CONTRIBUTION OF NON-RENEWABLE SOURCES FOR LIMITING THE ELECTRICAL CO_2 EMISSION FACTOR IN ECUADOR

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ABSTRACT

Electricity production based on fossil fuels emits air pollutants and greenhouse gases (GHG). Today electricity and heat production contribute up to 42% of CO_2 emissions. Therefore, the decrease of these emissions is considered a priority worldwide. One component of the Paris Agreement focused on decreasing the world's mean electrical CO_2 emission factor to 65.0 g CO_2 kWh^{-1} by 2040. Based on official statistics of 18 years (2001–2018), we obtained this indicator for Ecuador. It varied between 188.6 and 397.4 g CO_2 kWh^{-1}. The lowest values were 188.6 and 197.1 g CO_2 kWh^{-1}, corresponding to 2017 and 2018 respectively, which were the years with the highest participation of renewable sources (73.6% and 72.3%, respectively, mainly hydropower) and the lowest contribution of fossil fuels facilities (26.3% and 27.3%, respectively). The promotion of hydropower facilities produced a decrease in the emission factors during the last two years. From 2001 to 2018, the mean performance of the Ecuadorian power facilities has been 0.36. The lowest historical emission factor (188.6 g CO_2 kWh^{-1}) was three times the world's mean value expected in the Paris Agreement. Based on the trend of the historical emission factors, we estimated that the contribution of fossil fuel facilities should be lower than 9.0% for decreasing to 65.0 g CO_2 kWh^{-1}. The increase in the performance of power facilities in Ecuador is a priority to reduce the emissions of both air pollutants and GHG. If the efficiency of power facilities increases to 0.45–0.55, their contribution can increase to 11.3%–13.8%, respectively. Although the magnitude of electrical emission factors expected by the Paris Agreement is an essential reference, the proper participation of fossil fuel facilities in Ecuador must be defined, additionally taking into account the potential influence of climate change on hydropower production. As occurred in 2010, hydropower energy can be severely affected by dry seasons.

Keywords: energy mix, indirect emissions, ecological footprint, carbon footprint, sustainability.

1 INTRODUCTION

Electricity is a clue component to well-being and socio-economic development. However, its production demands the consumption of non-renewable resources (fossil fuels such as coal, diesel, bunker, gasoline, natural gas, liquid petroleum gas (LPG)); used in boilers, turbines or internal combustion engines. Using fossil fuels for electricity production implies the emission of air pollutants and greenhouse gases (GHG).

In generating electricity from fuels by conventional technologies, efficiencies (ratio between produced electricity and stored energy) are low, varying from 0.36 to 0.45 [1], [2]. New technologies, as combined cycled (electricity production and using the heat from combustion gases to produce additional electricity), have improved efficiencies to 0.55–0.60 [3], [4]. When producing a specific amount of electricity, low-performance technologies emit more of both air pollutants and GHG.

Renewable sources (e.g. hydropower, biomass, biogas, eolic, and photovoltaic) and nuclear energy, produce electricity with low or any GHG emissions, although they present other impacts and environmental risks [5].

Globally, in the year 2016, it was produced 25.1 PWh of electricity. The contributions from fossil fuels, hydropower, and nuclear facilities were 65.1%, 16.6%, and 10.4%, respectively [6]. Today the contribution of electricity production to GHG emissions is

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relevant. In 2015, the global emissions of carbon dioxide (CO_2) were 32.3 Gt. Electricity and heat production contributed 42% of these emissions [7]. Therefore, policies, programs, and actions to reduce electrical GHG emissions are priorities at all ambits (national, regional, local, institutional, personal).

The term "energy mix" is used to refer to the facilities for electricity production, which can include renewable and non-renewable sources. The energy mix configuration and its performance define the magnitude of air pollutants and GHG emissions. Therefore, the CO_2 emissions per unit of produced electricity vary a lot across countries and from year to year, depending on the energy mix [7]. The basic approach defines this emission factor as the ratio of the CO_2 emitted to the generated electricity [8]. For the period 1990–2010, the International Energy Agency (IEA) [9] reported values between 0.0 and 2,552.0 g CO_2 kWh^{-1}.

