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Understanding the failures in developing domestic ethanol markets: Unpacking the ethanol paradox in Guatemala

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ABSTRACT

Fostered by environmental and economic drivers, liquid biofuels are expanding in the global energy matrix. However, many countries with biofuel potential, such as Guatemala, have yet to develop domestic biofuels markets. During the last decade, ethanol production in Guatemala has increased significantly, yet a domestic market does not appear to be in the horizon. It is a kind of paradox: a world class sugarcane producer and ethanol exporter does not use any blend of ethanol and gasoline in vehicles. This paper presents a techno-economic analysis and review of barriers that have delayed ethanol-gasoline blends in Guatemala. The cost assessment considers data from an existing distillery in Guatemala. Results show that Guatemala could produce annually a maximum of 250 million liters of ethanol from molasses, more than the amount required to introduce E10. For the current conditions, results from the modelling indicate that the cost of ethanol has minimal impact on the price of E10, but taxes could represent one third of the cost of E10 at the retail level. Since supply conditions are favourable and technical barriers are not relevant, strong government intervention and a coherent price structure for ethanol-gasoline blends is needed to create an ethanol market in Guatemala.

1. Introduction

Since the 1970s, biofuels have been promoted as a substitute for liquid transport fuels. Despite this, the use of biofuels has become a reality in many countries, which now use ethanol and biodiesel blended with gasoline or diesel to power vehicles. New biofuel technologies, either improving conventional processes or introducing innovative routes through biochemical or thermochemical conversion, have created new opportunities to improve efficiency and cost-competitiveness. However, biofuels markets have been delayed, or not developed at all, in some countries because of trade barriers and/or weak energy policy. Guatemala is one such country. Identified as a leader in Central America for the production, trade and consumption of biofuels (USDA, 2013), the country has no domestic biofuels market and currently exports all the ethanol it produces. Guatemala's transport sector meets most of its internal demand with petroleum derivatives imported from USA (ECLAC, 2010; MEM, 2017), due to the limited supply capacity of the local refinery. This high dependency on imported fuels places a burden on the national economy and environment. Although Guatemala has attempted to create a domestic market for biofuels, to-date all efforts have failed.

The Guatemalan sugarcane industry is the fourth major sugar exporter worldwide and has high levels of agroindustrial productivity, similar to Australia and Brazil (ISO, 2018). Ethanol in Guatemala is produced from molasses, a by-product from sugarcane mills. Several studies (CEPAL, 2006; Cutz, and Nogueria, 2018; USDA, 2013) have evaluated the potential of sugarcane ethanol for transportation in Guatemala, indicating that the current installed capacity of the sugar industry is sufficient to supply a 10% ethanol blend in gasoline. A report of the USDA (2013) indicates that with an additional investment of US$ 60 million, Guatemala could reach a 15% ethanol-gasoline blend. High sugarcane yields, an innovative sector (Melgar, 2012) and ethanol exports to several countries indicate that ethanol production is cost competitive.

However, the introduction of a domestic biofuel mandate, which would replace a fraction of imported gasoline, has proved not to be a simple relationship between price and demand. Even during periods when gasoline was imported at high prices, the local ethanol market remained untapped and all ethanol produced in the country was exported. One explanation may be that Guatemala is an exporter of

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ethanol and an importer of oil. High prices of oil encourage local producers to export more ethanol due to high ethanol prices (Ciaian and Kancs, 2011). But at the same time, high prices of oil affect negatively the trade balance due to an increase in the country's import spending for oil (Gomes et al., 2018).

Therefore, it is a paradox that favourable conditions for biofuel production in Guatemala are insufficient to drive their domestic use. This paper investigates this paradox. It aims to address four questions: 1) what is the potential for ethanol supply and demand in Guatemala? 2) what is the production cost of ethanol and E10? 3) what are the barriers preventing the creation of a domestic biofuel market in Guatemala? and 4) can E10 support Guatemala to comply with the Nationally Determined Contribution (NDC) pledged under the Paris Agreement? To answer these questions, first, the paper determines the demand of ethanol for E10. We use as basis the gasoline consumption of the transport sector in Guatemala. The paper then examines the effects of creating a domestic market on the ethanol trade balance of the country. Second, we provide a techno-economic analysis of ethanol production from molasses. A revised ethanol cost will serve to estimate the potential cost of E10 and update ethanol cost assessments for Guatemala. The techno-economic analysis illustrates and confirms the economic competitiveness of ethanol. This suggests for a socio-political lens to study the lack of an ethanol programme in the country. The paper then draws on a range of documents and earlier research by the authors (Cutz, 2016; Tomei, 2014) to describe the barriers to a domestic biofuel market. This paper addresses an important gap in the literature, that of understanding the factors impeding or enabling the development of domestic biofuel markets in producer countries.

In the next section, we set out the global policy context for biofuels, focusing on the Guatemalan context. In Section 3 we describe the Guatemalan energy mix and sugarcane agroindustry. Section 4 provides the methods used to calculate the potential ethanol production, cost of ethanol and cost of E10. The results are presented in Section 5, followed by analysis of the key challenges to implementation of a domestic ethanol market in Guatemala (Section 6). Section 7 closes with key findings and concluding remarks.

2. Biofuel policy

Around the world, national governments have been critical in establishing demand for biofuels. By 2018, more than sixty governments had established support mechanisms for biofuels, including targets and mandates, and had invested public resources in RD&D and commercialization programs (Biofuel Digest, 2018). Many more are involved in the production of biofuel feedstocks for export markets.

The political institution of biofuel markets has been a key feature in major biofuel regions with specific drivers vary according to each: for example, in the European Union (EU) the use of biofuels has been driven by climate change mitigation and energy security, while for the US, key drivers have been energy security and farmer support (Rosillo-Calle and Johnson, 2010). These two regions have set targets that a certain percentage of transport fuel is to be supplied by biofuels by specified dates, in effect guaranteeing a market of a given minimum size to investors and suppliers of biofuel. Brazil provides another example of a country with a domestic biofuel market; here success was facilitated by an authoritarian political landscape which shaped the opportunities to introduce technological niches and involved all actors to develop an ethanol infrastructure (Johnson and Silveira, 2014). Biofuels were subsequently supported by growing international markets, public procurement, integration of transport systems and the creation of hubs for expertise and networking regarding biofuels (Johnson and Silveira, 2014). Another Latin American leader in biofuels is Colombia. Similar to Guatemala, Colombia produces its ethanol from molasses, although Colombian sugar mills can also produce ethanol from sugarcane juice (Valencia and Cardona, 2014). Colombia began its ethanol program in 2005 by introducing E5 in the biggest cities and by 2020 blending had reached E10. The Colombian state has fully supported and promoted biofuels through tax exemptions and subsidies.

A less successful example is provided by Nepal, which is one of the poorest and least industrialized countries in the world. Nepal shares some similarities with Guatemala as its transport sector is heavily dependent in petroleum products, it has nine operational sugar plants but no ethanol production and has introduced a number of regulations to reduce vehicle emissions without much success (Silveira and Khatiwada, 2010). Although the country has sufficient sugar mill infrastructure to satisfy an E10 demand, weak support from the government has delayed ethanol-gasoline blends (Silveira and Khatiwada, 2010). Across Africa, significant potential for production of ethanol from sugarcane has been assessed in some countries (Nogueira et al., 2019). African governments have expressed support for biofuels, yet few have policies and frameworks to mandate their consumption which partly accounts for their limited use on the continent (Mitchell, 2011). These examples demonstrate the importance of strong government support in creating domestic ethanol markets. In the next section, we turn to discuss biofuel policy in Guatemala.

2.1. Biofuel policy in Guatemala

Since the 1980s, biofuels have been promoted in Guatemala and successive governments have attempted to create a domestic biofuel market. The country has 28 laws applicable to biofuels, of which 23 relate to feedstock production and five to industrial activities (Hamelinck et al., 2011). Guatemala has passed two laws specifically focused on the development of a domestic market for biofuels. The first, Decree 17/85, proposed the substitution of petroleum with fuel produced from renewable domestic sources and established an E5 mix of ethanol in gasoline. The Decree also set production quotas and prices, as well as a tax payment from producers, equivalent to 2.5% of their ethanol production (USDA, 2013). The second, the Law of Incentives for the Development of Projects in Renewable Energy (DPRE), which establishes import tax exemptions on equipment/machinery related to alcohol processing and intermediate goods (USDA, 2013). However, neither law has been implemented and a domestic market for biofuels has yet to materialize.

There are several drivers of biofuels in Guatemala, including import substitution, export opportunities, impacts on air quality, rural development and tackling contraband (Tomei, 2014). As a result of these multiple drivers, several ministries are involved in biofuel policy including the Ministry of Energy and Mines (MEM), the Ministry of Agriculture, the Ministry of Natural Resources, Ministry of the Economy, and Ministry of Finance. The different policy functions and responsibilities of each ministry influences their interest in and attitudes towards biofuels (Tomei et al., 2014). However, a key challenge is that the development of a domestic biofuel market is not a policy priority and no single ministry is responsible for overseeing market development. The state has so-far played a minor role in developing a domestic biofuel market and it has been left to private actors, specifically the sugar sector, to determine how market develop (Tomei, 2014). As indicated by USDA (USDA, 2013), amongst the factors responsible for the failure of Law 17/85 were the lack of agreement on the alcohol sales prices to the refineries, and the lack of planning from port operators, sugar mill owners, government ministries and fuel distributors. This complex policy picture will be returned to in Section 6, but the paper next turns to a description of the Guatemalan biofuel sector.

