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Article

Anhydrous Ethanol Pricing in Economies with an Underdeveloped Biofuels Market: The Case of Mexico

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Abstract: Most gasoline currently consumed in Mexico continues to be oxygenated with Methyl Tert-Butyl Ether (MTBE) despite its proven effects on the environment and human health. Hence, the existence of a regulatory framework on biofuels and various institutional efforts have not been sufficient to develop a national market for anhydrous ethanol use as biofuel. The goal of this research is twofold: one, to review and analyze the governmental actions taken to incorporate bioethanol as a gasoline oxygenate, and, two, to design a tool to estimate the bioethanol price at the Storage and Distribution Terminals of PEMEX (Mexico's state-owned oil company). A price estimation model for bioethanol was developed through the microeconomic theory of the producer and the indifference price of a product methodology, which calculates the daily price of ethanol in the period 2015–2022; additionally, an MS Excel-based support tool was created for this analysis (namely: the Price-CEM). The analysis showed that incorporating bioethanol into the Mexican energy matrix would require policies of fiscal support for R&D, agricultural waste management and bioethanol production, as well as a new regulatory framework to both gradually eliminate MTBE and establish bioethanol/gasoline blending targets. Furthermore, institutional efforts would also be required to integrate all links in the biofuel production chain, including primary feedstock producers. The cost estimation method and tool have also shown to be valuable instruments to calculate both the prices at which a local bioethanol market would be competitive (with respect to the international market) and the most important cost contributions for local supply chains. This is the first tool to estimate the price of anhydrous ethanol at the local level, which can contribute to identifying opportunities and economic thresholds for the successful development of feasible bioethanol markets in Mexico.

Keywords: ethanol price; indifference price; ethanol in Mexico; gasoline oxygenation

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1. Introduction

Oil depletion, global warming and political instability have forced nations to diversify their energy matrix and use more efficient and local systems for energy production, consumption and security [1]. The current Russia–Ukraine war, where oil and natural gas are strategic resources for political negotiations, is a clear example of such interdependency between energy resources and politics [2]. Hence, governments are encouraged to pursue energy security, social equity and environmental impact mitigation. However, according to the Energy Trilemma of the World Energy Council (WEC), only two of those can be achieved simultaneously. The World Energy Trilemma Index, 2021 version, which measures the progress of the three goals in 127 countries, estimated that Sweden, Switzerland, Denmark, Finland, the United Kingdom, France, Austria, Canada, Germany, Norway, New Zealand, the United States, Luxembourg and Spain are the 10 best-performing nations [3]. Nonetheless, bioenergy in general, and biofuels in particular, are becoming increasingly important in the energy matrix of nations to improve these three pillars.

The production and use of anhydrous ethanol to oxygenate gasoline is geographically concentrated in a few countries, limited by a variety of feedstocks and based on two types of technologies [4]. According to OECD-FAO [5], the average annual production of ethanol worldwide in 2018–2020 was 126 billion liters, projected to increase to 132 billion by 2030. Out of global ethanol production in 2021, the United States produced 55%, Brazil 27% and the European Union 6% [6]; regarding feedstocks, 60% of ethanol comes from corn grain, 27% from sugarcane and 3% from wheat [5]. At the same time, 99% of ethanol is produced with first-generation technologies (1G), and only the remaining 1% with second-generation technologies (2G). The 1G technologies are mature and fully transferable, while the 2G technologies are in research and development (R&D), and in some cases in an early stage of commercialization [7–10].

Biomass consumption, at a rate higher than its natural replenishment, has brought negative environmental and social consequences. For example, burning biomass for cooking food in underdeveloped countries, especially in rural areas, continues to be a serious problem given its contribution to air pollution, global warming and negative impacts on human health [11].

Furthermore, the global potential to produce 2G biofuels has been estimated at 98,900 PJ/year from lignocellulosic biomass [12], highlighting 15 countries that together could generate approximately 80% of this amount of bioenergy, with China, Brazil, the United States and Russia occupying the top four places, with an individual capacity of more than 10,000 PJ/year.

Mexico is number eight in the ranking with a capacity of 2194 PJ/year, with 2.2% of the global bioenergy potential [12]. In this regard, Aleman-Nava et al. [13] calculated a biomass energy potential in Mexico of 2635 to 3771 PJ/year, a higher range than Shell Global's estimates (Table 1).

Table 1. Potential production of biofuels 2G from lignocellulosic biomass by country.