Electrical CO_2 emission factors are essential for estimating indirect emissions, due to the use of electricity. Delivering these emission factors promotes the use of parameters linked to sustainability, as the ecological footprint, see, for example, [10], [11] or the carbon footprint, see, for example, [12], [13].

The reduction of electrical GHG emissions is a crucial component of the Paris Agreement of the United Nations, for holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels [14]. One component of the Paris Agreement focuses on the reduction of the world mean electrical emission factor to 65.0 g CO_2 kWh^{-1} by 2040 [15].

According to the latest emission inventory of Ecuador, the emissions of 2012 reached 80.6 Mt CO_2-eq. The highest contribution (46.6%) came from the energy sector [16].

The Nationally Determined Contributions (NDCs) are essential components of the Paris Agreement. NDCs embody efforts by each country to reduce its emissions and to adapt to the impacts of climate change. For the energy, agricultural, industrial, and waste sectors, the first Ecuadorian NCD considers as a target, the GHG emission reduction between 9% and 20.9% by 2025, respect to the tendency (business as usual) scenario [17]. For this purpose, among other components, the Ecuadorian NCD is based on the promotion of efficient energy and change in consumption behavior.

Hydropower is the most important renewable source in Ecuador. During the period from 2001 to 2014, electricity came from renewable sources (43.5%–63.9%), fossil fuels (34.5%–52.2%) and importations (0.2%–11.5%). The Ecuadorian Government promoted new hydropower projects, increasing the contribution of this kind of source in the last years. The Government also promoted the migration from LPG-based stoves to electric induction stoves [18], [19]. Transportation projects, as the tram in the city Cuenca and the metro in Quito, will operate in the following months, increasing the consumption of electricity. Therefore, indirect CO_2 emissions by electric consumption are becoming more relevant in all ambits. Ponce et al. [20] recently analyzed the electrical sector in Ecuador.

Previously, we estimated the electrical CO_2 emission factors from 2001 to 2014 [21]. They have been used in energy and CO_2 emission studies, see, for example, [22]–[24].

As new hydropower facilities began to produce during the period from 2015 to 2018, significant variations occurred in the energy mix. In 2017 renewable sources have increased their contribution to 73.6%, which was the highest from 2001 to 2018. The Ecuadorian Electrical Plan for the period 2013–2022 is based mainly on new hydropower projects [25]. It is expected that hydropower will generate about 83.6% of electricity by 2022 [18].

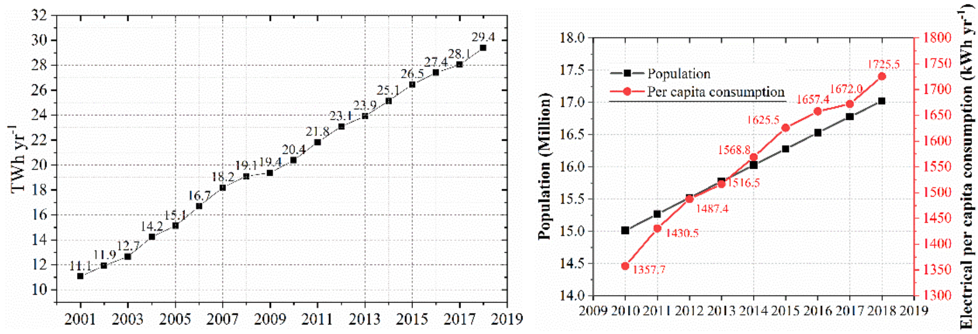
This article explores the following issues:

- The efficiency of the power facilities from 2001 to 2018.

- How the electrical CO_2 emission factors varied from 2001 to 2018.
- The contribution of the non-renewable power facilities to reduce the electrical CO_2 emission factor to 65.0 g CO_2 kWh^{-1}.
- Other concerns that should be considered to define the proper participation of fossil fuel facilities in Ecuador.

