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Use of Multi-Criteria TOPSIS Analysis to Define a Decarbonization Path in Colombia

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***Abstract* – In the past few years, Colombia has begun to implement new laws according to new global trends, however, carbon dioxide emissions have not decreased despite country commitments according to the Paris agreement and other international treaties. In this paper, a pathway to achieve full decarbonization of the energy system of the country has been analysed using a multi-criteria analysis tool and considering several options from previous studies, evaluating three different abatement scenarios obtained by different models. Then, a Strength, Weakness, Opportunities and Threats (SWOT) analysis is conducted in order to propose a set of environmental policies that aid in seeking greater reduction of greenhouse gas emissions (GHG) in sectors as agriculture, forestry, land use and transport. This set of measures is then summarized, and their abatement costs and GHG reduction potential are displayed. The outcomes show the country has great potential to exploit its renewable natural resources and indicates how a new electricity mix may not only decrease GHG emissions but also reduce the levelized cost of electricity for the end users.**

***Keywords* – Colombia; decarbonization; energy; TOPSIS**

Nomenclature

GCAM	Global Change Assessment Model
TIAM ECM	TIMES Integrated Assessment Model of the Energy Research Center of the Netherlands
PHOENIX	Dynamic recursive computable general equilibrium model

1. INTRODUCTION

Colombia is a country with a rich energetic matrix not only in fossil fuels but also in renewable resources. Although, according to [1], the energy production of the country in 2016 was represented by 92.5 % fossil fuels, 3.2 % hydropower, 3.8 % biomass and only 0.46 % of Non-Conventional Renewable Energy Sources (NCRES).

The country exports approximately 64 % of its produced primary energy, mainly coal and oil and uses 36 % of the produced primary energy, from which 79 % represent fossil fuels and 21 % some sort of renewable energy [1]. As seen in Fig. 1, approximately 80 % of the energy consumed in Colombia comes from fossil fuels and only 20 percent is supplied by Renewable Energy Sources (RES). The availability of RES not used in the country, added to the progressive reduction associated with their costs makes the integration of these energy sources relevant to the country because of their potential benefits [1].

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Due to the low share of coal in the energetic domestic market and the increasing demand for natural gas that has increased from 25 % in 2012 to 43 % in 2016 [1], the development of alternative local energy sources able to at least partially substitute for the use of traditional sources within the next decade, is highly important especially taking into account that Colombia has natural gas reserves only until 2025 [2], and the trends show that demand will keep growing [1]. One of the reasons why natural gas has become the principal fuel in Colombia energy consumption is because of the introduction and strong boost of gas fuelled vehicles since 2004, and the rapid development this had in the public transport sector, with the local government making tax exemptions for installing this technology in old public transport vehicles [3] and increasing the liquid fuel price on a monthly basis [4].

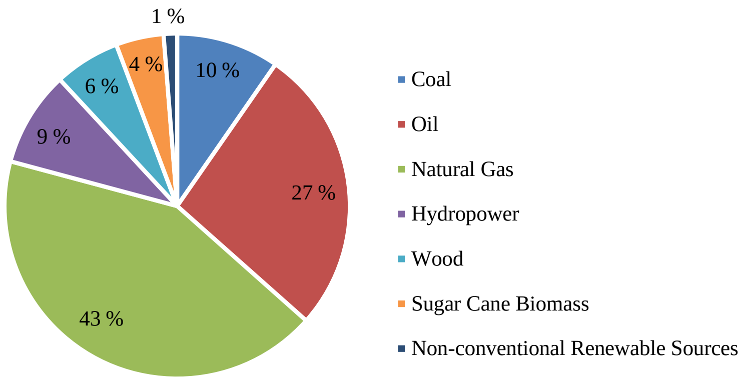

Fig. 1. Internal demand of primary energy resources in 2016 [1].

In the last years, as seen in Fig. 2, the energy sector represents the largest source of greenhouse gas (GHG) emissions mainly due to a bigger share of fossil fuels in the energy basket and the reduction in hydropower electricity production which decreased from 79 % in 2012 to 67 % in 2015 [5]. Besides that, the coal share in electricity generation increased from 3 % in 2011 to 10 % in 2015 [6]. In the meantime, natural gas had a stable share 14–15 % of the electricity produced, but due to the transport sector, its total share has risen from 38 % in 2010 to 43 % in 2016 [5]. Colombia has also not been able to increase the installed capacity of energy production from non-conventional RES such as solar PV or wind power. Only in 2017 The first two solar plants were integrated into the national grid and started to operate only in 2017 and there are three more already under construction with installed capacities between 86 and 100 MWp [6], which are expected to be operational around 2019–2020. In the Agriculture, Forestry, and Land Use sector (AFOLU), the main driver is deforestation for cattle and livestock production which is responsible for 36 % of the sector's emissions [6].

As 80 % of the energy consumption in the country comes from fossil fuels and the transport subsector accounts for 44 % of this consumption, using only 10 % share of biodiesel in the liquid fuels, this sector is the highest contributor to the release of GHG in Colombia with 18.2 % of the total GHG released per year [5]. It has also been estimated by the OECD [7], that the energy sector is the main driver of carbon dioxide emissions, followed by AFOLU, both together accountable for almost 90 % of the total emissions. This is also outlined by the International Energy Agency (IEA) [8] where similar data were gathered displaying the same results for CO_2 emissions per sector.

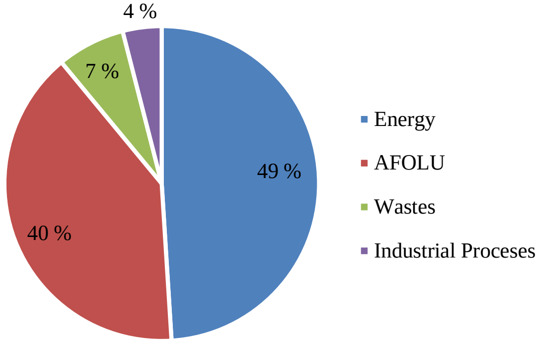

Fig. 2. GHG emissions distribution by sector in 2013 [7].

