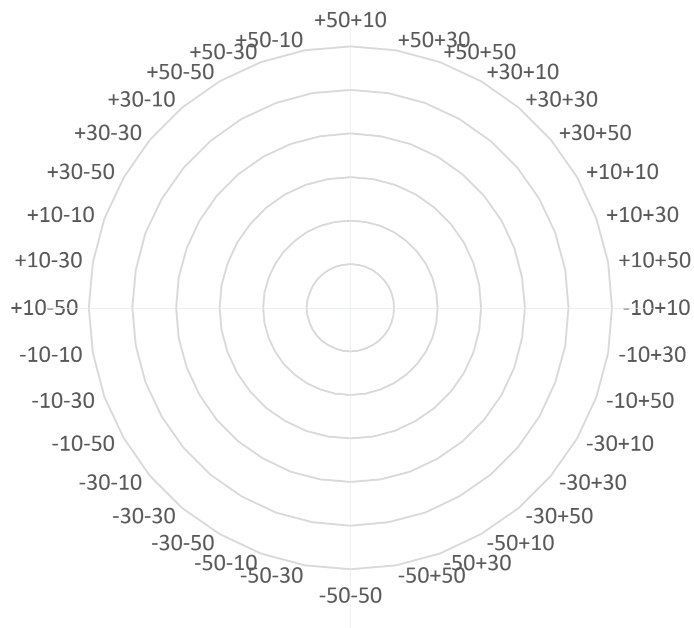


Figure 24 Distribution of alternative scenarios results in the radial figure

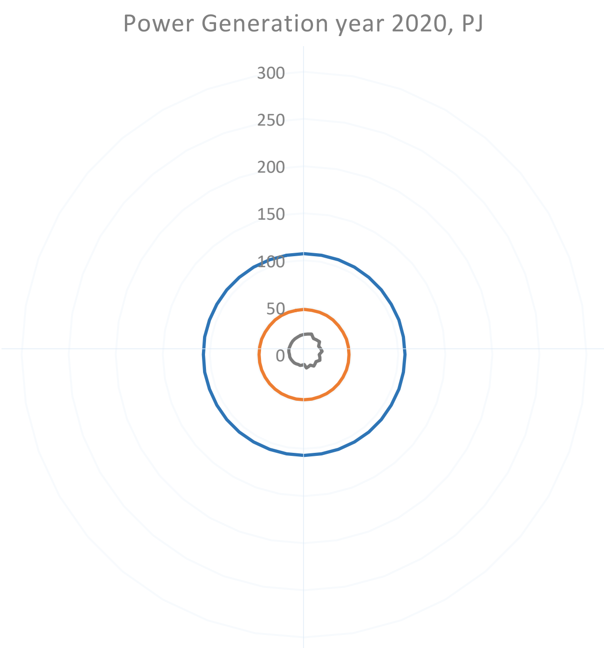
Figure 24 shows how the exact distribution of all 36 scenarios around the radial representation is. +50+10 represents a scenario in which there is a variation of +50% on GDP original change rate and +10% on population original projection, same for negative numbers.

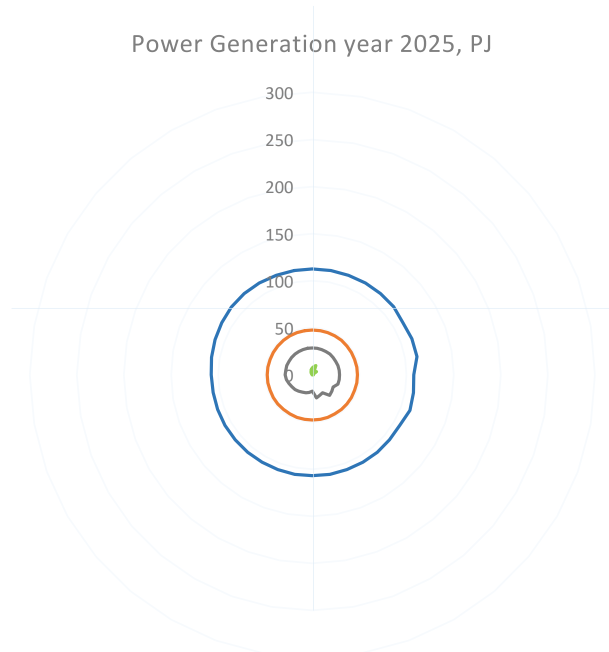
Such variations from the Business as Usual scenario are made to cover as many unexpected events as possible. Unexpected events, such as an economic crisis, which will decrease the change rate of the Gross Domestic Product. Or unexpected events, such as a good invest in new technologies which will decrease the pollution and hence some health problems, which will increase the GDP. It is good to clarify at this point that all of the latter is based on the OECD and UN projections of GDP and Population, respectively, therefore there is no guarantee that any of the results for the following years could be near to reality. Modelling scenarios is not a guessing science, but it could be appropriate for decision making on what kind of policies could be implemented in order to incentive and/or avoid specific circumstances. More on this is further covered on following results subsections.

5.2.1 *Power generation distribution in alternative scenarios*

The following set of figures represent from which source the electricity in Colombia comes from, each five years, starting on 2020. The units of each graph is Petajoules, and the level of each power source rises from the center to the outer part of the circle. Each color represent a source of Power. It goes as following: **HYDRO** power is **BLUE**, Thermoelectric fed with **NATURAL GAS** is **ORANGE**, Thermoelectric fed with **COAL** is **GRAY**, **SOLAR** photovoltaic is represented by **YELLOW** color, **WIND** power is represented by **PURPLE** color, **BAGASSE** power plant is **GREEN**, and **IMPORTS** are in **RED**.

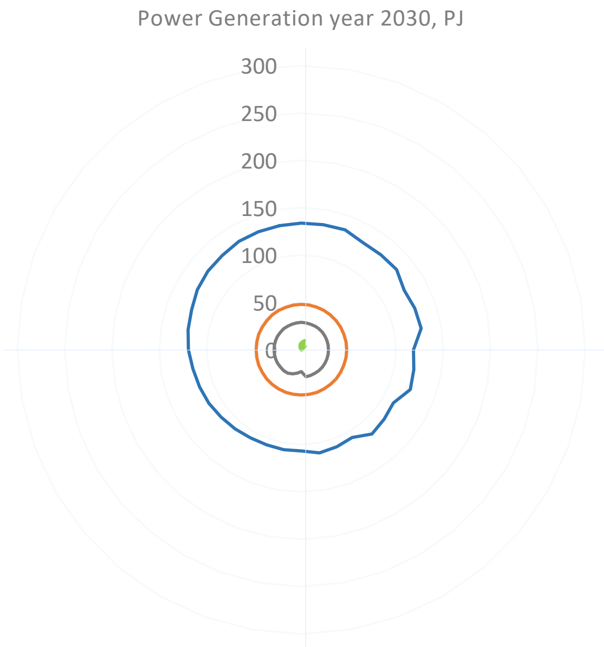
5.2.1.1 *Power generation distribution, keeping constant all inputs, but demands drivers*

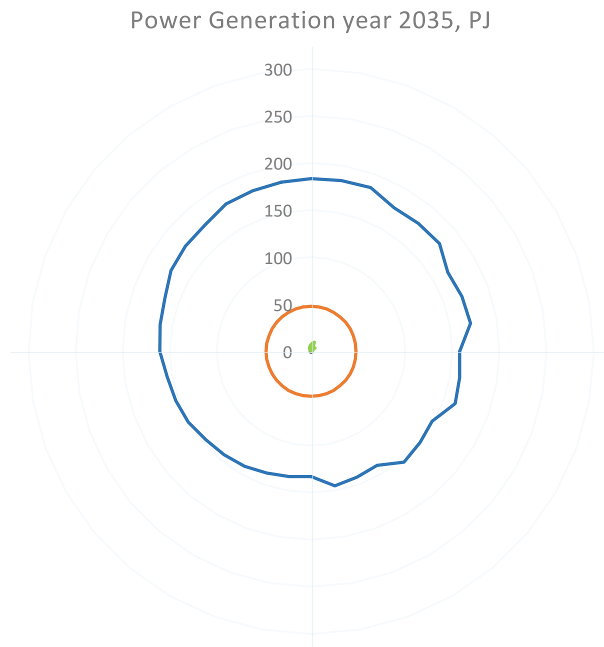




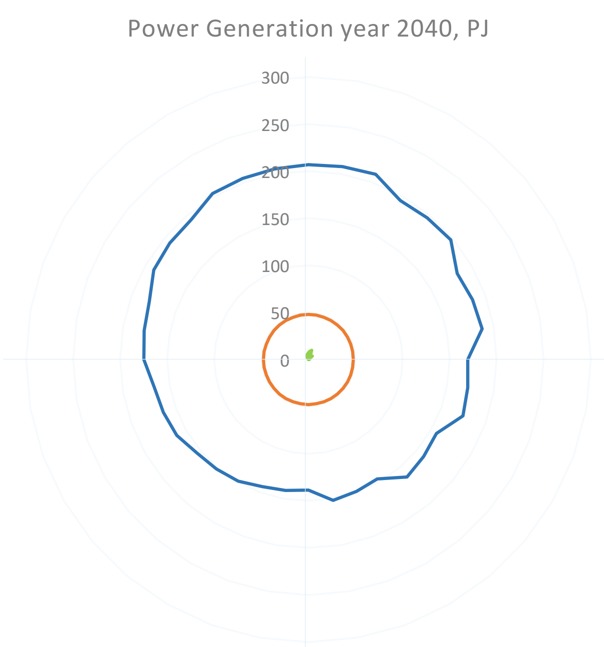
Years 2020 and 2025 have a similar behavior since hydro, natural gas and coal are the main sources for power plants in both of them. Some generation from bagasse is seen in year 2025, and it keeps being constant until year 2040. Then, some bagasse plants are installed to start working on year 2025 but they are not renew in the assessed time horizon, and as soon as they finish their lifetime (20 years) they stop their operation and no new capacity is apparently installed.

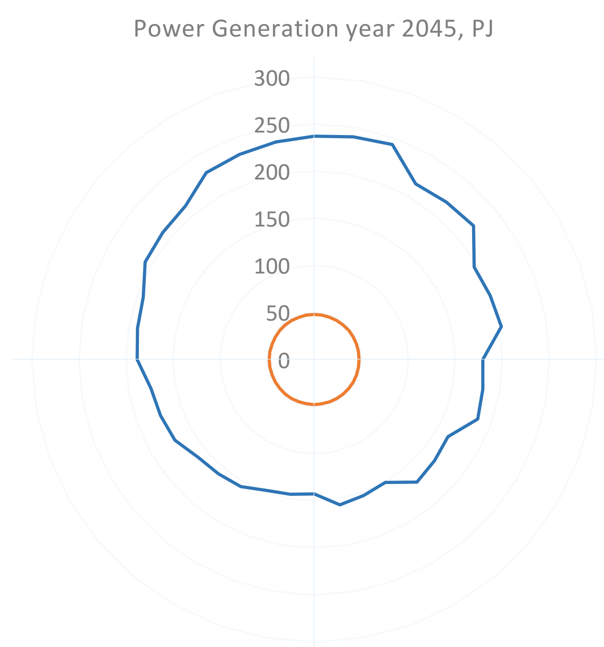
Also, in years 2020 and 2025 the four parts of the circle are homogeneous, which means that even the demand is different around the circle, the share of each power generation source is the same among scenarios. The latter changes starting on year 2035



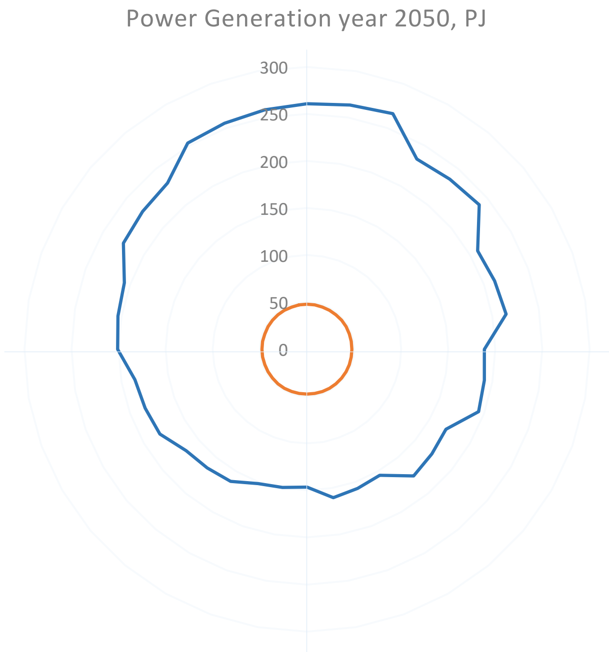


For years 2030 and 2035, it is visible how the circle stops being homogeneous and it seems to be growing on the upper part of the figure. On the other hand, left and right side of the circle does not seem to have different sizes. The latter means that GDP change rate has a bigger influence on the power generation levels than population growth. This behavior keeps increasing until year 2050. Most probably, if the time horizon would have been longer the same shape would have been observed.





