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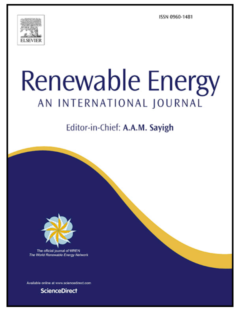

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Sugarcane can afford a cleaner energy profile in Latin America & Caribbean

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Latin American and Caribbean's (LAC) external dependency on fossil fuels and the pursuit for renewable energy leads to the need for a strategy to afford a cleaner and reliable domestic energy supply. Sugarcane presents high photosynthetic efficiency and it is a well-spread crop in LAC. Our study aims to explore the potential of different approaches of modern energy production from sugarcane, at a national level, and its implication to the environmental aspects. We found that Guatemala, Nicaragua and Cuba would be able to replace 10% of the gasoline and about 2-3% of the diesel consumption by only using the current molasses. With a slight expansion on sugarcane production, Bolivia can replace 20% of the gasoline and diesel, besides providing surplus ethanol for exportation or other purposes. With a minor investment, bagasse may enlarge the electricity access in many countries whereas in other may represent an alternative to replace fossil fuel sources. We also found relevant potential on reducing the GHG emissions specially in Bolivia, Paraguay and Nicaragua. However, the implementation of such strategies must be supported by appropriate policies to ensure competitive prices, overcome opportunity costs, and stimulate investments.

Keywords: Sustainability, biofuel, bioelectricity, developing countries

1. Introduction

Imports of gasoline and diesel account for more than half of the national consumption in most of the Latin America & Caribbean (LAC) countries; some nations such as Guatemala, Honduras, Panama and Paraguay depend entirely on external supply [1]. The liquid fuel consumption in South and Central America is expected to rise 35% from 2015 to 2035 [2]. Electricity access is also an issue for over 20 million people in Latin America, in which lack of electrification achieve 10-15% of the population in Bolivia, Guatemala, Honduras and Panama and 26% in Nicaragua [3]. The high rates of economic development and demographic growth in LAC countries has enlarged the electricity demand, which generation is expected to increase over 60% in the next 20 years [3].

Such situation, along with the need for strategies aligned to human development and environmental benefits, imposes challenges to governments and private sectors. Bioenergy can play a key role on providing cleaner and more accessible and affordable energy [4–6]. Among the options, sugarcane bioenergy is a promising alternative as it can reduce GHG emissions compared to fossil fuels [7], promote social development [8] and be produced at competitive costs [9].

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Initiatives of ethanol-gasoline blending, for instance, have already been established or are under discussion in LAC countries (Table 1). Paraguay and Brazil comprise the highest blends in LAC and other countries, such as Cuba, El Salvador, Honduras, and Nicaragua, have not yet established any mandate or plan for gasoline-ethanol blend.

Table 1.
Current gasoline-ethanol blend in LAC countries.

Countries	Blend
Argentina	10% [a]
Bolivia	Under discussion [b]
Brazil	27% [a]
Colombia	8-10% [a]
Costa Rica	0-8% [a,c]
Cuba	No blend
Dominican Republic	Under discussion [d]
Ecuador	5% [a,e]
El Salvador	No blend [a]
Guatemala	0-10% [f]
Honduras	No blend [a]
Jamaica	10% [g]
Mexico	6% [a,h]
Nicaragua	No blend [a]
Panama	Temporally suspended [a]
Paraguay	27.6% [i]
Peru	7.8% [a]
Venezuela	Temporally suspended [a]

Note: [a] [10]**.** [b] [11]. [c] Currently 0% until regulated. [d] Planning 5-25% blend [12]. [e] Only in Guayaquil. [f] Policy under implementation [13]. [g] [14]. [h] Only in Guadalajara, Monterrey and Mexico D.F. [i] [15]**.**

Despite the potential for sugarcane cultivation and bioenergy production in all LAC countries, Brazil is the only one in which sugarcane products have an expressive contribution on energy sector, comprising 16% of the national energy supply [16]. This scenario is justified by the 750 million tons per year of sugarcane, placing the country as the world largest sugarcane producer, which along with Mexico, Colombia, Guatemala and Argentina comprise 90% of the LAC supply [17].

Currently, sugarcane corresponds to less than 10% of the arable land [2] in most of the LAC countries, although it is higher in Colombia, Costa Rica and Guatemala – around 25% – and Mexico – up to 50% [17,18]. The land-use for bioenergy crops, however, has frequently been portrait as an issue because may face competition with food production [19,20]***.***

[2] According to FAO, arable land is defined as "land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years)".

Large tracts of land sparsely occupied, generally dedicated to degraded pastures in low productivity cattle ranching, characterize the Latin America countries [21]. Strategies such as pasture intensification can therefore enlarge the availability of arable land, avoid indirect land use change [22] and thus the carbon emission from sugarcane expansion over other crops or forest [23]. For instance, the pasture area in Brazil, about one quarter of whole national area, was reduced by 15% (180 to 152 Mha) between 1980 to 2010, while the cattle herd increased by 68% (127 to 213 million head) (data from IBGE, http://www.sidra.ibge.gov.br/bda/pesquisas/ca/ [24]). Better practices can also freed up land for other uses [25].

Regarding the competition between fuel and food, the sugarcane industry has the great advantage of allowing the production of both sugar and ethanol with considerable flexibility on choosing the share of the final products [26]. If desired, ethanol can be produced only from molasses, a coproduct from sugar production.

Sugarcane can also be produced in land not used or unsuitable for food crop production [25], or cultivated by using food-energy integrated approaches [27,28]. In addition, sugarcane is a semi-perennial crop and one of the most efficient solar energy converter, demanding a reduced plantation area when compared with other options [29]. As a semi-perennial crop, sugarcane areas can also be used to grow other crops during the rotation practices, usually every five years.

Given these opportunities, this study aims to explore the potential of sugarcane as energy supplier in Latin America & Caribbean, at country level, and its implication to the GHG emission savings. Ethanol is produced aiming to replace gasoline and diesel used as vehicle fuel. Bagasse feeds cogeneration system contributing to electricity generation.

In recent times, sugarcane has also been increasingly considered as a feasible feedstock for several chemical and biochemical products, from synthetic rubber to pharmaceutics products, including second-generation (2G) ethanol [30–32]. This study, however, addresses exclusively the production of ethanol and electricity as they comprise well-known technologies, the current state-of-art, and are consistent with the economic and development scenario in LAC countries.

2. Materials and methods

We estimate the potential supply of bioenergy from sugarcane in LAC for short and long-term contexts assuming two scenarios (Table 2):

- **Mature Context (MC):** represents a short-term framework. Ethanol is produced exclusively from molasses, considering the existing sugarcane production (Table 3). We assume that the sugarcane industries will be able to deploy a cogeneration system yielding 60 kWh/t cane, if it doesn´t exist. Surplus electricity corresponds to 30 kWh/t cane, at 42 bar and 450°C (low-efficiency boiler). Ethanol is used for gasoline replacement at a blend up to 10% (v/v), which does not require any change of technology [33]. Surplus ethanol, when available, is used to displace diesel in heavy-vehicle up to 10% (v/v). The use of ethanol in diesel engine is supported by the Scania technology which allows the use of pure ethanol with 5% ignition improver in a diesel engine (BioEthanol for Sustainable Transport project [34]).