2 METHOD

We collected data from the National Electrification Council (Conelec) from Ecuador – today renamed to the Electricity Control and Regulation Agency (Arconel) – about the gross production of electricity (Fig. 1) and the energy imported during the period from 2001 to 2018. In September of 2018, Arconel received from the National Institute of Statistics and Census (INEC), a quality certification due to its statistical management of the data and QA/QC activities of the electrical sector [26].



(a) (b)

Figure 1: (a) Gross production and imported electricity in Ecuador during the period from 2001 to 2018 [27]–[31]; and (b) Ecuadorian population and electrical per capita consumption during the period from 2010–2018 [32].

In 2001, the national production and importation totalized 11.1 TWh yr^{-1}. In the following years, consumption permanently increased, and it reached 29.4 TWh yr^{-1} in 2018.

Fig. 1 also depicts the Ecuadorian population during the period from 2010 to 2018, according to the projections by INEC [26], which varied from 15.0 to 17.1 million of inhabitants. The resulting electrical per capita consumption varied between 1,358 and 1,726 kWh yr^{-1}.

During the period from 2001 to 2018, electricity came from renewable sources (43.5%–73.6%), fossil fuels (26.2%–52.2%) and importations (0.1%–11.5%) (Fig. 2). Renewable sources include hydropower facilities, sugarcane waste (bagasse), biogas, eolic, and photovoltaic sources. Non-renewable sources include the combustion of fuel oil, diesel, naphtha, natural gas, bunker, oil, and liquid petroleum gas. Power facilities produce electricity mainly by internal combustion engines, steam turbines, and gas turbines. Percentages of importations correspond to electricity bought to Colombia and Perú.

We also collected the information of the fuel consumption for the gross production of electricity from 2001 to 2018 (Fig. 3). Historically, the most used fuels were fuel oil, diesel, oil, and natural gas. The maximum use of fuel oil occurred in 2014 (368.8 million of gallons, (M gal)). The maximum consumption of diesel took place in 2010 (315.2 M gal).

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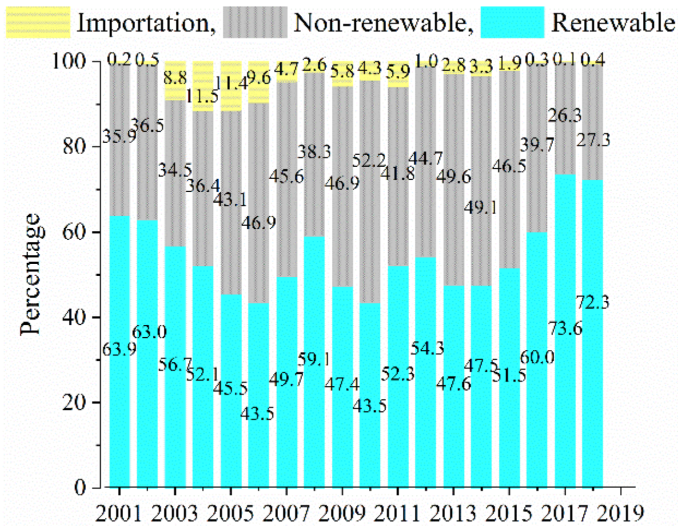

Figure 2: Percentages of contribution by type of sources to the electrical production in Ecuador in the period from 2001 to 2018 [27]–[31].