3. Biofuels in Guatemala: energy, agriculture and the sugar-ethanol sector

Primary energy supply in Guatemala relies on two resources - biomass and coal, which accounted for 80% and 10%, respectively, of country's primary energy supply in 2017 (MEM, 2017). The main types of biomass resources used in Guatemala are firewood and sugarcane bagasse, which accounted for 67% and 13% of the 2017 biomass energy supply, respectively. Fig. 1 shows the energy consumption by different sectors in Guatemala based on the most recent data available, year 2017. The bioenergy share presented in Fig. 1 only includes fuelwood consumption in the residential and tertiary sectors. This, since sectoral energy consumption of bagasse was not available at the time of this analysis. Nevertheless, the MEM (MEM, 2017) reports that power plants and autogenerators consumed 1333 ktoe of sugarcane bagasse in 2017.

Energy consumption in Guatemala is concentrated in the residential and transport sectors, which represent 61% and 27% respectively of national total consumption. In 2017, Guatemala had a fleet of around 3 million vehicles, of which 87% were running on gasoline and the remainder on diesel (SAT, 2016).

3.1. Sugarcane industry infrastructure in Guatemala

Sugarcane has been cultivated in Guatemala since colonial times and is today an important agroindustry. In 2019, there were eleven operational sugar mills in Guatemala. These mills were crushing sugarcane with a mean crushing capacity of about 14 thousand tonnes of sugarcane per day (tc/d). Table 1 presents the installed capacity of Guatemalan sugar mills and their corresponding distilleries. This includes data on sugar production, electricity generation and ethanol production.

As can be seen from Table 1 during the 2018–2019 crushing season, Guatemalan sugar mills processed about 27 million tonnes of sugarcane, harvested in 263 thousand hectares (CENGICAÑA, 2019a) to produce about 2.9 million tonnes of sugar. White refined sugar accounted for about 62% of the total sugar production (CENGICAÑA, 2019a).

In 2019 in Guatemala, there were 10 Combined Heat and Power (CHP) plants firing sugarcane bagasse with a total installed capacity of 572 MW (31% of national capacity) (ACI, 2019). During the crushing season 2018–2019, all sugar mill CHP plants combined generated around 2000 GWh from sugarcane bagasse, equivalent to 27% (ACI, 2019) of the country's electricity generation. Furthermore, around two-thirds of the Guatemalan sugar mill CHP plants operated during the off-harvest season 2018–2019, providing 5% (384 GWh) of the country's electricity generation from supplementary fuels such as coal and fuel oil (ACI, 2019).

With respect to ethanol production, it is estimated that Guatemala produces around 44% of Central America's sugarcane ethanol (USDA, 2013). Nevertheless, some social organizations within Guatemala are opposed to the production and use of biofuels (e.g. (Alonso-Fradejas, 2012; Mingorría and Gamboa, 2010)). For some, this is due to the potential conflict between food and fuel (Tomei and Helliwell, 2016). As can be seen from Table 1, Guatemala has five distilleries with a total installed capacity of 1.4 million liters per day. The individual capacity of the Guatemalan distilleries ranges from 120 kL/day to 600 kL/day. Guatemalan distilleries have a combined annual production of 269 million liters of ethanol operating at 89% of its capacity. Less than 26% (USDA, 2013) of this production corresponds to anhydrous ethanol, typically blended with gasoline for vehicular use. Only 1 out of the 5 Guatemalan distilleries, Grupo DARSA, is not annexed to a sugar mill and uses sugarcane molasses to produce spirits, liquors (e.g., rum) and ethanol. Fig. 2 summarizes the operational performance of all sugar mills in Guatemala in 2019 using typical indicators employed by sugar millers.

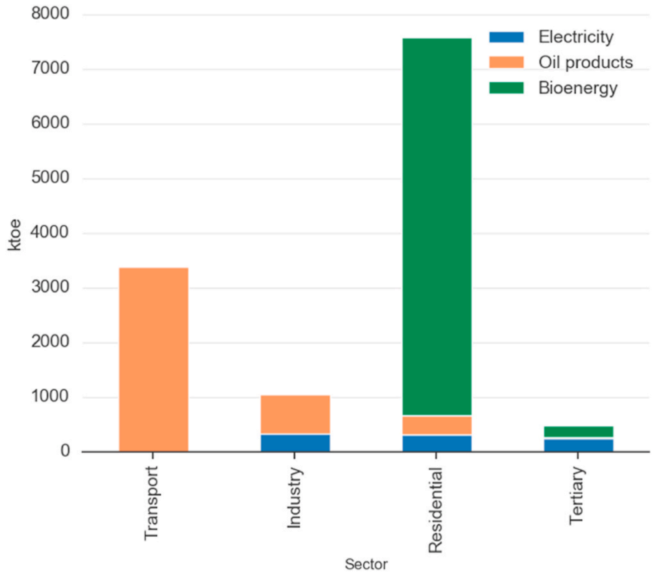

Fig. 1. Sectoral final energy consumption in Guatemala, 2016. Data obtained from (MEM, 2017).

During the 2018–2019 season, Guatemalan sugarcane mills reported a production of 105 tons of harvested cane on average per hectare of plantation (Fig. 2). Historical yields for the Colombian and Brazilian sugar industry report a mean value of 120 tc/ha (USDA, 2018) and 71 tc/ha (USDA, 2019) for the 2018–2019 season, respectively. Once at the factory, sugar production yields average 99 kg of sugar per ton of sugarcane crushed. All Guatemalan sugar mills operate with similar efficiencies, regardless of their installed capacity. Historical yields for the Colombian sugar industry report a mean value of 94 kg/tc for the 2018–2019 season (USDA, 2018). When it comes to ethanol production, two parameters are relevant for the comparative analysis of sugar mills: total reducing sugars (TRS) and molasses yield. The TRS are an indicator of the fermentable sugars contained in sugarcane that can be converted into ethanol. The molasses yield is a factory index that allows sugar millers to estimate how much molasses can be produced from one tonne of cut cane. Which of these factors is more important depends on the by-product of sugarcane used to produce ethanol, i.e. sugarcane juice (TRS yield) or molasses (molasses yield). For the 2018–2019 season, Guatemalan sugar mills recorded a mean TRS of 143 kg TRS/tc and a molasses yield of 26 L/tc. Historical yields for the Brazilian sugar industry report a mean value of 138 kg TRS/tc for the 2018–2019 season (USDA, 2019). Based on data reported from an existing sugar mill distillery in Guatemala, the ethanol yield from sugarcane molasses is around 8.7 L/t of cane (Mena, 2016). All these data confirm that the Guatemalan sugarcane agroindustry presents excellent performance, at world class level.

3.2. Guatemala ethanol exports

The annual exports of ethanol in million liters from the period 2000–2019 are presented in Fig. 3. Data presented in Fig. 3 has been extracted from the Central American Economic Integration Secretariat (SIECA).

As can be seen from Fig. 3, during the 2000–2004 period, Guatemala averaged an ethanol production of 27 million liters annually. Production started to take off in 2005 with an increase of 260% with respect to 2004 levels. Since 2012, Guatemalan exports of ethanol have been above 170 million liters per year, of which a majority has been exported to the EU. Fig. 4 presents the top 10 countries to which Guatemalan ethanol was exported between year 2000 and 2019.

During the 2000–2019 period, around 42% of the ethanol that Guatemala exported was delivered to the Netherlands (Fig. 4). Ethanol trade is affected by internal and external market prices for anhydrous and hydrated ethanol, as well as international trade agreements. In the case of Guatemala, ethanol production is also driven by the price of molasses, with high prices of molasses likely to result in a reduction in the production of ethanol. The complete list of importers of Guatemalan ethanol for the 2000–2019 period can be found in Supplementary Fig. 1. Fig. 5 presents the evolution of the price of Guatemalan ethanol during the 2000–2019 period. Values presented in Fig. 5 were obtained by dividing the total amount of ethanol exported per year by its

Table 1
Sugar mills and distilleries in Guatemala.

Sugar mills	Sugarcane crushed	Sugar production	Power generation	Annexed Distillery	Capacity	Load factor	Operation days	Annual production
	2018–2019	2018–2019	2018–2019					
	kt	kt	GWh		kL/day	%		ML/yr
Magdalena	6734	673	592	Alcoholes MAG	300	95	155	45
Pantaleón	4610	502	256	Bioetanol	600	95	155	89
La Unión	3168	335	193					
Santa Ana	2888	288	261	DARSA*	250	95	330	79
Trinidad	2167	244	305					
Madre Tierra	2145	232	128	Servicios Manufactureros**	120	95	330	38
El Pilar	1895	211	32					
Palo Gordo	1695	182	133	Palo Gordo	120	65	155	18
Concepción	1329	141	61					
Tululá	806	92	40					
La Sonrisa	25	3						

Source: The amount of sugarcane crushed and sugar production was extracted from (CENGICAÑA, 2019a). The power generation refers to the electricity generated during the crushing season 2018–2019 only from sugarcane bagasse and was extracted from (ACI, 2019). Data regarding distillery capacity was extracted from (Cutz et al., 2013) and complemented with data from (MEM, 2011). Distilleries load factors, operation days and annual production was extracted from (MEM, 2011). * DARSA is owned by Santa Ana sugar mill and operates as a stand-alone distillery. ** Servicios Manufactureros distillery is owned by Magdalena and Madre Tierra sugar mills.