- **New Framework (NF):** enhanced approach likely to be deployed under medium to long-term. Sugarcane is cultivated over 1% of the current pasture land (Table 3). Besides molasses, ethanol is also produced from direct juice (additional sugarcane). The gasoline-ethanol blend is up to 20% (v/v), which requires relatively simple changes on engine technology [33]. After supplying the E20 blend, surpluses of ethanol are allocated to diesel displacement. Diesel replacement is up to 20% (v/v). Cogeneration system presents higher efficiency compared to MC scenario, working at 65 bar and 480°C and able to provide 80 kWh/t cane of surplus electricity. Population and energy consumption for 2030 are presented in Table 4.

Table 2.
Scenario assumptions.

Parameters	Mature Context	New Framework
Mill crushing capacity (t/year)	10^6	10^6
Ethanol yield from molasses (L/t cane) [a]	10	10
Ethanol yield from direct juice (L/t cane) [b]	Not applied	80
Ethanol source	Molasses	Molasses and juice
Pasture area allocated for sugarcane cropping [c]	0%	1%
Surplus electricity (kWh/t cane) [d]	30	80
Gasoline replacement limit	10%	20%
Diesel replacement limit	10%	20%

Notes: [a] Data from United Nation [35]. [b] Average from Brazilian South-Central region [36]. [c] Available pasture land according to FAOSTAT, http://faostat.fao.org [37]. [d] Ethanol distillery consumes 30 kWh/t cane (mechanical and electrical energy) [38]. Electricity production in the MC and NF scenarios are 60 kWh/t cane (42 bar, 450 ºC) and 110 kWh/t cane (65 bar, 480 ºC), respectively [30].

Table 3.
Current sugarcane overview and pasture land.

Country	Sugarcane production [10^3 t/year] [a,b]	Sugarcane area [10^3 ha] [a,b]	Current pasture land [10^3 ha] [a,b]	Sugarcane expansion [10^3 ha] [c]	Sugarcane yield [t/ha] [a,d]
Argentina	19,766	360	108,500	1,085	59
Bolivia	7,692	159	33,000	330	48
Colombia	33,364	397	39,165	392	90
Costa Rica	4,440	58	1,300	13	71
Cuba	14,700	361	2,834	28	36
Dominican Republic	4,866	107	1,197	12	48
Ecuador	7,379	95	4,976	50	79
El Salvador	6,487	73	637	6	87
Guatemala	23,653	256	1,950	20	95
Honduras	5,861	70	1,760	18	83
Mexico	1,475	28	229	2	53
Nicaragua	50,946	735	80,897	809	73
Panama	6,732	67	3,275	33	96
Paraguay	2,276	33	1,540	15	67
Peru	4,186	115	17,000	170	48
Venezuela	10,369	81	18,797	188	128

[a] Data from FAOSTAT, http://faostat.fao.org [37]. [b] 2012 values. [c] New Framework scenario; 1% of the current pasture land. [d] Average value from 2010 to 2014.

Table 4.
Population and energy consumption for MC and NF scenarios.

Country	Population [1000 people] [a]		Electricity consumption [GWh/year]		Gasoline [10^6 L/year]		Distillate fuel oil [10^6 L/year]	
	Current [2012]	Projection [2030]	Current [2012] [b]	Projection [2030] [c]	Current [2012] [b]	Projection [2030] [d]	Current [2012] [b]	Projection [2030] [d]
Argentina	41,087	49,365	110,699	181,270	7,735	11,370	13,138	19,313
Bolivia	10,496	13,177	6,457	10,573	1,143	1,680	1,620	2,381
Colombia	47,704	53,175	52,671	86,248	4,799	7,055	8,275	12,165
Costa Rica	4,805	5,413	8,987	14,716	1,001	1,471	1,075	1,580
Cuba	11,271	11,237	14,463	23,683	597	877	1,375	2,022
Dominican Republic	10,277	12,087	11,958	19,581	1,545	2,271	1,594	2,344
Ecuador	15,492	19,563	19,020	31,145	3,778	5,554	4,874	7,165
El Salvador	6,297	6,408	5,655	9,260	589	865	713	1,048
Guatemala	15,083	21,424	7,902	12,940	1,260	1,852	1,524	2,240
Honduras	7,936	9,737	5,238	8,577	690	1,015	897	1,318
Mexico	120,847	148,133	246,508	403,657	602	885	538	790
Nicaragua	5,992	7,033	3,264	5,345	45,090	66,282	24,988	36,732
Panama	3,802	4,781	7,128	11,672	328	482	550	809
Paraguay	6,687	7,845	8,125	13,305	918	1,350	1,443	2,122
Peru	29,988	36,855	35,688	58,439	494	726	1,271	1,869
Venezuela	29,955	36,674	93,821	153,632	2,078	3,054	5,365	7,886

[a] Data from FAOSTAT, http://faostat.fao.org [37]. [b] Data from EIA [1]. [c] Increasing rate from 2012 to 2030: 64% [3]. [d] Increasing rate for liquid fuels from 2012 to 2030: 47% [39].

Our scope considers LAC's countries with sugarcane production higher than 4 million tons per year, which correspond to 95% of the LAC production [17]. We exclude Brazil due to the well-known contribution of sugarcane on the national energy supply [40–43]. We assume 5-years average (2010-2014) for the sugarcane yield at country level (Table 3). Currently, sugarcane yields between 35 t/ha (Cuba) to 130 t/ha (Peru) in the Latin America regions [37].

In both scenarios, the priority is to use ethanol for gasoline replacement and then as diesel displacement up to an adopted threshold (Table 2). Surplus ethanol is possible after attending these demands. Such conditions are summarized in the following equations and inequations:

$Q_{GR_x} = \{x: 0\% \leq x \leq 10\%\} = [0\%, 10\%]$, as for MC scenario. (1)

$Q_{GR_y} = \{y: 0\% \leq y \leq 20\%\} = [0\%, 20\%]$, as for NF scenario. (2)

$Q_{DR_x} = \{x: 0\% \leq y \leq 10\%\} = [0\%, 10\%]$, as for MC scenario. (3)

$Q_{DR_y} = \{y: 0\% \leq y \leq 20\%\} = [0\%, 20\%]$, as for NF scenario. (4)

If $(S_t \leq Q_{GR_{10}}) \rightarrow (Q_t = Q_{GR_x})$ (5)

If $(S_t > Q_{GR_{10}}) \rightarrow \left(Q_t = Q_{GR_{10}} + Q_{DR_y}\right)$ (6)

$$\text{If} \begin{cases} \left(S_t > (Q_{GR_{10}} + Q_{DR_{10}})\right) \rightarrow (Q_t = Q_{GR_{10}} + Q_{DR_{10}} + E_s), as\ for\ MC\ scenario;\ and \\ \left(S_t > (Q_{GR_{20}} + Q_{DR_{20}})\right) \rightarrow (Q_t = Q_{GR_{20}} + Q_{DR_{20}} + E_s), as\ for\ NF\ scenario \end{cases} \quad (7)$$

Where, Q_{GR} and Q_{DR} are the gasoline and diesel replacement, respectively, which blend varies from x=0 to x=10% for MC scenario, or y=0 to y=20% for NF scenario. S_t is the total supply, Q_t is the total demand and E_s the surplus ethanol. The potential gasoline and diesel replacement are calculated considering the direct relation of lower heating values (LHV) between the fossil fuels and the ethanol. For instance, consider the LHV of 32.36 MJ/L and 21.27 MJ/L for gasoline and ethanol, respectively (refer to note on Table 5). For each liter of gasoline, it is required 1.52 liters of ethanol to deliver the same amount of energy (1 MJ).