Hydro power plants and natural gas thermoelectric plants are the ones which supply the most of electricity, starting on year 2035. Therefore, no matter what the demand is, the coal plants will stop being on operation after 2030. Instead, bagasse has some little participation on the gross power supply, but only for few years. If the time horizon would have been longer, possibly there would have been more investment on bagasse power plants and they would have been working at least until year 2050.

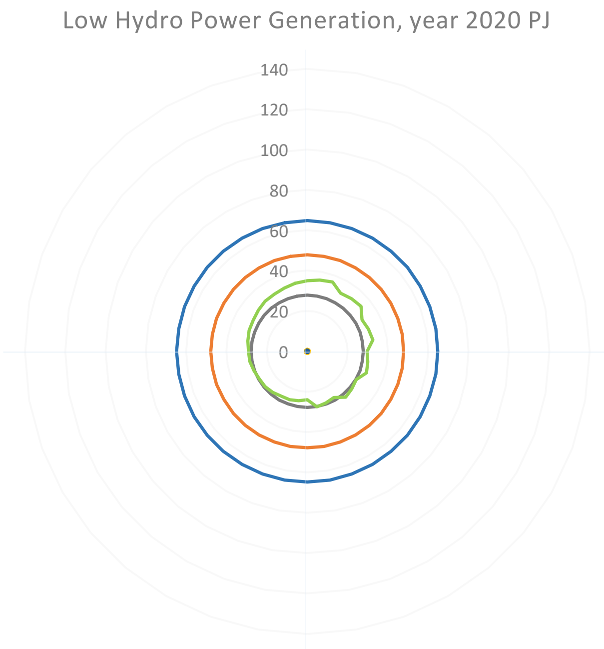


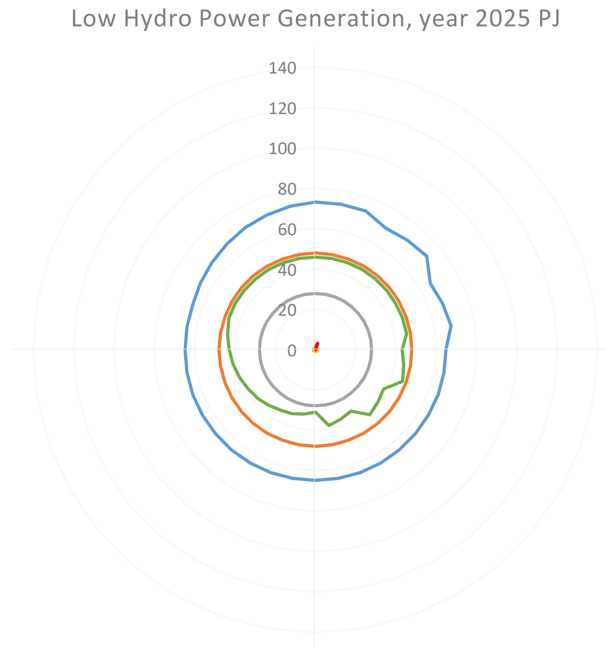
5.2.1.2 Low Hydro availability scenario

In a future with a low Hydro power generation availability it is clear that the Hydro share will decrease in comparison to previous scenarios.

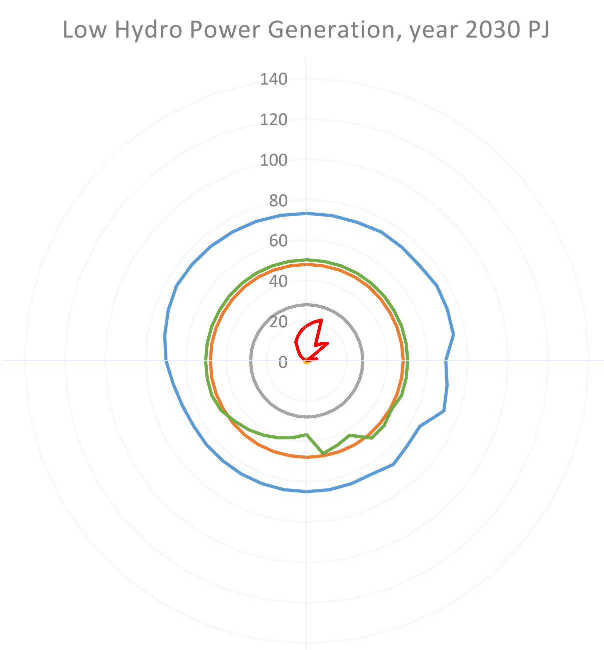
The four parts of the circle are less homogeneous in years 2020 and 2025 with respect to the last assessed set of scenarios. Bagasse fueled power plants start operating since year 2020, but in a less magnitude for scenarios where the change rate of GDP is low. Bagasse installations rise quickly and already in year 2025 it has a share larger than coal fired power plants in all scenarios, even for low change rate of GDP (lower side of the circle).

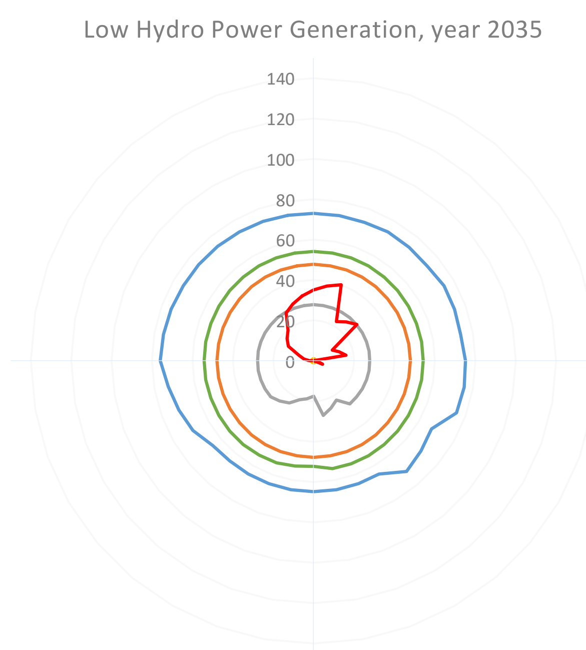
Already in year 2025 there is a smooth sight of electricity imports. Which means that in a low hydro availability scenario, the grid system has to be prepared to start transporting electricity coming from Ecuador and from Venezuela.

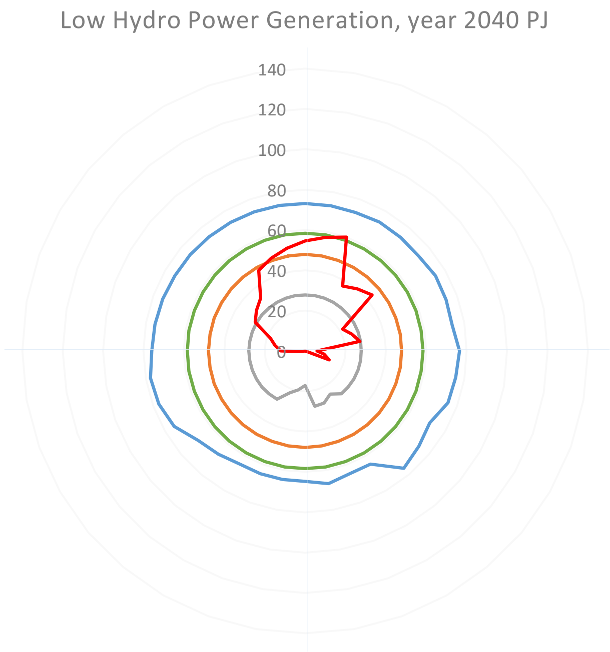


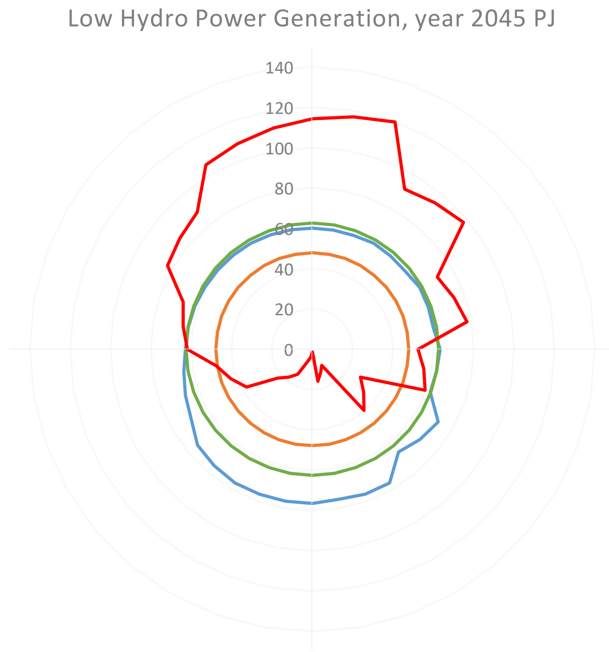


Bagasse power production keeps increasing during years 2030 and 2035, rising its share on the total electricity production to a level higher than Natural Gas fired power plants. On the other hand, coal fired power plants keep operating until year 2040, in contrast to the previous set of scenarios in which they stop operating earlier.









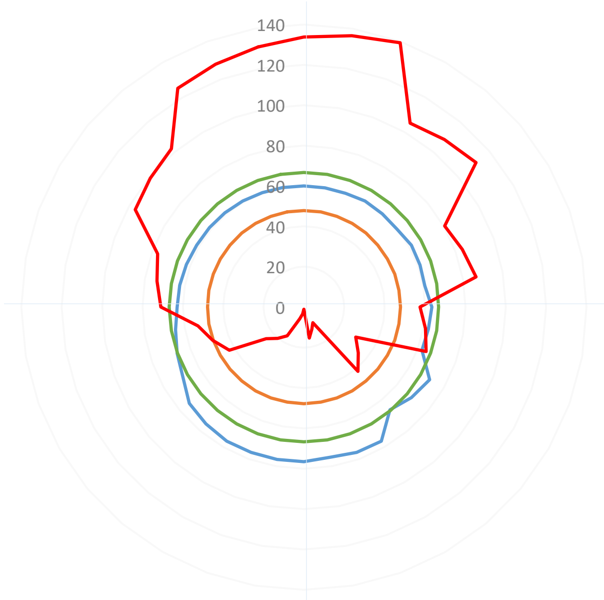
Electricity imports do not stop growing until the end of the time horizon. Apparently the cost effective solution consists on stop investing in generation technologies and start paying the electricity to other countries.

Year 2045 and 2050 shows something particular: Hydro power generation for the zone of low GDP has a larger share than bagasse fired power plants. Instead in the side of high GDP the proportion of Hydro to bagasse power plants is either equal or lower, in years 2045 and 2050, respectively. The Hydro power generation plants have the largest generation capacity share when the economic growth is not that big (lower side of the circle), nevertheless, the gap between bagasse in water for low GDP scenarios becomes shorter with time. It might be the possibility that in a longer time horizon, bagasse fired power plants will overpass the hydro power generation also in low GDP scenarios. The latter is because there is no more investment on Hydro power plants and it reaches its maximum in year 2045, bagasse fired power plants instead keep increasing on capacity even on year 2050.

Natural gas fired plants reach their maximum capacity since the beginning of the time horizon, there is no new investment on increasing the natural gas generation capacity over the years, and in this case, there is no difference among scenarios: the circle is homogenous in all four zones, for low and high GDP and population change rates.

The rise on electricity imports will make Colombian electric system to depend mostly on international affairs in case of a large changing rate on GDP, from any point of view, even when this might be the cost effective solution, it is not a suitable long-term solution.