With the signing of the Intended Nationally Determined Contribution (iNDC) according to the Paris agreement of the United Nations Framework Convention on Climate Change (UNFCCC) [9], Colombia needs to define a strategic plan for decarbonization to accomplish its commitments. Several studies regarding possible decarbonization paths for Colombia have been already published. In Rocio et al. study [10] the analysis of the synergy between energy consumption and Gross Domestic Product (GDP) in the country and decoupling elasticity analysis enabled to conclude that transport and industrial sub-sectors are the main drivers for CO_2 emissions in the energy sector. The authors of [11] also give some glimpse on the directions the country's policies should take. It is explained [11] how Colombia through changes in economic policies has reached the fourth biggest GDP in Latin America, also pushing forward its CO_2 emissions [8], concluding that the government has failed in its attempt to decouple economic growth from CO_2 emissions.

In this work, all mentioned studies were considered for defining a strategy for improving the country's policies, paying special attention to the energy sector, which produces most of Colombia's CO_2 emissions. The Kaya Identity Decomposition analysis was carried out to find results on the main drivers for CO_2 emissions and see if there is any correlation with the previous studies. The study carried out by Calderon et al. [12] was reviewed and a multi-criteria analysis conducted for estimating the optimal path from the proposed ones.

As a result, some general policies were deducted by a SWOT analysis and a Marginal Abatement Cost (MAC) curve was built to analyse the GHG abatement cost for Colombia 2050, considering similar aspects as was outlined by the authors of [13]. In these projected decarbonization paths, the authors came with a holistic view of the country's opportunities and barriers, for fulfilling Brazil's iNDC for 2050.

This paper is structured as follows. After this introduction, in Section 2, the RES background is briefly explained with its barriers and opportunities for each of the main already assessed energy sources available in Colombia. In Section 3 the methodology is applied for the multi-criteria analysis and for the Kaya Identity Decomposition. Section 4 presents the results from the multi-criteria analysis for the energy sector, the considered paths for the transport sub-sector, AFOLU sector, and the strategy is developed represented by proposed policies Colombia could adopt according to the presented results. In Section 5, the economical assessment for the deployment of new technologies is presented and then a MAC curve summarizing the GHG reduction potential measures and their abatement costs are presented. Lastly, Section 6 presents conclusive remarks for the strategy developed.

2. Renewable Energy Sources Background

The climate change drivers in Colombia have been changing during the last decade as Colombia's GHG emissions increased from 57.9 ktCO_2 equivalent in 2000 to 84.1 ktCO_2 eq. in 2014 with a higher share of the energy sector in most recent times [6]. Nevertheless, nowadays Colombia does not have an official GHG inventory and this makes it extremely hard to track the actual performance of the country in reducing GHG emissions.

Recently Colombia has adopted a series of policies and laws that aim to mitigate and adapt the country to climate change effects. In 2015 in Paris, Colombia committed to reduce its greenhouse gas emissions by 20 % (or by 30 % with international support) by 2030 compared with the business-as-usual scenario and current trends [14]. Colombia published its iNDC and declared its willingness to search for the economic instruments to achieve this goal [9]. By 2016, the president signed Decree 298 according to which the National System for Climate Change (SISCLIMA) was created [15]. SISCLIMA is comprised of public, private and non-profit entities, its objectives are to coordinate measures and actions to fight climate change through different instruments such as rules, strategies, policies, resources and plans. To reach the goals, Colombia established a carbon tax within its last and broad tax reform brought in 2017 and some other instruments are under development, like clean development mechanism, the payment for environmental services along with already established agreements such as the *Energy and Climate Partnership of the Americas (ECPA) – Tropical Glacier Retreat Adaptation*, *the National Biodiversity Strategy and Action Plan* and *the Caribbean Planning for Adaptation to Climate Change Project* [16], and by the commitment and signing of the *Reducing Emissions from Deforestation and Forest Degradation* (REDD+) programme. In 2017, by Law 1844 [17], Colombia ratified the Paris Agreement. In August of the same year, the Ministry of Environment and Sustainable Development presented the Law proposal 73 to the parliament, in which guidelines for climate change management and compliance were given. Finally, it was approved in Law 1931 of 2018 [18].

2.1. Opportunities and Challenges

Some countries like the United States of America, Brazil, and Germany are leaders in the use of bioenergy in the transport sector, while the United States of America, Norway, China, Japan and the European community lead in the use of renewable electricity. China and Turkey lead in the use of renewable thermal energy – solar and geothermal [19].

Given the availability of at least one renewable source in any geographical position of the planet, and the relative abundance of at least one or more of these sources in some favoured regions within Colombia [5], renewable energy sources represent immense energy potential and are to be taken advantage of in a cost-effective way for research, development and commercial deployment of associated technologies [20].

Due to Colombia's high dependence on its hydroelectric resources [5], the country is susceptible to the risk of periodic energy shortages and high energy prices, as it actually happened in the energy crisis generated by the El Niño phenomenon in 1992 and 1993 or more recently in the high energy prices experienced in 2009, 2010, 2013, 2014 and 2016 [2].

Moreover, recent analyses have predicted that vulnerability to drought will increase significantly in Colombia due to climate change [21]. Meanwhile, there are examples in other countries that depend on their dams and hydroelectric generation plants, which have had to face continuous energy crises due to drought and the growth of electricity demand (for example, Uganda and Albania). Some of these countries have chosen to install thermal generation plants with high operating costs (for example, generation by combustion of oil) as a complement to supply the energy deficits that cannot be covered with waterpower. Consequently, such thermal plants have exposed these countries to the risks associated with price volatility of the international market for fossil fuels. Meanwhile, other countries, such as Uruguay, have responded to the risk of hydroelectric plants by installing a significant amount of non-conventional renewable energy, avoiding the high and uncertain operating costs of thermal plants [19].

Studies from Vergara et al. [22] and the generation and transmission expansion plans from the Ministry of Mining and Energy for 2013, have demonstrated the existence of patterns of seasonal complementarity between national wind resources and water.