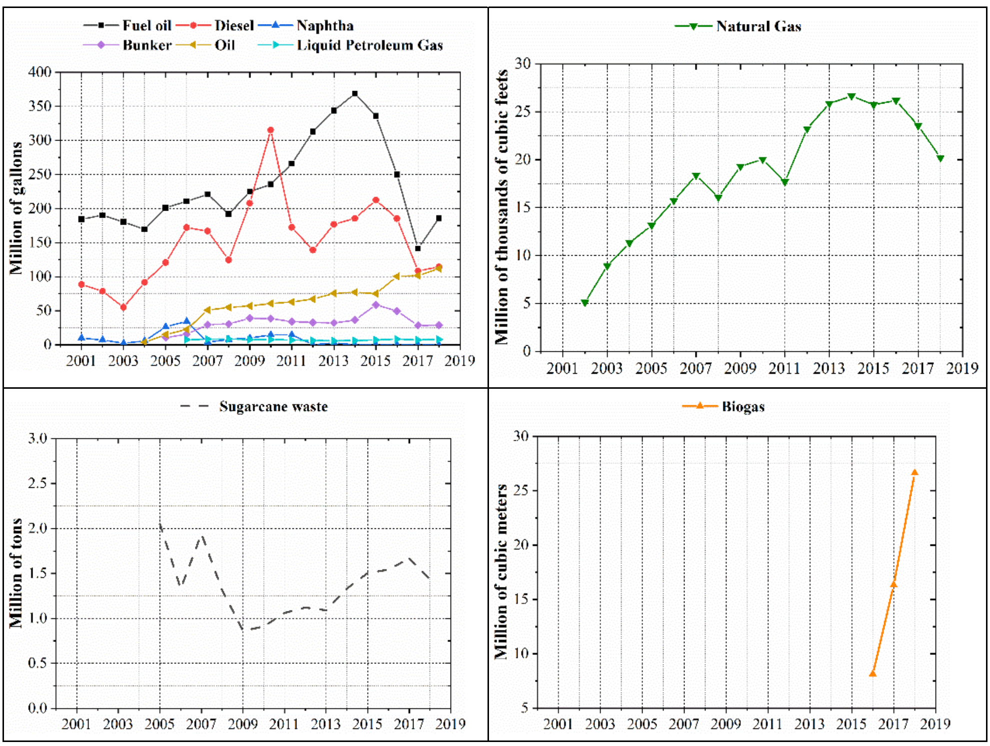

Figure 3: Amounts of fuels used for gross generation of electricity in Ecuador during the period from 2001 to 2018 [27]–[31].

In 2017 the use of fuel oil dropped to 141.1 M gal, being the year with the lowest fuel oil consumption of the period 2001 to 2018.

About fuel properties, we used the calorific power, CO_2 emission factor by combustion, and density, presented in Parra [21].

3 RESULTS AND DISCUSSION

We estimated the energy stored in fossil fuels (fuel oil, diesel, bunker, natural gas, naphtha, oil, and liquid petroleum gas (Fig. 3)) and the corresponding efficiencies (ratio between produced electricity and stored energy in these fuels (Fig. 4)). Performances varied between 0.34 and 0.38, with 0.36 as the mean value. The lowest efficiency (0.34) corresponded to 2010, which was the year with the highest contribution of fossil fuels (52.2%) (Fig. 2). The increase of diesel in 2009 and 2010 (Fig. 3) was produced during drought periods, which reduced the hydropower generation, and forced the increase in the production of diesel power facilities [33]. This drought period highlighted the vulnerability of the Ecuadorian energy mix, which in the future can be affected owing to similar situations.

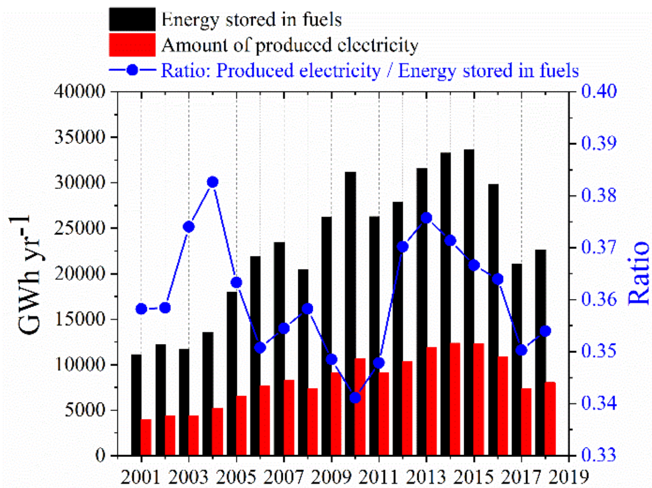

Figure 4: Left vertical axis: Energy stored in fossil fuels (GWh yr^{-1}), and amount of electricity generated with the respective power facilities (GWh yr^{-1}). Right vertical axis: Efficiencies (ratio between produced electricity and stored energy in fuels) during the period from 2001 to 2018.