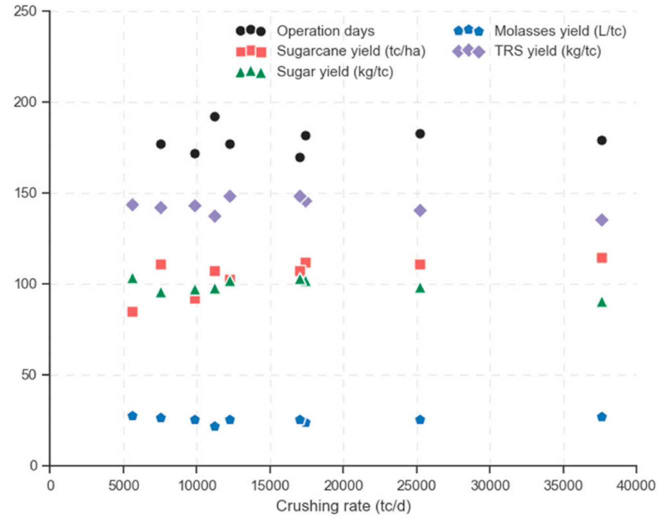

Fig. 2. Comparative performance of the sugar industry in Guatemala for 2018–2019 crushing season. Source: (CENGICAÑA, 2019b, 2019a). The total reducing sugars (TRS) yield was estimated based on data reported by (CENGICAÑA, 2019b) regarding the total cane crushed in 2015–2016 (ha), pol in cane, reducing sugars (RS) and fibre in cane for each of the Guatemalan sugar mills under operation. Fig. 2 presents data for 9 out of the 11 sugar mills. There was no data available for "La Sonrisa" and "El Pilar".

corresponding traded value reported by SIECA (SIECA, 2019).

Based on data reported in Fig. 5, it is observed that in recent years (2015–2019), Guatemala sold its ethanol at an average price of 0.54 US $/L.

4. Materials and methods

An assessment of the potential ethanol supply and demand for E10 is presented as follows. Ethanol-gasoline blends are usually labeled with a letter "E" and the number next to it indicates the volume percentage of ethanol in the blend. For example, E10 means that 10% anhydrous ethanol (99.9% purity) was blended with 90% gasoline by volume. A cost model was developed to estimate the cost of producing 1 L of ethanol from molasses under Guatemalan conditions. Based on the results of the model, we calculate the cost of producing 1 L of E10 if Guatemala decided to create a domestic market for ethanol. For the cost model, we adopted 2019 as the baseline year. Other results presented in this work are analyzed over a larger time span since data regarding gasoline prices, ethanol prices, ethanol exports and gasoline consumption in Guatemala are now becoming available.

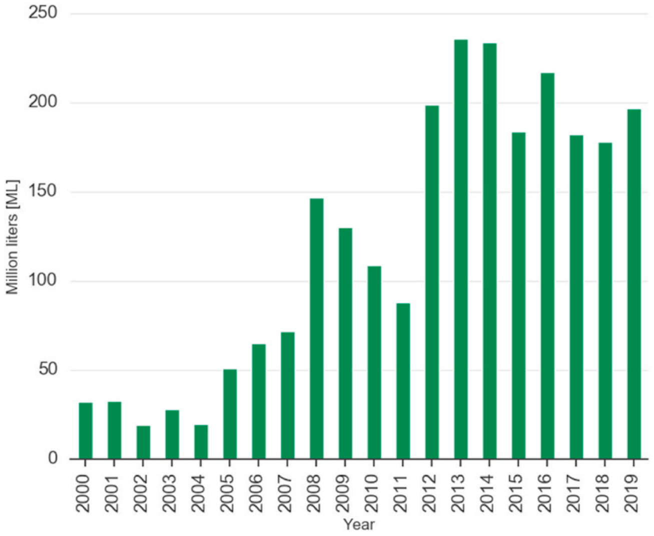

Fig. 3. Guatemala's exports of ethanol during the period 2000–2019. Source: (SIECA, 2019), commodity code: 2207. The most recent data available for year 2019 dates until September 2019. In 2019, there is no specific commodity code assigned to fuel ethanol in SIECA's system. The commodity code 2207 includes denatured alcohol and undenatured alcohol, both can be used for fuel ethanol.

4.1. *Ethanol supply and demand for E10 in Guatemala*

Ethanol supply and demand for E10 was evaluated for the 2000–2019 period. The ethanol required to achieve E10 was estimated considering 10% of the gasoline consumption reported by MEM (MEM, 2020). We evaluated two scenarios to rule out the possibility that Guatemala has not created a domestic market for ethanol due to the limited current capacity of the supply chain.

- Ethanol balance – current production: we compared the ethanol required to achieve E10 with the annual ethanol production in Guatemala. The annual ethanol production was assumed to be equal to the annual ethanol exports reported for the period 2000–2019 (Fig. 3).

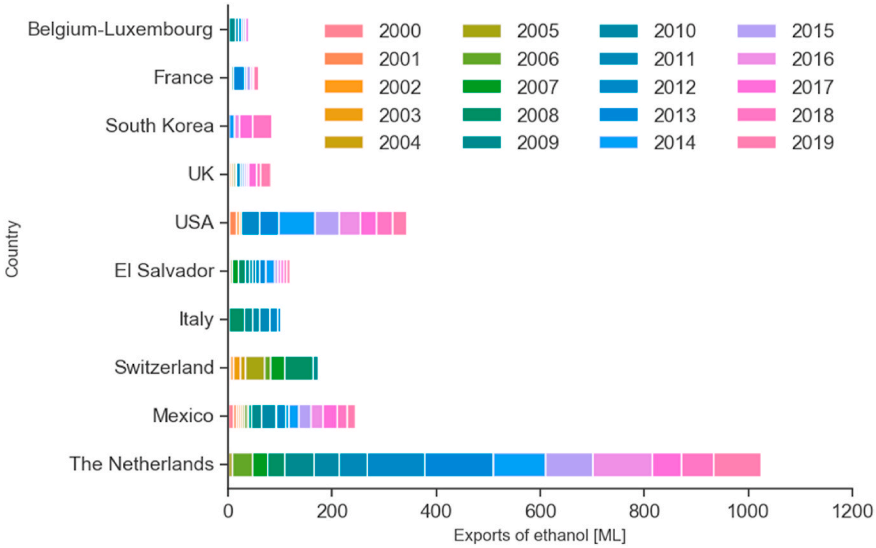

Fig. 4. Top 10 major importers of Guatemalan ethanol during the period 2000–2019. Source: (SIECA, 2019), commodity code: 2207. The most recent data available for year 2019 dates until September 2019. It is important to note that although the SIECA database treats USA and Puerto Rico as two different countries, other databases (e.g. (International Trade Centre, 2019)) consider these as one. Therefore, we have decided to sum the values reported by SIECA for USA and Puerto Rico.

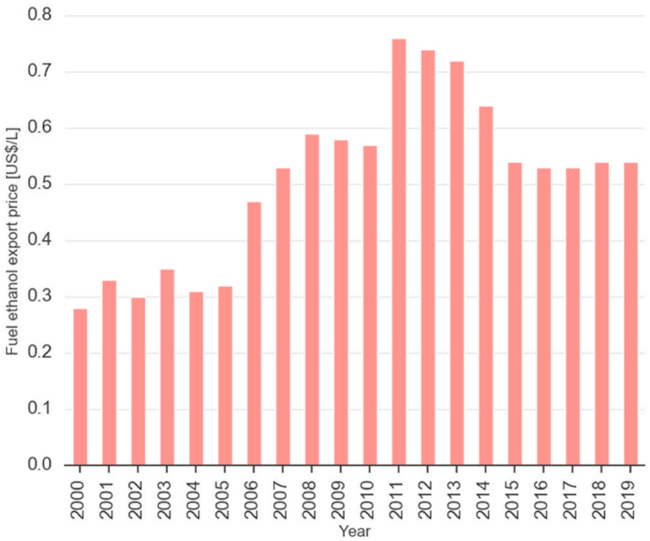

Fig. 5. Guatemalan fuel ethanol export price in US$/L for 2000–2019 period. HS code 2207.

- Ethanol balance – maximum ethanol production: we compared the ethanol required to achieve E10 with the maximum ethanol production that could be obtained if all molasses produced by sugar mills were transformed into ethanol. The maximum ethanol production that can be obtained from molasses was set to 9.1 L of ethanol per one ton of cut cane. This value was established based on the performance of the sugar mills in Guatemala (CENGICAÑA, 2014). Thus, the maximum ethanol production was obtained by multiplying the amount of sugarcane crushed annually during the 2000–2019 period times 9.1 L/tc. The amount of sugarcane crushed was extracted from (CENGICAÑA, 2020).

An ethanol surplus results when ethanol exports are higher than the ethanol demand for E10. Ethanol deficit results from ethanol exports lower than the ethanol required to achieve E10.