Colombia has a national electric system with relatively low carbon emissions (compared to other countries with the highest participation of fossils fuels in the electricity mix) [23], not depending on imported energy, and at the same time with enough existing and developing generation capacity to meet the demand for electricity in the short term (at least for the next 5 years) [2]. There seems not to be strong reasons to boost the development of alternative energy sources, other than the need to reduce GHG emissions, the need to avoid dependence on imported fuels or the pressure to attend to increases in demand through new capacity installed based on domestic resources [24]. At the same time, having abundant fossil resources such as coal and possible deposits of gas and oil not yet exploited, the country does not seem to face the imminent need to turn to unconventional resources and technologies as some other countries do [2].

However, with the Paris agreement, Colombia has committed itself to reduce its GHG emissions by 20 % compared with 2005 and 30 % if international aid is obtained.

During the recent years, the price of electric power in the stock market in Colombia has maintained a constant trend to rise, reaching prices close to 0.14 EUR/kWh. In April 2018, the average cost per kilowatt was 0.13 EUR/kWh which shows how the price has been stable if compared with 2014. But, just for example, during El Nino effect on January 2017, Colombia was pushed to buy electricity from Ecuador and prices went up to 0.16 EUR/kWh [2].

It is of high importance to mention that prices of renewable energy public tenders in the region have decreased in recent years, to values below the above mentioned. This is how, for example, long-term contracts for energy wind energy subscribed in countries such as Peru, Brazil and Uruguay through auctions held between 2012 and 2016, were in the range of 0.02–0.05 EUR/kWh, whereas the offers of solar PV carried out in Brazil in November 2014 also nearly reached that range (108.9 USD/MWh) [19]. However, it is worth mentioning that these types of projects with modern renewable technologies are not exempt of facing the uncertainty associated with projects relying on conventional technologies in terms of issues such as the rejection of the communities or the opposition of certain sectors for social or environmental issues [5].

2.2. Wind Energy

Some Latin-American countries, like Peru, Panama, Mexico, Chile and Brazil, now have wind capacities installed or are close to being commissioned in the amounts of 148 MW, 220 MW, 2.3 GW, 836 MW and 5.9 GW, respectively, while Colombia has 19.5 MW connected to the National Power Integrated System (SIN), a capacity that has not increased since its installation in 2003 [5]. Furthermore, for a better understanding of the major barriers for renewable energy development, surveys and analysis similar to the one presented in [25] should be conducted in Colombia.

Although wind resource in Colombia is not characterized as being one of the best, the potential capacity in certain regions located on La Guajira and a large part of the Caribbean region, and also areas in the Santander and Norte de Santander states, specific areas of Risaralda and Tolima, Valle del Cauca, Huila and Boyaca, have usable resources, which in the specific case of La Guajira, are considered as some of the best in South America [5].

In La Guajira state, where highest regimes are concentrated with winds that the country receives throughout the year with average speeds close to 9 m/s (at 80 m height), and prevalent direction east-west [26], which are estimated to represent an energy potential that can translate into an installable capacity of 18 GW [27], this is an increase of almost 120 % the generation capacity installed in the SIN for December 2014 (15 465 MW) [2].

Meanwhile, if one adds the rest of the Caribbean coast that presents slightly lower speeds to those of La Guajira with coastal zones that are similarly attractive, under technical feasibility assumptions made by [26], the potential of the entire Colombian Caribbean region would increase to an installed capacity of 20 GW while the potential for other regions of the country would correspond to the numbers presented in Table 1.

TABLE 1. ENERGY POTENTIAL FROM WIND POWER [5]

Area	Wind potential, MW
North Coast	20 000
Santander	5 000
Boyacá	1 000
Risaralda	1 000
Huila	2 000
Valle del Cauca	500

The displacement of thermal generation with fossil sources by renewable wind energy would represent an environmental benefit in terms of savings in greenhouse emissions, as stated values by life cycle analysis indicate values of emissions of 15 kg CO_2eq/MWh for wind power plants, 450 kg CO_2eq/MWh for natural gas plants, 850 kg CO_2eq/MWh for plants with liquid fuels and 1 000 kg CO_2eq/MWh for coal plants.

2.3. Solar Energy

Solar energy has become the second non-conventional renewable energy source with the largest penetration around the world, after wind, growing at a rapid pace in the last decade. The installed PV capacity increased from 6.1 GW at the end of 2006 to 291 GW at the end of 2016 [19]. For the first time, in 2013, solar energy net additions for that year were even higher than the growth of wind in the same period, with 39 GW compared with 35 GW of wind, the highest growth for solar in the last decade [19].

Meanwhile, in Colombia's case, the sources available from solar resource information indicate that the country has an average irradiation of 4.5 kWh/m^2/day [5], which is above the world average of 3.9 kWh/m^2/day and is also a greater value than the average received in Germany (3.0 kWh/m^2/d), a country that makes the greatest use of solar PV in the world, with approx. 36 GW of installed capacity to 2013.

According to the atlas of solar radiation in [5], specific Colombian regions such as the north Coast (La Guajira), an extensive area of the Atlantic Coast and some other regions in the departments of Arauca, Casanare, Vichada and Meta, among others, have radiation values higher than the national average of 6.0 kWh/m^2/day, a resource that can be compared to some of the best regions in terms of solar irradiance in the world [5], as is the case of the Atacama desert in Chile or the states of Arizona and New Mexico in the United States of America. On the other hand, regions such as the Pacific Coast receive levels below the average, which however continue being, for example, above the average annual levels received in Germany. Table 2 presents the average irradiation values for different regions of the country.

TABLE 2. AVERAGE IRRADIATION VALUES FOR DIFFERENT REGIONS [5]

Region	Average solar irradiation, kWh/m^2
Guajira	6.0
Atlantic Coast	5.0
Orinoquia	4.5
Amazon	4.2
Andean Region	4.5
Pacific Coast	3.5

Similar to the case of wind energy, there exist several reasons that enable to consider PV solar energy as a core opportunity with the potential to bring important benefits to the national energy sector. Firstly, there are the decreasing costs of technology, especially of the PV modules or solar cells, which have led to lower the cost of solar PV today, making it, in some cases competitive with electricity retail market rates, especially at commercial and residential levels [23]. On the other hand, through the implementation and scaling up small systems of distributed self-generation can achieve positive impacts, like allowing users to generate their own energy, thus reducing the risk to be subject to certain volatility and usual increases in electricity costs. Similarly, the use of solar PV can produce a marginal displacement on the generation of thermal plants with greater environmental impact, considering that, according to the life cycle analyses of different technologies, the associated emission factors for solar PV systems are around 50 kg CO_2eq/MWh, compared to values above 450 kg CO_2eq/MWh for plants operated with fossil fuels [19].

