

GHG diffuse emissions estimation, and energy security to ENSO using MERRA-2 for largely hydroelectricity-based system

Estimación de emisiones difusas de GEI, y seguridad energética ligada al Fenomeno del Niño utilizando MERRA-2 para sistemas basados en hidrogenación



Harold David Cuadros Tejeda ¹, Yohen Cuellar ¹, J. S. Chiriví Salomón ¹, Marco Guevara^{1,2*}

¹Conservación, Bioprospección y Desarrollo Sostenible (COBIDES), Escuela de Ciencias Agrícolas, Pecuarias y del Medio Ambiente (ECAPMA), Universidad Nacional Abierta y a Distancia. Calle 14 Sur # 14 – 23. C. P. 3443700. Bogotá, Colombia.

²GICA-Grupo de Investigación de Calidad del Aire, Departamento de Ingeniería Química y Ambiental, Universidad Nacional de Colombia. Calle 44 # 45-67. C. P. 111321. Bogotá, Colombia.

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ABSTRACT: In Colombia, hydropower share was 70 % of the total installed capacity and more than 50 % of the monthly generation share in 2015, which coincided with the strongest El Niño Southern Oscillation (ENSO) phenomenon reported in the region. ENSO has been recognized as an influential climate pattern on meteorological variables. The generation via hydropower implies the construction of dams and water reservoirs; these flooded areas generate an important amount of Green House Gases (GHG). In this regard, the main aim of this research was to quantify the diffusing emissions of CO₂ and CH₄ in the flooded areas of the main hydroelectric power generation facilities in Colombia. GHG emissions were calculated by the implementation of an IPCC methodology. The obtained results show that more than 1,042,500 t CO₂-Eq (i.e. CO₂ and CH₄) are emitted in Colombia per year from this source, representing 4.4 % of the total GHG emissions in the country. As the second aim, the vulnerability of Colombia's energy independence, in terms of power supply to ENSO and climate change was analyzed using the MERRA-2 dataset from NASA, for the years between 2010 and 2017.

RESUMEN: En Colombia, la participación de la energía hidroeléctrica fue del 70% de la capacidad instalada y más del 50% de la participación de la generación en 2015, lo que coincidió con el más fuerte Fenómeno del Niño reportado históricamente en la región. El Fenómeno del Niño ha sido reconocido como un patrón climático influyente en las variables meteorológicas. La generación a través de hidroelectricidad implica la construcción de represas de agua; estas superficies inundadas generan emisiones importantes de Gases de efecto invernadero (GEI). El objetivo principal de esta investigación es cuantificar las emisiones de CO₂ y CH₄ en las áreas inundadas del país. Las emisiones de GEI se calcularon mediante la implementación de una metodología del IPCC. Los resultados obtenidos muestran que esta fuente emite más de 1,042,500 t de CO₂-Eq (es decir, CO₂ y CH₄) en Colombia, lo que representa el 4.4% del total de emisiones de GEI en el país. Como segundo objetivo, se analizó la vulnerabilidad de la independencia energética de Colombia, en términos de suministro de energía durante periodos de Fenómeno del Niño y cambio climático, utilizando los datos del modelo MERRA-2 de la NASA para los años entre 2010 y 2017.

Symbol	Term	Units SI
A	Area	m ²
V	Volume	m ³
W	Watt	J/s
Gg	Gigagram	10 ⁹ g
t	Tone	10 ⁶ g

Abbreviation	Term
GHG	Green House Gases
CO ₂	Carbon Dioxide
CH ₄	Methane
CO ₂ -Eq	Equivalent Carbon Dioxide
OM	Organic Matter
EF	Emission Factor
SIN	Sistema Interconectado Nacional (National Interconnected System)

* Corresponding author: Marco Guevara

E-mail: maguevaral@unal.edu.co

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1. Introduction

In Colombia, 70 % of the electricity is generated by hydropower plants located along the mountains of the country (Figure 1). This share will increase in the next years with the estimated internal energy demand, aiming to use the big power potential of the country. Accordingly, the construction of new hydropower plants is planned by the government [1, 2]. Even though the electricity generation has been historically supplied by hydropower, there is 30 % of the energy mix produced by thermoelectric plants, which use coal, natural gas, and other fossil fuels. Furthermore, during the strongest *El Niño* Southern Oscillation (ENSO) phenomenon reported, the one that occurred in 2015, the electricity produced by hydropower plants reached 50 % of contribution in the national generation mix [3], evidencing an important vulnerability to the climate change. This situation led to water-resource cutoffs in many cities and towns along the country.

The dams required by the hydroelectric power plants are built to contain the water reservoirs based on flooded areas [4], which are mainly located in tropical mountain forests in Colombia [5]. The water reservoirs based on flooded areas in tropical weather have been recently studied for the purpose of estimating their environmental impact based on the Green House Gases (GHG) diffuse emissions to the atmosphere [6–10]. The share of hydropower in the Latin American countries such as Ecuador is about 40 %, which is a lower percentage in comparison with the share in Colombia [8, 11, 12]. This circumstance became an important case of study for strategic energy planning in Colombia [13].

ENSO is recognized as an influential climate pattern on meteorological variables such as global solar radiation, wind speed, and precipitation rates, affecting directly the hydropower supply [14, 15]. Colombia, as a dependent country on hydroelectric power generation technologies, is sensitive to climate change [13]. This strong dependency makes climate change an issue to be included in the development plan of the country. Because of this, ENSO phenomenon has been analyzed during the last years in order to determine the sensitivity of the country to global warming [16–20]. Subsequently, the main aim of this research is to quantify the diffusing emissions of CO₂ and CH₄ in the reservoirs corresponding to flooded areas located in the main hydroelectric power facilities in Colombia. To achieve this, we first summarized the energy production by technology in terms of the available installed capacity. Then, the IPCC methodology for diffusing GHG emissions calculation was implemented over the flooded areas in each of the listed hydropower facilities [21, 22]. As for last consideration, the dependency analysis of the country energy generation to ENSO was performed using

data from the MERRA-2 dataset from NASA for the years of 2014 to 2017 [5, 23–26]