Electricity is produced from sugarcane bagasse. After supplying the sugarcane industry demand, surplus electricity is available. We determine the spare electricity based on the sugarcane production (Table 3) and on the estimated surplus electricity productivity, as described in Table 2 (refer to 'Surplus electricity'). We estimate the future electricity demand for 2030 (NF scenario) by considering an increasing rate of 64% over the 2012 consumption [3]. The contribution of bagasse as electricity source for each country is thus estimated by considering the surplus electricity and the current and projected electricity consumption (Table 4).

2.1. GHG emission savings

We evaluate the GHG emissions for the New Framework scenario aiming to identify the potential carbon savings if the countries invest on rethinking their energy generation profile for 2030, i.e., using ethanol as fuel instead of gasoline and diesel, and bagasse for electricity generation rather than maintaining the current electrical generation system. We identify the GHG emission factor (t CO_2e/GWh) for the electricity sector according to the countries current profile (Table 6) and considering the life-cycle perspective (Table 5) for ethanol, gasoline, diesel and electricity from bagasse cogeneration. Emission factors also correspond to the life-cycle approach.

Table 5.
Life-cycle GHG emissions from electricity and fuels.

Electricity generation	t CO_2e/GWh
Oil [a]	840
Coal [a]	1001
Natural gas [a]	469
Hydro [a]	4
Nuclear [a]	16
Solar PV [a]	46
Solar CSP [a]	22
Geothermal [a]	45
Bio-power [a]	18
Wind [a]	12
Electricity from bagasse [b]	66.5
Fuels	**t CO_2e/TJ**
Sugarcane ethanol [b]	18.5
Gasoline [c]	95.6
Diesel [c]	92.8

Note: [a] Data from IPCC [44]. [b] GHG emissions (Well-to-Wheel) for bagasse electricity and sugarcane ethanol were adapted from Souza et al. [45] considering 30% of mechanized harvesting and 70% of burning harvesting. GHG emissions were allocated by energy basis. [c] GHG emissions (WTW) refers to pure gasoline blended with 10% of MTBE and were modelled by using Argonne GREET Model 2014 [46]. The avoided emission due to gasoline replacement is 77 t CO_2e/TJ [95.6 – 18.5 t CO_2e/TJ]. The lower heating values assumed for pure gasoline, ethanol and diesel were 32.36 MJ/L, 21.27 MJ/L and 35.8 MJ/L, respectively [46].

Table 6.
Electricity generation in LAC countries by source and the associated emission factors.

Countries	Total generation [GWh/year] [a]	Source [a]									t CO_2e/GWh [b]
		Coal	Oil	Gas	Biofuels	Nuclear	Hydro	Geo thermal	Solar PV	Wind	
Argentina	135,199	3%	15%	54%	2%	5%	22%	-	-	-	406
Bolivia	7,661	-	2%	66%	2%	-	31%	-	-	-	327
Colombia	62,337	5%	1%	14%	3%	-	76%	-	-	-	131
Costa Rica	10,174	-	8%	-	2%	-	71%	14%	-	-	79
Cuba	18,428	-	85%	11%	3%	-	1%	-	-	-	767
Dominican Republic	16,907	13%	52%	23%	-	-	11%	-	1%	-	678
Ecuador	22,847	-	35%	10%	1%	-	54%	-	-	-	344
El Salvador	5,866	-	36%	-	6%	-	31%	26%	-	-	316
Guatemala	9,412	13%	20%	-	17%	-	47%	3%	-	-	305
Honduras	7,740	1%	49%	-	9%	-	36%	-	-	-	431
Mexico	293,862	12%	19%	51%	1%	3%	11%	2%	-	-	519
Nicaragua	4,031	-	57%	-	11%	-	10%	13%	-	8%	490
Panama	8,606	8%	29%	-	-	-	63%	-	-	-	327
Paraguay	60,235	-	-	-	-	-	100%	-	-	-	4
Peru	39,909	2%	4%	39%	2%	-	54%	-	-	-	236
Venezuela	121,653	-	16%	16%	-	-	67%	-	-	-	215

[a] Data from International Energy Agency [47]; [b] According to Table 5.

2.2. Investments

New investments are required in the NF scenario to expand the sugarcane cropping and build new factories. Based on the sugarcane expansion and sugarcane yield (Table 3), we estimated the total sugarcane supply for the NF scenario. By considering a mill crushing capacity of one million tons of sugarcane (Table 2), we identified the number of mills. We assumed an investment of 132.2 US$/t cane for the industrial sector (including mill and cogeneration system) [48] and 7.5 USD/t cane for the sugarcane area expansion (average value for the sugarcane expansion region in Brazil) [49]. All values are based on 2014 current price. The total investment was split over 10 years. We do not consider investments on power distribution and transmission system assuming it would happen anyway with the increasing on the power demand.

3. Results and Discussion

We evaluated the potential of sugarcane to provide a cleaner energy source in Latin American & Caribbean by considering a short-term framework, named Current Molasses (CM) scenario, and an enhanced approach likely to be deployed over the medium to long-term, entitled New Framework (NF) scenario. Results show the potential of energy supply, the GHG emissions savings, and the total investment required to enlarge the sugarcane production, with further discussion on challenges to implement such bioenergy system in Latin America. We found that building new sugarcane mills would represent a large potential on replacing fossil fuels and providing bioelectricity in most of LAC countries.

3.1. Sugarcane ethanol as energy source

Our results indicate that both scenarios can bring important contribution on replacing fossil fuel in LAC. By only using the current availability of molasses to produce ethanol it would be able to replace at least 10% of gasoline in Nicaragua, Guatemala and Cuba (Fig.1a). Additionally, these countries could also replace diesel by 2-3%. El Salvador and Honduras, which do not have any blending program, could displace more than 5% of the gasoline consumption by using molasses. Over 80% of these countries' gasoline consumption is provided by international market (EIA, 2012). In Nicaragua, in which net gasoline imports are 50% of the total consumption, the production of ethanol from molasses could reduce on 25% the external dependency. As for Guatemala, which is totally dependent on external gasoline supply, MC scenario could cut down 10% of its fossil fuel imports. Cuba is already a gasoline exporter and, therefore, ethanol production can displace gasoline and then increase exports, or provide ethanol for international market. With about 330 million liters of ethanol, Colombia could pledge E5 blend;

though the current ethanol-gasoline mandate is 8-10% (Table 1) – also produced exclusively from molasses. The difference is because the ethanol yield from molasses in Colombia is 19 L/t cane [50] – almost twice the one adopted in this study (Table 2).