Ranking	Country	PJ/Year	Individual Share
1	China	15,721	15.9%
2	Brazil	13,924	14.1%
3	USA	10,681	10.8%
4	Russia	10,429	10.5%
5	Australia	7783	7.9%
6	Argentina	6436	6.5%
7	Canada	3034	3.1%
8	Mexico	2194	2.2%
9	Ukraine	1935	2.0%
10	India	1360	1.4%
11	Indonesia	1225	1.2%
12	Congo	1182	1.2%
13	South Africa	1166	1.2%
14	France	997	1.0%
15	Colombia	981	1.0%
	Rest	19,850	20.0%
	Total	98,901	100.0%

Source: Shell Global (elaboration with energy database) [12].

Through the thermochemical route, one of the technologies available for the production of cellulosic ethanol and other advanced biofuels was developed by Enerkem Alberta Biofuels (Edmonton, AB, Canada) [https://enerkem.com]. This company produces 38 million liters of biofuels from 100 thousand tonnes of Municipal Solid Waste (MSW) per year [10]. Currently, through strategic alliances with Shell and other global companies, Enerkem has three plants under construction: (a) Verennes, Quebec, Canada, with a capacity of 125 million liters of ethanol and renewable chemicals; (b) Tarragona, Spain, with a capacity of 220 million liters of methanol; and (c) Rotterdam, Netherlands, with a capacity of 80 thousand tonnes of aviation fuel (75%) and naphtha (25%) [10].

Through the biochemical route, there is also a group of commercial-level technologies, which use agricultural residues as input, mainly corn stover, bagasse and sugarcane stubble, rice straw, wheat, forest residues, etc. A well-known case is that of POET-DSM Advanced Biofuels (Sioux Falls, SD, USA) [https://poet.com]. This plant, although it paused its production at the end of 2019 given the changes in the implementation of the Renewable Fuel Standard (RFS) by the Environmental Protection Agency (EPA) [14], is currently conducting R&D to improve its technology and the operational efficiency of the rest of the biorefineries of the same business group [15,16]. Another example is Verbio Nevada LLC (Nevada, IA, USA), a company that acquired the *DuPont* plant in 2018 and is transforming 100 thousand tonnes of corn stover into renewable natural gas and plans to start cellulosic ethanol production in 2023 [17]. There are other cases in Brazil, where cellulosic ethanol is produced from sugarcane bagasse and straw. The company Raízen SA (São Paulo, Brazil) already has two cellulosic ethanol plants, one in Piracicaba, Sao Paulo State, with a capacity of 40 million liters (2014); and another plant (50% of the works finished) in Bioenergy Bonfim Park in Guariba, Sao Paulo, with a capacity of 82 million liters, which will be completed by the end 2023 [18,19].

The United States is expected to produce 2233 million liters of cellulosic ethanol by 2030, while the global volume of cellulosic ethanol production will approach 4.5 billion liters by 2030, raising the worldwide share of 2G ethanol from 1% to 3.4% [5].

There is also sufficient empirical evidence of the environmental benefits of using ethanol as a gasoline oxygenate [6,8,13,19,20]. For example, the Mexican Petroleum Institute, in a pilot test conducted in 2009 to evaluate a 6 v/v% blend of bioethanol/gasoline (E6), found no substantial differences in combustion performance when using the blend compared to traditional gasoline [20]. In addition, the biofuel blend behaved in a stable manner and with a reduction of GHG (Greenhouse Gases). Similarly, García et al. [21] estimated that an E10 blend generates 2722.8 kg CO_2eq/tonnes versus 3104.6 kg CO_2eq/tonnes of traditional gasoline, there being a net emissions benefit. Likewise, Rendon-Sagardi et al. [22] concluded that E10 gasoline in Mexico could reduce CO_2 emissions by an annual amount of 1283 million tonnes between 2014 and 2030. In the same vein, Galicia-Medina et al. [23] stated that the environmental impacts of producing cellulosic ethanol could lead to a net GHG reduction of 60 to 120%. However, they acknowledge that this amount can vary greatly depending on the type of lignocellulosic biomass used, modification in the cropping pattern and change in land use.

Hence, the successful development of a locally feasible biofuel market requires a comprehensive understanding of both the policies and regulations context, as well as the market price at which the local production would be economically competitive. Therefore, this paper addresses the questions: What type of policies would be required to promote the use of ethanol as biofuel in Mexico? And, at what price would a locally produced bioethanol be economically competitive? By simultaneously addressing these two questions, this paper sheds light on policy needs and the price thresholds to develop a competitive bioethanol market in Mexico. Hence, this research has two objectives. To analyze the Mexican government's efforts to incorporate ethanol as a gasoline oxygenate and to develop a method and a tool to estimate the indifference price of anhydrous ethanol for any Storage and Distribution Terminal (TAD by the Spanish acronym) of PEMEX (Mexico's state-owned oil company).