Low Hydro Power Generation, year 2050 PJ



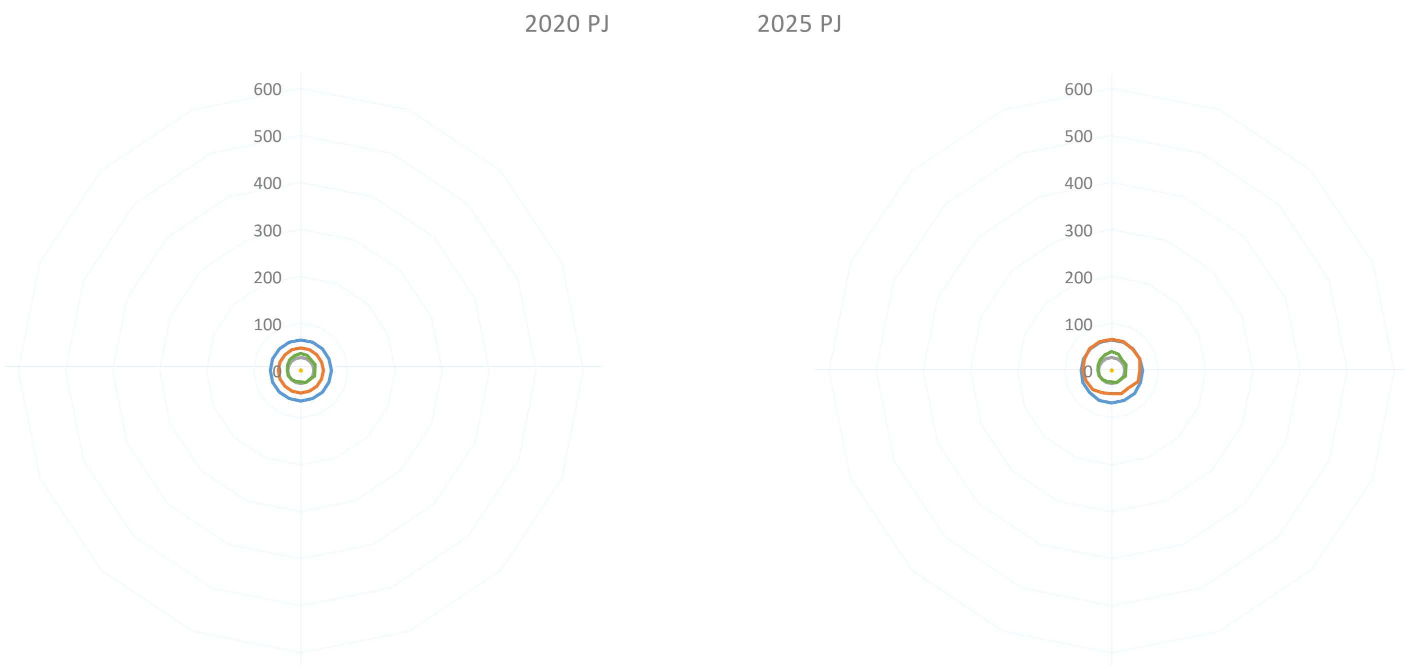
Knowing how the power generation matrix behaves under low hydro availability could help to understand better what could be incentivize from now on, in order to avoid results as the one showed in the last set of scenarios.

Importing electricity is not a suitable solution, also if one of the main points is to reduce emission levels, since it is not clearly known where the electricity in Ecuador and Venezuela comes from, and it is not considered in this model if they will count on 2050 with such a big capacity to cover extra Colombian demand.

Forcing the model to low Hydro scenarios brings to another key result: even in the far future (year 2050) there is not investment on solar or wind power generation. Since MARKAL is a cost effective model, the conclusion is that Solar and Wind power are not economically viable, it is even preferred to invest on new transmission grids and pay for electricity coming from foreign countries than to invest on wind farms and photovoltaic fields. Nevertheless, the latter is not a phenomenon only in Colombia, to invest in renewable energy sources is expensive and it needs incentives from the governmental side in order to get to be installed and operated.

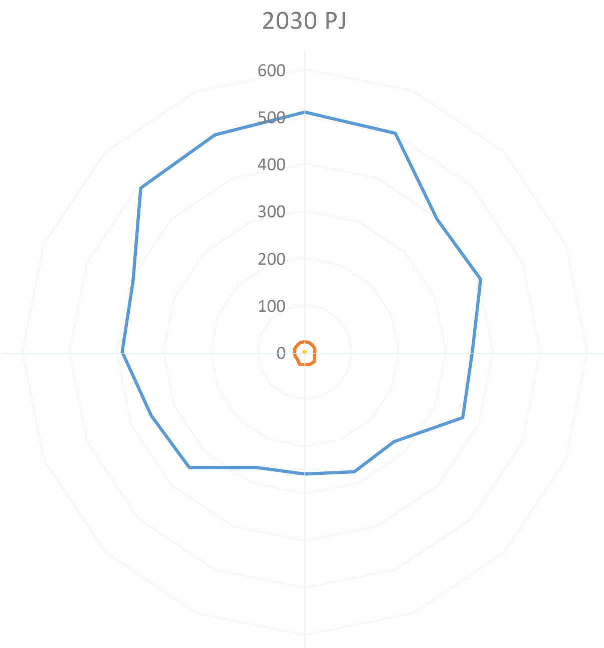
5.2.1.3 Low Hydro plus emission cap plus no imports

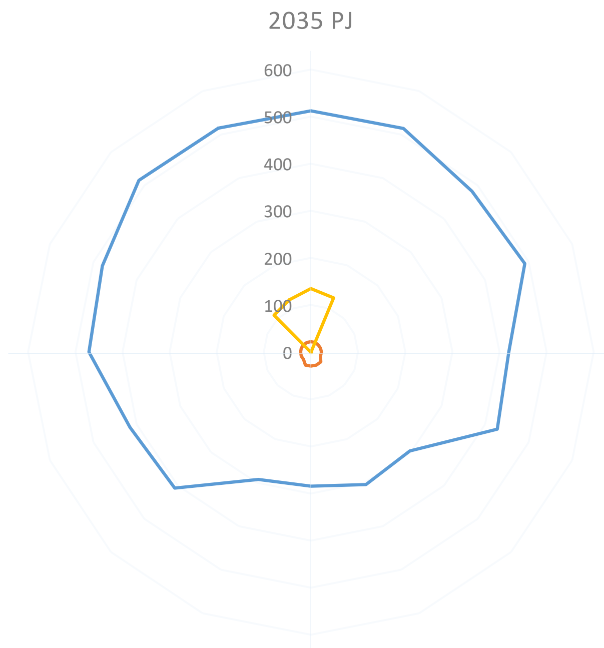
The last set of scenarios in the current analysis covers an extreme group of future conditions: In case of rise in the average world temperature, it is expected lower basins levels and hence lower hydro power generation availability (such as the previous set of scenarios assessed in section 5.2.1.2). Moreover, as seen in section 5.2.1.2, as the hydro power generation availability decreases, the imported electricity does the opposite, it increases, and this is why in this set of scenarios the electricity imports is set to be zero starting on year 2025. The latter will force the model to find national solutions to cover the total electricity demand.
As a last condition of this set of extreme scenarios, eventually the country should impose an emission cap if what Colombia wants to do is to accomplish with its compromises regarding climate change. Emissions should decrease at least by 30% by year 2030, with respect to the BAU projected results [2]. The latter is set as exogenous input, taking as base the emissions resulting from the BAU scenario assessed in section 5.1.2**,** which will be commented later in this chapter, an upper limit to emissions corresponding to 70% of these results is set as emission constraint.



Years 2020 and 2025 have a lower power generation level than the rest of the time horizon. It does not seem to be a gradually increase on power generation investment, as it has been seen in the previous set of scenarios, on the contrary, it jumps from a maximum generation level of ca 50 Petajoules in year 2025 to 500 Petajoules in 2030.

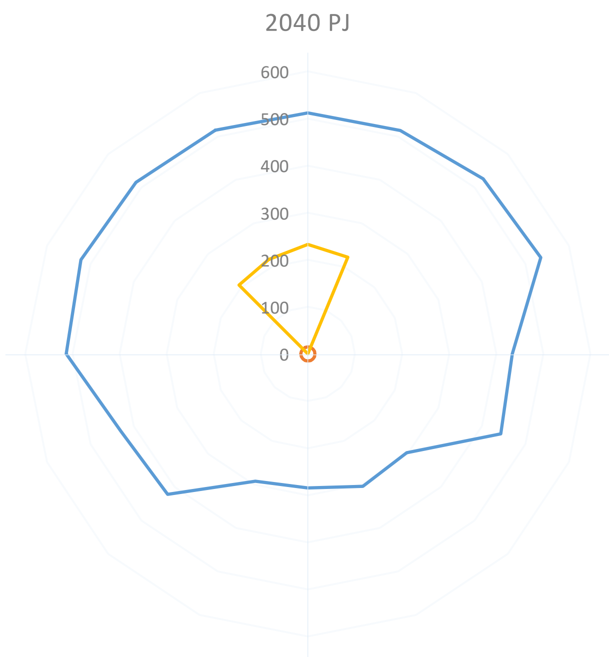
Bagasse and coal have similar shares on the total power production in both representative years, 2020 and 2025. Natural gas fired power plants share increases from one year to the other, reaching the Hydro power generation level. Emission factor of natural gas is lower than the one of bagasse and coal, then it makes sense that natural gas, among the other fuels, will be the default choice if an emission cap is imposed.

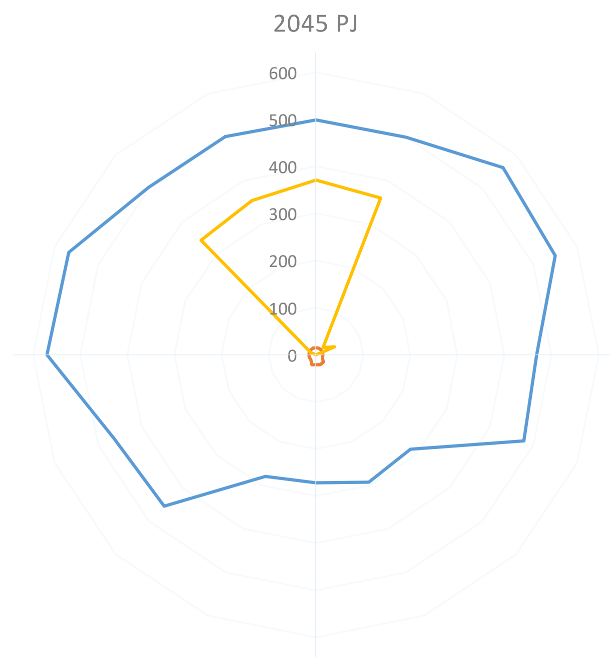




Generation levels in this section, starting on year 2030, are at least twice larger than the BAU and low Hydro availability sets of scenarios for the same years. The reason for this is that when the emission cap is placed on MARKAL inputs, it is valid for all sectors, not only for the power generation. Then, industrial, commercial, residential and transportation sectors change fully to electricity appliances as soon as the old technologies have finished their lifetimes and as soon as the new installed capacity (with new technologies, and apparently new electricity fueled technologies) has been erected. Later in this results section the emissions of the same set of scenarios are assessed, but what can be anticipated from this set is that emissions in year 2030 decreases, as the model forces it, and power generation has a small share in the total emissions level.

Therefore, as the model forces the scenarios to go "green", the electricity consumption and generation increases to so far unexpected levels in this analysis. The latter are good news environmentally speaking, but economically speaking it means that most of current technology has to be replaced by electrical appliances and that many power plants have to be planned and erected. If no measure is taken, it is going to be very hard to comply with both the emissions limits and the demand supply in all scenarios, because even at low GDP and low population scenarios have a rise on electricity demand. This is where the work of politicians and decision makers start being crucial to guarantee a smooth transition to the coming future, if no policies and incentives regarding new technologies are imposed, and if it is followed the business as usual path still for some years, it is going to be impossible to contribute positively to the global warming issue. Changes have to start being planned now.



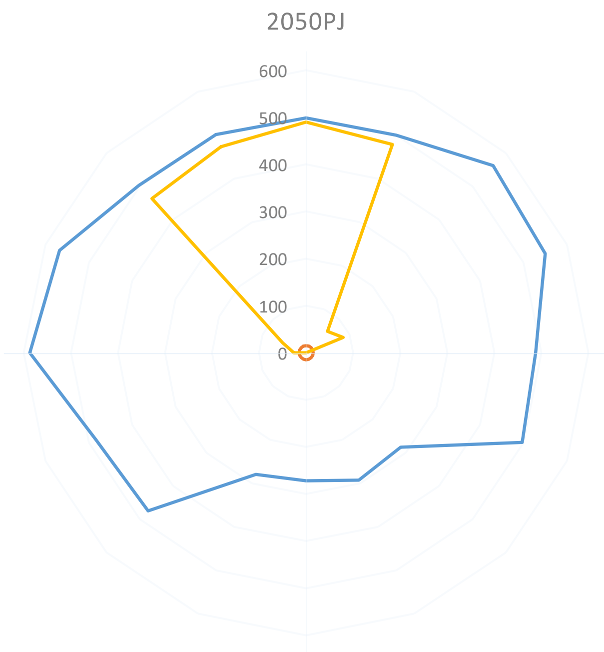


A fact that is interesting from this set of scenarios is that finally a non-conventional type of power generation starts appearing: solar power. As part of the MARKAL inputs, there is an estimate of the solar potential in Colombia, therefore, if it results that there is a large share of solar power in year 2045 for high GDP scenarios, it means that it is possible. Nevertheless, it was necessary to force a lot the model in order to make solar power to be a viable solution. Other non-conventional sources of power, such as wind parks, still are not an economically viable solution, not even at high GDP scenarios. Wind parks need a high initial inversion and even if they have a higher availability along the year (not only for some during the day as solar power), without an economic incentive there is no chance for wind parks to be part of a cost effective solution.

For low GDP change rates (lower side of the circle), hydro power and natural gas seem to be the chosen solution to cover the electricity demand. And it seems to be that by lower population (left side of the circle) hydro generation seem to be larger than for higher population scenarios.