<< Figure 1 here >>

Fig. 1. Potential ethanol supply. **a,** MC scenario (Venezuela value is less than 1%). **b,** NF scenario. Identifications (Ex) indicate potential diesel replacement and gasoline blend. Values calculated based on equations and inequations (1-7) presented on Section 2.

As for New Framework scenario, sugarcane ethanol could offer E10 gasoline-blend in most of the countries. Paraguay and Bolivia would be able to displace 20% of the gasoline and diesel (Fig. 1b). Currently, the gasoline blending mandate in Paraguay is 24% (v/v) of ethanol, and none in Bolivia (Table 1). Bolivia could eliminate its gasoline imports and reduce about 40% the diesel external dependency by using 1% of the pasture land for sugarcane ethanol production. Paraguay could reduce 80% and 20% of its gasoline and diesel external dependency, respectively. Gasoline and diesel imports can drop down by 80% and 30% in Nicaragua, respectively.

Despite the potential on eliminating the external dependency on gasoline and diesel, countries may not be interested on interrupting international relationships. Sugarcane ethanol can represent an export opportunity, especially for USA and Europe in which renewable fuel national programs impose the use of biofuel able to reduce the GHG emissions [51–53].

3.2. Potential electricity supply

Currently, sugarcane bagasse has low contribution on power energy mix in LAC. In Colombia and Guatemala, this coproduct contributes to 1% [54] and 1.5% [55] of the current electricity generation, respectively. We found that there is potential to enlarge the use of bagasse. In the MC scenario, Colombia, Guatemala and Mexico show the higher electricity production due to the current sugarcane supply. By using 1% of the pasture land to enlarge the sugarcane cropping, Argentina, Peru, Guatemala and Bolivia can also significantly increase the electricity generation from bagasse (Fig. 2). However, the contribution of this coproduct on electricity generation profile will depend on the national demand. In Bolivia, 11.5% of the population lack access to electricity [3]. Bagasse can supply 3.5% of the current electricity demand in Bolivia, El Salvador and Honduras, considering the existing sugarcane (MC scenario) (Fig. 3). The higher potentials are in Guatemala and Nicaragua in which bagasse can contribute to 9% and 7% of the electricity demand, respectively. In these countries, around 15% and 30% of the population still lack access to electricity, respectively [3]. Thus, producing electricity from bagasse may enlarge the energy access whereas in other countries may represent an alternative to replace fossil fuel sources. In Bolivia, for example, in which renewable energy represents only 1.6% of the current electricity generation, excluding hydropower (Table 6), bagasse can contribute to improve the energy profile by providing an alternative to fossil fuel.

By expanding the sugarcane production (NF scenario), bagasse could afford 1,900 GWh per year (Fig. 2) of electricity in Bolivia, 15% of the total national generation in 2030. Despite the potential, laws and programs on renewable energy are still under development in Bolivia, in which one of the targets is to provide 183 MW from renewables by 2025 [10]. In Guatemala and Colombia bagasse could attend 16% and 7% of the national supply in long-term scenario, respectively. Significant potential to Nicaragua as well (Fig. 3).

<< Figure 2 here >>

Fig. 2. Potential electricity generation**.** New Framework scenario considers a projection in the electricity consumption. MC = Mature Context scenario. NF = New Framework scenario.

<< Figure 3 here >>

Fig. 3. Potential contribution of sugarcane bagasse on electricity generation.

3.3. GHG emissions implication

We found relevant potential on reducing the national carbon emissions specially in Bolivia, Paraguay and Nicaragua, (Fig. 4). GHG emission savings from replacing gasoline and diesel and promoting a cleaner electricity generation would be 18% in Bolivia (2.6 Mt CO_2e); larger contribution from diesel displacement. Paraguay savings correspond to 15% of the 2012 fossil fuels emissions – about 1.2 Mt CO_2e, especially from diesel displacement – despite the increasing on carbon emissions from electricity generation justified by the hydropower contribution. Nicaragua can reduce 14% (0.9 Mt CO_2e) by implementing NF scenario. The electricity generation in Cuba is mainly from fossil fuel, which justifies the significant potential of bagasse on improving the power mix. Argentina and Mexico present the larger potential in absolute values, able to avoid 11.5 and 12.5 Mt CO_2e in 2030 compared with 2012, respectively. By applying the NF scenario, Argentina can accomplish over 10% of its pledge announced at the COP21 [56].

<< Figure 4 here >>

Fig. 4. Potential GHG emission savings due to gasoline, diesel and electricity displacement. Graphs split for better visualization. **a**, smaller-scale graph. **b**, larger-scale graph. Red markers correspond to the relative GHG emission savings compared with the fossil fuel emissions (2012 baseline; considering carbon emissions attributed to the goods and services consumed in the country discounted from emissions from cement manufacture. Data [57,58,39] were retrieved from the Global Carbon Atlas http://www.globalcarbonatlas.org/?q=en/emissions [59]).

3.4. Investments

The total capital required to implement the NF scenario in all LAC countries, including the sugarcane cropping and about 230 mills, would be around USD 35 billion (Table 7), which represents around the same investment in renewable energy in LAC from 2012 to 2014, excluding Brazil [60]. Argentina and Mexico would each spend around USD 9 billion to implement about 60 new industries. In most of the LAC countries, such investment over 10 years would represent less than 1% of the national investment in fixed capital (Table 7). Although Mexico would require an investment four times higher than that applied on renewable energy in 2014, cleaner energy projects have increased in the past years in this country [60]. With around USD 2 billion (16 new plants), Bolivia would displace 20% of gasoline and diesel, besides producing surplus ethanol. Such capital represents about 3% of the total investment (gross fixed capital formation, Table 7) in this country in 2014, which could pose barrier to implement the NF scenario. This condition, however, could be overcome by using foreign investments [61].

Colombia targets 6.5% of renewable energy on electricity generation by 2020, excluding large hydropower [10]. By investing on 35 new 1Mt-sugarcane mills, bagasse would supply 6% of the Colombian demand. Nicaragua can replace 20% of the gasoline and 16% of the diesel by investing USD 464 million in only three new sugarcane mills. This investment represents 10% of the country plans in renewable energy over the next 15 years, although biomass has not been included in the framework [62]. Currently, there is no ethanol blending mandate in Nicaragua (Table 1) and the country imports about 50% of its gasoline consumption [1], confirming the opportunity for ethanol as alternative fuel. In addition to biofuels, sugarcane bagasse can afford 15% of the electricity demand in Nicaragua in 2030. This country has established a goal of generating 90% of its electricity from renewable sources by 2027 [63]. Paraguay can attend the NF scenario by investing USD 1 billion, 2.5% of its investment in fixed capital in 2014. The capital required for Costa Rica and Panama to replace at least 5% of the gasoline (one single sugarcane plant) correspond to 25% of their total investment on renewable energy in 2014 [60]. With an investment of USD 3.5 billion, which correspond to less than 1% of the gross investment in fixed capital, Peru displace at least 20% of gasoline and 10% of diesel. Currently, the blending mandate of ethanol in Peru, which is also produced from sugarcane, is 7.8% [10] and, despite of the high biomass potential, hydro and gas contribute to over 90% of the electricity generation (Table 6).