Table 1 Mean monthly generation per technology type in Colombia 2015 year [3]

Technology	Generation, GWh	Share, %
Diesel	259.77	4.55
Hydroelectric	2,906.03	50.95
Co-generation	50.12	0.88
Coal	737.37	12.93
Oil	111.10	1.95
Gas	1,419.62	24.89
Jet-A1	0.00	0.00
Gas-Coal Mixture	0.00	0.00
Kerosene	17.14	0.30
Small Hydroelectric	150.31	2.64
Small Gas	45.76	0.80
Wind	6.67	0.12
Solar	0.00	0.00
TOTAL	5,703.88	100.00

Table 2 Installed capacity per Technology type in Colombia 2015 year [3]

Technology	Power, MW	Share, %
Hydraulic	11,500.50	69.97
Thermal gas	1,619.50	9.85
Thermal coal	1,348.40	8.20
Liquids	1,92.00	9.69
Gas-Liquids	264.00	1.61
Wind	18.40	0.11
Biomass	93.20	0.57
Solar	0.00	0.00
Total	16.436.00	100.00

2. Materials and methods

2.1 Energy Generation in Colombia

The energy generation infrastructure in Colombia consists of different technologies, which are operating under the total installed capacity. This current situation represents the reference for the comparison between technologies and their impact on the national GHG emissions to the atmosphere. The mean monthly energy production in Colombia is presented based on the data of energy production during the year 2015 (Table 1). The installed capacity by technology in Colombia is shown (Table 2) to assess the distribution of available infrastructure in the country, which is compared with the monthly energy production previously described.

Table 3 Summary of Main Hydroelectric power plants in Colombia (Adapted from XM S.A. E.S.P. [2017])

Hydroelectric Power Plant	Department/Town	Flooding area, ha	In service since	Storage Capacity*, m3	Useful Volume*, m3	Location (rivers)	Height, m.o.s.l	Installed Capacity, MW
San Carlos	Antioquia/San Carlos	340	1,984	61.7	53.23	Reservoir Guatapé river Carlos River	775	1,24
El Guavio	Cundinamarca/Ubalá	1,5	1,992	1,043	950	Guavio river Batatas river Chivor river	1,642	1,213
Chivor	Boyacá/Santa María	1,26	1,977	760	668	Reservoir La Esmeralda Batá river	1,28	1
Sogamoso	Santander/ Girón and Betulia	7	2,014	4,8		Reservoir Topocoro Sogamosos river	320	820
Porce III	Antioquia/Amalfi, Anori, Gómez Plata and Guadalupe	461	2,01	169	127	Porce river	680	660
Guatapé	Antioquia/San Rafael, Guatapé and Peñol	6,24	1,978	1,071		Reservoir Peñol-Guatapé Nare river	1,887	560
Betania	Huila/Campoalegre, Hobo and Yaguará	7,4	1,987	1,971		Magdalena river Yaguará river	564	540
Porce II	Antioquia/Amalfi and Anori	890	2,001	142		Porce river	869	405
El Quimbo	Huila/Gigante, El Agrado, Garzón, Paicol and Tesalia	8,25	2,015	3,215	1,824	Suaza river	720	400
Miel I	Caldas/Norcasia	1,22	2,002	571	445	Reservoir Amani La Miel river	445	396
Alto Anchicayá	Valle del Cauca/Buenaventura and Dagua	170	1,974	45	30	Verde river Anchicayá river	655	365
Urrao I	Córdoba/Tierra Alta	7,4	2	1,74	1,234	Sinú river	130.5	340
Salvajina	Cauca/Suarez	2,031	1,985	906	753	Cauca river	1,155	285
Jaguas	Antioquia/San Rafael, San Roque and Alejandria	1,06	1,988	208	180	Nare river Guatapé river	1,247	170
Calima	Valle del Cauca/ Calima Darién	1,934	1,966	530	437	Calima river Bravo river	1,45	132

*The reported data is divided by 10⁶.

**Weather in all hydroelectric power plants locations is Tropical Wet.

The amount of energy generated achieves 5,703.88 GWh per month in the country. The hydroelectric has the biggest share of the energy mix in the country, even during the year 2015 when the strongest ENSO phenomenon was reported, which affects the generation performance due to the low level in water reservoirs. Nevertheless, the national energy demand increases from 3.9 to 4.4 % by year [2], showing the situation above as an important risk for the national energetic security in the country [13].

2.2 Studied power plants

In this research, the main hydroelectric power plants in Colombia were considered as the hydropower facilities with the biggest flooded areas associated with their operation (Table 3, Figure 1). Table 3 summarizes the main hydroelectric power plants in the country. Data about the flooded area and reservoir capacity were detailed for GHG diffuse emissions calculations, which are described in the next sections.

2.3 MERRA-2 datasets

MERRA-2 is a dataset which contains results of simulations developed by NASA that hosts meteorological variables along the globe with a spatial resolution of $0.5^\circ \times 0.625^\circ$ [55.5 km x 69.375 km] [26]. This dataset incorporates observation types not available for its predecessor and includes updates to the Goddard Earth Observing System (GEOS) model and an analysis scheme to offer an advanced product suite suitable for the weather and climate applications. The M2TINXFLX v5.12.4 variable [or Total Surface Precipitation] and M2IMNXLFO v5.12.4 variable [Surface Air Temperature] were used for the sensitivity to climate change analysis. Data were retrieved from the online platform GIOVANNI from NASA [23, 24, 27, 28].

2.4 Methodology

The methodology implemented in the calculation of diffusing GHG emissions, CO_2 , and CH_4 , from the main hydroelectric power plants in Colombia, was based on the following equations (Equation (1) and Equation 2) [21] and measures (Table 4 and 5):

Method for CO_2 :

$$\text{CO}_2 \text{ diffuse emissions} = \left[\left(P_f * E_f(\text{CO}_2)_{\text{dif}} \right) + \left(P_i * E_i(\text{CO}_2)_{\text{dif}} \right) \right] * \left(A_{\text{flooded surface}} * f_A * 10^{-6} \right) \quad (1)$$

Where:

$\text{CO}_2 \text{ diffuse emissions}$ = total emissions of CO_2 from flooded areas, Gg $\text{CO}_2 \text{ year}^{-1}$.