With the information from Figs 1 and 3, we estimated the CO_2 emissions due to the gross production of electricity (Table 1). Total net emissions do not include the contribution from both of sugarcane waste and biogas, under the assumption that the combustion of these two fuels does not generate net CO_2 emissions [34]. Annual net emissions varied between 3,050.2 and 8,706.1 Gt CO_2 yr^{-1}.

We obtained the electrical CO_2 emission factors (Fig. 5), from the total net emissions and the values of the gross production and imported electricity. The CO_2 emission factors varied between 188.6 and 397.4 g CO_2 kWh^{-1}. The highest value corresponded to 2010, the year with the highest contribution of fossil fuels (52.2%). On the contrary, the lowest values corresponded to 2017 (188.6 g CO_2 kWh^{-1}) and 2018 (197.1 g CO_2 kWh^{-1}), the years with the lowest participation of non-renewable sources (26.3% and 27.3% respectively).

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Table 1: CO_2 emissions (kt yr^{-1}) due to the gross production of electricity in Ecuador during the period from 2001 to 2018.

Year	Fuel									Total net emiss-ions*
	Fuel oil	Diesel	Naphtha	Natural gas	Bunker	Oil	LPG	Sugar-cane waste	Biogas	
2001	2,059	901	90	0	0	0	0	0		3,050
2002	2,124	802	65	262	0	0	0	0		3,253
2003	2,012	562	21	458	0	0	0	0		3,052
2004	1,893	935	53	581	0	38	0	0		3,499
2005	2,249	1,229	242	675	119	154	0	1,599		4,669
2006	2,353	1,753	314	807	175	231	45	1,037		5,678
2007	2,468	1,700	36	943	329	522	49	1,513		6,047
2008	2,144	1,270	72	825	344	564	51	1,022		5,271
2009	2,514	2,118	91	990	435	585	45	671		6,778
2010	2,630	3,212	134	1,028	429	621	46	710		8,101
2011	2,971	1,756	134	909	381	644	42	827		6,837
2012	3,493	1,418	1	1,192	367	689	38	874		7,198
2013	3,838	1,802	25	1,328	359	776	35	850		8,162
2014	4,120	1,891	0	1,368	405	791	38	1,037		8,612
2015	3,751	2,164	0	1,320	657	771	44	1,173		8,706
2016	2,793	1,888	0	1,343	554	1,029	50	1,203	10	7,657
2017	1,577	1,105	0	1,207	318	1,041	42	1,301	21	5,290
2018	2,078	1,165	0	1,037	320	1,148	47	1,121	33	5,794

* Total net emissions do not include the contribution from both of sugarcane waste and biogas.

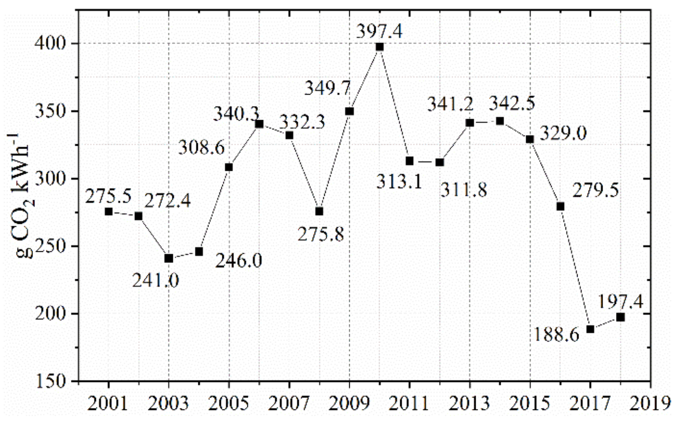

Figure 5: CO_2 emission factors for the gross production of electricity in Ecuador during the period from 2001 to 2018.

The IEA [9] reported the Ecuadorian emission factors during the period from 2003 to 2010, which were consistent with the corresponding magnitudes presented in this study (Fig. 6). The mean values of these emission factors were 329.3 and 311.4 g CO_2 kWh^{-1}, respectively, which were 5.4% different.