Table 7.
Number of new 1Mt-sugarcane mills and total investment for New Framework scenario.

Countries	Number of mills [a]	Total investment [MUS$] [b]	Investment related to GDP at market price [%] [c]	Investment related to gross fixed capital formation [%] [d]
Argentina	64	9,368	0.2%	1.1%
Bolivia	16	2,355	0.7%	3.4%
Colombia	35	5,206	0.1%	0.5%
Costa Rica	1	136	0.0%	0.1%
Cuba	1	152	0.02%	0.3%
Dominican Republic	1	85	0.01%	0.1%
Ecuador	4	576	0.1%	0.2%
El Salvador	1	81	0.0%	0.2%
Guatemala	2	273	0.0%	0.3%
Honduras	1	215	0.1%	0.5%
Mexico	59	8,652	0.1%	0.3%
Nicaragua	3	464	0.4%	1.4%
Panama	1	151	0.0%	0.1%
Paraguay	8	1,206	0.4%	2.5%
Peru	24	3,538	0.2%	0.7%
Venezuela	12	1,833	0.0%	0.2%
Total	**233**	**34,309**		

[a] Crushing capacity: 10^6 t/year. [b] 2014 current price; R$ 2.35 = US$ 1.00. Include sugarcane field (soil preparation, planting and cultural treatment; average value for the sugarcane expansion region in Brazil) [49] and industrial sector (mill and cogeneration system) [48]. [c] Considering that the total investment will occur over 10 years. Related to 2014 current price. [d] Related to investment in fixed capital.

4. Conclusions and policy implications

This study confirms the large energy potential of the sugarcane in Latin America & Caribbean. Just a slight share of pasture areas and minor investment may be enough to significantly displace fossil fuel, enlarge the electricity access, reduce the external dependency on fuel imports and mitigate the GHG emissions in the energy sector. These results are achieved by using the most traditional technology to produce ethanol (i.e., first generation). Once 2G ethanol is fully developed and economically feasible, it could certainly improve the opportunities for LAC countries. The competition between bioelectricity and 2G ethanol, however, requires a strategic investigation to identify the optimal allocation for bagasse use [64]. Other sources for electricity production, such as sugarcane straw, can also increase the electricity supply. Nevertheless, many benefits to the soil functions are associated to the straw left on the ground, and thus the amount of straw that can be harvested without impacting the crop production is still unclear [65,66].

Yet, investments on sugarcane sector, and especially on bioenergy, depend on stable policies and long-term contracts [67], such as international agreements on carbon emission mitigation. Also, optimize the use of the coproducts must be a priority to make the investment feasible. For instance, producing electricity from bagasse makes sense once it is a residue from the sugarcane mill – thus low-cost source –, and can attend the industry demand and moreover offer surplus electricity.

Despite appropriate policies, opportunity costs and competitive prices are also key issues to put in place such strategy. Opportunity costs are related to the alternative to produce sugar instead of ethanol. The international market for sugar and derivatives and the price parity between ethanol and gasoline will drive the decision with regard the use of sugarcane for ethanol production and the replacement of fossil fuel by the biofuel. The price of ethanol must be competitive with the gasoline one. Under some policies and incentives to enlarge the use of ethanol with more aggressive blending mandate, the biofuel production can be more attractive and overcome any distortion in the price parity or opportunity costs. However, such engagement must be consistent with the car manufacturers in order to adequate the vehicles for higher blends (greater than E10), whose feasibility has been proven by the Brazilian experience. In case of surplus ethanol, there is also opportunity for exports.

In closing, significant growth is expected for biomass power generation and biofuels in the next few years and LAC region can play an important role on promoting modern energy and supplying international demand. Moreover, our study shows the opportunity to improve the countries' energy security as long as appropriate conditions are built in the energy and agricultural fields.