2.4. Biomass Energy

As far as electricity production is concerned, out of a total of 21 431 TWh of electricity produced worldwide in 2010, biomass participated with the production of 331 TWh, which is approximately 1.5 % of the total produced [28]. Meanwhile, the information available for 2013 indicates that such generation increased to 405 TWh (REN21, 2014), a growth of 22 % in just three years.

TABLE 3. ENERGETIC POTENTIAL FROM AGRICULTURAL WASTE [5]

Harvest	Tons of waste	Energetic potential, TJ/year
Palm oil	2 166 150	20 895
Sugar bagasse	23 995 564	202 541
Coffee	5 855 490	56 925
Corn	1 707 150	18 332
Rice	5 910 964	26 191
Banana	11 284 153	6 444
Plantain	19 689 075	11 242
Total		342 570

In Colombia, approximately 62 200 GWh of electricity produced in the Integrated National System (SIN) in 2013, 804 GWh, equivalent to 1.3 % of such generation, corresponded to the use of biomass or, to be precise, to the energy use of sugarcane bagasse [5]. The use of biomass for heat production in the industry, especially represented using bagasse, some firewood, charcoal and other waste (such as those from palm oil and rice, generally used for exclusive heat production), represent approximately 11 % of the total final energy used by the consumer sector. On the other hand, the participation of biofuels in the national energy basket contributes, according to year 2012, with approximately 4.8 % of the final energy consumption in the transport sector and 7.04 % for 2013 in the case of road transport (that is, excluding air transport, fluvial, maritime and rail) [5].

However, beyond the energy use of biomass that is already done in Colombia, the potential to achieve a better use of agricultural waste resources is considerable. Table 3 shows the potential represented in the waste of 7 agricultural products.

3. METHODOLOGY

According to the assessment of the potential for renewable energy in Colombia, there are several possible strategies that can be proposed. The analysis undertaken begun with scientific studies from [12] to make it more consistent with a 2 °C-compatible global emissions target. This Colombia Decarbonization Pathway assumes that most of the economy-wide emission reductions will be accomplished through actions in the energy sector [10], [12]. This includes actions that must be taken in the short and midterm to set in motion the huge infrastructure changes that could allow energy-related emissions to decrease until acceptable levels after 2030, due to big investments in renewable energy facilities, energy efficiency and changes related to transportation technologies. Consequently, Colombia's energy-related emissions are expected to grow in the immediate future until 2030, and then decline through to 2050 [24].

This project aimed for a Deep Decarbonization Pathway of the energy grid that would be achieved by fuel switching, as well as new technologies such as electric vehicles and the deployment of new technologies such as wind and solar farms for electricity generation. This strategy has been developed after analysing the three types of policies the country could overtake according to [12], the first one oriented to high CO_2 taxes, the second aimed at abatement in GHG emissions and finally one intended to reduce the CO_2 emissions from fossil fuels combustion and industry (FF&I).

The FF&I abatement was chosen over the GHG abatement scenario mainly because when striking a restriction on FF&I CO_2 emissions only, most models in [12], predict lower carbon prices than in the GHG emission constraint scenario because the models find that actions aimed at CO_2 reductions in the energy system are cheaper than non-CO_2 reductions. The scenario with a 50 EUR/tCO_2 was disregarded because it was found that abatement scenarios deliver better results in reducing CO_2 emissions, no matter the model (TIAM ECN or GCAM)) due to fossil fuel combustion is reduced by the introduction of new energy technologies. Furthermore, the carbon tax scenario was not considered because the economic cost of a tax policy highly depends on what is done with the revenue collected from said tax. Unfortunately, the allocation of carbon tax revenue back into the country's economy as subsides to the representative consumer is not possible in Colombia, as 75 % of this income is going to be invested in rural development projects [12], that, even when they can be environmentally sustainable, would not impact heavily in the energy matrix. In [29], it is shown how only with a carbon tax around 165 EUR/tonne would the country see an emission abatement of 60 % but the effect on GDP varies from one model to another. It is also mentioned that to achieve the best results, the carbon tax should also be applied to fossil fuel exports, (which are currently excluded of [30]), resulting in a decline of coal exports, just to recover around 2040 when carbon capture and storage (CCS) had been deployed for electricity production from coal [29]. Furthermore, it is established that carbon tax value is 5 EUR/tCO_2 and it will be increased annually by 10 % until reaching 10 EUR$/ton$CO_2$, when a tax reform for this should be implemented again [29].

Since Colombia has substantial biological CO_2 sinks [31], and they are expected to rise until 2030 through its commitment to reforestation and afforestation efforts (REDD+), the decarbonization strategy will be powerfully supplemented by entrepreneurial initiatives promoting CO_2 sinks to compensate for energy-related GHG emissions.

3.1. Multi-Criteria Analysis

In order to develop a better strategy for reducing GHG emissions for Colombia, a Kaya Identity decomposition was done taking into account the main indicators, as annual GDP growth, the annual change of CO_2 intensity (kgCO_2·kg oil equivalent energy use^{-1}), energy use per GDP Annual Growth (%) in terms of kg of oil equivalent per 1 000 USD-GDP and the annual carbon dioxide emission change.

As can be observed in Fig. 3, the main driver for CO_2 emissions is CO_2 intensity followed by GDP growth. Energy efficiency in economic terms (Energy use per GDP) seems to have no big effect on CO_2 emissions and some years GDP growth appears to be completely decoupled from an improvement in energy efficiency in the country.