Year 2050 shows a solar power generation, which almost reaches the level of hydro power generation by high GDP and Population change rates. Maybe for years coming after the end of this time horizon, the solar power generation will overpass the electricity generated by hydro power plants.

On the other hand, natural gas seem to be a constant for all scenarios along the complete time horizon: it is homogeneous in the four parts of the circle and it keeps its share, even if it is small, all over the years. Natural gas maximum availability is also part of MARKAL exogenous input, which means that even in a low scale, natural gas has a share in the cost effective solutions, even for extreme set of scenarios as the one assessed currently.



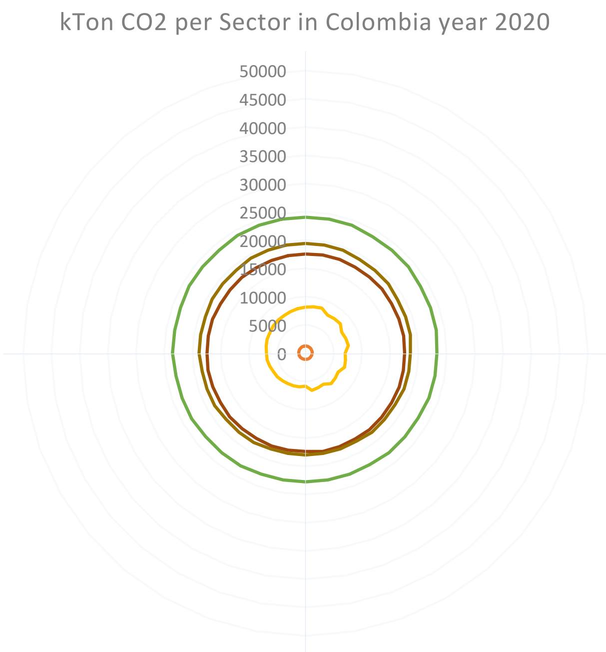
5.2.2 *Emissions of Alternative scenarios*

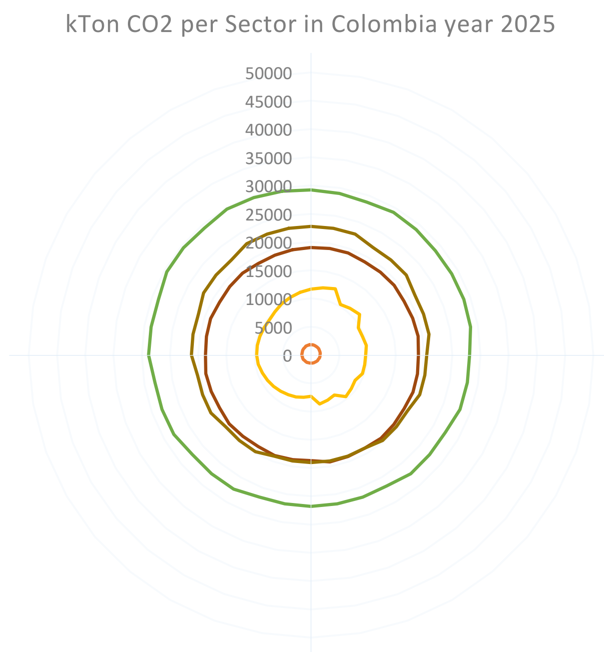
5.2.2.1 *Power generation distribution in alternative scenarios*

In section 5.2.1 the power generation system composition is assessed. For set scenarios in which the power generation system is mainly composed by burning fuels, such as bagasse, coal and natural gas, it is expected to have larger emission levels than the sets in which hydro or solar power generators cover the most of electricity demand.

Besides the power generation sector, in this section it is assessed the emissions coming from activities in the industrial, commercial and transportation sector, plus the ones emitted by population households.

The radial representation in this section works in the same way as in the power generation section figures. The emission level increases from the center to the outer part of the circle. Emission units are kTon of CO2. Each color represents the emissions from a sector, which activities have emitting appliances. **GREEN** represents **INDUSTRIAL** sector, **BROWN-GREEN** represents **TRANSPORTATION** sector, **YELLOW** represents **POWER GENERATION** sector, **BROWN** represents **RESIDENTIAL** sector, and **ORANGE** represents **COMMERCIAL** sector.

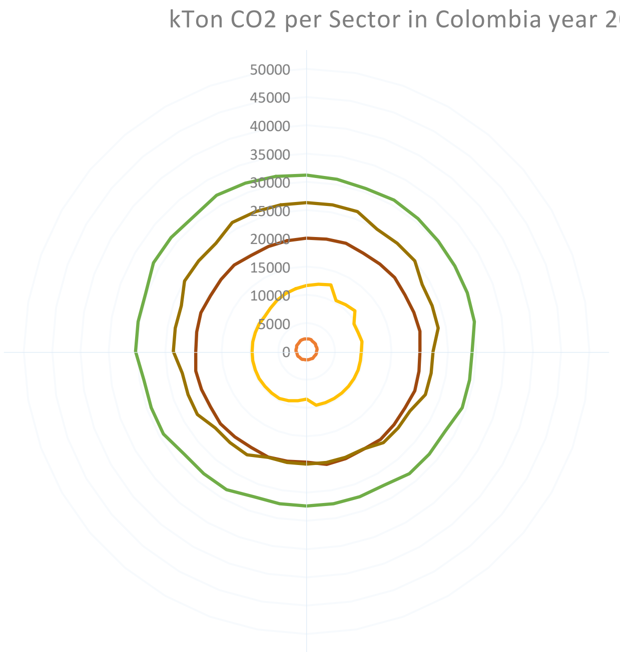


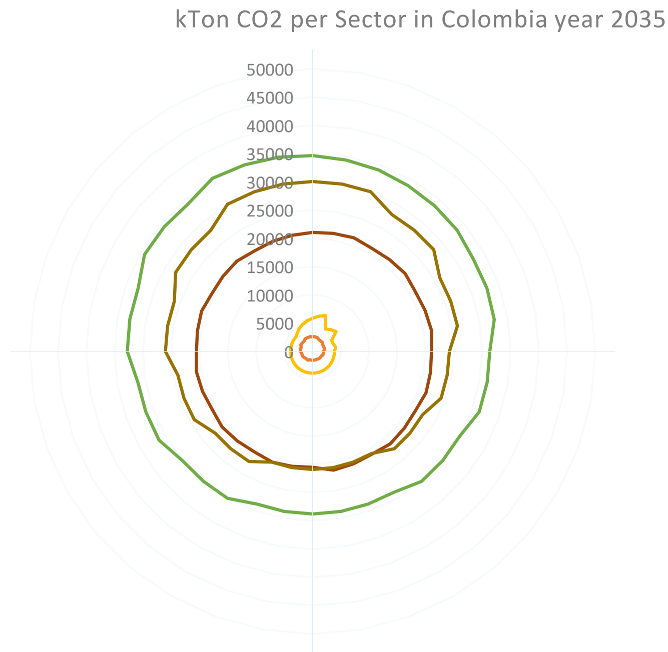


Emissions of each sector are in year 2020 homogenous among all scenarios, but already in year 2025 is possible to see how transportation emissions increase the gap between then and the residential sector ones, for scenarios with higher change rate of Gross Domestic Product.

Residential emissions circle does not seem to have big alteration from scenario to scenario, all four parts of the circle seem to have the same emission level coming from household activities. The latter means that even at high or low population projected change rate, emissions level from this sector keeps constant due to the investment on household appliances that use mainly electricity, that is why that even if the demand year by year changes, the emission keeps being constant: they are indirectly passed to power generation sector. Then, the more the household use electric appliances, the lower emission level the residential sector has, but at the same time the power generation matrix has to be checked to be sure it does not become the largest emission source.

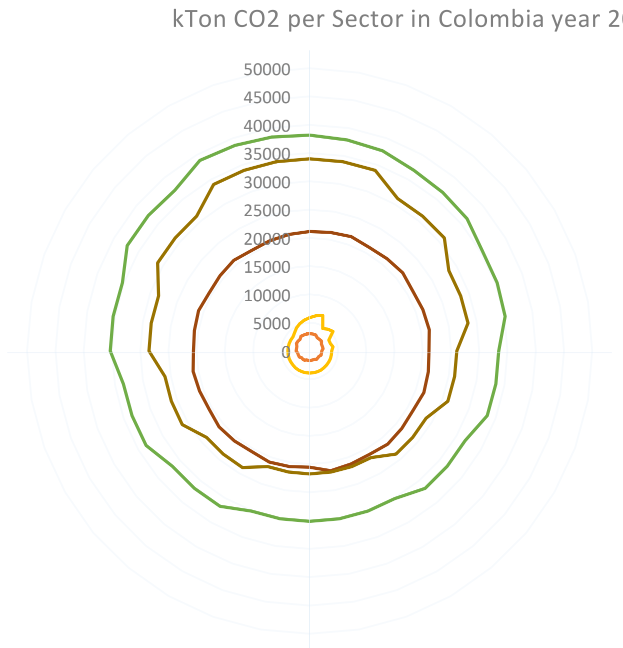
In this case, it is clear that emissions go from residential to power generation sector since the part of the radial figure with the higher population change rate (right side of the circle) seems to be bigger for power generation (yellow line), than what it is on the left side for both high and low GDP change rate.

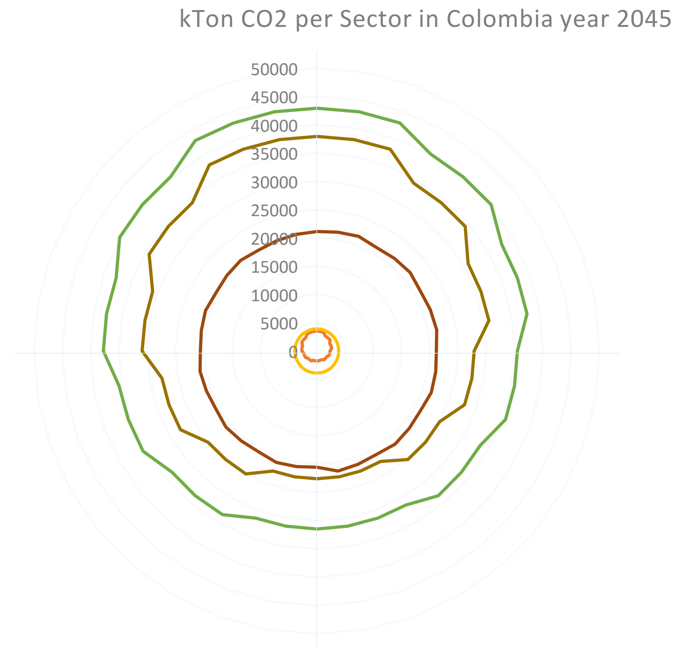




Year 2030 seems to be the last year in which many thermoelectric supply part of the electric demand in Colombia, because in year 2035 the yellow line is nearer to the center. This reflects what is explained and assessed in section 5.2.1.1 of this document, as in this section it is shown that coal fired power plants stop operating.

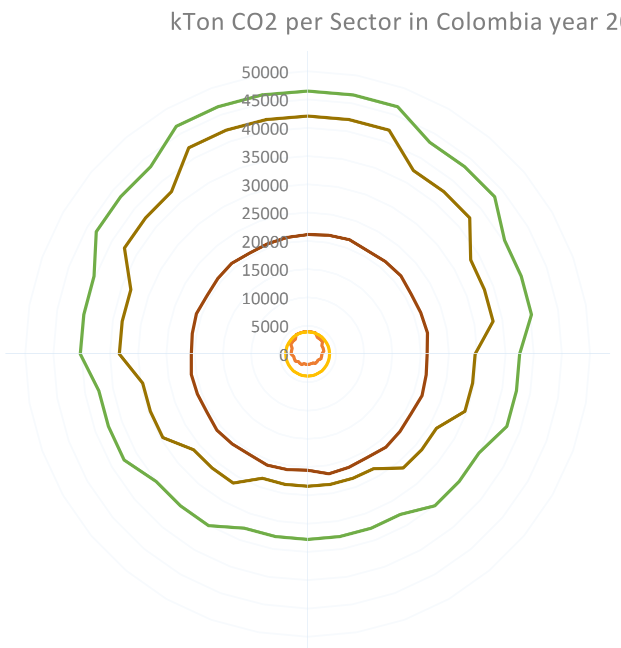
Residential sector emissions keep being constant for all scenarios, and it behaves so until the end of the time horizon in year 2050. The latter is due to the fact that the cost effective solution for high and low GDP change rate scenarios is to invest in new capacity for residential sector that only consumes electricity. Then, this decision is represented in the





power generation sector line, which always seem to be slightly larger to the right side of the circle, which is the side where population change growth is larger.

On the other hand, commercial sector keeps being the sector with the lowest share on the total emission level in Colombia. Commercial activities are not energy intensive, but still at high GDP change rates, when it is expected that also commercial sector grows faster, the emissions seem to be larger than in the "poor" scenarios where economy has a slower develop. That is why from year 2025 commercial emissions level are larger in the upper part of the radial figure.