P_f = ice-free period, days year^{-1}

P_i = period with ice, days year^{-1} (not applicable over Colombia).

$E_f(\text{CO}_2)_{\text{dif}}$ = Daily average of diffuse emissions from the air-water interface during the ice-free period, kg $\text{CO}_2 \text{ ha}^{-1} \text{ day}^{-1}$.

$E_i(\text{CO}_2)_{\text{dif}}$ = Diffuse emissions related to the ice-covered period, kg $\text{CO}_2 \text{ ha}^{-1} \text{ day}^{-1}$.

$A_{\text{flooded surface}}$ = Total surface area of the reservoir, including flooded lands, lakes and rivers, ha.

f_A = Fraction of the total area of the reservoir that was flooded in the last 10 years, dimensionless.

Method for CH_4 :

Table 4 Measured CO_2 emissions from flooded [21]

Weather	Diffuse emissions (Ice free period) $E_f(\text{CO}_2)_{\text{dif}}$ (kg. de $\text{CO}_2 \text{ ha}^{-1} \text{ day}^{-1}$) *				
	Median	Min.	Max.	N_m	N_{res}
Polar / Boreal very wet	11.8	0.8	34.5	1,011	20
Medium cold, wet.	15.2	4.5	86.3	633	20
Medium warm, wet.	8.1	-10.3	57.5	507	33
Medium warm, dry.	5.2	-12.0	31.0	390	43
Tropical, very wet.	44.9	11.5	90.9	642	7
Tropical, dry.	39.1	11.7	58.7	197	5

*The values in the second column represent the means of CO_2 emissions, which correspond to the arithmetic means of the flows measured on the individual reservoirs. The Min and Max values correspond to the lowest and the highest of all the individual measurements within a given climatic region; they are given only as an indicator of the variability N_m = a number of measurements; N_{res} = number of reservoirs sampled. These measures may include non-anthropogenic emissions (e.g., Emissions from carbon in the upstream basin) and possible double counts of anthropogenic emissions (e.g., wastewater from urban areas of the reservoir region) and thus may overestimate emissions [21].

$$\text{CH}_4 \text{ diffuse emissions} = P * E(\text{CH}_4)_{\text{dif}} * A_{\text{flooded Surface}} * 10^{-6} \quad (2)$$

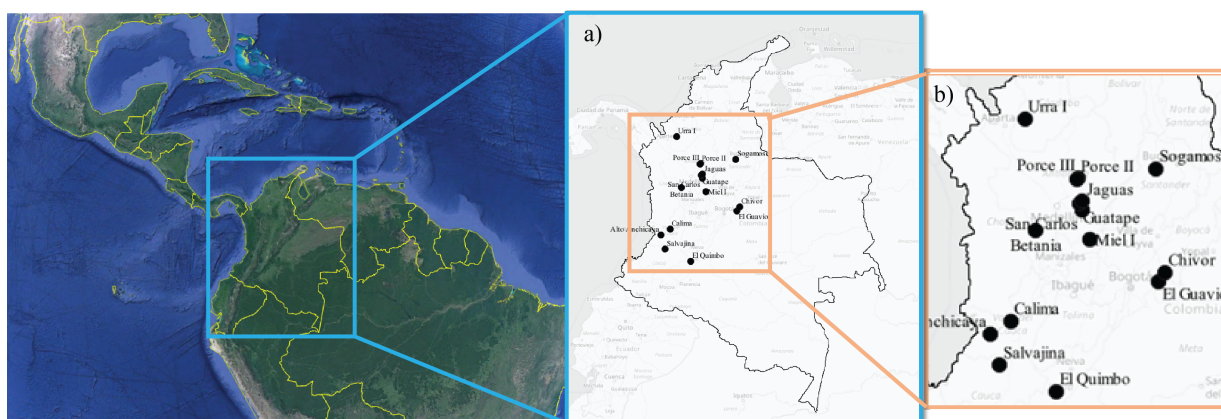


Figure 1 Main hydroelectric power plants in Colombia: a) General map of Colombia, b) Detailed area of hydroelectric potential in the Colombian Andes Mountains. (Source: This study)

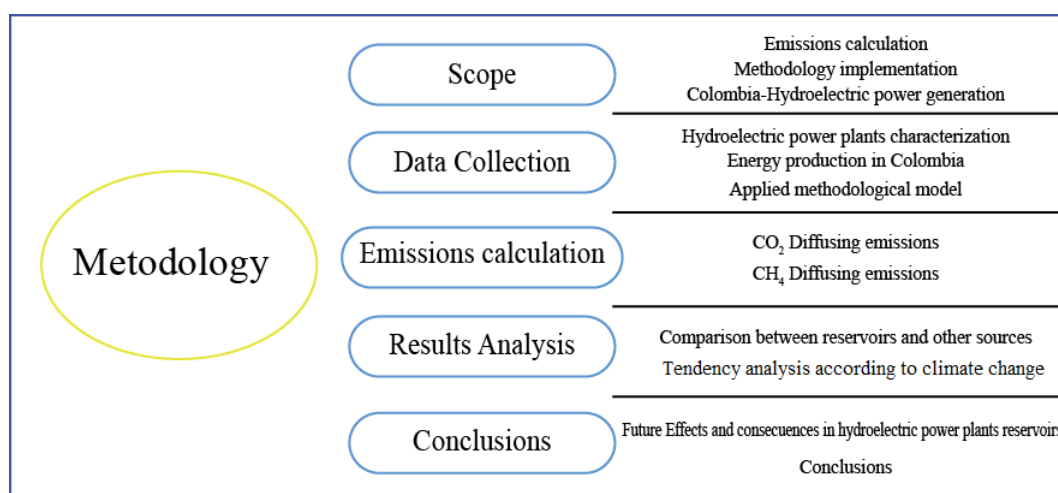


Figure 2 Methodological scheme for calculation and analysis of diffuse emissions of GHG from hydroelectric reservoirs (Source: This Study)

Where:

CH_4 diffuse emissions = total diffuse emissions of CH₄ from flooded areas, Gg CH₄ year⁻¹.