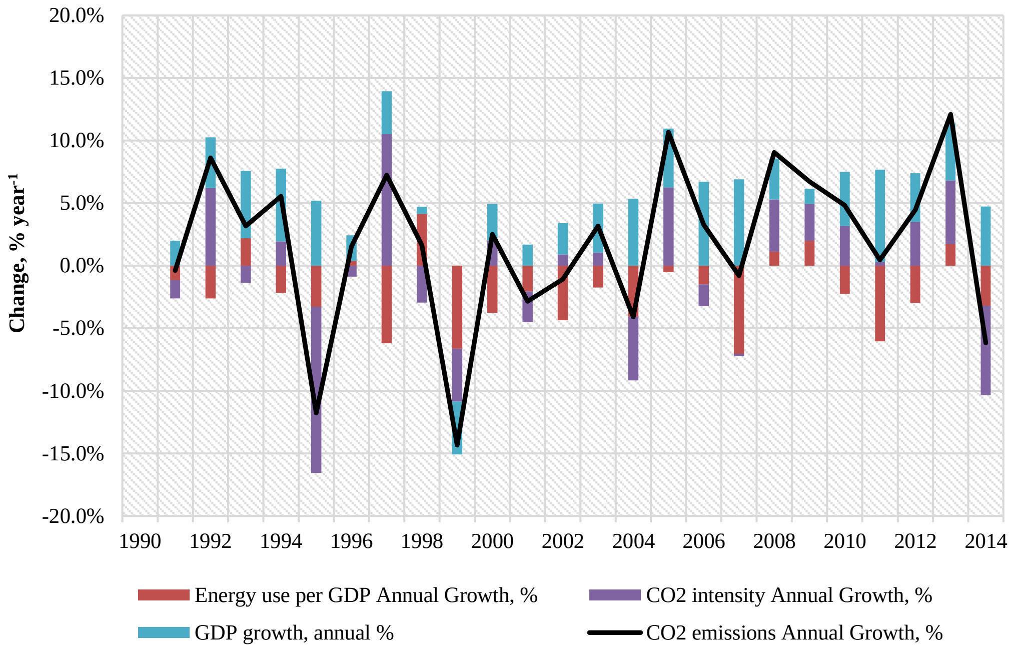

Fig. 3. Kaya Identity Decomposition. Own elaboration and using data from [22].

In Fig. 3 it is observed how carbon dioxide emissions are always dragged by CO_2 intensity (kg of CO_2 per kg of oil equivalent in energy use) which can be translated into the higher the energy consumption, the higher the GHG emissions due to the low share of RES in the energy matrix. This once again shows the urgency for pathways that make decarbonization of the energy matrix in the country possible.

After defining the types of available resources in the region under study, several attributes were taken into consideration to choose the model that brings the best results for Colombia according to the energy growth expectations and the scientific study performed by S. Calderon. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodology was the chosen one as multi-criteria analysis system for selecting the path to follow in the energy sector. This method concept relies on the chosen alternative that should have the shortest distance from the ideal solution and the farthest from the negative-ideal solution and it has been used before for selecting application methods within the environmental field [32], [33].

For doing so, it is necessary to transform the various attribute dimensions into non-dimensional attributes, allowing comparison among them:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \tag{1}$$

where

x_{ij} Dimensional attribute for determine alternative;

r_{ij} Non-dimensional attribute.

Then, a weighted normalized decision matrix is developed, by multiplying the non-dimensional factor by the given weight of each attribute:

$$v_{ij} = r_{ij} \cdot w_j, \tag{2}$$

where

v_{ij} Weighted normalized non-dimensional attribute;

w_j Given weight for determined attribute.

With these values, a weighted normalized decision matrix can be constructed:

$$\begin{bmatrix} v_{11}, v_{12}, \ldots & v_{1j}, \ldots & v_{1n} \\ v_{i1}, v_{i2}, \ldots & v_{ij}, \ldots & v_{in} \\ v_{m1}, v_{m2}, \ldots & v_{mj}, \ldots & v_{mn} \end{bmatrix}. \tag{3}$$

Later, the Ideal and Negative-Ideal solution must be determined:

$$A^+ = \{(\max_{v_{ij}} \mid j \in J), (\min_{v_{ij}} \mid j \in J') \mid i = 1, 2, \ldots, m\} = \{v_1^+, v_2^+, \ldots, v_m^+\}, \tag{4}$$

$$A^{-} = \{(\min_{v_{ij}} \mid j \in J), (\max_{v_{ij}} \mid j \in J') \mid i = 1, 2, \ldots, m\} = \{v_1^{-}, v_2^{-}, \ldots, v_m^{-}\}, \quad (5)$$

where

$J = \{ j = 1, 2, \ldots, n \mid j \text{ associated with benefit criteria}\}$;

$J' = \{ j = 1, 2, \ldots, n \mid j \text{ associated with cost criteria}\}$;

v_m^{+} Ideal solution for attribute;

v_m^{-} Negative ideal solution for attribute.

Afterwards, separation from Ideal solution for each alternative is calculated:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (v_j^{+} - v_{ij})^2}, \quad (6)$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} (v_j^{-} - v_{ij})^2}, \quad (7)$$

where

S_m^{+} Ideal Separation;

S_m^{-} Negative-Ideal Separation.

Finally, the relative closeness to the Ideal solution for each alternative is calculated as follows:

$$C_i^{*} = \frac{S_i^{-}}{(S_i^{+} + S_i^{-})}, 0 < C_i^{*} < 1, i = 1, 2, \ldots, m. \quad (8)$$

The attributes considered in this paper were: GDP per capita as from 2005–2012 the country has been growing at an annual ratio of 3.5 % - a higher value than the Latin America average [12] and any future policy should not go in detriment of the economy; CO_2 reduction potential as this is the proposed way to achieve the main goal of limiting the increase in temperature below 2 °C within the Paris agreement; Carbon capture and Storage (CCS) technologies deploy dependency as it is considered by the International Panel for Climate Change (IPCC) as a key factor to accomplish a global two degree target by the year 2100; and a new matrix for energy production in terms of primary energy composition and investment.

The models under study (alternatives) were the GCAM, TIAM ECM and PHOENIX, for the scenario of FF&I abatement, which are analysed in [12] and their results used here in this paper for the TOPSIS analysis.