Acknowledgments

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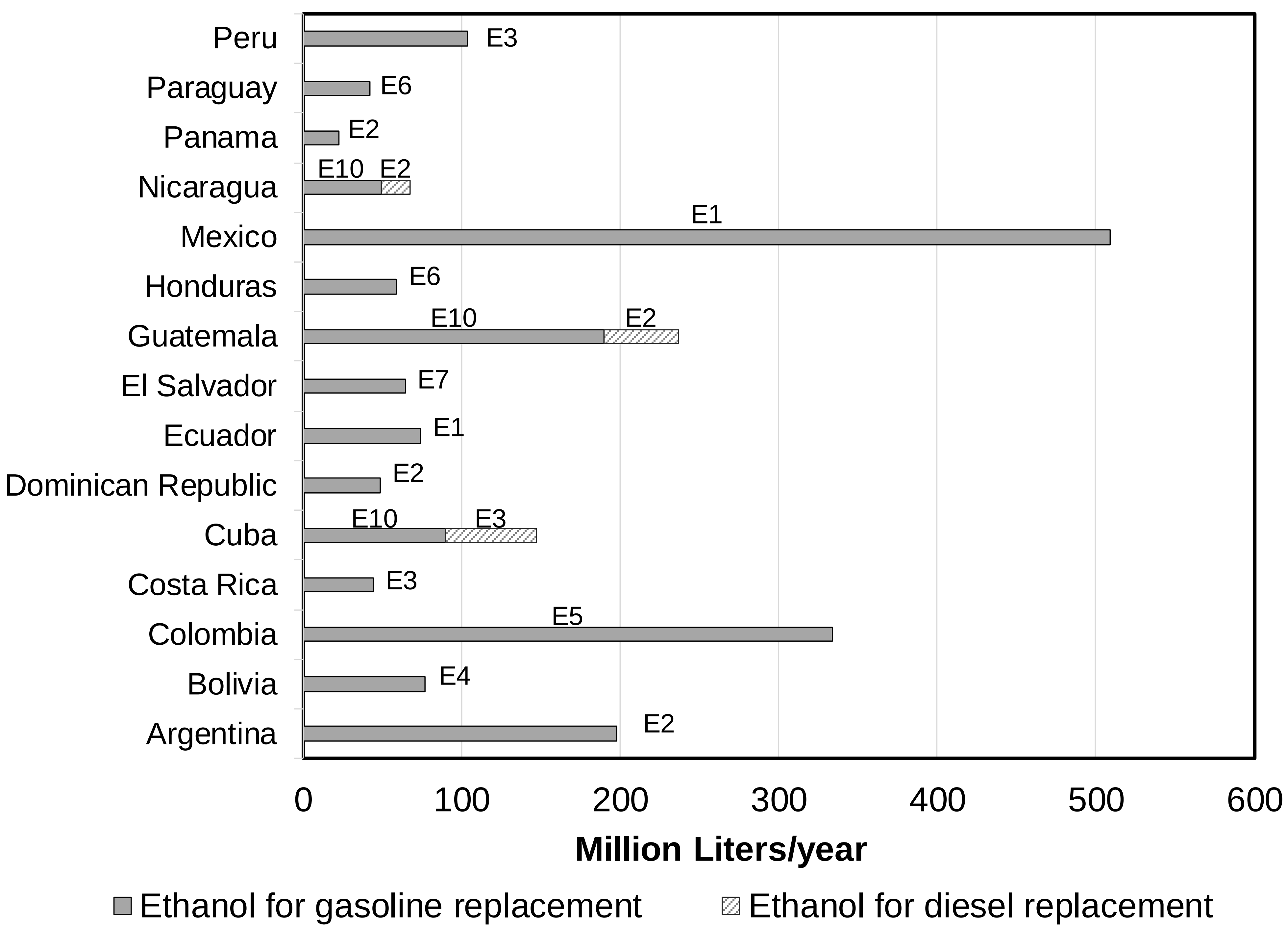
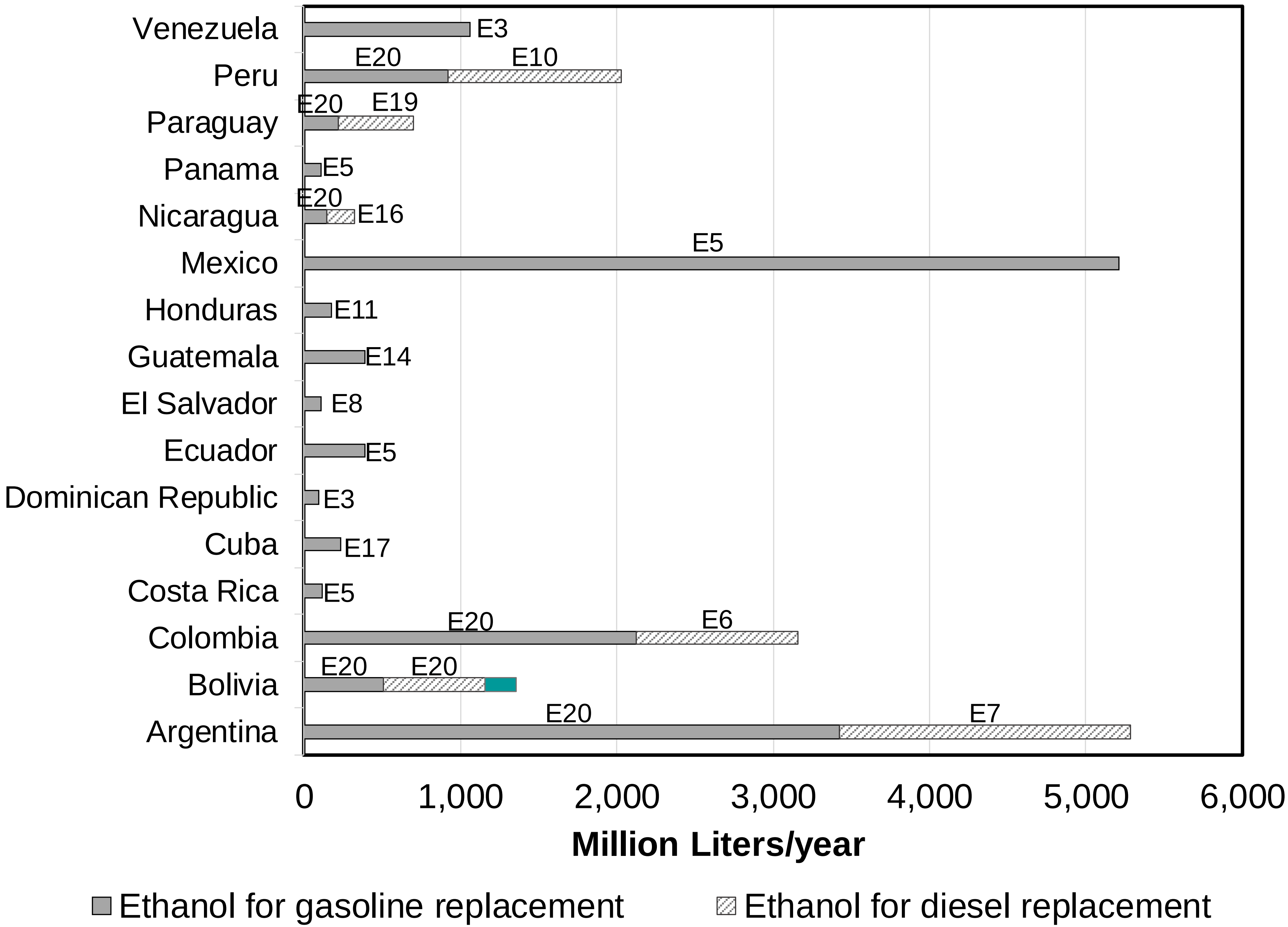
Figure 1a



Peru
Paraguay
Panama
Nicaragua
Mexico
Honduras
Guatemala
El Salvador
Ecuador
Dominican Republic
Cuba
Costa Rica
Colombia
Bolivia
Argentina
E3
E6
E2
E10
E2
E1
E6
E10
E2
E7
E1
E2
E10
E3
E3
E5
E4
E2
0
100
200
300
400
500
600
Million Liters/year
Ethanol for gasoline replacement
Ethanol for diesel replacement