Transportation and Industrial sectors have constant growing on their emission levels. From the beginning to the end of the time horizon, their share on the total emissions level keep increasing, and most probably if the time horizon would have been longer, they would have kept increasing until the end. Industrial and transportation sector are very energy intensive, and since no incentive has been given for investing in new cleaner technologies, they keep using fossil-fueled appliances to cover the total demand of the sector.

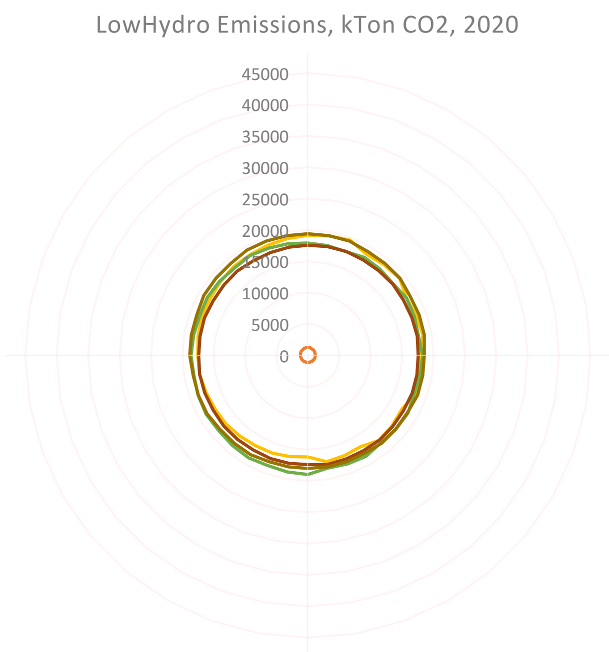
Transportation sector according to the model results has replaced some of its vehicle fleet to natural gas, which is the cost effective solution, but it might not be close to reality. Compressed Natural gas fueled vehicles are not the type preferred in Colombia since they have a lower force with respect to gasoline ones, and traction power is needed in the country because of the many mountains and inhomogeneous land.

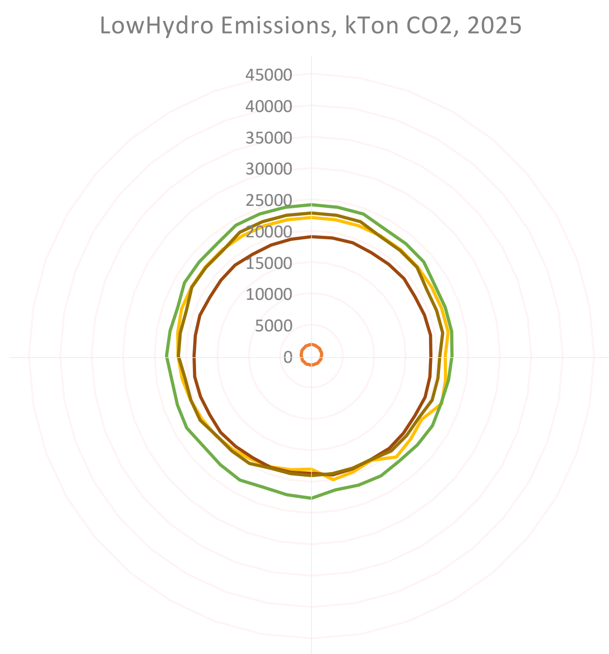
Transportation sector and residential sector have similar emission levels when population and GDP change rate are low, which means that transportation levels is governed by both parameters.

Then, no matter which is the scenario demand projection, transportation and industrial emission levels keep having the majority of the share in the long-term. If the latter is willing to be avoided, then, incentives on technologies that use electricity and electric vehicles (or at least hybrid vehicles) must be implemented. As mentioned in chapter two, vehicle emissions are the reason for many respiratory problems in urban areas, and according to this results, they do not seem to go lower if always the cheapest option is chosen (cost effective option). This is why decisions have to be made at government level, decisions which cover these two sectors and incentive the use of higher efficient technology and/or implement taxes on emissions.

5.2.2.2 Low Hydro availability

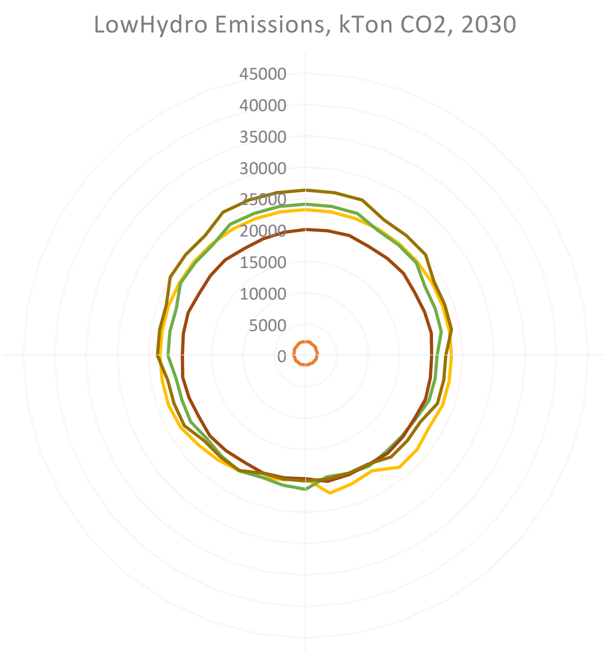
This set of scenarios forces the model to find alternative solutions to replace electricity generation from hydro power plants, since their availability is considered low in a possible future in which the global average temperature is rising.

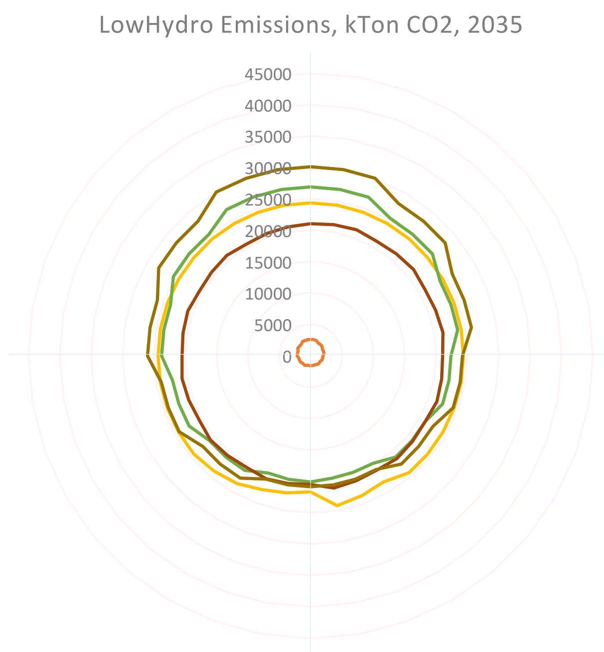




Commercial sector keeps being the sector with the lowest share on total emissions level for this set too, but same as has been seen in the previous section, when the Gross Domestic Product change rate is larger, the emissions of this sector tend to be larger as well. It is not affected by the change in population, it grows uniformly to the upper part of the circle.

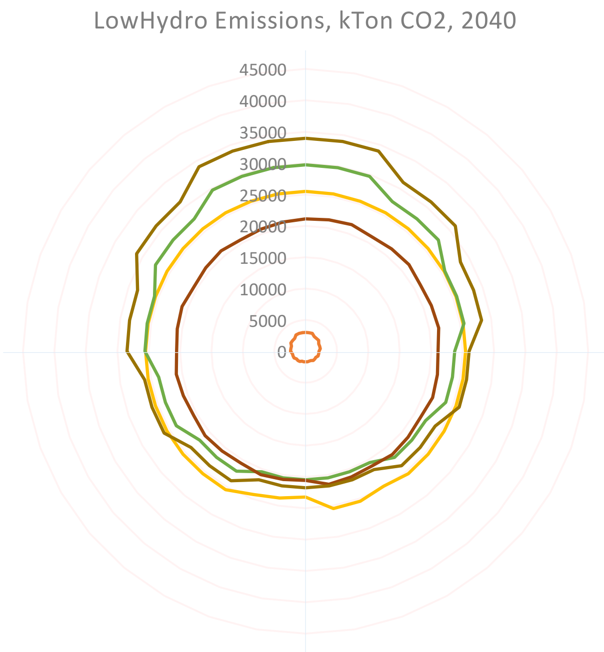
There is a singular phenomenon in year 2020, where the remaining four sectors, industrial, residential, transportation and power generation, have similar emission levels, which has not been seen so far, because normally transportation and industrial sector have a noticeable gap between them and the rest of sectors. Nevertheless, the latter rapidly changes in year 2025, where industrial starts having its usual behavior among the sectors, taking the first place on the emissions range. Residential sector is left behind in scenarios where the GDP change rate is high (upper part of the circle). Residential emission level is constant along the time horizon, which means that until year 2050 in order to supply the residential energy demand, all the new installed capacity consumes mainly electricity, and once again, as seen in the previous set of scenarios, the emissions go from residential to the power generation sector.

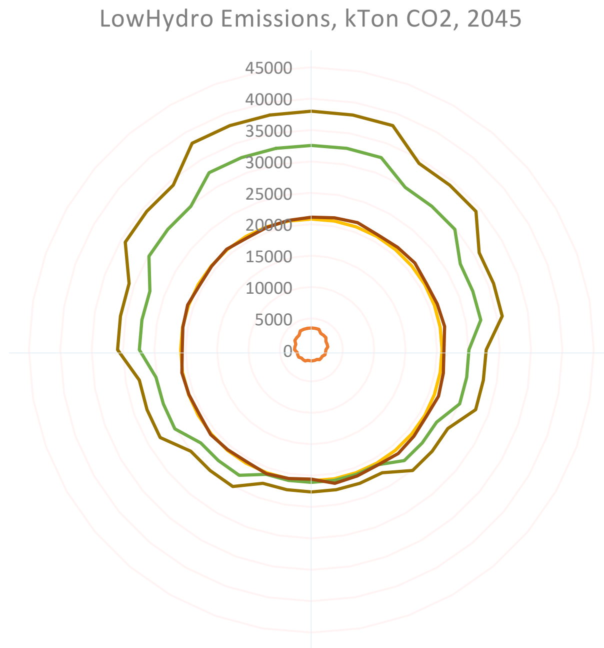




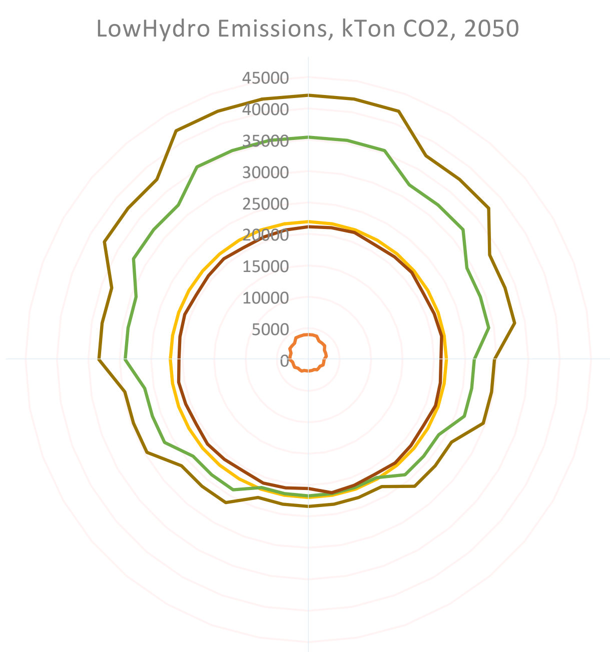
Already in year 2030, transportation sector has the largest share on the total emission in the upper side of the circle (in a future with better economy). Nevertheless, when population and GDP projections are low, emissions tend to have a similar level still in year 2030, as it happened in year 2025.

In this set of scenarios power generation emissions is expected to be larger than in other sets of scenarios with high hydro availability. Thermoelectric power plant have a larger share in the total electricity production, therefore it is expected to be more emissions. The latter indeed happen for some years, emissions coming from power generation sector rises until year 2040, but then they decrease, because imports of electricity starts having the largest share starting in that year, as seen in section 5.2.1.2.





Transportation sector emissions level is the largest one since 2030 until the end of time horizon for scenarios with high GDP. This is due mainly to the fact that industrial sector starts investing on technologies which use electricity instead of fossil fuels. Plus, since the electricity imported has a large share starting on 2040 for the same kind of scenarios (high GDP, together either with high population or low population), then, there is no increase on emissions of the power generation system.



Imported electricity has such a high level that power generation emissions is equal to the residential one, for all scenarios, even if the demand increase is high (as in the upper part of the circle). Nevertheless, on year 2050 there seems to be a slight rise on the emissions level of power generation sector for all scenarios, which could lead to a point in which national power generation plants share increase in low GDP scenarios (thermoelectric ones, since hydro is not highly available). These thermoelectric plants share will keep growing until they reach a point in which these low GDP scenarios should import electricity as well. For more information about behavior of low hydro power generation sector go to section 5.2.1.2.