A SWOT analysis was then undertaken to create the best possible strategy in order to develop the deployment of RES and other measures that assure the pathway for a decarbonization economy.

4. RESULTS

For the TOPSIS analysis, different weights were given to each attribute upon corresponding author consideration. GDP per capita prediction with 30 %, CO_2 reduction potential 25 %, Primary energy forecasted composition 15 %, the relying in CCS technologies with 10 % and the implementation cost considering proposed energy matrix [12] with 20 %.

TABLE 4. DECISION TABLE

Alternative	GDP per capita	CO_2 Reduction	Relying in CCS	Primary Energy Composition	Implementation Cost
GCAM	0.56	0.7	2	5	7
TIAM ECM	0.5	0.72	2.5	8	5
PHOENIX	0.3	0.8	1.5	4	8

Dimensional attribute values (x_{ij}) shown in Table 4, were given considering the results obtained from a simulation performed at [12]. Then, non-dimensional values (r_{ij}) were calculated using Eq. (1), and results are displayed in Table 5.

TABLE 5. NON-DIMENSIONAL ATTRIBUTES

Alternative	GDP per capita	CO_2 Reduction	Relying in CCS	Primary Energy Composition	Implementation Cost
GCAM	0.693	0.545	0.566	0.488	0.596
TIAM ECM	0.618	0.561	0.707	0.781	0.574
PHOENIX	0.371	0.623	0.424	0.390	0.319

Then, using Eq. (2), the weighted normalized attributes were calculated and displayed in Table 6.

TABLE 6. WEIGHTED NORMALIZED TABLE

Alternative	GDP per capita	CO_2 Reduction	Relying in CCS	Primary Energy Composition	Implementation Cost
GCAM	0.208	0.136	0.057	0.073	0.119
TIAM ECM	0.186	0.140	0.071	0.117	0.115
PHOENIX	0.111	0.156	0.042	0.059	0.064
A^+	0.208	0.156	0.071	0.117	0.119
A^-	0.111	0.136	0.042	0.059	0.064

Table 6 also shows the calculated values (using Eq. (4) and Eq. (5)) for ideal solution and non-ideal solution for each attribute. Subsequently, ideal separation and negative-ideal separation for each alternative was calculated with Eq. (6) and Eq. (7). Results are presented in Table 7. Closeness to ideal solution results, using Eq. (8), are also displayed in Table 7.

TABLE 7. IDEAL SEPARATION AND CLOSENESS TO IDEAL SOLUTION

Alternative	Si^+	Si^-	C^*
GCAM	0.050	0.113	0.693
TIAM ECM	0.028	0.111	0.802
PHOENIX	0.129	0.019	0.131

Using multi-criteria analysis, it was determined that the most suitable results for changing the energy matrix reducing CO_2 and maintaining an economical growth by using the available energy sources, were obtained by the TIAM ECM model in [12]. According to data obtained in [12], the country would obtain a rapid decarbonization in several sectors through the deployment of new cleaner technologies, as wind and solar.

Under this scenario of 50 % abatement of FF&I CO_2 emissions, projections in [12] show how the electricity sector might become CO_2 neutral, even when the carbon price is around half of that presented for the GHG abatement scenario, which is more consistent with current policies in Colombia. This is achieved thanks to the increase in installed capacities for hydro, wind and solar electricity generation. But, according to the TIAM ECM model, by 2050, almost 75 % of electricity should be generated from wind, about 5 % from solar and only 20 % from hydro. Such an increase in electricity capacity is well explained at [2] and [24] where demand growth by 2050 is expected to double the country installed capacity in 2016.

Not relying on high cost GHG mitigation technologies such as CCS or BECCS, allows investments in other sectors to reduce GHG, though the main efforts must be directed to transport, agricultural and commercial and residential buildings.

Having defined TIAM ECM as the model to follow for the energy sector strategy, it is necessary to look at other GHG emission sectors as agriculture, LULUCF, and waste. Therefore, strategic guidelines were developed to achieve the mentioned goals depending on each GHG emission sector using a SWOT analysis.

The considered strengths were rapid decarbonization after 2030 [12], deployment of clean energies [14], and high correlation between models about CO_2 reduction [12]. Within the weaknesses, the aspects were: no GHG emissions direct reduction [9], coal use with CCS in the primary energy composition [12], and an under developing country economy [7]. The opportunities considered were conventional energy demand reduction for transport sub-sector [6], increase in biological CO_2 sinks [31], money received through grants from Partners countries such as Norway, UK and Germany [9]. Finally, the identified threats are: Amazon forest deforestation [6], CCS not economically feasible for developing countries, CCS currently not available on a large scale, increase of natural disasters [4], [34]. The list of summarized strategies after the SWOT analysis was performed are as follows:

– Use the grants and loans from the World Bank, EU and donor countries under the scope of the Paris agreement to develop the required RES power plants as fast as possible;
– Use income from the carbon tax to promote sustainable development projects in rural areas to avoid further deforestation up to 2020;
– Create a mechanism that effectively starts to work in the Amazon region under the REDD+ programme. This organization or governmental body must be integrated by at least 50 % of native inhabitants of this region as they play a key role in identifying the main drivers for deforestation and usually, their tribes are the most affected by it;
– Continue with the adoption of adaptation measures all over the country to protect inhabitants and infrastructure, in high-risk areas from natural disasters that might become stronger and more prevalent due to climate change thus putting in danger

mostly populations in remote areas, the countryside and indigenous tribes;

- Create initiatives promoting CO_2 sinks to compensate for energy-related GHG emissions different from CO_2;
- As fossil fuels become less used within the energy matrix in the country, especially after 2030, use the increase in revenue from exports, to increase reforestation efforts and budget;
- Stimulate the growth of biofuels such as ethanol and biodiesel with second-generation facilities to take advantages of biomass waste as shown in Table 3, reducing the pressure on natural forests, increasing food security, strengthening the share of these fuels in the national market until achieving at least a 15 % mix of the used fuel by 2030;
- Generate financial aid and tax subventions to encourage the population to buy electric and fuel flex vehicles with at least 15 % of biodiesel fuel starting from 2025. After 2040 and depending on the technological diffusion of hydrogen cells in light-duty cars, create a policy that allows inhabitants with lower income to change their gas propel vehicles for new ones using the latest available technology;
- Perform a rural census where number of farmers, type of land use or activity, owner information, and total area per farmer are identified to be able to create an adaptation plan for the agricultural sector;
- Development and implementation of the adaptation plan for the agricultural sector and maintain a yearly basis update according to reports;
- Implementation of a mandatory one to two-year course on climate change within public and private elementary schools to make new generations more aware of the new challenges in this area and how everyone can reduce the footprint from their homes;
- Develop and articulate laws and regulations in order to enter into an emissions trading system that allows to increase revenue in the public and private sector for climate change mitigation measures;
- New hydropower facilities should be constructed with capacities not higher than 10 MW, to reduce environmental impacts on the surrounding communities and ensure nutrients carried by river streams.