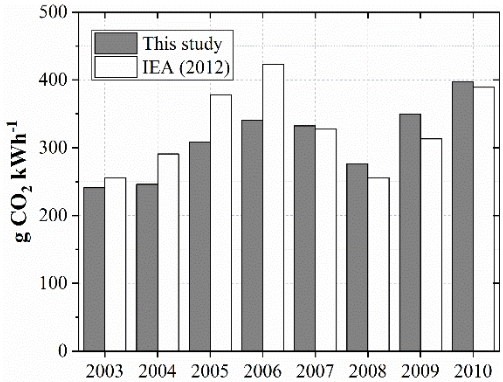

Figure 6: Ecuadorian electrical CO_2 emission factors in the period from 2003 to 2010. Values reported by the IEA [9] and the corresponding magnitudes presented in this study.

All the CO_2 emission factors were lower than 515.0 g CO_2 kWh^{-1}, which is the current global mean value of this indicator [15]. Although the values of 2017 and 2018 were the lowest of 2001 to 2018, they still were about three times larger than the world mean value expected into the Paris Agreement toward 2040 (65.0 g CO_2 kWh^{-1}).

The linear correlation between the percentages of participation of non-renewable sources and the CO_2 emission factors of 2001–2018 (Fig. 7) showed a high correlation (Pearson' r = 0.999), and indicated the following relationship (eqn (1)):

$$CO_2EF = 7.21 \text{ x Nonren\%}, \quad (1)$$

where CO_2EF = CO_2 emission per unit of produced electricity (g CO_2 kWh^{-1}); and Nonren% = percentage of participation of fossil fuels power facilities.

As the Ecuadorian Electrical Plan for 2013–2022 is based mainly on new hydropower projects [25], eqn (1) can provide the CO_2 emission factor directly for the following years after 2018. For this purpose, only the percentage of participation of non-renewable sources is required, which becomes available sooner than the complete official statistics. If, as expected, hydropower will generate 83.6% of electricity by 2022 (16.4% produced by fossil fuels), the CO_2 emission factor would be 118.2 g CO_2 kWh^{-1}.

Eqn (1) suggests that to reduce the emission factor to 65.0 g CO_2 kWh^{-1}, the contribution of non-renewable resources must be lower than 9.0% (Fig. 7). This value corresponded to the historical mean efficiency of 0.36, which is low performance in the range reported for conventional technologies [1], [2]. When exploring the effect of increased efficiencies to 0.45 and 0.55, we obtained the eqns (2) and (3) (Fig. 7):

$$CO_2EF = 5.77 \text{ x Nonren\%}, \quad (2)$$

$$CO_2EF = 4.72 \text{ x Nonren\%}. \quad (3)$$

These correlations indicate that to reduce the Ecuadorian emission factor to 65.0 g CO_2 kWh^{-1}, the contribution of non-renewable resources can be lower than 11.3% or 13.8%, in case of efficiencies increased to 0.45 or 0.55, respectively. These contributions even can increase if more efficient technologies – as combined cycled – will be incorporated in the Ecuadorian energy mix.