P = period with ice, days year⁻¹ (not applicable in Colombia).

$E(CH_4)_{dif}$ = daily mean diffuse emissions, kg CH₄ ha⁻¹ day⁻¹.

$A_{flooded\ surface}$ = total area of the flooded area, including flooded lands, lakes and rivers, ha.

of the scope founded on available information to generate a new one. The analysis consisted of the comparison with other types of generation technologies using different resources available in the country. An analysis of the main disadvantages of the hydropower generation technology in the tropical areas during the effects of ENSO phenomenon was also performed [13, 29]. This last aspect results to be important in the energy development planning of the country, the intermittency in the resource affects directly the rate of energy production in a stable way. The effect of this situation is rapidly increasing, leading to critical and unsustainable the energy production in the near future, mainly driven by the global warming and the increasing demand for energy.

The methodology used for this calculation of GHG from water reservoirs in hydropower plants consists of the scheme (Figure 2), which is deeply related with the inductive approach, taking as starting point the definition

Table 5 Measured CH₄ from flooded land [21, 22]

Weather	Diffuse emissions (Ice free period) Ef(CO ₂) _{dif} (kg. de CO ₂ ha ⁻¹ day ⁻¹) *				
	Median	Min.	Max.	N _m	N _{res}
Polar / Boreal very wet	11.8	0.8	34.5	1,011	20
Medium cold, wet.	15.2	4.5	86.3	633	20
Medium warm, wet.	8.1	-10.3	57.5	507	33
Medium warm, dry.	5.2	-12.0	31.0	390	43
Tropical, very wet.	44.9	11.5	90.9	642	7
Tropical, dry.	39.1	11.7	58.7	197	5

*Same as table 4.

3. Results and discussion

3.1 Calculation of diffuse emissions for the San Carlos hydroelectric power plant

The data for the water reservoir in San Carlos hydroelectric power plant was obtained (Table 6). This input data was required for the calculation of GHG diffuse emissions. Carbon dioxide and methane were calculated for the main hydroelectric power plants in Colombia using this approach, only the calculation for San Carlos plant was documented as a detailed example, but the results are presented for all the plants involved in this research (Table 7).

Table 6 General data extracted for reservoir Punchiná – San Carlos [Source: This Study]

Variable	Magnitude	Units
Weather	Tropical wet	-
$E_f(CO_2)_{dif}$	44.90	kg CO ₂ ha ⁻¹ day ⁻¹
$E(CH_4)_{dif}$	0.63	kg CH ₄ ha ⁻¹ day ⁻¹
Free Ice period	365.00	days
Flooded Area	340.00	ha
In service Since	1984.00	-
Flooded fraction of total area	1.00	-

Calculation of CO₂ diffuse emissions for the San Carlos hydroelectric power plant

Using the equations: Equation (1) for CO₂. The diffuse emissions are computed according to Equation (3), Equation (4) and Equation (5):

$$CO_2 \text{ emissions} = \left[\left(\left(\frac{365 \text{ days year}^{-1}}{44.9 \text{ kg CO}_2 \text{ ha}^{-1} \text{ day}^{-1}} \right) + (0) \right) * (340 * 10^{-6}) \right] \quad (3)$$

$$CO_2 \text{ emissions} = \left[\frac{(16388.5 \text{ kg CO}_2 \text{ ha}^{-1} \text{ year}^{-1})}{(3.4 * 10^{-4} \text{ ha})} \right] \quad (4)$$

$$CO_2 \text{ emissions} = 5.6 \text{ Gg CO}_2 \text{ year}^{-1} \quad (5)$$

Calculation of CH₄ diffuse emissions for the San Carlos hydroelectric power plant

Using the equations: Equation (2) for CH₄. The diffuse emissions are computed according to Equation (6) and Equation (7): in a similar way as CO₂ in the section above.

$$CH_4 \text{ Emissions} = 365 \text{ day year}^{-1} * 0,630 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1} * 340 \text{ ha} * 10^{-6} \quad (6)$$

$$CH_4 \text{ Emissions} = 0.08 \text{ Gg CH}_4 \text{ year}^{-1} \quad (7)$$

3.2 Calculation of diffuse emissions for all the main hydroelectric power plants in Colombia

This section summarizes the results of the calculation shown in detail in the last section, in this case for all the hydroelectric power plants in this research. The results in terms of each GHG, i.e. CO₂ and CH₄, are shown, as well as their equal in CO₂ for the CH₄, and the total emissions of both pollutants (Table 7).

3.3 Comparison of diffuse emissions between hydroelectric power plants and other available resources in Colombia

The total emissions and power generation rates were compared with the generation of other resources available in Colombia (Table 8, Figure 3). From these data, we remarked that hydropower is the resource that generates less GHG emissions per MWh produced, due to a large amount of hydropower production activities in the country. The total emissions from hydropower are larger than the sugar cane residues or kerosene burning for energy generation purposes.

Regarding the total emissions from other resources, the full amount of energy generation in 2015 was 38,938,000 MWh, to produce this amount of energy 23,458,556 t CO₂-Eq year⁻¹ were emitted to the atmosphere (Table 9).