4.2. *Ethanol cost for Guatemalan conditions*

One of the main barriers to the use of ethanol-gasoline blends is the high cost of the blends relative to gasoline. It is therefore critical to analyze the cost of producing ethanol, or an ethanol blend. This section presents all costs related to the production of 1 L of fuel ethanol under Guatemalan conditions. Here we consider two scenarios since not all sugar mills in Guatemala have annexed distilleries.

- Existing – Dist.: ethanol is produced in an already operating distillery, and thus no investments in the sugar mill are required. Yet, this scenario considers the investment required to develop an E10 infrastructure in the country.
- New – Dist.: considers the construction of a new ethanol distillery annexed to an existing sugar mill and includes the investment required to develop an E10 infrastructure.

The model presented in this section to calculate the ethanol cost is meant to be representative of an average sugarcane ethanol distillery annexed to a sugar mill in Guatemala. This model of cane processing was found to be adopted by 4 of the 11 sugar mills reported under operation in 2019 in Guatemala (Table 1). The comparison of both scenarios has been made on the basis of their cost including a minimum desired profit margin. The production cost for ethanol (COEt) expressed in US$/L has been estimated based on Equation (1). This expression is partly based on the model proposed by Van den Broek (van den Broek et al., 2000) to calculate the costs per kWh of electricity produced from sugarcane bagasse. The cost model presented here includes the cost of sugarcane production, the cost of converting molasses into ethanol and the rate at which the sugars contained in molasses are transformed into ethanol. COEt is described in terms of the Net Present Value (NPV) of the frequency that a cost item occurs during the total project lifetime. This is because sugarcane in Guatemala is replanted approximately every five years, while some activities such as weeding and irrigation can be performed several times during a year.

$$COEt = \frac{(1 - F_{SJM}) \cdot \sum_{i=1}^{i_t} \left[ecc_i \sum_y^n \frac{f_i(y)}{(1+dr)^y} \right]}{\varepsilon \cdot yld \cdot rot \cdot \sum_y^n \frac{f_{yld}(y)}{(1+dr)^y}} + \frac{\sum_{j=1}^{j_t} \left[edc_j \sum_y^n \frac{f_j(y)}{(1+dr)^y} \right]}{C_{inst} \cdot Op \cdot \sum_y^n \frac{f_e(y)}{(1+dr)^y}}$$

Equation 1

For $i = 1, \ldots, i_t$, $j = 1, \ldots, j_t$, i_t and j_t being the cost items related to the sugarcane plantation and distillery, respectively. The sugarcane plantation items comprise planting, weeding, harvest and land costs, if applicable. Distillery cost items include operation and maintenance costs and fixed costs. The operating costs include direct labor and materials expenses involved in the operation and maintenance of the distillery. The fixed costs include electricity, security, transport and insurance. The frequency of the cost items associated with sugarcane and ethanol production is provided in the Supplementary Material (Supplementary Table 1) and represents the parameters $f_i(y), f_j(y), f_{yld}(y)$ and $f_e(y)$. $(1 - F_{SJM})$ is the mass allocation factor, ε is the ethanol yield [L/t$_c$], *yld* denotes the sugarcane yield [t$_c$/ha], *rot* is the number of rotations of sugarcane per year, C_{inst} is the installed capacity of the distillery [L/d], *Op* is the operation time of the distillery [d/yr], *dr* is the discount rate, ecc_i denotes the cost related to sugarcane production [US$/ha], and edc_j stands for the distillery costs [US$/yr]. For the scenario where a new ethanol annexed distillery is built, the investment item $f_1(1)$ in Equation (1) has a value of 1 (Supplementary Table 1).

We defined a mass allocation factor, $(1 - F_{SJM})$, based on the proportion of reducing sugars that can be recovered from the sugar process. This, since not all reducing sugars in cane are transformed into ethanol. A large part of the reducing sugars is used in sugar production and some remain in sugarcane bagasse. The fermentation process uses the reducing sugars in molasses for ethanol production. The F_{SJM} is a factor used by sugar millers to estimate the available sugar on the raw material. Table 2 presents the parameters used to estimate the SJM factor (F_{SJM}) and ethanol yield (ε) shown in Equation (1). Both parameters were calculated based on operational data from an existing sugar mill and distillery in Guatemala.

$$F_{SJM} \approx \left[\frac{P_{sugar}}{P_{CJ}}\right]\left[\frac{P_{CJ} - P_{molasses}}{P_{sugar} - P_{molasses}}\right] \qquad \text{Equation 2}$$

Where, P_{sugar} is the apparent purity of the sugar product, P_{CJ} is the apparent purity of the clarified juice and $P_{molasses}$ refers to the apparent purity of molasses. The methodology used to estimate the ethanol yield (ε) is provided in the Supplementary Material. The ethanol yield depends on the total amount of TRS available in sugarcane to be fermented to ethanol, the theoretical yield of ethanol derived from reaction stoichiometry and efficiency of the distillery. Detailed calculation of the sugar losses at different stages of the process is provided in the Supplementary Material. Table 3 presents physical data concerning sugarcane and cost assumptions for sugarcane cultivation and sugar mill distillery operation and maintenance. The costs related to sugarcane are based on data reported by a sugar mill in Nicaragua, but adapted to Guatemalan conditions based on the opinion of local experts (González, 2016; Melgar, 2017). Data of the installed capacity, efficiency and operating costs of ethanol production were collected from an existing distillery in Guatemala. This analysis is based on a 10% discount rate of return. Table 3 has been adapted from (Cutz and Santana, 2014). Prices have been updated to December 2019 using inflation.

Table 2
Parameters used to estimate the SJM factor (F_{SJM}) and ethanol yield (ε).

Item	Value	Unit
Pol in cane	13.06	%
Purity of first expressed juice	86.77	%
Fibre in cane	13.85	%
RS in first expressed juice	0.74	%
Purity of mixed juice	86.06	%
Purity of clarified juice	85.53	%
Blackstrap molasses losses	1.13	%
Filter cake losses	0.03	%
Bagasse losses	0.59	%
Undetermined Losses	0.46	%
Cane yard losses	0.14	%
Distillery process efficiency	80.00	%
Moisture of sugar product	0.04	%
Brix of sugar product	99.96	%
Pol of sugar product	99.80	%
Purity of sugar product	99.84	%
Purity of molasses	32.82	%
Sugar yield	97.6	kg/t
Alcohol grade	99.3	% w/w

Source: Data for Palo Gordo sugar mill for the 2018–2019 crushing season (CENGICAÑA, 2019b).

For the scenario where ethanol is produced in new annexed distilleries, the capital investment needed to build a distillery with a capacity of 12 kL/day was set to US$ 12.4 million (cost updated from 2007 to 2019) (ACTIONAID, 2010). For comparison of different scenarios, the installed capacity of the new ethanol distillery was fixed to 120 kL/day, equivalent to a US$ 62.3 million investment.

The cost of ethanol was varied in terms of the installed capacity of the sugar mill distilleries, from 120 kL/day to 1000 kL/day. The methodology to estimate the operating costs for different installed capacities is provided in the Supplementary Material. We used a cost-capacity index of 0.7.

4.3. *Cost of E10 at the terminal and retailer level in Guatemala*

The cost of producing a liter of E10 at the import terminal was estimated on the basis of 90% Reformulated Gasoline Blendstock for Oxygenate Blending (RBOB) and 10% ethanol (Equation (3)). We assume that E10 is made from RBOB gasoline due to limited data availability regarding the CIF price of regular gasoline in Guatemala.

$$P_{E10-TER} = 0.9 * P_{RBOB} + 0.10 * P_{ETHANOL} + Cost_{INFRA-TER} + M_{TER} \qquad \text{Equation 3}$$

where, $P_{E10-TER}$ denotes the average cost of the E10 at the terminal [US $/L]. P_{RBOB} refers to the average price of gasoline for the baseline year. $P_{ETHANOL}$ represents the cost of producing a liter of ethanol under Guatemalan conditions. $P_{ETHANOL}$ was obtained from the modeling presented in Section 4.2 and assumed to be equal to the average ethanol cost between 120 kL/day to 1000 kL/day distilleries. $Cost_{INFRA-TER}$ includes the investment required to upgrade the import terminals to handle E10. Furthermore, it includes the cost of transport and distribution of ethanol from the sugar mills to the terminals [US$/L]. The importer's margin (M_{TER}) was set to 0.07 US$/L (MEM, 2019a, 2019b), which corresponds to the average importer's margin between the 21st of January and 25th of November 2019 for regular gasoline in Guatemala.

The RBOB gasoline price (P_{RBOB}) for the baseline year was extracted from Fig. 6, which shows the monthly RBOB gasoline future price, ethanol future price, ethanol exports and the corresponding blending margin for the period 2005–2019. We also present data for the price of regular gasoline (CIF) in Guatemala during the period 2016–2018, the most recent data available. During the period 2016–2018, the CIF price of regular gasoline at Guatemalan ports was on average 1.8% less than RBOB prices, which validates our assumption to use RBOB prices to calculate the cost of E10. With respect to the blending margin, the difference between the RBOB gasoline future price and ethanol future price (blue line, Fig. 6-b) can be seen as the margin associated with blending and delivering an ethanol blend. Positive (negative) margins are obtained from blenders buying ethanol at a lower (higher) price than RBOB gasoline and selling the blend at the retail level at an equivalent price to RBOB gasoline.