Figure 1b


Venezuela
Peru
Paraguay
Panama
Nicaragua
Mexico
Honduras
Guatemala
El Salvador
Ecuador
Dominican Republic
Cuba
Costa Rica
Colombia
Bolivia
Argentina
E3
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E16
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E11
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E8
E5
E3
E17
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E20
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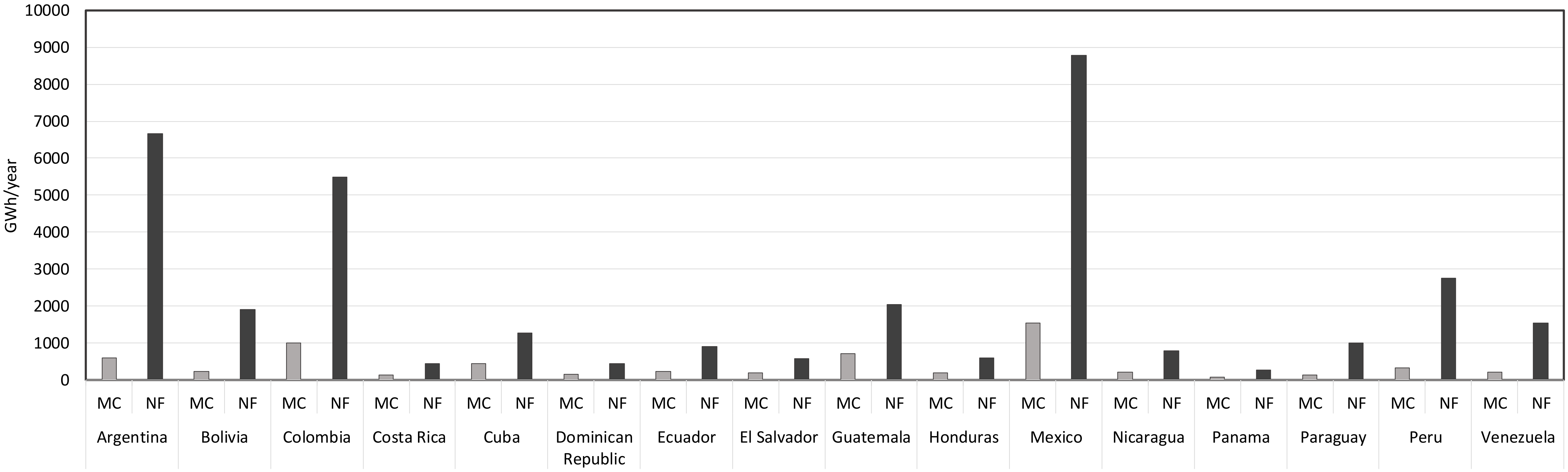
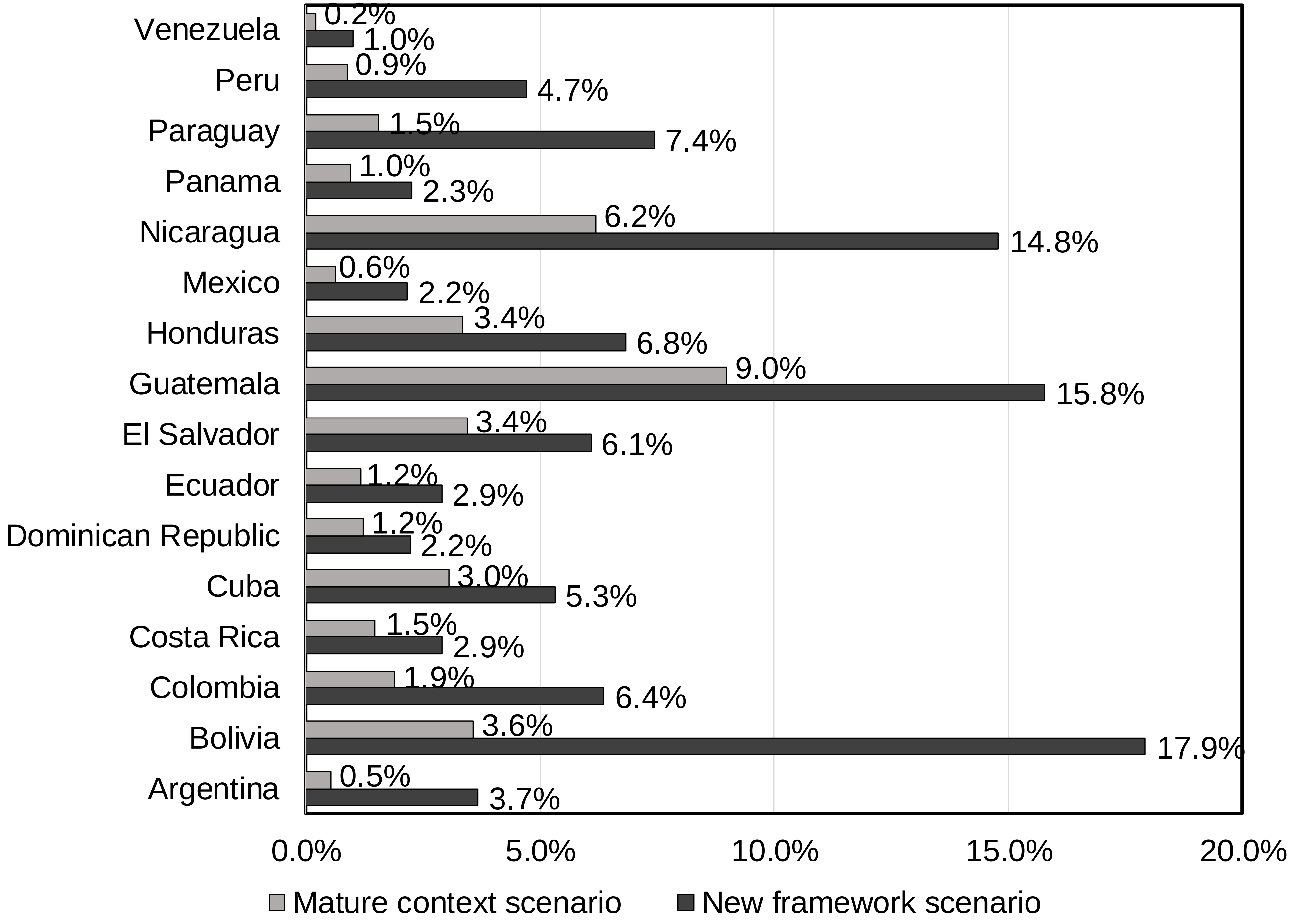
E20
E20
E20
E7
0
1,000
2,000
3,000
4,000
5,000
6,000
Million Liters/year
Ethanol for gasoline replacement
Ethanol for diesel replacement

Figure 2



10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
GWh/year
MC
NF
Argentina
Bolivia
Colombia
Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guatemala
Honduras
Mexico
Nicaragua
Panama
Paraguay
Peru
Venezuela

Figure 3



Venezuela
0.2%
1.0%
Peru
0.9%
4.7%
Paraguay
1.5%
7.4%
Panama
1.0%
2.3%
Nicaragua
6.2%
14.8%
Mexico
0.6%
2.2%
Honduras
3.4%
6.8%
Guatemala
9.0%
15.8%
El Salvador
3.4%
6.1%
Ecuador
1.2%
2.9%
Dominican Republic
1.2%
2.2%
Cuba
3.0%
5.3%
Costa Rica
1.5%
2.9%
Colombia
1.9%
6.4%
Bolivia
3.6%
17.9%
Argentina
0.5%
3.7%
0.0%
5.0%
10.0%
15.0%
20.0%
Mature context scenario
New framework scenario