Table 7 CO₂ and CH₄ diffusing emissions for main hydroelectric power plants in Colombia [Source: This study]

Hydroelectric power plant	Energy generation, GWh	CO ₂ Emissions, Gg year ⁻¹	CH ₄ Emissions, Gg year ⁻¹	CH ₄ Emissions in terms of CO ₂ -Eq, year ⁻¹ Gg	CO ₂ -Eq Total emissions, Gg year ⁻¹
San Carlos	6,020	5.6	0.08	2.00	7.60
El Guavio	5,700	24.6	0.34	8.50	33.10
Chivor	3,626	20.6	0.28	7.00	27.60
Sogamoso	5,056	114.7	1.60	40.00	154.70
Porce III	3,605	7.6	0.11	2.75	10.35
Guatapé	1,945	102.3	1.40	35.00	137.30
Betania	2,304	121.3	1.70	42.50	163.80
Porce II	1,294	14.6	0.20	5.00	19.60
El Quimbo	2,216	135.2	1.90	47.50	182.70
Miel I	1,460	20.0	0.28	7.00	27.00
Alto Anchicayá	2,291	2.8	0.04	1.00	3.80
Urra I	1,421	121.3	1.70	42.50	163.80
Salvajina	1,050	33.3	0.47	11.75	45.05
Jaguas	770	17.4	0.24	6.00	23.40
Calima	180	31.7	0.44	11.00	42.70
TOTAL	38,938	773.0	10.78	269.50	1,042.50

Table 8 CO₂-Eq GHG Emissions from different types of energy generation[3]

Resource	Generated energy, MWh	Total emissions, t CO ₂ -Eq year ⁻¹	Emission Factor (EF), t CO ₂ -Eq/MWh
Water	38,938,000	1,042,500.00	0.03
Diesel	3,117,240	10,500,081.36	3.40
Sugar cane residues	601,440	376,606.32	0.63
Coal	8,848,440	8,211,919.20	1.00
Fuel-oil	1,333,200	3,175,320.72	2.40
Gas	17,035,440	1,102,604.16	0.10
Kerosene	205,680	92,024.52	0.45

The hydropower is 50.95 % of the total energy generation during 2015, a low value considering the installed capacity is about 70% (Table 2). In terms of GHG emissions, the 4.4 % of the GHG were emitted from hydropower generation during 2015.

3.4 Uncertainty Analysis

The uncertainty of the used method for CH₄ and CO₂ is mainly affected by two aspects: emission factors, and the estimation of the flooded area [21, 32].

According to the input data used for this study, the emission factors vary between 1 and 2 orders of magnitude depending on the reservoir location, and selection of the emission factor. This corresponds to relatively high uncertainty, and the obtained results are perhaps an overestimation. For this study, we consider the location

of the reservoirs and their size according to official data, based on this, we assume the emission factor vary with 1 order of magnitude in the worst case.

In terms of flooded areas estimations, the data is accurate with a range of 10% for flooded areas larger than 100 km². For the flooded areas with less than 100 km², the range of accuracy may vary from 10 to 50%[21]. For this study, the data was taken from official sources, according to this, we assume the accuracy of the data about the flooded areas is ±25%.

In this case, the best scenario in terms of error is ±10% in the flooded area values, and 1 order of magnitude variation in the emission factors. The worst-case scenario, in terms of error, is ±25% in the flooded area values, and 1 order of magnitude variation in the emission factors.

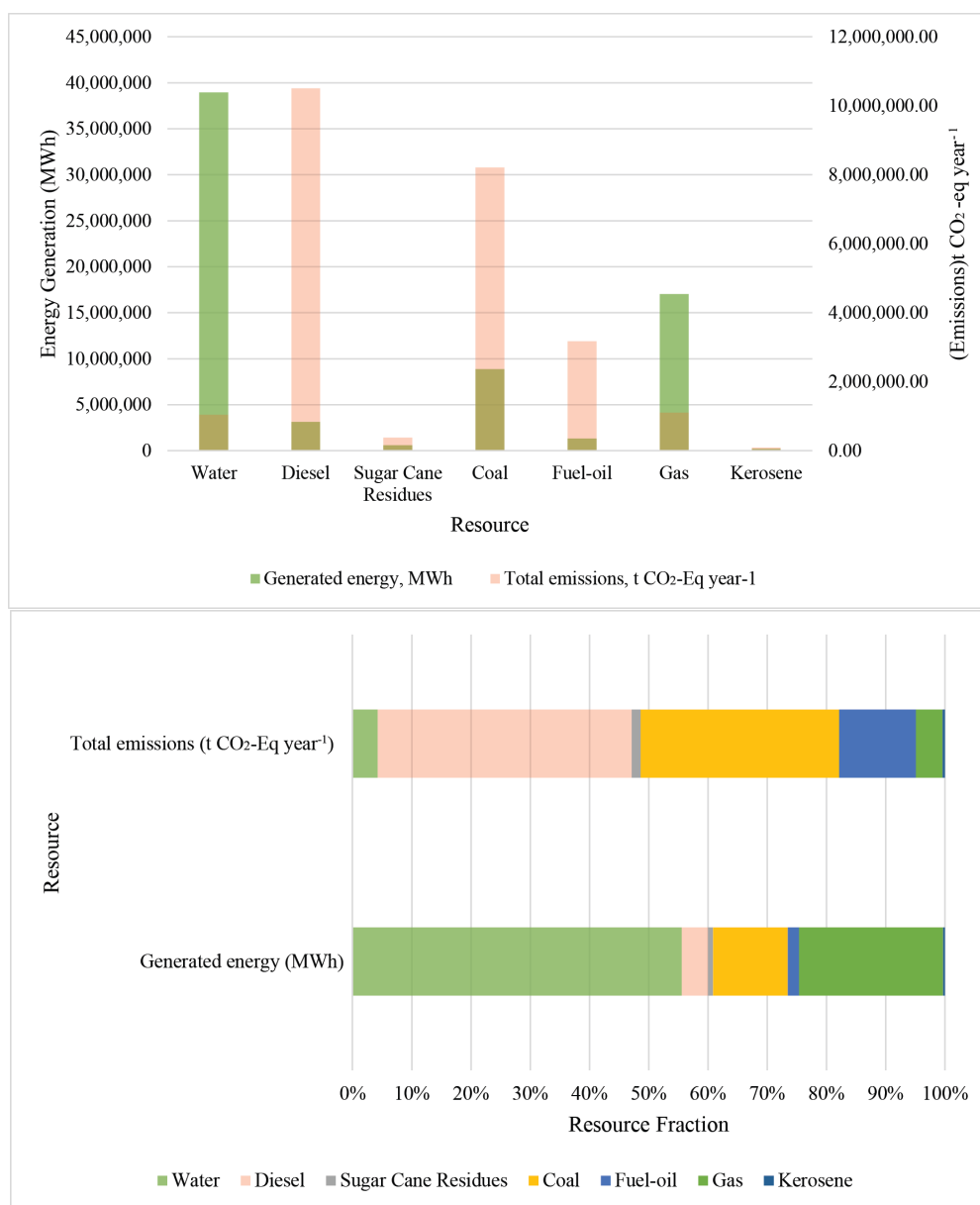


Figure 3 Generated energy and GHG emissions for each energetic resource available in Colombia: a) Columns of emissions and energy generated by source, b) Participation of each source in the total energy generation and emissions. (Source: This Study)