From Fig. 6-a, it is seen that the difference between the price of RBOB gasoline and ethanol has narrowed significantly during 2005–2019. Furthermore, the trends observed for Guatemala are in agreement with findings from (Gomes et al., 2018), where low prices of oil (below 56 US $/barrel) led to higher exports of ethanol after 2014. The highest blending margins are observed between January 2012 and September 2014, reaching 0.3 US$/L. For the baseline year (2019) used in the cost model, the price of ethanol was slightly lower than the price of RBOB gasoline. This led to tight blending margins that varied between 0.01 US $/L to 0.21 US$/L (Fig. 6-b), with an average of 0.09 US$/L. For our

Table 3
Physical data for sugarcane and cost assumptions for sugarcane cultivation and sugar mill distillery operation.

Parameter	Value	Unit	Ref.
General financial data			
Required IRR	10	%	Vanegas (2012)
Land rent cost	152	US$/(ha*yr)	Vanegas (2012)
General physical data			
Sugarcane yield	110	t/(ha*yr)	González (2016)
M.c sugarcane	75	%w	Vargas (2013)
Density of sugarcane	0.96	t/m^3	Chávez (2013)
LHV of sugarcane	17.9	MJ/kg	Chávez (2013)
Establishment			
Land preparation	311.4	US$/ha	Vargas (2013)
Tractor; deep ploughing	109.0	US$/ha	Vargas (2013)
Tractor for ploughing	109.0	US$/ha	Vargas (2013)
Tractor for egalising	30.5	US$/ha	Vargas (2013)
Removal old ratoon	62.9	US$/ha	Vargas (2013)
Seed cost	233.5	US$/ha	Vargas (2013)
Transport of seed	40.3	US$/ha	Vargas (2013)
Maintenance of plantation			
Manual Weeding	12.0	US$/ha	Vargas (2013)
Transport of personnel	40.3	US$/ha	Vargas (2013)
Mechanical weeding	31.5	US$/ha	Vargas (2013)
Harvesting			
Cultivation labour	220.4	US$/ha	Vanegas (2012)
Harvesting			
Transport of personnel	40.3	US$/ha	Vargas (2013)
Fertilizer	275.6	US$/ha	Vargas (2013)
Fertilizer application	5.0	#/yr	Vargas (2013)
Herbicide	31.5	US$/ha	Vargas (2013)
Herbicide application	3.0	#/yr	Vargas (2013)
Insecticide	13.1	US$/ha	Vargas (2013)
Insecticide application	2.0	#/yr	Vargas (2013)
Irrigation cost	208	$/ha	Castro et al. (2018)
Irrigation cost	1.2	US$/mm*ha	Castro et al. (2018)
Harvesting labour	63.7	US$/ha	Vanegas (2012)
Labour cost of activities related to harvesting	89.4	US$/ha	Vanegas (2012)
Loading cost	0.5	US$/ha	Vargas (2013)
Transportation cost	791.3	US$/ha	Vargas (2013)
Transportation cost per km	0.1	U$/(km*t)	Vargas (2013)
Average distance between field and plant	55.0	km	González (2016)
Distillery Data			
Installed capacity	120000	L/day	Mena (2016)
Distillery efficiency	80	%	Mena (2016)
Operation days	162	d/yr	Mena (2016)
Operation costs; labour	103550	US$/yr	Mena (2016)
Operation costs; materials	283400	US$/yr	Mena (2016)
Maintenance costs; labour	49050	US$/yr	Mena (2016)
Maintenance costs; materials	207100	US$/yr	Mena (2016)
Fixed costs	1143164	US$/yr	Irwin (2016)

calculation we set the value of P_{RBOB} in Equation (3) to 0.46 US$/L.

$Cost_{INFRA-TER}$ was derived from Table 4 for a market size of 240 million liters of ethanol. This market size corresponds to the demand required to achieve E10 nation-wide in year 2019. With respect to the investment required to develop an ethanol infrastructure in Guatemala, we considered findings from a study on the expansion of ethanol-gasoline blends in the US (E&C, 2014). This study indicates that the investment required to upgrade the fuel distribution system, including transport equipment, new and retrofitted storage tanks, blending equipment and upgrading retail stations is 1.6 US$ cents per liter of annual additional capacity of ethanol blended (E&C, 2014). Thus, an investment of 3.8 million USD would be required for a market size of 240 million liters of ethanol.

At the retail level, the cost of E10 was estimated based on Equation (4). Since there is no domestic market for ethanol and E10 in Guatemala, we had no information regarding a regulatory framework for pricing biofuels. Therefore, we assumed that E10 has the same price structure as regular gasoline for Guatemalan conditions. No excise tax credit will be considered in the overall cost of E10.

$$P_{E10-RET} = \left[P_{E10-TER} + Tax_{DIST} + Other_{exp} + M_{RET}\right](1 + VAT_{RET})$$

Equation 4

Where, $P_{E10-RET}$ is the average cost of the E10 blend at the retailer [US $/L]. The fuel tax ($Tax_{DIST}$), other expenses associated to the retailer operation and retailer margin (M_{RET}) were set to 0.16 US$/L, 0.02 US $/L and 0.05 US$/L, respectively (MEM, 2019a, 2019b). Each of these values correspond to the average value between the 21st of January and 25th of November 2019. The value-added tax (VAT) was set to 12% (MEM, 2019a, 2019b). In order to put these values into context, in 2011/2012 in the State of Sao Paulo in Brazil, with a blend mandate of 23%, the fuel tax on gasoline and anhydrous ethanol was 0.73 US$/L[1] and 0.03 US$/L,[2] respectively (Moncada et al., 2018).

The E10 cost was compared to the regular gasoline retail price in Guatemala because typical E10 blends are a combination of regular gasoline and ethanol (Li and Stock, 2019). The average regular gasoline retail price for the baseline year was set to 0.82 US$/L (MEM, 2019c).

4.4. CO_2 mitigation due to the use of E10 blends in Guatemala

Within the frame of the recent Brazilian National Biofuel Policy (RenovaBio), a detailed environmental assessment of ethanol from sugarcane production was developed in a large number of operating sugar mills. In the reference case of Renovabio (RenovaBio, 2017), when ethanol is used as vehicular fuel to replace gasoline, it is reported an emission reduction of 60,400 kg CO_{2e}/TJ or 1.347 kgCO_2/liter anhydrous ethanol. We used this factor to estimate the GHG mitigation impact provided by the adoption of E10 nation-wide. This assumption is valid considering the similarities between the sugarcane agroindustry of Brazil and Guatemala. CO_2 emissions from burning motor gasoline were estimated using the International Panel on Climate Change (IPCC) emission factors for the Tier 1 approach, 69,300 kg CO_2/TJ. CO_2 emission factors were converted to tons of CO_{2e} using the 100-year GWP factors reported in the IPPC Guidelines in 2007 (IPCC, 2006).

5. Results

Fig. 7 presents the maximum ethanol production in Guatemala if all available molasses were converted into ethanol and the demand required to achieve E10. Fig. 7 also presents the exports of ethanol during the period 2000–2019 and the ethanol balance under a potential E10 domestic market.

During the period 2012–2014 (Fig. 7-b), Guatemala produced annually on average 86 million liters of ethanol more than the amount required to achieve E10. The increase in ethanol production during 2012–2014 was driven by a sharp increase in ethanol price that began in 2011 and reached a record high of 1 US$/L in 2014 (Trading Economics, 2017).

If Guatemala adopted E10 this would create a 240-million-liter domestic market for ethanol, based on the gasoline consumption in 2019. A mandate of E10 could reduce the gasoline import bill by US$ 197 million. Furthermore, based on the amount of cane crushed in Guatemala in 2019, and under the assumptions made in Section 3.1, it is

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[1] Prices were converted from R$/L to US$/L using an average exchange rate of 1.6736 BRL for year 2011.

[2] Prices were converted from R$/L to US$/L using an average exchange rate of 1.6736 BRL for year 2011.