Figure 4a

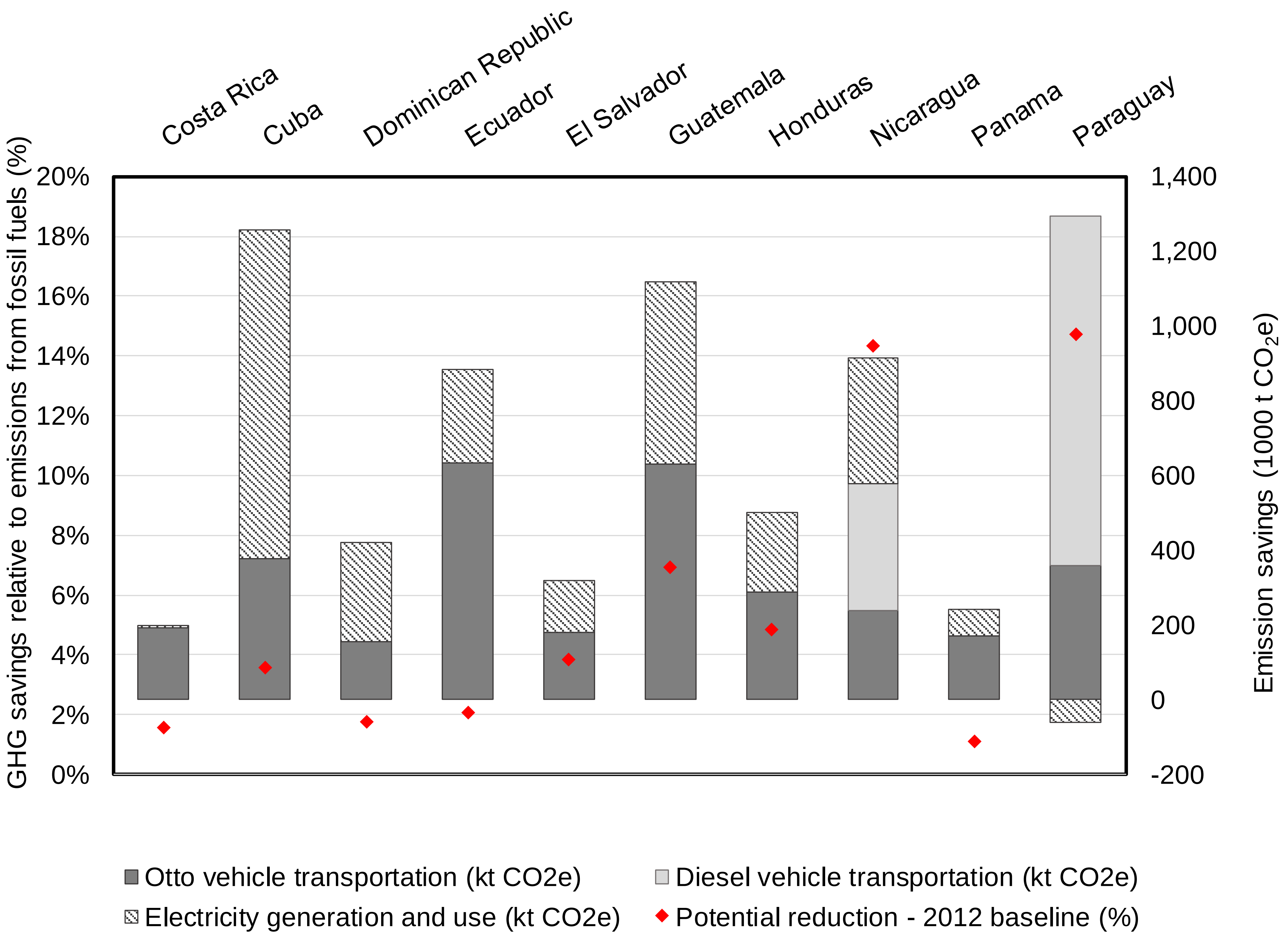
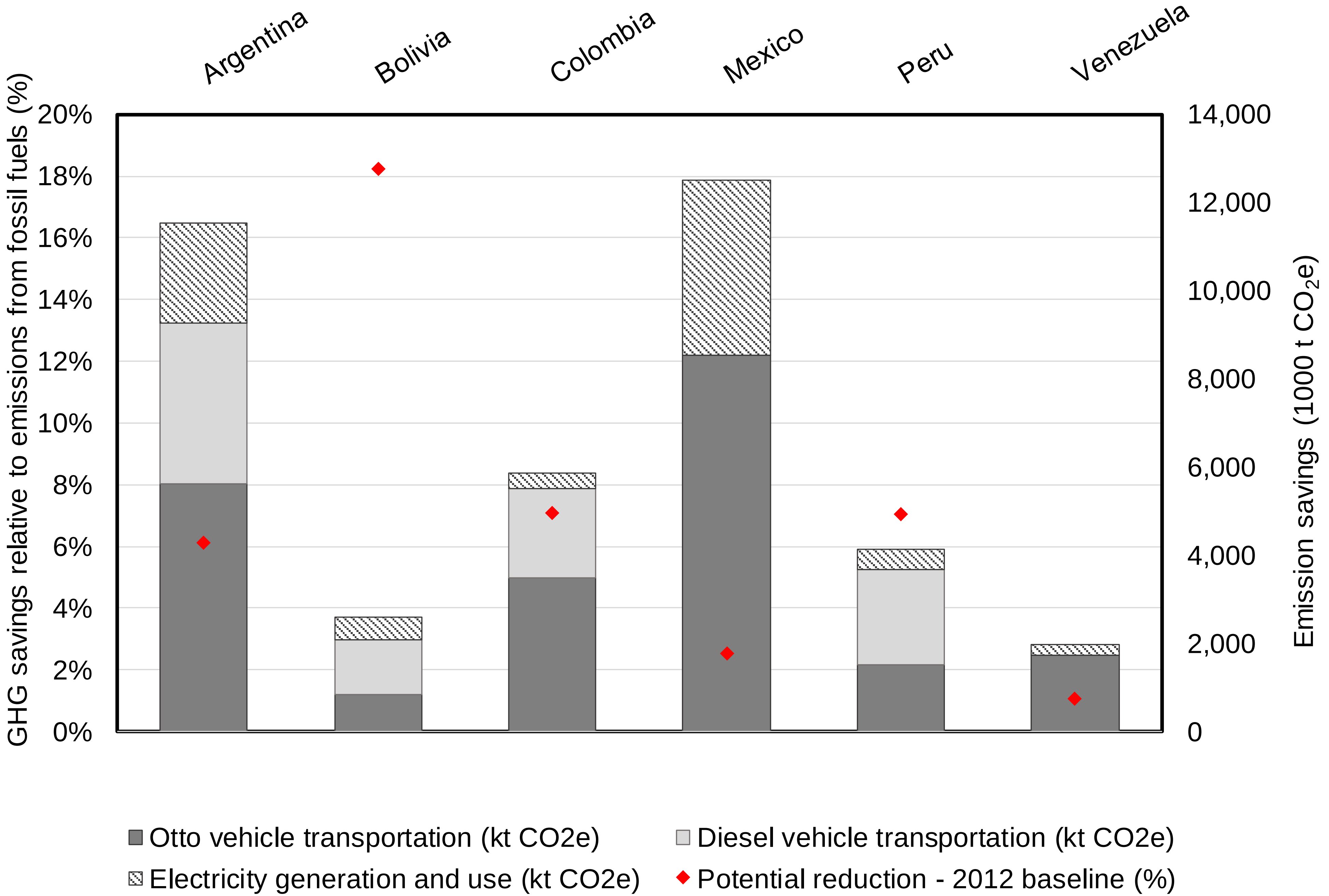

Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guatemala
Honduras
Nicaragua
Panama
Paraguay
GHG savings relative to emissions from fossil fuels (%)
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
1,400
1,200
1,000
800
600
400
200
0
-200
Emission savings (1000 t CO2e)
Otto vehicle transportation (kt CO2e)
Diesel vehicle transportation (kt CO2e)
Electricity generation and use (kt CO2e)
Potential reduction - 2012 baseline (%)

Figure 4b



Argentina
Bolivia
Colombia
Mexico
Peru
Venezuela
GHG savings relative to emissions from fossil fuels (%)
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Emission savings (1000 t CO_2e)
Otto vehicle transportation (kt CO2e)
Diesel vehicle transportation (kt CO2e)
Electricity generation and use (kt CO2e)
Potential reduction - 2012 baseline (%)

Highlights

- Sugarcane offers a large potential as renewable energy
- Sugarcane ethanol can reduce the fossil fuel imports in LAC countries
- Bagasse can contribute to enlarge the electricity access
- Sugarcane can promote the GHG emission savings
- Appropriate policy is key issue to put in place such strategy