Table 9 GHG emissions from hydroelectric reservoirs and energy production in Colombia [3, 30, 31]

Segment of share	Energy generation 2015, MWh	Total Emissions per year, t CO ₂ -Eq year ⁻¹	Emission Factor (EF), t CO ₂ -Eq/MWh
Hydroelectric power plants reservoirs in this research	38,938,000.00	1,042,500.00	0.027
Full Colombian Energy production	68,446,505.16	23,458,556.28	0.340

3.5 Analysis of ENSO phenomenon effect on the hydropower generation in Colombia

Colombia is strongly affected by ENSO due to its geographical location [20]. Occurrences of ENSO

have been more frequent, gradually stronger, and more severe over the last 20–30 years than they were during the preceding hundred years [33]. The recent years in Colombia have been characterized by an increase in the area averaged temperature [13]. The precipitation rates

and surface temperature for Colombia, specifically in the region of -81.5625 long, -4.5703 lat, -64.6875 long, and 14.0625 lats (Figure 1), were retrieved for the years between 2010 and 2017 to graphically represent the effect of ENSO phenomenon that took place in 2015, and the climate change through these variables (Figure 4). The regions of the western Pacific presented the highest precipitation rates. The Sierra Nevada de Santa Marta and the eastern mountains also showed an important precipitation rate in the analysis domain: spatially and temporally [5]. The large red spot in the country map for the precipitation variable is located in the region with the biggest hydropower potential, where also coincided with most of the hydropower generation facilities (Figure 1).

In Colombia, the Andes mountains are divided into three big mountains ranges; called Western, Central and Eastern mountains ranges (*Cordilleras Occidental, Central, and Oriental*). These mountains have heights of thousands of M.A.S.L (Meters Above Sea Level). The higher mountain peaks are characterized by low temperatures, the cold areas which correspond to main mountains are represented by the MERRA-2 database (Figure 4). The hot-spots are mainly located in the oriental planes and Caribbean coast.

The 2010 year has been lately the year with the highest precipitation rates (Figure 4). This is explained by the area covered by stronger precipitations, which is larger in comparison to 2015 when the strongest ENSO phenomenon took place. In 2010, precipitations on the Eastern Mountain range and *La Sierra Nevada de Santa Marta* were registered, data is observed in the contour of Figure 4. Conversely in 2015, smaller precipitation rates were presented in the same areas indicating a reduction in the hydrologic resources available for energy production and other activities such as agriculture. ENSO phenomenon is also perceived by the temperature maps, in 2010 and 2017; during this period, both cold and hot years were clearly registered. Considering 2010 in comparison with 2015, the areas with temperatures above 30 °C are smaller.

According to MERRA-2 dataset, the year 2011 was the coldest year without any area (in the Colombian territory) with surface temperature values above 30°C. Even so, after the year 2011, the temperature showed an increase until 2015. Figure 4 shows that the affected areas by ENSO are the northern Caribbean coast, in Colombia and Venezuela. After 2015, the temperature decrease gradually, and the precipitation increased according to the natural cycle of the tropical weather.

In order to quantitatively analyze the effect of ENSO macroscale phenomenon over Colombia, the internal

energy demand and energy production by hydropower technology must be considered simultaneously with precipitation rates and temperature along the country. Figure 5 summarizes this data between the years 2010 and 2015 [2, 31, 34]. Figure 5-a compares the internal energy demand and production by hydropower technology against precipitation, showing the increasing demand and energy production in the same proportion along the 2010 to 2015 period. Meanwhile, the precipitation decreases in 2012, and again in 2015 to its lowest value. Figure 5-b shows the internal-national energy demand and energy production by hydropower technology with temperature, as mentioned above temperature has its lowest value in 2011. After this year, the surface temperature increases gradually until its highest value in 2015, according to the presence of the ENSO phenomenon in the region.

From Figure 5, energy production by hydropower has an increase in 2011, reaching the higher production value (48,427,000 MWh), after this year the energy production decreased to 38,938,000 MWh (Table 8) in the year 2015. This gradually decreases between 2011 the coldest year and 2014 one year before ENSO (5,000,000 MWh). In 2015, energy hydropower energy production decreases 9,036,300 MWh (about 15 % of the demand) evidencing a direct affectation of ENSO in the hydropower capacity of the country to meet the increasing demand. The energy demand tends to keep increasing, due to several aspects such as social and industrial development, population increasing, and now immigrants from Venezuela reaching one million new inhabitants in August 2018.

3.6 Energy risk analysis

Colombia has been historically affected by ENSO in the near past; diseases, drinking water supply, food and energy production have been sensitive points to this phenomenon. Based on the data collected from MERRA-2, and the increasing local demand (data plotted in Figure 5), it is possible to conclude that in the year 2015, characterized by strong ENSO in the region, the energy generated from water reservoirs, by hydropower plants, was not enough.