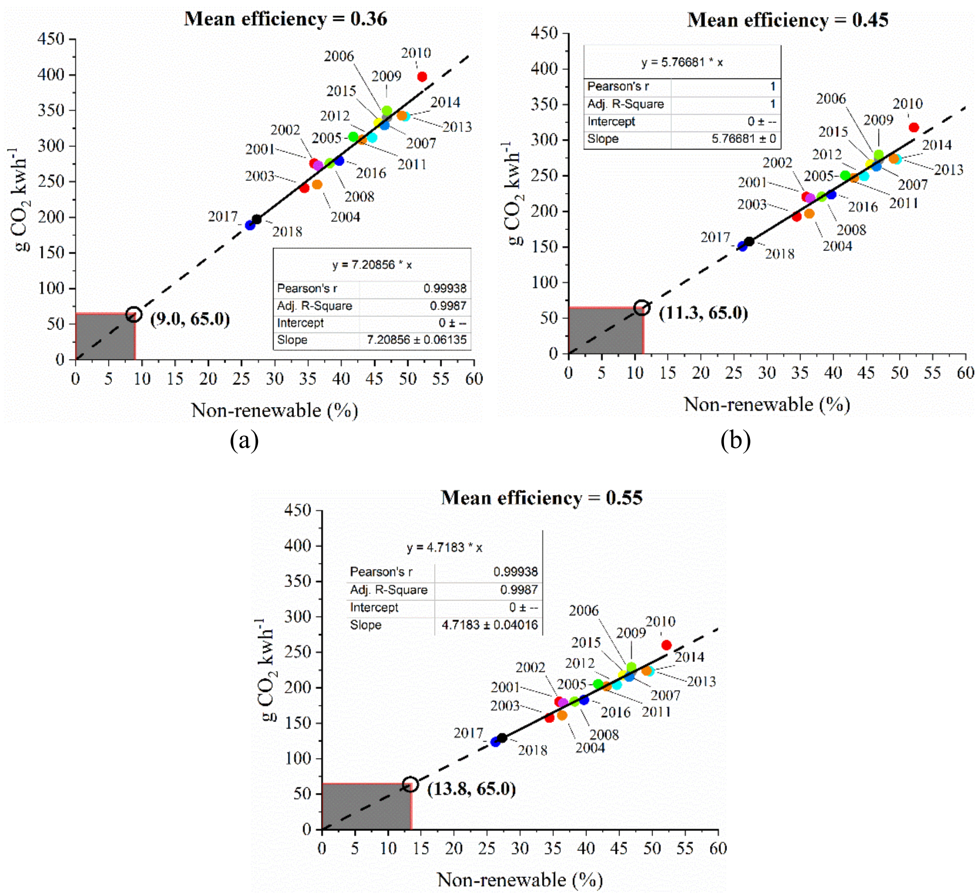

Figure 7: Correlation between the percentages of non-renewable sources and the CO_2 emission factors for the production of electricity in Ecuador during the period from 2001 to 2018. (a) Mean efficiency of 0.36, which corresponds to the historical value of Ecuador; (b) and (c) In case of mean efficiencies of 0.45 and 0.55 respectively.

Hydropower is vulnerable to climate change. Studies revealed that hydropower capacity could display significant sensitivities to variations in rainfall patterns, which can alter the rivers streamflow regime in Ecuador [35], [36]. High Tropical Andean regions could be more affected by changes in precipitation patterns [37]. The Ecuadorian government policy assumed there would be small changes in future hydrological conditions. The hydropower designs in Ecuador would not have adequately considered the vulnerability to climate change [38].

Drought seasons, as occurred at the end of 2010, can seriously affect the capacity of hydropower. Therefore, the study of the effects of climate change on hydrological variability and energy capacity is a priority field of research in Ecuador. Modeling climate change and its effects is a challenging task in Ecuador, which is a small country with different weather and climate conditions. The country is under the influence of the Intertropical Converge Zone's movements, the El Niño-Southern Oscillation, and showing strong atmospheric convective motions, influenced by the complex topography of the Andean mountains.

Although the electrical emission factor expected by the Paris Agreement is an essential reference, the proper participation of fossil fuel facilities in Ecuador must be defined, additionally taking into account the potential influence of climate change on hydropower production. This field of research should be included in the actual or future Ecuadorian NDCs.

The Ecuadorian emissions during 2012 (80.6 x 10^{-3} Gt CO_2-eq.) represented only 0.15% of the total global emissions of 2018 (55.3 Gt CO_2-eq. [39]). Although the Ecuadorian contribution is small, it is necessary to reduce its GHG emissions. It is particularly crucial in Ecuador to take into account the air pollutant emissions from power facilities. Some of them have contributed between 5% and 72% of the $PM_{2.5}$ emissions in selected Ecuadorian municipalities (Table 2). We highlight the case of the Municipality of Milagro, where sugarcane power facilities (null net CO_2 emissions) contribute up to 72.1% of the $PM_{2.5}$ emissions. Ecuadorian NDCs should consider not only the mitigation of GHG emissions but also the corresponding reduction of air pollutant emissions, which can directly affect human health, even emitted by null net CO_2 sources.

Table 2: $PM_{2.5}$ emissions (t yr^{-1}) from power facilities in selected municipalities from Ecuador.