In this set of scenarios, the total level of the emissions is slightly lower than the one in which water was available, but this is because most of electricity and the end of the time horizon is imported. Importing goods is not a way of decreasing the environmental emission issues, it only passes the emissions to another part in the world but the problem will still be there. Also, depending on imports to supply the most of the demand of the country is never going to be a suitable solution.

Moreover, with low hydro availability, it does not seem to be a real reduction on emissions level, on the contrary, there are unexpected expenses in new technologies which are not necessarily environmental friendly, as the transportations sector, which will keep contaminating urban areas and which has the same emissions level as in the first sit of scenarios (section 5.2.2.1). As mentioned in Chapter 2, Colombian incentives are not very strong in what is related to the purchase of new vehicles and we are behind with the emissions control technologies for the vehicle fleet. Also, there is no strong control on old vehicles which are the ones that pollute the most. The cost effective solution reported here is based on a certain vehicle fleet lifetime, but in Colombian reality, the people will use these vehicles for more time and avoiding the emissions controls. Policies around this topic have to be stronger and incentive for new technologies, such as electric and hybrid cars, have to be better. So far, no scenario seems to result in a transportation system with a share of electric vehicles.

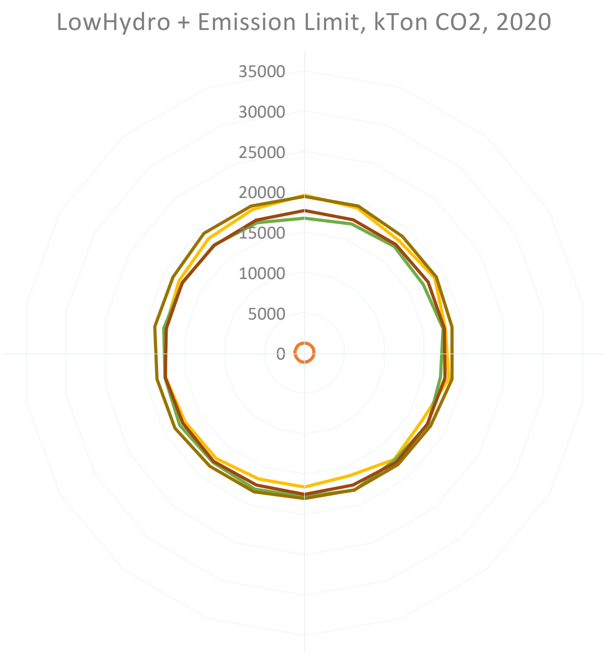
To keep emissions growth, means that the global warming effect will keep causing damages and rising the global temperature, which will lead to even lower basin levels and hence lo lower hydropower availability.

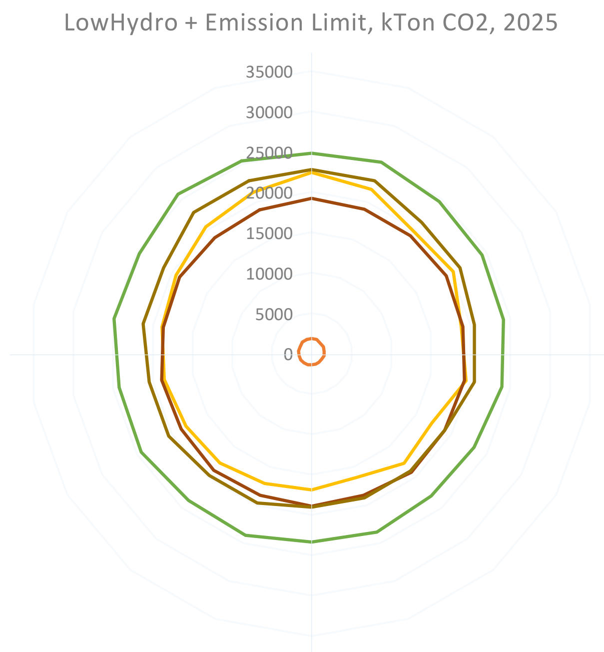
5.2.2.3 Low Hydro plus emission cap plus no imports

This last set of scenarios takes the model to extreme conditions: low Hydro availability, emission cap and restriction in electricity imports.

The first years in the time horizon behaves as the one from the last set of scenarios in which there was only low Hydropower availability. Emissions levels among sectors are similar, excluding commercial sector which now is demonstrated to have the lowest emission level.

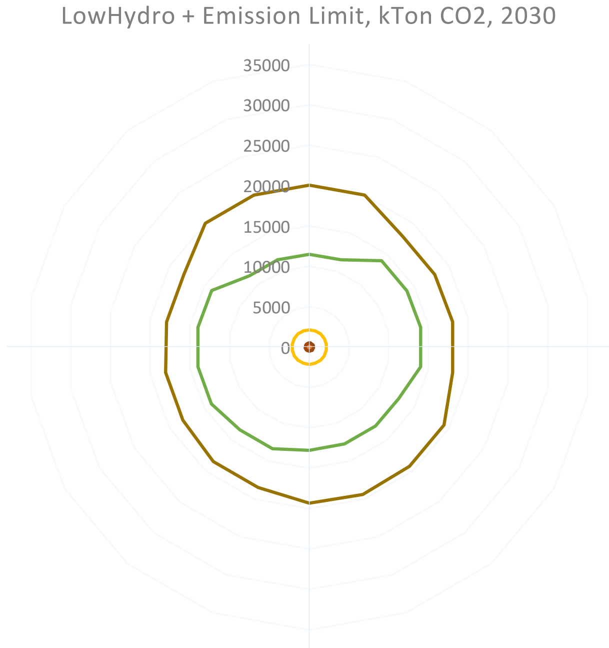
In 2025, industrial emissions level start increasing as usual, but as soon as the emission cap starts being imposed, which is in year 2030, the emission level of this sector decreases and it is situated below the emissions of the transportation sector.

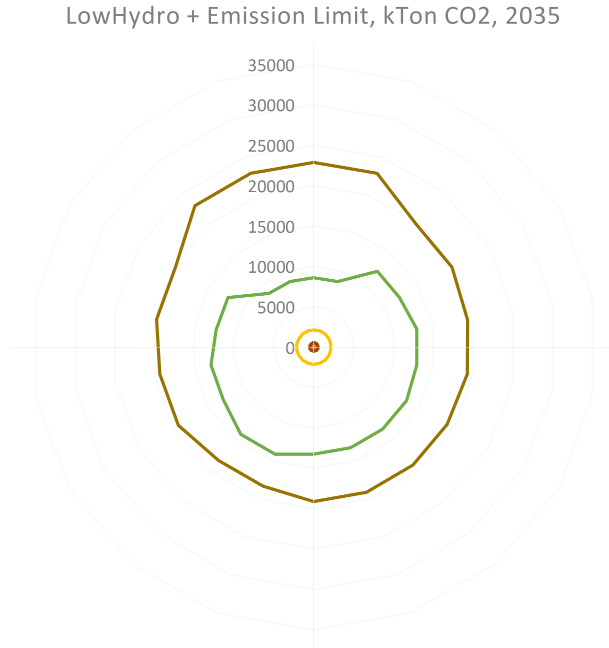




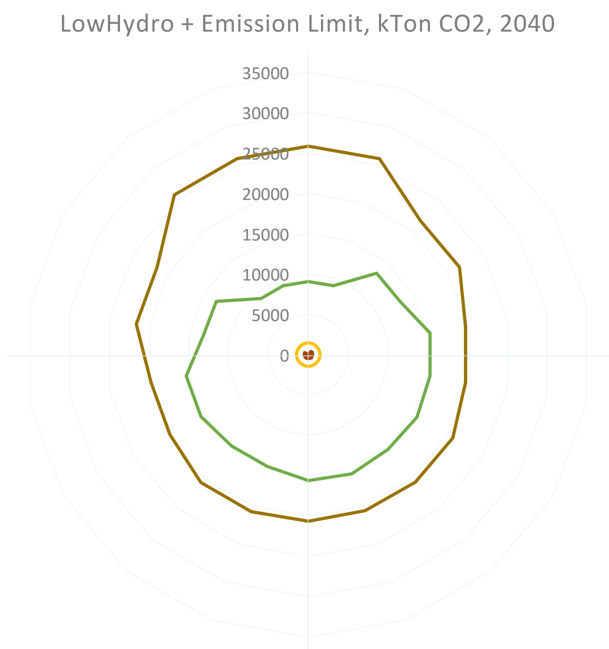
Under the extreme conditions of this scenario, all sectors start investing on technologies that use electricity, this is why in year 2030 the emissions from all sectors decrease and as it was assessed in section 5.2.1.3, most of electricity is generated by hydropower plants and the share of solar plants starts increasing for high GDP scenarios.

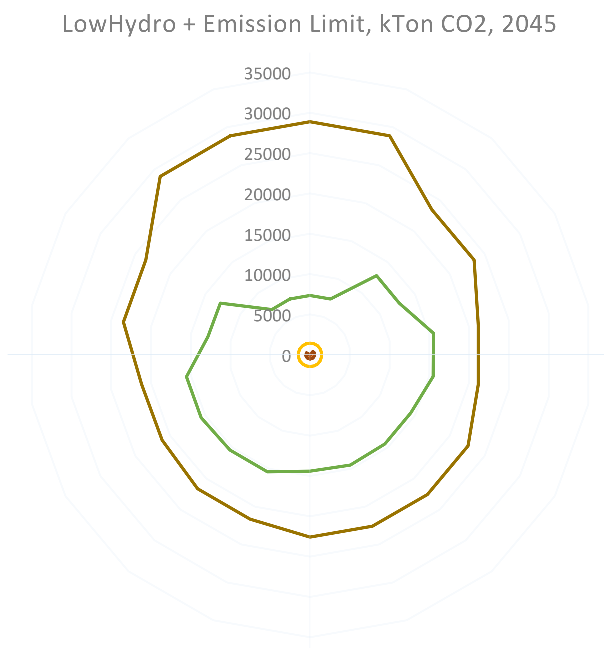
Industrial sector has one of the biggest energy demand along the years in this analysis. Nevertheless, in scenarios with low GDP change rate (lower side of the circle) emissions from the Industrial sector are less than in scenarios with high GDP (upper part of the circle). Cost effective solutions for scenarios with lo GDP still allows them to use fossil fueled, or bagasse fueled technologies, in order to cover the existing demand. Due to the fact that the demand is lower for low GDP change rates, it still can be covered by emitting technologies without crossing the emission gap. Instead for high GDP change rate, the model is forced to find long term solutions to cover the existing demand, this is why it invests on new capacity which uses electricity and increases the existing power generation plant production, and it even invests in solar power, which was not seen in the past scenarios set.





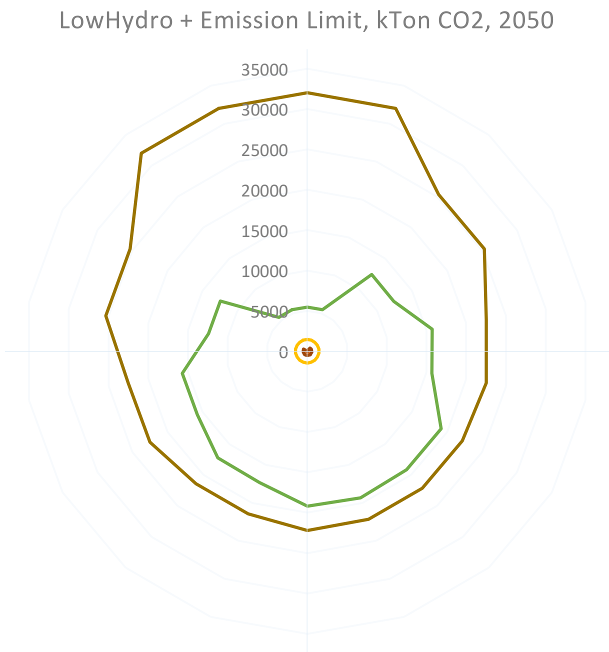
Industrial, Residential and Commercial sector have more options than transportation one on what regards electrical technologies. This set of scenarios is the first which shows some electrical vehicle share in the transportation sector, nevertheless, on contrary to industrial sector, its emissions level still increases with demand. The upper side of the circles show a larger level on transport emissions than the lower part, starting on year 2030.





It is true that emissions of transportation sector are lower in this set of scenarios than in previous sectors, but this is only because of the set emission cap. If the time horizon would have been longer, the emissions from transportation sector most probably would have kept increasing as much as the emission cap allows it, because no cost effective solution will tend to decrease the emissions of this sector.

It is clear that without subsidies the people will not agree on changing their vehicles to low emission ones, and Colombia is not excluded from this situation, since it is a medium income country.