With the increasing demand, in part due to air conditioning requirements during hot seasons, ENSO produces a decrease in the water reservoir levels, leading to lack of energy supply. During the year 2015, the energy generated from hydroelectric resource was less than 50% of the installed capacity. The mean level in the water reservoirs was 65% of the total capacity of water storage. Additionally, during the last years, the thermoelectric generation systems have a deficit in the generation (about 70 GW), this deficit has been covered by hydropower systems. This situation leads to a more risky situation in

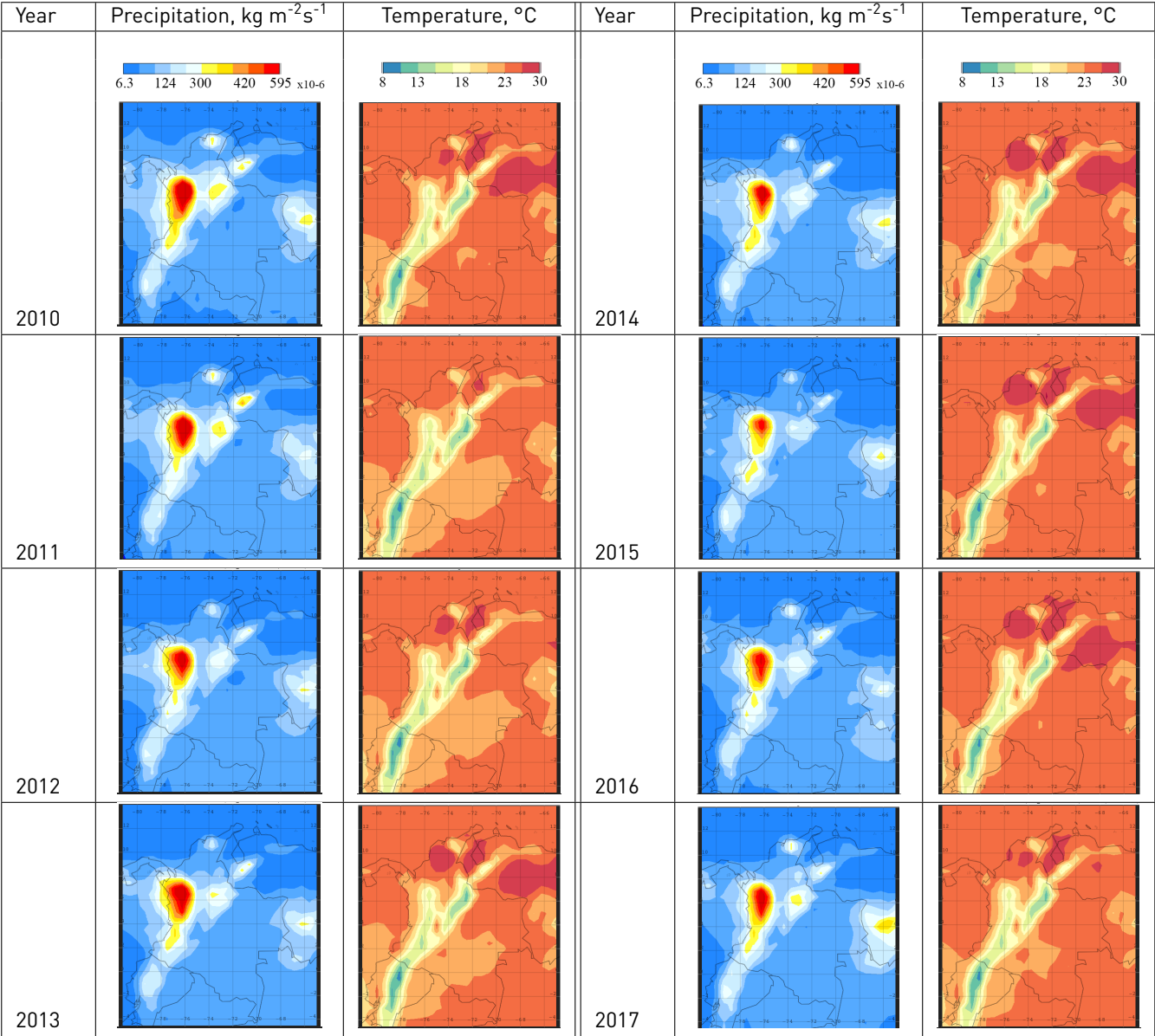


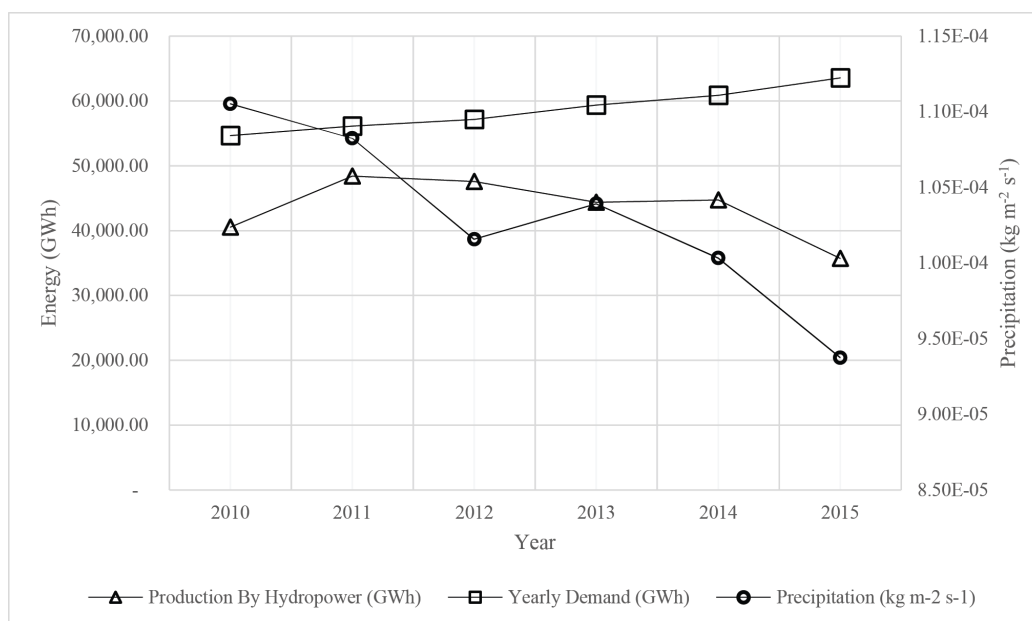
Figure 4 Yearly time averaged contours for Colombia during the time-period of 2010 to 2017. Variables: Total Surface Precipitation and Surface Air Temperature retrieved from NASA's MERRA-2 (Source: This study)

terms of National Energy Security.