5. ECONOMIC ASSESSMENT AND ABATEMENT POTENTIAL

If Colombia successfully embraces the mentioned kinds of policies, its energy production could become CO_2 neutral by 2050 [12], and its total GHG could decrease down to 80 % as shown in the MAC curve at Fig. 4.

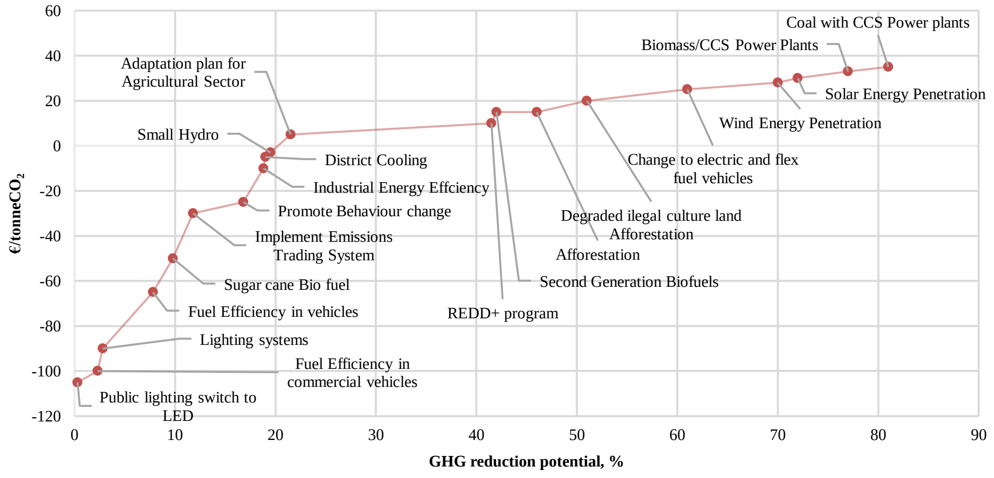

Fig. 4. MAC curve for technology diffusion in Colombia.

Due to the high importance of the deployment of wind and solar energy and the country's available resources, a cost analysis was performed to estimate the investment costs for the required energy in 2050, according with results from [2] and [12]. Development of this energy is not only important for fulfilling the forecasted electricity demand growth, but also because the country must aim for the electrification of its energy matrix. By doing so, Colombia might introduce the use of clean energy sources in the transport subsector displacing the use of liquid fossil fuels, sell electricity for the manufacturing subsector as well, and eliminate, on a large scale, the fugitive emissions from CHP plants used to cover the electricity demand during drought seasons.

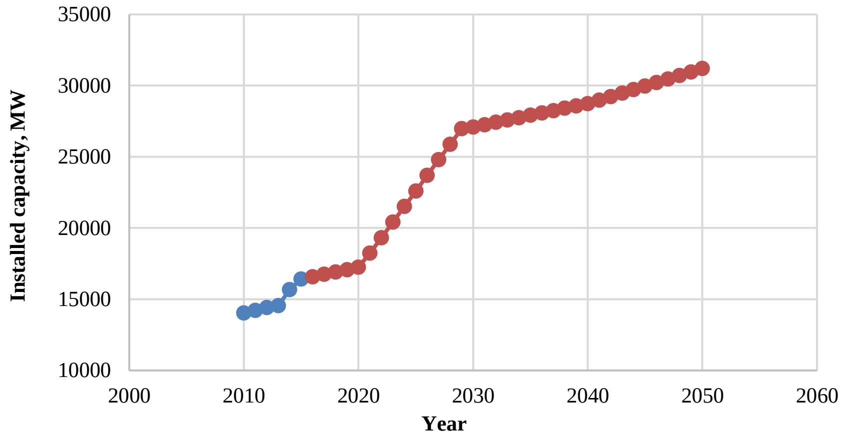

Fig. 5. Demand for electrical power until 2050.

Having in mind the results from [12] and the forecast from [2] and [24], the electricity market must grow rapidly and mainly from wind and solar power to reach an extra 90 % of its now installed capacity by 2050, as can be seen in Fig. 5. The deployment of new electrical capacity must be achieved mainly from 2020 until 2030 [2], [12], [29], where it has been estimated the country will have a considerable increase in its GDP with an economy still depending on energy consumption and the necessity of reducing its GDP intensity in terms of CO_2 emissions. Once the country has achieved an electrical grid with a higher share of non-conventional renewable energy sources, its GDP may keep growing with a lower energy intensity and lower upward behaviour. If by 2045, CCS and BECCS come to be economically feasible and available on a large scale, the economy of the country might be boosted by increasing once again the coal exports [12], [29].

As shown in Fig. 5, the installed electricity capacity must be increased by 90 % before reaching 2050, which means a total installed capacity of 31 424 MW and according to [12], and results from multi-criteria analysis, 60 % should come from wind power. For these calculations, the operational and maintenance costs were estimated at 60 USD/kW/year [19] and general inputs are shown in Table 8.