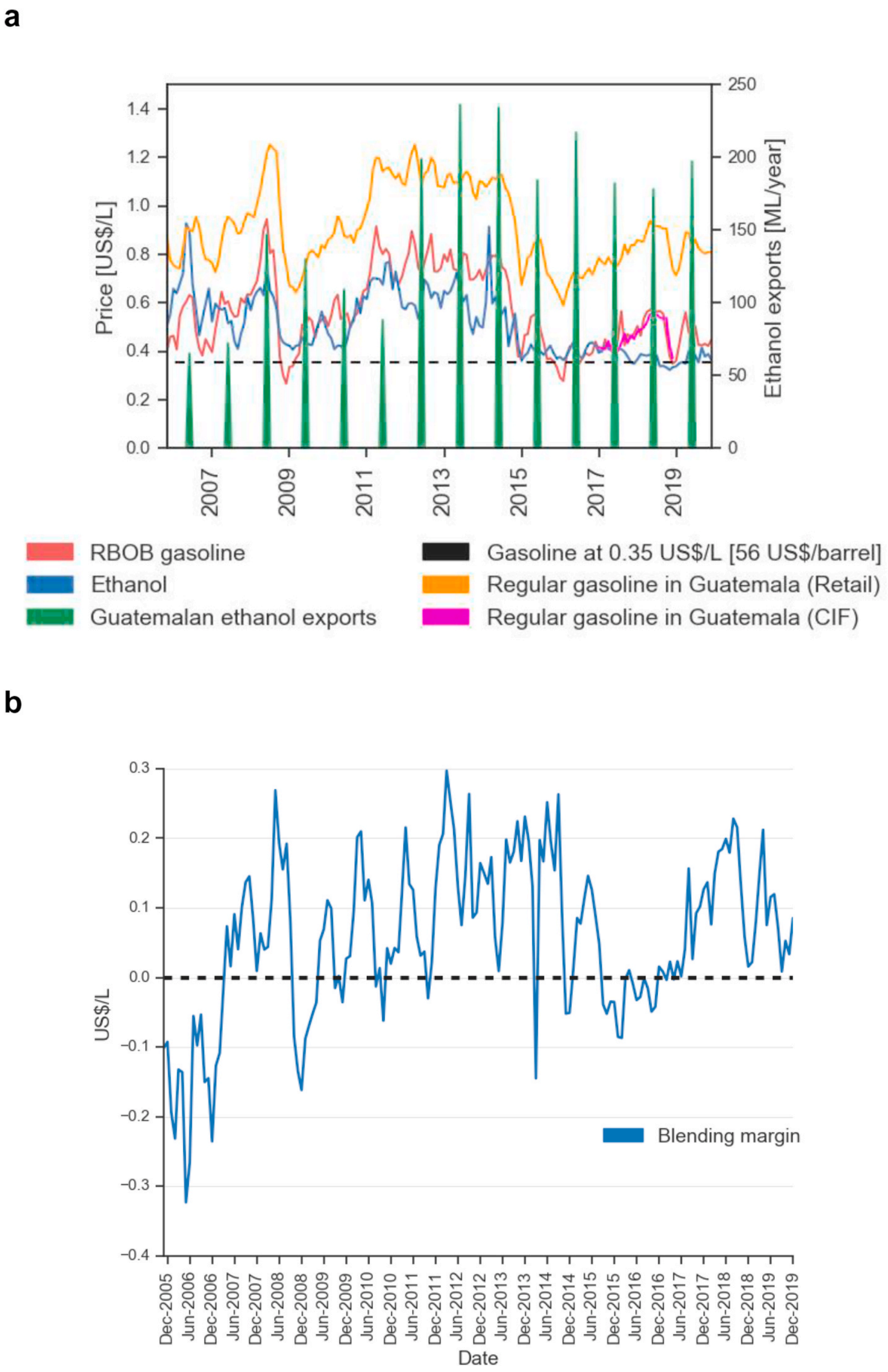

Fig. 6. a, Monthly RBOB gasoline price, wholesale ethanol price, Guatemalan ethanol exports, regular gasoline (CIF) and retail price in Guatemala for period 2005–2019. b, ethanol blending margin for period 2005–2019. Data concerning the price of RBOB gasoline and wholesale ethanol was extracted from (Investing.com, 2019).

Table 4
Estimated investment to develop an infrastructure to handle and distribute E10 in Guatemala.

Investment [MMUS$]	Value
Investment required to upgrade the fuel distribution system, including transport equipment, new and retrofitted storage tanks, blending equipment and upgrading retail stations (E&C, 2014)	3.8
Operating costs [MMUS$/year]	
Transport & distribution of ethanol to the blending terminals[a]	0.9

Source: [a] Values provided by (Hart Energy, 2010) have been updated to 2019.

estimated that the maximum ethanol production that could be obtained if all molasses were converted into ethanol is around 250 million liters of ethanol. This would imply that Guatemalan sugar mills would be able to meet a potential E10 demand through local production alone and still export surpluses, equivalent to 10 ML of ethanol per year.

5.1. *Producing ethanol in existing and new annexed distilleries in Guatemala*

The production cost of ethanol for different installed capacities in existing and new annexed distilleries is shown in Fig. 8.

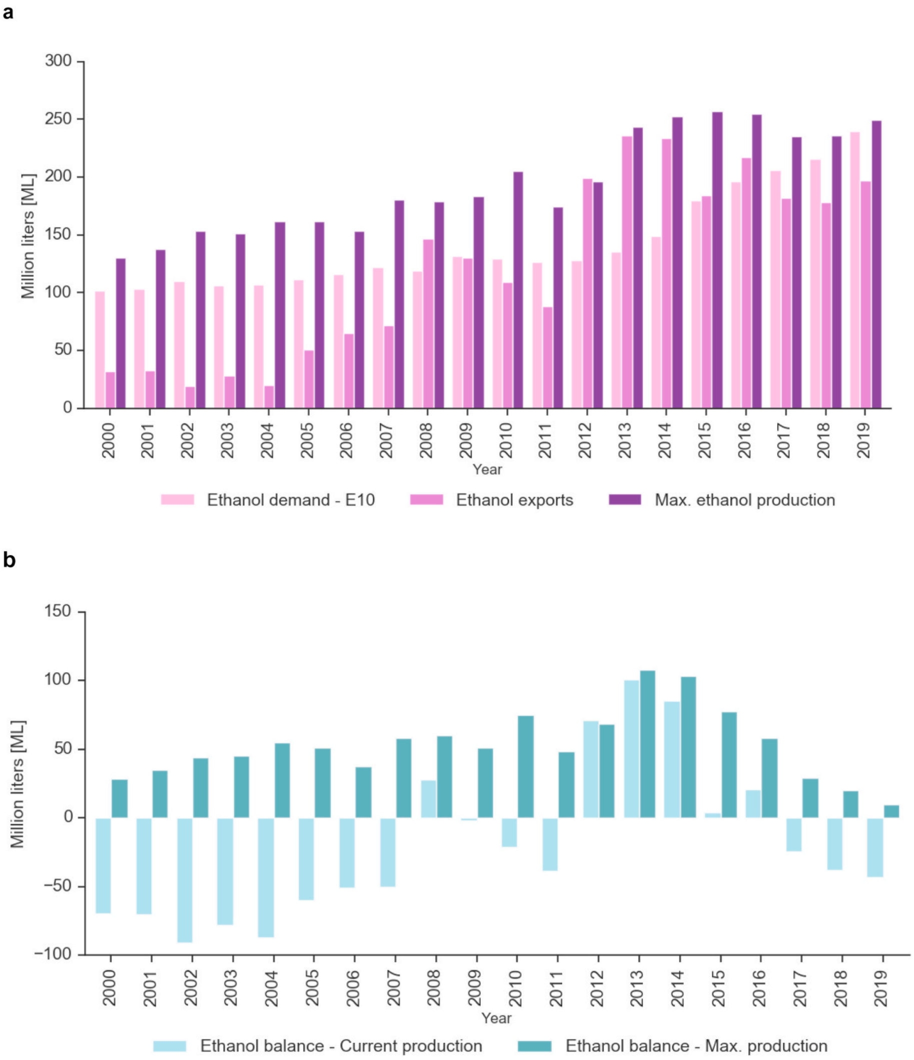

Fig. 7. Ethanol potential in Guatemala for the period 2000–2019. **a**, Ethanol demand for E10, ethanol exports and maximum ethanol production. **b**, Ethanol balance based on the current and maximum ethanol production. Exports of ethanol during the period 2000–2019 were extracted from SIECA, 2019.

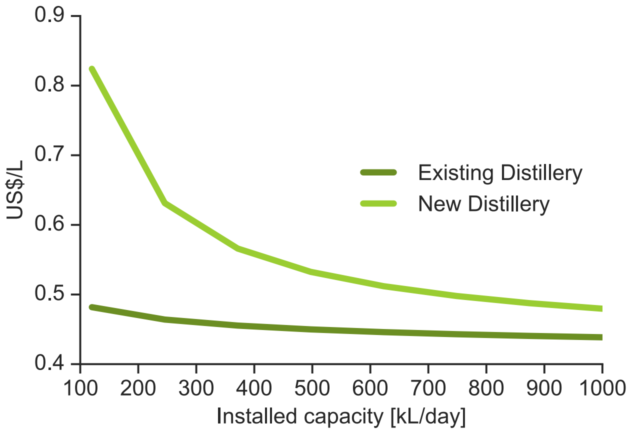

Fig. 8. Cost of producing ethanol in existing and new distilleries in Guatemala.

For a sugarcane yield of 110 t/ha, results from the cost model indicates that sugarcane has a farm-gate price of 34 US$/t under Guatemalan conditions. At this price, ethanol produced from molasses at an existing distillery with an installed capacity of 120 kL/day costs around US$ 0.48 a liter (Fig. 8-a). Results from the modeling indicate that around 73% of the cost of producing a liter of ethanol in existing distilleries comes from raw materials. For existing distilleries with installed capacities of 1000 kL/day, the cost of producing ethanol is 0.44 US$/L (Fig. 8-a). When ethanol is produced in new annexed distilleries with an installed capacity of 120 kL/day, results indicate that in order to obtain a 10% return on equity, sugar millers would need to sell their ethanol at 0.82 US$/L. In this sense, economies of scale are hugely beneficial. The cost of transforming molasses into ethanol in new 1000 kL/day distilleries is estimated to be 0.48 US$/L. In new distilleries, raw materials comprise in average 44% of the total cost of 1 L of ethanol.