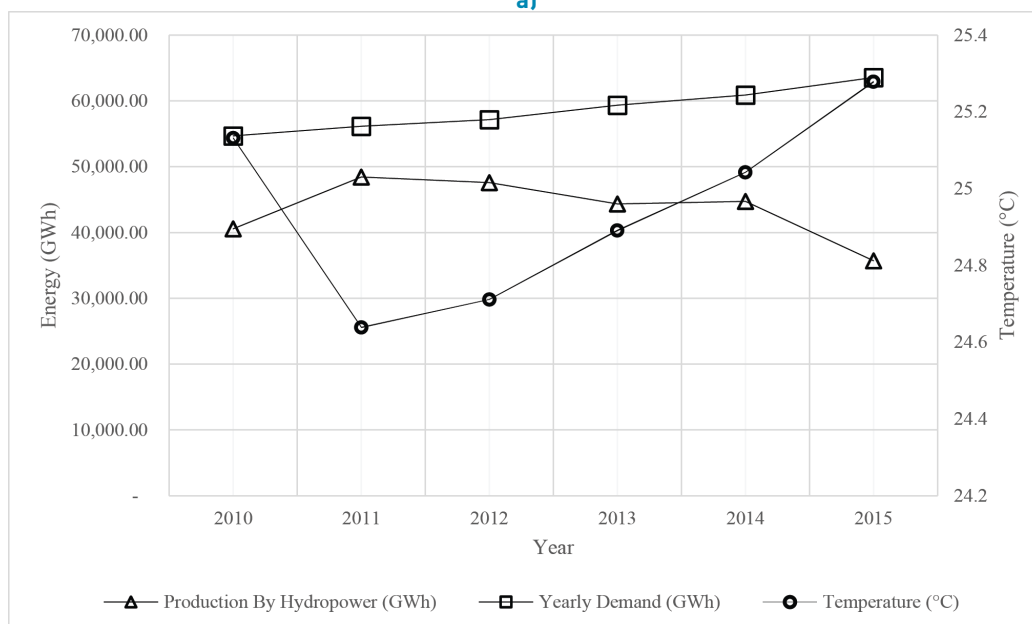
In the year 1992, blackouts and hour change were implemented by the government to compensate the climate effects in the performance of energy infrastructure, even so, in 2015 these measures were not necessary. In the future with a suitable and sustainable energy development, the need of measures such as blackouts or hour changes will be less. This means the probability of undesirable events (blackouts, hour change, and curfew, among others) tend to be low. Based on the two last big affectations in the energy supply by the effect of climate, it is possible to estimate the probability of undesirable events: 25 to 30%.

4. Conclusions

The methodology described by IPCC [2006] was implemented to calculate the GHG diffuse emissions from the hydroelectric power plants water reservoirs in Colombia. This calculation allowed the comparison of the GHG emissions from this energy source available in great quantities along the country of Colombia against other types of energy. The share of use of this energy source was more of 50 % in the year 2015. The emission associated with this anthropological activity was estimated as $1,042,500.00 \text{ t CO}_2\text{-Eq year}^{-1}$. The impact of energy generation is lower than other energy production



a)



b)

Figure 5 Yearly time series for Colombia during the time-period of 2010 to 2015, includes data on Demand, Hydropower Production and: a) Total Surface Precipitation, and b) Surface Air Temperature [Source: This Study]

alternatives, where fossil fuels or mass burning are the technological basis. The Emission Factor (EF) was estimated for hydroelectric energy generation as 0.027 t CO₂-Eq/MWh. The results obtained show that flooding is an important source of GHG emissions to the atmosphere. The local effects in public health must be studied in detail in further works. Local communities not only will be exposed to higher GHG level when new projects of hydropower generation begin, but also the vital water resource for local communities will be affected.

Further analysis and exploration of this phenomena should be applied for the case of Colombia. More accurate modeling of the dispersion of GHG emitted from water reservoirs can be performed using CFD simulation. This is a more detailed microscale approach which can be implemented for future research. CFD technology due to its features can be applied to this complex not steady fluid flow phenomena, and quantitatively describe the receptors exposition in each particular location

considering transport phenomena such as turbulence, mass, and heat transfer[35–40].

Infrastructure development will lead to challenges to meet the increasing regional demand. Such development must be performed considering important implications, in several aspects, to avoid issues like the one taking place in *Cauca* River, with the hydroelectric power plant construction of *Hidroituango*. Interconnection and new projects are required in the near future, not only hydropower based but solar and wind as well.

The high dependency on water reservoirs in Colombia to generate electricity represents a national issue, directly related to global change. ENSO phenomenon has led in the past years to reduce the energy production in the country, which affects the utility coverage, even in main cities such as *Bogotá*, *Medellín*, *Cali* or *Bucaramanga*.

In 2015, the hydropower generation decreased 9,036,300 MWh (about 15 % of the demand) evidencing a direct effect of ENSO on the hydropower capacity of the country to meet the increasing demand. This situation put in evidence the sub-utilization of the installed capacity during dry seasons and ENSO periods as a great weakness. With 70 % of installed capacity for energy generation through hydropower plants, the year 2015 only 50 % of the energy generation was achieved by hydropower technologies.

The last analysis leads to conclude that Colombia has an important national issue depending mainly on hydropower to meet the internal energy demand. Within the next years, the government must promote the development of energy production infrastructure, and interconnection, to ensure the energy required to meet the increasing demand in an actual context of development, increasing population and new immigrant's presence in the Colombian society. The development and upgrading of the energy infrastructure in Colombia must consider other clean technologies to take advantage of different renewable resources, such as wind and solar. The development plan of the country must be focused to achieve the best energy mix for the future through the implementation of optimization algorithms with energy planning as the main scope.

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