There is one last interesting point from this set of scenarios: Low GDP and demand does not mean that emissions will be lower. Total emissions are higher in the lower part of the circle, where GDP is projected to be lower.

6 CONCLUSIONS

Detailed and accurate projections about possible future scenarios is a way to understand which are the actions that can be taken today in order to avoid or to enhance situations that can affect positively or negatively a definite system.

In the case of the current analysis, the energy system in Colombia is the one which can be enhanced by national policies which are still in baby steps or that have not been set at all, and as the worldwide situation need actions to be taken now, also Colombia government needs to make strong decisions about future emissions and in what technologies to invest as soon as possible.

To do the latter, it is possible to see which sectors have the largest share on emissions and how these emissions change under different possible future scenarios, and the latter is possible thanks to the detailed inputs of MARKAL model and to the cost effective solutions it gives to supply the national demand of Industrial, Commercial, Transportation and Residential sectors.

Business as Usual scenario reflects a very clean power generation matrix: it is going to be invested mostly in hydro power plants and coal fired thermoelectric plants will disappear starting on year 2030, which shows what could the reality of the worldwide situation, when all countries are against the use of coal as fuel to produce electricity. On the other hand, there is no investment on non-conventional sources of power, such as solar and wind. It is not a good idea to depend only in hydropower in a future where most probably Temperature keeps rising, incentives must be placed for investors to install new generation capacities based on renewables.

Business as Usual projected emissions show transportation and industrial sector to be the most polluting ones. Incentives could help to avoid this situation, such as promoting investment in more efficient technologies in industrial sector plus giving incentives for population to invest in electric vehicles and its infrastructure

In the alternative scenarios in which the demand drivers are the only changed inputs, which means that the rest of the model stays as the BAU scenario, power generation and emissions projections do not differ from the resulting of the original projections. Power generation keeps working based mainly in hydropower and Natural Gas after 2030, and emissions keep being governed by Industrial and transportations sectors.

In a low Hydropower availability future, bagasse fired power plants and imported electricity will be the main source of electricity in high projected GDP scenarios in the long term (rich country with high demands), instead, in low demand scenarios, hydropower still can cover most of electricity demand, but still imports and bagasse has a share in the total electricity production. There is no way in which Colombian electricity safety can depend on imports, this is why starting from now, infrastructure has to be planned in order to avoid this situation. There is the urgency to start incentivizing the installation of renewable sources of electricity, otherwise there could be the possibility of scarcity and electricity crisis in the long-term.

Industrial sector and transportation sector keep being the ones in the long term which pollute the most, also in this low hydropower availability set of scenarios.

Extreme scenarios, such as low Hydropower availability plus an emission cap (which could be equivalent to place taxes for polluting technologies), result finally in investment on renewable sources of electricity, and in the long term the capacity of this sources seems to keep growing.

Transportation and industrial sector keep being on top of emissions level, nevertheless, a strange phenomenon is observed: at lower demands the total emissions level is larger than at higher demands. The latter is because at higher demands, the emission cap forces the system to use mainly electricity, which at the same time is produced by renewable sources.

Actions has to be taken now, industrial and transportation sectors cannot keep working in the same way they are doing now. Under cost efficient results, these two sectors tend to be always the most polluting ones and that is due to the lack of incentives for investing in newer and cleaner technologies. These incentives and policies have to be made at government level so they can be applied at national level, not only regional solutions are needed.

Moreover, without incentives for renewable sources or taxes on emissions, the installation of non-conventional power plants will never be part of a cost effective solution.

It is important to point out that the limited time horizon has no influence on the final results, because it might happen that the investment made in new technologies capacity would have changed having more time to pay it back. Moreover, all demand drivers are made based on projections, and it is not sure that this projections represent what will happen in reality. As it has been mentioned along this analysis, to simulate scenarios is not a guessing activity but at least it gives some general idea of the magnitudes and of which actions to take in order to avoid unwanted situations.

7 Annex A [30] [31] [18]

Following section is fully taken from MARKAL User Manuals.

MARKAL calculates an equilibrium on energy markets between the time periods, which means that the quantities and prices of the various fuels and other commodities are in equilibrium, i.e. their prices and quantities in each time period are each that at those prices the suppliers produce exactly the quantities demanded by the consumers. This equilibrium maximizes the surplus over the whole horizon, or equivalently minimize the net total cost, while satisfying the constrains made by the user, as for example a cap on CO2 emissions or a cap on available hydric sources.

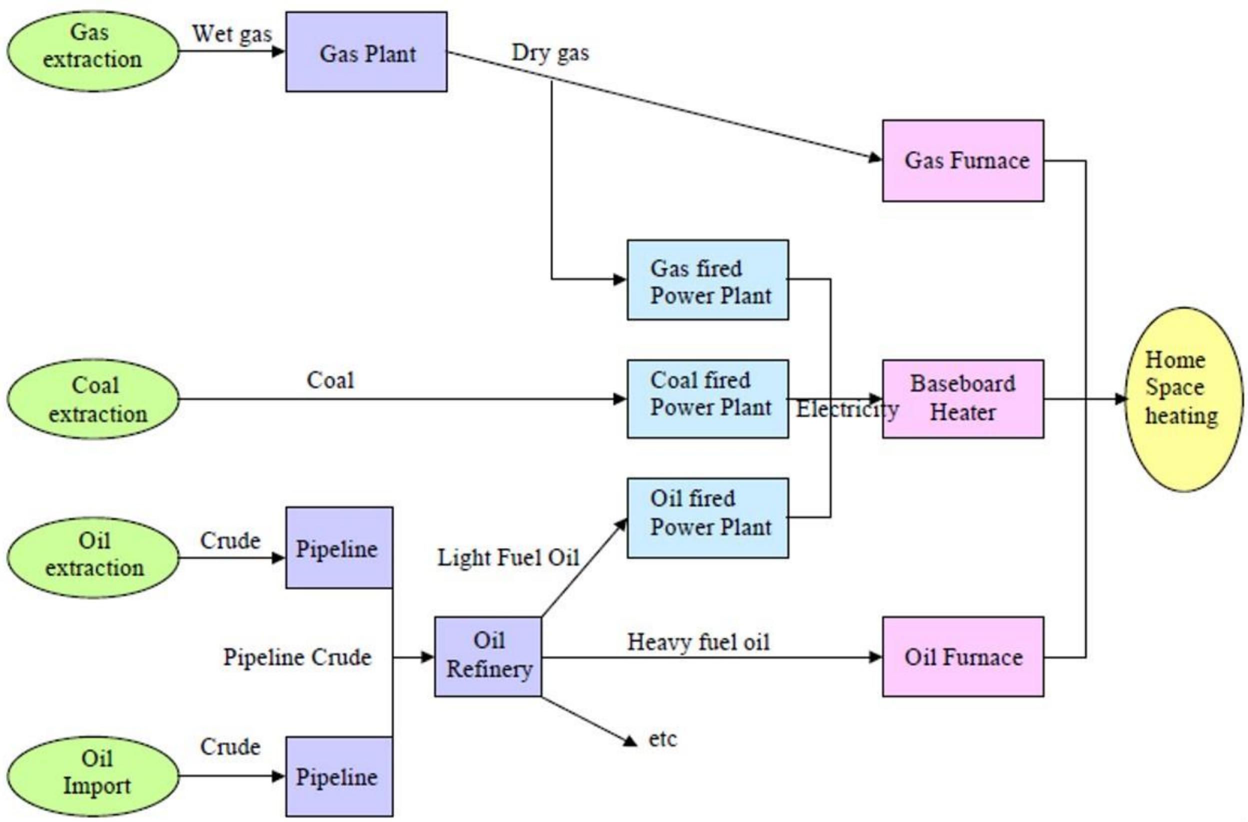
It is possible to differentiate the type of data for each season in Markal, such as heating in winter or higher photovoltaic use in summer, but nevertheless, in Colombian case, since there are no seasons there will not be different considerations for technologies along the year or along the time periods. A time period for this case has 5 years, then, every input or output related to a time period applies to each of the 5 years in that period. Emissions levels and energy flows reported in the results represent annual flows in each of the 5 years, but the period's investments are assumed to occur at the beginning, which means the resulting installed capacity at the first year of the period will be available throughout that period.

7.1 MARKAL Energy System

MARKAL works with following inputs:

- Demands, that represent the activities which consume energy, without specifying where that energy comes from and which technology will be used, i.e. if there is energy needed for residential lightning, on the demand section it is not specified if this energy is supplied by an incandescent light bulb or an electronic one.
- Energy sources, this represents the way in which the energy is acquired, it could be by means of mining or imports.
- Sinks, which is all the energy that is not used in the system but still mined, which means, it is the exports.
- Technologies, they transform an energy carrier to another form or into a useful energy service (demand).
- Commodities, they represent the energy carriers, intermediary energy services, materials and emissions that are involved in the whole system (coal, natural gas, steam, electricity, etc.)

In the figure below it is shown an example of how MARKAL organizes a line of an energy system, in which the demand is the home space heating. The paths follow from the energy sources to the energy service connect all the intermediary technologies and consider all the sinks. The squared boxes represent the technologies and the lines represent the commodities (energy carriers) between them.



7.2 A simplified Mathematical Formulation of the MARKAL Linear Program

An optimization problem formulation consist of three types of entities:

- Decision variables: i.e. the unknowns, to be determined by the optimization
- Objective function: expressing the criterion to minimize or maximize. In this case the net present value is to be minimized
- Constraints: equations or inequations involving the decision variables, that must be satisfies by the optimal solution

In following sections these three parts are going to be presented always related to MARKAL model.

7.3 Decision variables

Decision variables represent the choices made by the model.

- INV (t,k), new capacity addition for technology k, in period t. Typical units are Petajoules (PJ) /year for most energy technologies, billion vehicle-kilometers/ year for road vehicles and GW for electricity equipment. Note that an investment made in a period t is assumed to occur at the beginning of that period, and remains available until the end of its lifetime. Note that the life of a technology may be a fractional multiple of the period length.

- CAP (t,k), installed capacity of technology k, in period t. Typical units: same as for investments
- ACT (t,k): activity level of technology k, in period t. typical units: PJ/year for all energy technologies. ACT variables are not defined for end-use technologies, for which it is assumed that activity is always equal to available capacity. With the exception of the conversion technologies, only annual activity is tracked.
- MINING (t,c), quantity of commodity c (in energy equivalent units PJ per year) extracted in period t; the coefficient in the objective function is the unit cost of extracting the commodity, as provided exogenously by the user.
- IMPORT(t,c) EXPORT (t,c), quantity of commodity c (PJ per year) exogenously imported or exported in period t. It is important to note that the model does not automatically balance the quantities exported and imported.
- D(t,d), demand for end-use d in period t.
- ENV(t,p), emission of pollutant p in period t.

7.4 MARKAL objective function: total system cost

Markal objective is to minimize the total cost of the system, adequately discounted over the planning horizon. For each year, following elements are included in the objective function:

- Annualized investments in technologies, in each period, the investment costs are first annualized before being added to the other annual costs
- Fixed and variable annual Operation and Maintenance O&M costs of technologies
- Cost of exogenous energy carriers imports and domestic resource production (mining)
- Revenue from exogenous energy carriers exports
- Fuel and material delivery costs
- Taxes and subsidies associated with energy sources, technologies and emissions

The above mentioned costs are summed up and the result they are discounted to a reference year in order to allow MARKAL to compute the total Net Present Value.

The objective function can be visualized as follows:

$$NPV = \sum_{i=1}^{i=NPER} (1+r)^{NYRS*(1-t)} * ANNCOST(t) * [1 + (1+r)^{-1} + (1+r)^{-2} + \cdots + (1+r)^{1-NYRS}]$$

Where:

- NPV is the net present value of the total cost (the sum of the discounted annual costs)
- ANNCOST(t) is the annual cost for period t
- r is the general discount rate
- NPER is the number of periods in the horizon
- NYRS is the number of years in each period t

As mentioned before, all the costs are yearly added up before applying the discount rate. Following it is shown the annual cost equation:

$$ANNCOST(t) = \{Annualized_{Invcost(t,k)} * INV(t,k)$$

$$+Fixom(t,k) * CAP(t,k)$$

$$+Varom(t,k) * \sum_{s,s} ACT(t,k,s)$$

$$+\sum_{c} \left[Delivcost(t,k,c) * Input(t,k,c) * \sum_{s,s} ACT(t,k,s) \right\}$$

$$+\sum_{c,s} \{Miningcost(t,c) * Mining(t,c)$$

$$+Importprice(t,c) * Import(t,c)$$

$$-Exportprice(t,c) * Export(t,c)\}$$

$$+\sum_{c} \{Tax(t,p) * ENV(t,p)\}$$

Where:

- Annualized_Invcost(t,k) is the annual equivalent of the lump sum unit investment cost, obtained by replacing this lump sum by a stream of equal annual payments over the life of the equipment, in such a way that the present value of the stream is exactly equal to the lump sum unit investment cost, for technology k, in period t.
- Fixom (t,r), Varom (t,k) are unit costs of fixed and operational maintenance of technology k in period t
- Delivcost(t,k,c) the delivery cost per unit of commodity c (energy carrier) to technology k in period t
- Input(t,k,c) is the amount of commodity c required to operate one unit of technology k in period t
- Miningcost(t,c) is the cost of mining commodity c in period t
- Importprice(t,c) is the exogenous import price of commodity c, in period t
- Exportprice(t,c) is the exogenous export price of commodity c in period t
- Tax(t,p) is the tax on emission p, in period t
- ACT(t,k,s) is the activity level of technology k, in period t, during time slice s. As mentioned before, this analysis will be carried out without considering time-slices, due to the geographical position of Colombia (no distinction between winter and summer).