TABLE 8. LCOE AND INCREMENTAL COSTS (WIND ENERGY)

	North Coast	Santander	Huila	Boyacá
LCOE wind, USD/kWh	0.084	0.101	0.101	0.101
LCOE baseline, USD/kWh	0.115	0.115	0.115	0.115
Max. electricity output possible, GWh	59 229	12 437	5 046	2 355
Capacity installed per zone, MW	16 946	4 270	1 579	0

As can be seen from Table 8, for the deployment of wind energy, it would be necessary to use different percentages of land regarding the region in the four main wind power potential departments (Table 1) and it was assumed that 20 % of the investment will come from aid received under the framework of the Paris agreement.

Fig. 6 shows the calculated LCOE that can vary from 0.084 USD/kWh to 0.1 USD/kWh depending on the region, after calculating a new 24 788 MW of newly installed facilities for electrical generation from wind power. The consumer tariff was taken from [2], while the marginal grid mix cost of electricity was calculated for the current grid mix conditions.

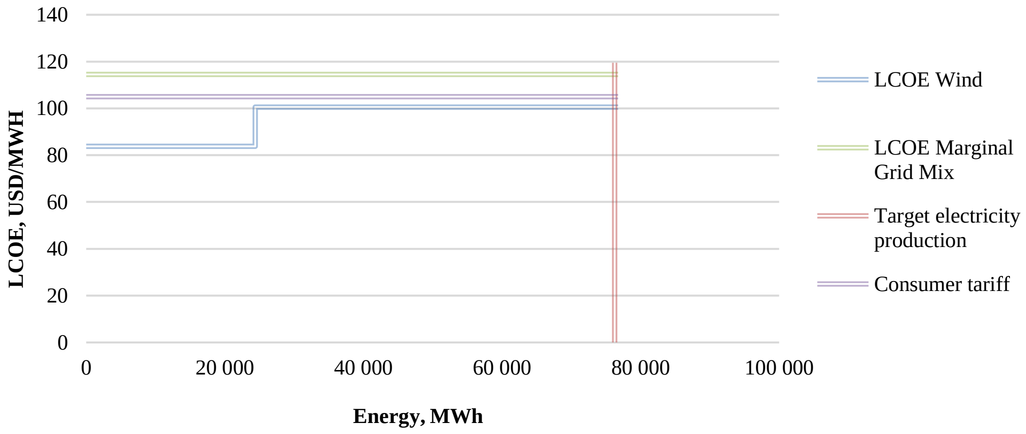

Fig. 6. LCOE comparison for wind energy.

6. CONCLUSIONS

This paper presents a summarized set of policies Colombia might take on to fulfil with its current international commitments in the reduction of GHG emissions. Even when the scenarios investigated are only illustrative, these previous studies have been carried out considering a wide set of variables that might simplify in a comprehensive way the reality the country faces, the opportunities and barriers and the simulated results obtained.

TOPSIS multi-criteria analysis, is a tool widely used for academic, business, industrial and finance purposes, and now in this paper it was used as a tool for selecting the model with closer results to what is expected from the country considering the RES availability and its obstacles. It was found that the TIAM ECM model from [12] was the one closer to the ideal solution, by taking advantage of the great wind potential Colombia has in the northern area of its geography. It was found that, by using only 17 % of the available land in this region, the country might obtain almost 17 GW of new installed capacity, which is almost equal to the present day total electric capacity. In addition to another two deployments of new wind capacity in other regions of the country and by increasing the technological diffusion of PV, the electricity grid of the country could become CO_2 neutral by 2040 due to the high hydropower production already in motion.

After a SWOT analysis was conducted, a set of policies was proposed and considering them, a MAC curve for the technological diffusion of these measures was made to show the total abatement potential such policies might have on the reduction of GHG emission finding a total abatement of 80 %, value that is way beyond the intended goal of the country [9]. It is important to notice that this abatement potential would only be achieved if the country rapidly deploys new electricity capacity from the mentioned RES and this is accompanied by regulations that push sectors such as industrial, transport, manufacturing and residential towards the electrification of needs that are currently covered by fossil fuels.

The GHG emissions associated with the AFOLU sector can be, in theory, easily reduced if the country uses revenue from the carbon tax and to some extent the revenue from exports of fossil fuels into the REDD+ programme. Of course, in practice, Colombia faces enormous challenges in this area due to illegal crops, illegal mining and the increasing use of land for agriculture and cattle; issues that only can be solved with policy changes in the international combat of drugs, strengthening local regulations against illegal mining and behavioural changes of inhabitants towards food production and consuming.

It is also worth mention, that this proposal path for the decarbonization of the economy, might be accomplished in several ways, especially in regard to the energy sector. In [35], it is proposed a different alternative for the energy grid matrix, with the deployment at a large scale of PV systems due to the abundance of the resource thanks to the geographical position of the country. This only reflects how there might be several paths for reducing GHG emissions, but the most important is the development of clear policies that aid to eliminate legal and financial barriers to non-conventional renewable energy sources.

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ANNEX

TABLE 1. GENERAL INPUT FOR LCOE CALCULATION (WIND ENERGY)

Country	Colombia
Renewable energy target	60.0 %
Target renewable electricity production, GWh	76 266 00
Lifetime of investment, years	30
Wind investment costs, USD/MW	2 000 000
Public cost of capital	6.0 %
Investment grant	20.0 %

TABLE 2. GEOGRAPHICAL AND TECHNOLOGY CHARACTERISTICS

	North Coast	Santander	Huila	Boyacá
Land availability	17.0 %	4.0 %	2.5 %	1.0 %
Density factor for 2 MW wind turbine, MW/km^2	3.5			
System Availability	95 %			
Maximum Energy Potential to install, MW	20 000	5 000	2 000	1 000
Wind capacity factor	42.0 %	35.0 %	35.0 %	35.0 %
Full load hours, FLH	3 679	3 066	3 066	3 066
Area, km^2	28 480	30 500	19 800	23 100
Usable land, km^2	4 841.6	1 220.0	495.0	231.0
Max. capacity possible, MW	16 945.6	4 270.0	1 732.5	808.5
Max. electricity output possible, GWh	59 228.9	12 437.2	5 046.3	2 354.9
Energy extracted per zone, GWh	59 228.9	12 437.2	4 599.8	0.0
Capacity installed per zone, MW	16 945.6	4 270.0	1 579.2	0.0

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