5.2. *E10 price for Guatemalan conditions*

The relationships between the cost of ethanol, E10 price and gasoline price are presented in Fig. 9. Here, two scenarios are presented depending on whether E10 was produced in an existing (resp. new) distillery, including the investment to develop a biofuel infrastructure.

As can be seen from Fig. 9-b, at the import terminal, blending ethanol produced from an existing distillery yields a production cost of about 0.58 US$ per liter of E10. After transportation from the distribution terminal to the dispensing station and including a retailer margin, a liter of E10 would cost to the end consumer 0.91 US$. On the other hand, for ethanol produced in new distilleries, the cost of E10 at the terminal and

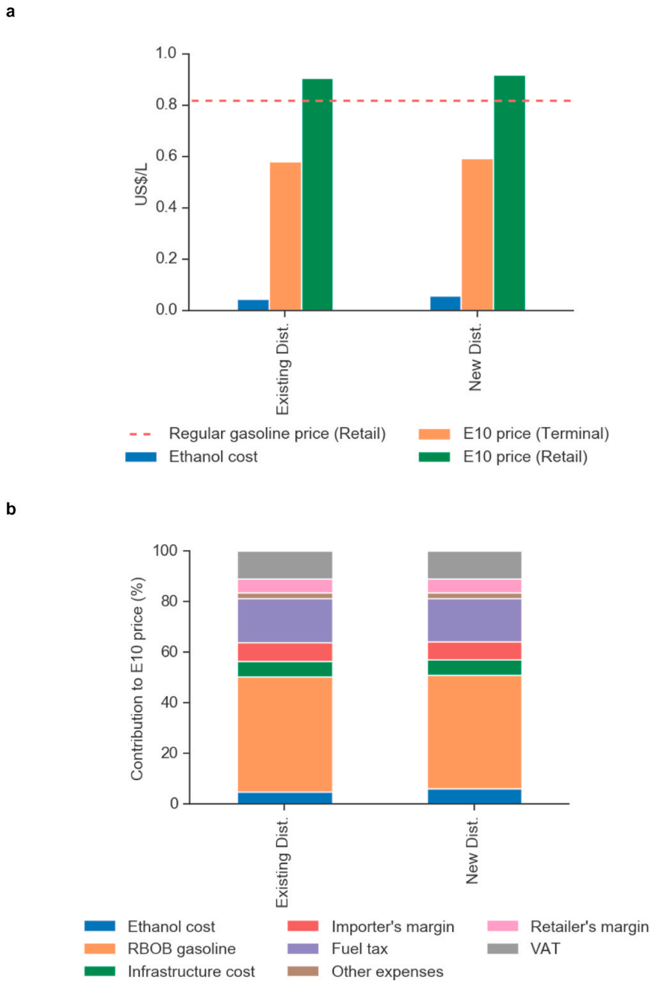

Fig. 9. E10 price for Guatemalan conditions. a, Price of E10 made from ethanol produced in new and existing distilleries and comparison with the regular gasoline price. b, Cost breakdown for E10 at the retail level.

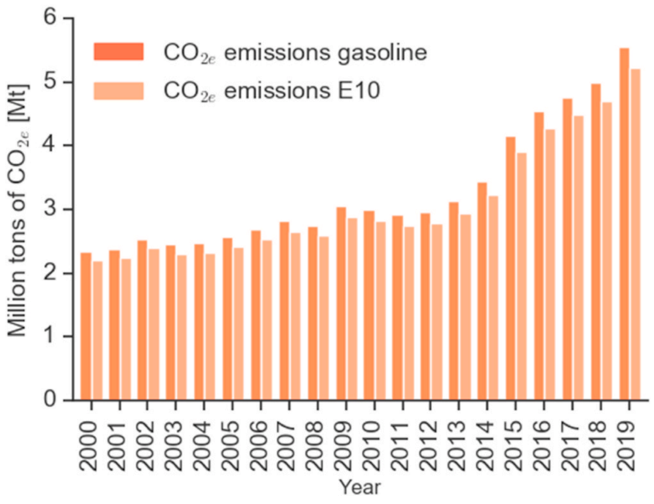

Fig. 10. Comparison of CO$_{2e}$ emissions between gasoline and E10 in Guatemala.

retail level would be around 0.59 US$/L and 0.92 US$/L, respectively.

5.3. CO$_{2e}$ mitigation due to the use of E10 blends in Guatemala

The potential CO$_{2e}$ mitigation that could be achieved by introducing E10 nation-wide is presented in Fig. 10. To a great extent, the mitigation is directly linked to the amount of gasoline that is replaced with ethanol, in this case, 10% for each liter of gasoline that is consumed.

As can be seen from Fig. 10, gasoline consumption and corresponding CO$_{2e}$ emissions have constantly increased since the 2000s. Between 2000 and 2019, the CO$_{2e}$ emissions from gasoline used in the transport sector increased in 136% (3 Mt CO$_{2e}$). The increase in gasoline consumption is related to population growth and, consequently, enlargement of the vehicle fleet. Also, it is important to note that even when gasoline price has increased, gasoline consumption in Guatemala has never fallen (2012–2014 period, Fig. 6-a). Thus, adoption of E10 nationwide would be hugely beneficial for reducing transport sector emissions. Introducing E10 would provide an average annual reduction in CO$_{2e}$ emissions of 6% compared to a scenario of 100% gasoline. To put this value into context, we compared this impact with the Guatemalan NDC. In COP 21, the Guatemalan State informed a voluntary 11% reduction in emissions of GHG in the baseline scenario (54 Mt CO$_{2e}$). This value is equivalent to 6 Mt CO$_{2e}$ emissions reduction by 2030 (ECLAC, 2019). Thus, for an annual consumption of 240 million liter of ethanol, correspondent to E10 adoption (Fig. 7, year 2019). We estimate that the associated GHG mitigation would mean 5% of the Guatemalan NDC.

6. Discussion

Sugarcane is the only feedstock available in sufficient quantities in Guatemala to supply a domestic market with E10. In 2019, the vehicle fleet in Guatemala would have required 240 million liters of ethanol to meet a 10% ethanol-gasoline blend. Our results indicate that the ethanol supply chain in Guatemala is saturated. Under the current productivity level, Guatemalan distilleries are not able to meet a potential E10 demand through local production alone (Fig. 7). Nevertheless, from Table 1 it is known that ethanol distilleries have a production capacity of 269 million liters per year, which indicates that in 2019 sugar mills were operating at 89% of their capacity. Under a scenario of maximum efficiency, where all molasses are converted into ethanol. Guatemalan sugar mills would be able to meet a potential E10 demand through local production and still export surpluses. As long as ethanol demand remains at E10, there is no need to increase the installed capacity of sugar mill distilleries nor use more land. This is because ethanol is produced from molasses and not sugarcane juice. Thus, there is no direct competition with sugar production.

Results from the modeling indicates that ethanol is produced at a cost between 0.48 US$/L and 0.44 US$/L depending on whether ethanol is produced existing distilleries of 120 kL/day or 1000 kL/day, respectively. These findings echo other studies which report ethanol production costs from molasses of 0.46 US$/liter in distilleries up to 425 kL/day (Arshad et al., 2019) and 1 US$/L in a 30 kL/day distillery (Silveira and Khatiwada, 2010). Results from the cost model indicate that ethanol produced in new distilleries of 120 kL/day is 71% more costly than ethanol produced at existing distilleries with the same installed capacity. Economies of scale are observed in new distilleries of 1000 kL/day. The difference in the cost of ethanol between existing and new distilleries of 1000 kL/day is 9%. Considering the tight blending margins during the last few years, for Guatemalan distilleries it would be at least equally profitable to supply the local ethanol market than to export it overseas. The low economic value of ethanol may be one reason why few sugar mills in Guatemala have invested in an ethanol distillery, highlighting the need for economic incentives and strong policy.

Under the assumptions made in this work, it is estimated that producing E10 from ethanol produced in an existing distillery would cost around 0.58 US$/L at the terminal. This is a third cheaper than the average regular gasoline price for the baseline year (2019), 0.82 US$/L. However, the scenario is completely different at retail level, where the price of E10 is 11% higher than the average regular gasoline price for the baseline year. That means, consumers would have to pay at least 9 US$ cents more for 1 L of E10 compared to 1 L of regular gasoline. The cost of E10 at retail level is largely dependent on taxes. Under the assumptions made in this work, which considered a similar price structure to gasoline in Guatemala, the main component affecting the price of E10 is the fuel tax and VAT. The fuel tax and VAT accounts almost for one-third of the cost of a liter E10. The margin to the importer and retailer represents about 13% of 1 L of E10 at the gas station. For retailers, whether the ethanol is produced in new or existing distilleries has little impact; similarly, for the end consumer. The difference at retail level between the cost of E10 made from ethanol produced in new distilleries compared to existing distilleries is 1%.

Our analysis has shown that it is not the technology itself that hinders the use of ethanol blends in Guatemala, since significant amounts of ethanol are already produced. Indeed, there are few technical obstacles either in sugarcane cultivation or ethanol production that limit the development of a biofuel market in Guatemala. This highlights the critical importance of political and social factors in creating biofuel markets in Guatemala and beyond. These include: the role of the state; lack of stakeholder buy-in; investment in infrastructure; and, sustainability concerns.