Municipality	Power facilities		Other sources		Total		Year	Observations
	t yr^{-1}	%	t yr^{-1}	%	t yr^{-1}	%		
Distrito Metropolitano de Quito [40]	133.0	9.6	1,258.0	90.4	1,391.0	100.0	2007	Internal combustion engines (bunker, diesel)
Cuenca [41]	102.1	11.3	804.9	88.7	907.0	100.0	2014	Internal combustion engines (bunker, diesel)
Esmeraldas [42]	30.8	8.8	319.2	91.2	350.0	100.0	2010	Vapor turbine (diesel). Internal combustion engines (bunker)
Manta [42]	5.5	4.8	110.5	95.2	116.0	100.0	2010	Vapor turbine and internal combustion engines (diesel)
Milagro [42]	1,061.3	72.1	409.7	27.9	1,471.0	100.0	2010	Vapor turbine (sugarcane)
Quevedo [43]	232.7	49.1	241.3	50.9	474.0	100.0	2010	Internal combustion engines (diesel)

The energy mix is the result of the energy policy, plans, and projects. The Ecuadorian electric sector is operated and controlled by the state [18]. Therefore, entities as industries, institutions, and citizens, buy power to the state. These entities do not influence on the energy mix, and consequently, neither on the emission factor.

When estimating sustainability indicators, it is necessary to identify if the reduction of CO_2 emissions was produced only by a decreased electrical emission factor. Entities should reduce their electricity consumption, using efficient facilities, devices, and processes.

Electrical CO_2 emission factors are essential for estimating the emissions owing to the consumption of electricity. They are crucial for strategic energy plans, GHG emission inventories, in assessing new energy mix configurations, in estimating sustainable indicators, as the ecological or carbon footprint, and in verifying the compliment of decrease emissions goals.

The most recent electrical Ecuadorian per capita consumption reported by the World Bank [32], which corresponds to 2014, is 1,376 kWh yr^{-1}. This value is consistent with the respective per capita consumption of 1,569 kWh yr^{-1} showed in Fig. 1. During the period from 2010 to 2018, this indicator increased from 1,358 to 1,726 kWh yr^{-1}. Although these values are lower than the other countries or regions (e.g. 2,156, 3,927, 5,908, 13,254 kWh yr^{-1} for Latin America, China, European Union, and North America respectively [33]), it is necessary to work both in saving the consumption of electricity and in the decrease of the electrical CO_2 emission factor.

4 CONCLUSIONS AND SUMMARY

The mean efficiency (0.36) of fossil fuel power facilities in Ecuador corresponds to low values of the range reported in the literature for conventional technologies.

In the period from 2001 to 2018, the Ecuadorian electric CO_2 emission factors varied between 188.6 and 397.4 g CO_2 kWh^{-1}. All of them were lower than 515.0 g CO_2 kWh^{-1}, which is the current world mean value of emission per unit of electricity. The lowest values corresponded to 2017 and 2018, the years with the lowest participation of non-renewable resources (26.3% and 27.3% respectively), due to the increase in the contribution by hydropower facilities in the last years. Nevertheless, these emission factors were still about three times the world mean value expected into the Paris Agreement (65.0 g CO_2 kWh^{-1}) by 2040.

The correlation between fossil fuels participation and CO_2 emission factors of the period 2001 to 2018, suggests that to reduce its electric emission factor to 65.0 g CO_2 kWh^{-1}, the contribution of non-renewable resources must be shorter than 9.0%. This value corresponds to the historic mean efficiency of 0.36 for the Ecuadorian power facilities. If the efficiency improves to 0.45 or 0.55, the contribution of non-renewable resources could rise to 11.3% or 13.8%, respectively.

Although the electrical emission factor expected by the Paris Agreement is an essential reference, the proper participation of fossil fuel facilities in Ecuador must be defined, additionally taking into account the potential influence of climate change on hydropower production.

Ecuadorian NDCs should consider not only the mitigation of GHG emissions but also the corresponding reduction of air pollutant emissions, which can directly affect human health, even emitted by null net CO_2 sources.

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