7.5 Some main MARKAL model equations

While the net present value is minimized, the model must obey to a certain quantity of constrains, which are the model equations. These equations represent the physical and logical relationships that must be satisfied in order to properly relate all system items.

7.5.1 Satisfaction of Demands

Energy service demand projections are developed for the entire forecast horizon based on exogenous regional economic and demographic projections. These will be the drivers of the model. The model must satisfy these demands in each time period by using the existing capacity and/or by installing new capacity for end-use technologies, such as follows:

$$Sum\{\ over\ all\ end - use\ technologies\ (k), such\ that\ k\ supply\ the\ energy\ service\ (d)\}\ \ of\ CAP(t,k) \geq\ D(t,d)$$

Where CAP(t,k) in the total capacity of a technology k in the time period t, including the new installations and the residuals from previous periods, and D(t,d) is the total demand of an energy service d in the time period t.

7.5.2 Conservation of investments on new capacity

Investing in a particular technology increases its installed capacity for the duration of the physical life of the technology. When computing the available capacity in some time period the model takes into account the capacity resulting from all investments up to that period, some of which may have been made prior to the initial period but are still in operation condition (the latter is called residual capacity and it is an exogenous input in MARKAL)

7.5.3 Use of capacity

The availability factor, AF, represents the fraction of the technology that will be accessible during the time period t. The model could decide to use less capacity than the available one, but never more. The user can force the model to fully use all the available capacity of a technology:

$$ACT(t,k) \leq AF(t,k) * CAPUNIT * CAP(t,k)$$

Where CAPUNIT is the unit of conversion between capacity units and activity units, for example, in a thermoelectric plant the capacity CAP is given in POWER units, and the activity ACT is given in energy units.

Note that this constraint is not written for end-use technologies (the ones that directly satisfy the demand in the model), because an activity variable is not defined for them. Activity foe end-use technologies is always assumed to be directly proportional to their installed capacities.

7.5.4 Balance of energy carriers

In each time period, the production plus imports of an energy carrier must be at least as much as the amount consumed and exported.

$$Sum\{over\ all\ k\} of : Output(t,k,c) * ACT(t,k)$$

$$+\ Sum\ of : MINING(t,c)$$

$$+Sum\ of : IMP(t,c)$$

$$+XCVT(c,i) * TRADE(t,c,i)$$

$$\geq$$

$$XCTV(c,o) * TRADE(t,c,e)$$

$$+Sum\ of: EXP(t,c)$$

$$+Sum\{over\ all\ k\} of: Input(t,k,c,) * ACT(t,k,c)$$

Where:

- Input(t,k,c) is the amount of commodity c (energy carrier) required to operate one unit of technology k in period t
- Output (t,k,c) is the amount of commodity c produced per unit of technology k
- XCVT(c,i) and XCVT(c,0) are transaction or transport costs of importing or exporting one unit of commodity c.

Example: Gasoline consumed by vehicles plus gasoline exported to must not exceed gasoline produced from refineries plus gasoline imported.

7.5.5 Peaking reserve constraint for electricity

This constraint requires that in each time period total available capacity of electricity generation technologies exceeds the average load of the peaking time-slice by a certain percentage. This percentage is the Peak Reserve Factor and is chosen to insure against possible electricity shortfalls due to uncertainties regarding electricity supply that may decrease capacity in an unpredictable way. (E.g. water availability in a reservoir, or unplanned equipment down time).

7.5.6 Base Load

The user may identify which technologies should be considered as base load technologies by MARKAL; i.e. those whose operation must not fluctuate from day to night. Typically, thermoelectric plants and hydroelectric plants are included in the base load set, since they are controllable in their loads and also require considerable delays to be shut down or restarted.

7.5.7 Emission constraint(s)

The user may impose upper limits on emissions of one or more pollutants. The limits may be set for each time period separately, so as to simulate a particular emission profile (also called emission target). By suitably naming emissions the user may also separately constrain emissions from specific sectors.

7.6 GAMS Modeling Language and MARKAL Implementation

MARKAL consists of generic variable and equations constructed from the specification of sets and parameter values depicting an energy system for each distinct region in a mode. To construct a MARKAL model, a preprocessor first translates all data defined by the modeler into special internal data structures representing the coefficients of the MARKAL variables in the respective equations (both showed above). This step is called Matrix Generation. Once the model is optimized a Report Writer assembles the results of the run for analysis by the modeler. The matrix generation, report writer and control files are written in GAMS (the General Algebraic Modeling System), a powerful high-level language specifically designed to facilitate the process of building large-scale optimization models. HAMS accomplishes this by relying heavily on the concepts of sets, compound indexed parameters, variables and equations. Thus the fit with the overall concept of the Regional Energy System specification embodied in MARKAL is very strong.

Furthermore, GAMS is so designed that the GAMS code assess in a very accurate way the mathematical description of the equations provided above. The latter makes it simpler to follow the code and understand what and why is being done with each input, variable and equation.

8 References

[1] "EL ACUERDO DE PARÍS. Así actuará Colombia ante el Cambio Climático," Ministerio de Ambiente y Desarrollo Sostenible, 2016.

[2] "Emisiones Indicadas de Colombia".

[3] "Plan de Acción Indicativo de Eficiencia Energética 2017-2022," Ministerio de Minas y Energía - UPME.

[4] "Emisiones Vehiculares en Colombia," Ministerio del Ambiente y Desarrollo Sostenible, 2017.

[5] "Analisis de Emisiones del Parque de Camiones de Colombia," Sistemas Sustentables - ANDEMOS.

[6] E. D. A. E. C. A. D. G. S. I. A. E. A. J. Marcucci. A, "Diagnosticos, Perspectivas y Lineamientos para Definir Estrategias Posibles Ante el Cambio Climatico," Universidad de los Andes, Emgesa - Codensa, 2010.

[7] "Historicos Producto Interno Bruto," DANE.

[8] "Balance de Energía en Colombia BECO," UPME.

[9] "Inventario Nacional y Departamental de Gases Efecto Invernadero," Ministerio de Ambiente y Desarrollo Sostenible - IDEAM, 2016.

[10] "Inventario Emisiones de Vehiculos en Colombia," Asociacion Colombiana de Vehiculos Colombianos, 2017.

[11] "Informe del Estado de la Calidad del Aire en Colombia," Ministerio de Ambiente y Desarrollo Sostenible - IDEAM, 2017.

[12] Informe Del Estado de la Calidad del Aire en Colombia 2016, Ministerio de Ambiente y Desarrollo Sostenible, 2017.

[13] "Mineria en Colombia, 2015-2016," Ministerio de Minas y Energías.

[14] "Cadena del Carbón," Ministerio de Minas y Energía - UPME, 2012.

[15] "Coal Industry Advisory Board submission to the International Energy Agency to inform its forthcoming Special Report on Energy & Climate for UNFCCC COP21 decision makers," 2015.

[16] "Boletin Estadistico de Minas y Energías 2010-2015," UPME.

[17] "Informes XM 2016".

[18] K. J., "Application of Markal Model Generation Optimizing Energy Systems," *Journal od Sustainable Mining,* pp. 35-39, 2013.

[19] "Determinación de la demanda real de Gasolina Corriente, Gasolina Extra, Diesel Oil y GNV en el territorio nacional," UPME, 2014.

[20] "Operación del Transprte de carga por carretera en Colombia," Ministerio de Transporte, 2001.

[21] "Caracterizacion Energética del Sector Transporte de carfa y pasajeros, Yrbano e Interurbano en Colombia," Ministerio de Minas y Energía - UPME, 2010.

[22] "OECD GDP Forecast consulted on 05.05.2019," OECD.

[23] "United Nations Population Forecast consulted on 05.05.2019," UN.

[24] "Primer balance de Energía Útil para Colombia y Cuantificación de las Perdidas energéticas relacionadas y la brecha de eficiencia energética - First Version," UPME, 2018.

[25] "Costos de Operación del Sector Petrolero en Colombia en 2017," acp, 2017.

[26] "Informe de costos de Prestación de Servicio," Superservicios, 2017.

[27] "Proyección de precios de los energéticos para generación eléctrica Enero 2017 - Diciembre 2035," UPME, 2017.

[28] "Análisis sectorial: Coque Metalurgico," Banca Mercantil de Colombia, 2017.

[29] "Informe del sector Gas Natural," PROMIGAS, 2017.

[30] N. Z. Y. A. S. K. Reza Faraji. M, «A Review of MARKAL Energy Modeling,» European Journal of Scientific Research, 2009.

[31] N.-S. S. P. Ltd, ANSWER-MARKAL User Manual.

[32] "Integración de las energías renovables no convencionales en Colombia," UPME, 2016.

[33] "Boletín estadistico de Minas y Energía 2012-2016," UPME, 2016.

[34] "Plan de Acción Indicativo de Eficiencia Energética 2016-2021," Ministerio de Minas y Energia - UPME.

[35] "Determinación del Consumo Final de Energía en los Sectores Residenciales Urbano y Comercial y Determinación de consumos para Equipos Domesticos de Energía Eléctrica y Gas," UPME, 2006.

[36] "Determinación del Potencial de Reducción del Consumo Energético en los Subsectores Manufactureros Codigos CIIU 10 A 18 En Colombia," Ministerio de Minas y Energía - UPME, 2013.

[37] "Determinación y Priorización de Alternativas de Eficiencia Energética para los subsectores Manufactureros Codigos CIIU 19 a 21 En Colombia a partir de la caracterización del consumo energético para sus diferentes procesos, usos y equipos de uso final," CORPOEMA-UPME, 2014.

[38] "Determinación del potencial de reducción del consumo energético en el sector servicios en Colombia," Consorcio Génesis - UPME, 2013.

[39] "Caracterización Energética del Sector Residencial Urbano y Rural en Colombia," Consorcio Corpoema-CUSA - UPME, 2012.

[40] "Documentation for the MARKAL Family of Models," Energy Technology Systems Analysis Programme, 2004.

[41] "Proyección de Demanda de Gas Natural en Colombia," UPME, 2014.

[42] N. a. Resolutions, *Resolución 2254 de 2017 - Por la cual se adopta la norma de calidad de aire ambiente y se dictan otras disposiciones,* Ministerio de Ambiente y Desarrollo Sostenible, 2017.

[43] "Política de Prevención y Control de la Contaminación del Aire," Ministerio de Ambiente y Desarrillo Sostenible, 2010.

[44] "Valoración Económica de la Degradación Ambiental en Colombia," Departamento Nacional de Planeación, 2015.

[45] "Caddena del Gas Licuado de Petroleo (GLP)," Ministerio de Minas y Energía - UPME, 2017.

[46] "Cadena del petroleo," Ministerio de Minas y Energía - UPME, 2013.

[47] "Balance de Gas Natural," Ministerio de Minas y Energía - UPME, 2017.

[48] "Plan Transitorio de Abastecimiento de Gas Natural," UPME, 2016.

[49] "Estudio sobre la estructura del mercado nacional de equipos sujetos al proyecto de RETIQ, y el comportamiento del mercado frente a la inclusión del etiquetado obligatorio de parámetros de eficiencia energética," UPME - PNUD, 2015.

[50] "Plan Indicatico de Abastecimiento de Gas Licuado El Petroleo," UPME, 2018.

[51] "Nueva Propuesta de transporte de GAS NATURAL," CREG, 2016.

[52] "Revisión de la regulación de Precios de Gas Natural en Colombia," CREG, 2012.

[53] "Modelo regional de producción y transporte de buocombustibles en Colombia".

[54] "Producción y Exportaciones de Carbón en Colombia," Ministerio de Minas y Energía, 2017.

[55] "Resumenes de los productos básicos - BIOCOMBUSTIBLES," OECD.

[56] "Sector Energía Eléctrica," 2010.

[57] "Indorme del Sector Gas Natural 2011," Promigas, 2011.

[58] "Informe del Sector gas natural 2018 cifras 2017," Promigas, 2019.

[59] "Peqieña y mediana minería de carbón del interior del país: alternativa de comercializacion y financiación a partir de la conformación de alianzas estratégicas," FEDESARROLLO, 2011.

[60] "Carbón térmico," UPME - CRU Consulting, 2018.

[61] "Departamente Administrativo Nacional de Estadistica," DANE.