The role of the state. A major challenge for the implementation of a domestic biofuel market in Guatemala relates to the role of the state. Although the introduction of biofuels into the national supply chain is considered within the Guatemalan energy policy 2013–2027 (MEM, 2013), no clear targets are defined with respect to blend ratios or goals to decarbonize its transport sector. Objectives towards 2027 are oriented to approve regulation that establishes standards to produce, distribute and sell ethanol in Guatemala. Nevertheless, discussions about improving or creating new regulation for biofuels have a long history in Guatemala and to date have had little impact. The extent to which countries with abundant resources are successful in promoting renewable energy policies is strongly related to the quality of their institutions (Mehlum et al., 2006). Guatemala is characterized by weak institutions and has high levels of bureaucracy and corruption, which prevents the country from taking full advantage of its resources (Mehlum et al., 2006). Although the anti-corruption framework has been enforced in the last years, the public sector in Guatemala is still perceived to be highly corrupt (Transparency International, 2016). This raises the question of the extent to which the country's biofuel policy is influenced by more powerful actors for whom the creation of a domestic biofuel market represents a potential threat, for example, to profit margins.

The development of a national biofuel market requires more than just the creation of demand. It also requires broader supportive policies and institutional frameworks that will govern their use. This will require, for example, the development of biofuel standards to reduce the risk of misbranding and adulteration of ethanol (USDA, 2013). Several international organizations have been supporting countries across Central America to establish regional standards for biofuels, which would help to ameliorate such concerns (Bailis et al., 2014). While the Guatemalan sugar sector is highly innovative – in part due to CENGICAÑA, a private research center set up and funded by the sugar mills – policies are required to support RD&D into efficient processes and locally appropriate technologies which would reduce production costs.

Further, a domestic biofuel market requires a new price structure for ethanol-gasoline blends. Results from the cost model indicates that, if a similar price structure to gasoline is assumed, taxes are responsible for increasing the price of E10 by 30%. The state needs to be cautious as certain taxation schemes can encourage or discourage the production of ethanol. As shown by Moncada et al. (Moncada et al., 2018) for Brazilian conditions, a high gasoline tax and ethanol tax-free scheme can boost ethanol production.

Successful implementation of ethanol-gasoline blends in Guatemala will also be based on the readiness of the actors involved in the biofuel supply chain to deliver a blend at a competitive price. Thus, the government must remain neutral about who produces the biofuels and the amount of ethanol to supply the domestic market. Creating an efficient ethanol market demands careful design of the biofuel policy since the ethanol program must not be limited to those sugar mills that already have annexed distilleries. Rather the policy should ensure equal opportunities for all sugar mills/distilleries to access the biofuel market. The state must also create favourable conditions to secure investment and, initially at least, implement policy tools to incentivize biofuel production. Developing this enabling policy requirement needs strong state support for biofuel. While there is no shortage of laws promoting biofuels, at present the government lacks capacity and willingness to enforce and implement these ambitions.

Stakeholder buy-in. No sector has yet been motivated to lobby for domestic consumption and, without this support from key stakeholders, policy change is unlikely (Tomei, 2014). The sugarcane and oil sectors are particularly important for biofuels, yet neither sector has strong incentives to support a domestic market. For example, as evidenced in this paper, the Guatemalan biofuel sector has to date been driven by the sugarcane sector – primarily in response to growing global demand for biofuels. Ethanol offers an opportunity for economic diversification of the sector, but one that has yet to be taken up by all sugar mills. While the cost model developed for this paper demonstrates the cost competitiveness of ethanol, it remains a marginal product for the sugarcane sector and does not yet justify investment in annexed distilleries. Stronger market and policy drivers will be required to create the right conditions for investment in annexed distilleries.

For oil companies, the use of domestic ethanol would represent a loss of market share. The sector has expressed concern about the use of biofuels citing restrictions on consumer choice and the large up-front investments required to develop infrastructure (USDA, 2013). Furthermore, the oil industry in Guatemala is the largest source of tax revenue for the state, around 3% of the public income (USDA, 2013). The creation of a domestic biofuel market could be disadvantageous not only for the oil industry, but also for the state, as it would likely lead to a reduction in tax revenue.

Investment in infrastructure. Local regulation requires significant modifications to the import terminals and distribution systems. This is the case of the mandate DGH-CIRC-18-2016, which sets guidelines to blend, distribute and sell ethanol in Guatemala (MEM, 2016). For example, it requires that ethanol must be blended either at the import terminals or in "blending terminals" (which do not yet exist) prior to being trucked to fuel stations. At the retail level, Guatemalan law requires that fueling stations are upgraded using the latest technology to sell ethanol-gasoline blends. Such demands seem exaggerated if compared to the investments required to achieve ethanol-gasoline blends in other countries (E&C, 2014). One of the most recent studies sponsored by the Organization of American States (Hart Energy, 2010), indicates that making improvements and expand areas of operation at the import terminals, upgrading retail stations, increasing fleet capacity and storage at distilleries to achieve E10 in Guatemala would require an investment around 28.5 million USD (updated to 2019). This figure is nine-fold higher than the value we assumed in the cost model for developing an ethanol infrastructure in Guatemala. This makes the transition to biofuels more difficult as regulation mandates a transformation of the entire gasoline supply chain. Thus, requiring large investments from oil importers, distributors and retailers. Moreover, the regulatory framework does not specify who is responsible for this investment nor how this will be financed by the sectors involved.

E10 can use the existing infrastructure of gasoline without any investment in new storage tanks and pumps to solely store and sell the blend. A study by NREL (2015) indicates that installed tanks should be able to store blends up to E15 without any issue. As this analysis has shown, upgrading fuel stations to sell E10 should not impose a significant cost burden on retailers. Indeed, in countries such as Brazil, it was not until E20 that significant investments in biofuel infrastructure were made, requiring new fuel transportation infrastructure and new automobiles that could handle higher blends of ethanol (Hira and de Oliveira, 2009). Furthermore, engines running on E10 blends do not require modifications as long as the blends meet the quality standards defined by mandate DGH-CIRC-18-2016. Concerns have been raised about the water sensitivity of ethanol-gasoline blends, but ethanol is highly soluble in water and its solubility increases as the ethanol content increases. Thus, potential damage to engines due to phase separation will not occur and there is little risk to consumers from using E10 in their vehicles. The perception of risk within the sectors involved in the biofuel infrastructure must be addressed in Guatemala. With regards to the creation of technological niches such as flex-fuel vehicles, their adoption at large scale is challenging to foresee in the mid-term due to the high cost of these vehicles and the low-income of Guatemalans. Nevertheless, the use of ethanol-gasoline blends in government and bus fleets seems reasonable and should be prioritized.

Sustainability concerns. As discussed in the introduction, numerous authors have raised concern about the negative social and environmental impacts of biofuels. This also applies to the Guatemalan context where the sugarcane sector has been criticized for poor working conditions, underage labor, excessive water use, diversion of rivers, land concentration, and forced evictions (Alonso-Fradejas, 2012; Arce and Rodríguez Pellecer, 2012; Bailis et al., 2014; Hurtado, 2008; Mingorría and Gamboa, 2010). In response, the sugarcane sector highlights its compliance with certification schemes approved by the EU, which means all ethanol produced is “sustainable” (Tomei, 2015). However, biofuel production in Guatemala is relatively recent and many of these concerns relate less to biofuels than to the wider agricultural system in which ethanol is embedded, to the country’s highly unequal land distribution, and to the history of the sugar sector (Tomei, 2015). Addressing these criticisms is highly complex and requires commitment from state and other actors to address the country’s land and other inequalities.

7. Conclusions and policy implications

This paper shows that the Guatemalan ethanol industry has enough installed capacity to supply the demand for E10, around 240 million liters of ethanol in 2019. As ethanol is produced from molasses, the creation of a domestic biofuel market is unlikely to drive direct land use change nor affect food production. Ethanol production costs are estimated to range between 0.48 US$/L and 0.44 US$/L, depending on whether ethanol is produced existing distilleries of 120 kL/day or 1000 kL/day, respectively. Under the assumptions made in this work, the average cost of E10 at Guatemalan gas stations is 0.91 US$/L. Taxes could account for one third of the price of E10 if a proper tax structure is not implemented. Thus, tax advantages to end-users could make the transition to biofuels easier. The associated GHG mitigation would mean 5% of the Guatemalan NDC.

This paper has shown that a key barrier in developing a domestic market in Guatemala is a lack of buy-in from key actors, namely the state, oil companies, sugar mills and fuel retailers. The tacit opposition of some powerful sectors and the absence of the Guatemalan state in the biofuel sector has meant that it has been left to the sugar sector to determine the direction of biofuels in the country. Driven by economic interests, the mills have pursued a large-scale, export-oriented production model. Our findings suggest that the current regulatory framework for the development of Guatemala’s ethanol sector urges a revision. Factors to consider are technical and economic aspects that have worked in neighboring countries on ethanol programmes. At present, it appears that Guatemala can only develop a domestic biofuel market in the short term with greater involvement of the state. Thus, the creation of a biofuel market requires public and private sectors to work together to develop a comprehensive national biofuel policy with firm targets for sustainability and overcome the barriers identified in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

L. Cutz: Conceptualization, Methodology, Formal analysis, Validation, Writing - original draft. **J. Tomei:** Writing - review & editing. **L.A. H. Nogueira:** Conceptualization, Writing - review & editing.

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Appendix A. Supplementary data

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