The paper is divided into four sections, in addition to the introduction. The problem definition and theoretical framework, which establishes the concepts and theoretical basis of the research; materials and methods, where the methodology used is specified; results and discussion, a section that shows the institutional framework and actions taken by Mexico regarding biofuels, presents the tool to estimate the price of ethanol, including a section of policy recommendations. Finally, conclusions are presented.

2. Problem Definition and Theoretical Framework

2.1. Problem Definition

Despite having a legal framework on biofuels and a trade agreement with the United States and Canada that allows free imports, ethanol has not yet been officially incorporated into the Mexican market. It should be noted that fuel ethanol has been marketed for years in countries of equal or lesser development than Mexico (Brazil, Argentina, Colombia and Costa Rica, among others).

In 2005, after verifying the environmental and human risks of MTBE, the United States eliminated the oxygen requirement in reformulated gasoline and established a renewable fuel standard, which led to the incorporation of ethanol in gasoline [24]. Given the high degree of solubility of MTBE in water, there is sufficient empirical evidence of contamination of rivers and streams. Consequently, most local governments in the United States have expressly banned using MTBE in gasoline.

To date, Mexico continues to use MTBE as an oxygenate and no regulations prohibit, or even limit, it. Mexican imports of MTBE from the United States have increased since 2004, reaching a record 9.4 million barrels in 2018 (the latest year with data) (see Figure 1) [25]. The United States only exports MTBE to Mexico (67%), Chile (17%) and Venezuela (13%); with the former being the largest buyer of this fossil-based oxygenate. In addition to representing an annual outflow of approximately one billion dollars, this affects human health due to the contamination of groundwater that supplies cities, and the environment due to the increase in polluting gas emissions.

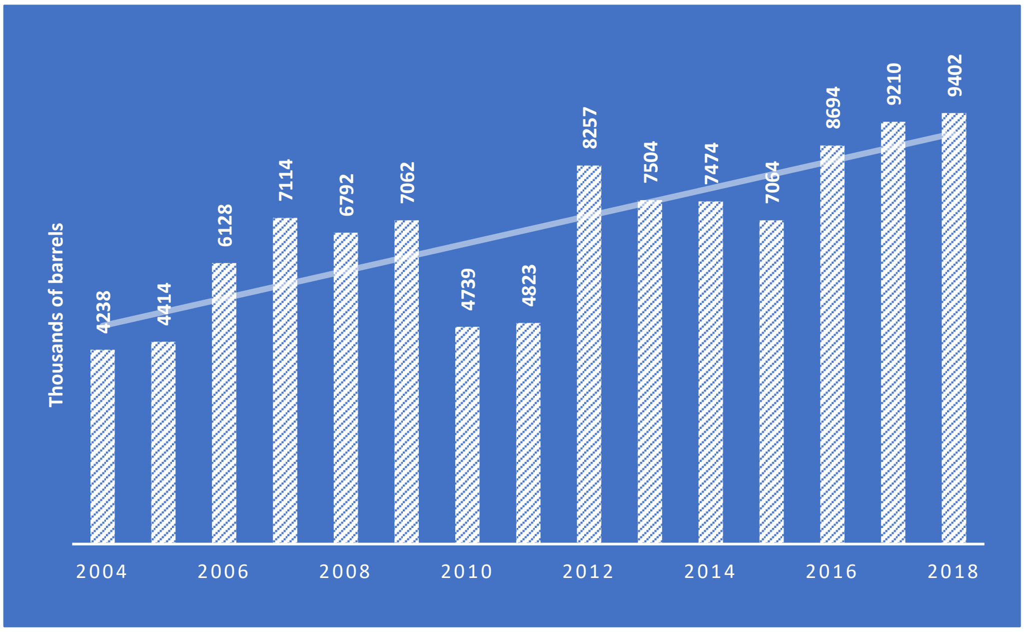


Figure 1. Imports of MTBE to Mexico from the United States. Source: own elaboration, data from US EIA, 2023 [25].

From a purely economic perspective, there is sufficient reason to promote the incorporation of anhydrous ethanol into Mexico's energy matrix. The information available on international prices of MTBE and ethanol shows an important differential. Although the prices of these two oxygenates depend on their own supply and demand, in the long term, there is a premium to the cost of MTBE. Figure 2 presents the daily prices of both oxygenates for the last 14 years (2008–2022), revealing that ethanol is generally cheaper [26].

To clarify this difference, the spread between MTBE and ethanol was estimated. Figure 3 shows their price spread, where positive values mean that the price of MTBE was higher, while negative values mean the opposite—the price of ethanol was higher. Most of the time (days) MTBE was more expensive. Therefore, Mexico would have economic savings by simply substituting MTBE for ethanol, without considering other benefits such as environmental and social aspects. For example, in the first quarter of 2022, the average price spread was US $0.62 per gallon, implying that Mexico could save approximately US $250 million annually just by replacing MTBE with ethanol.

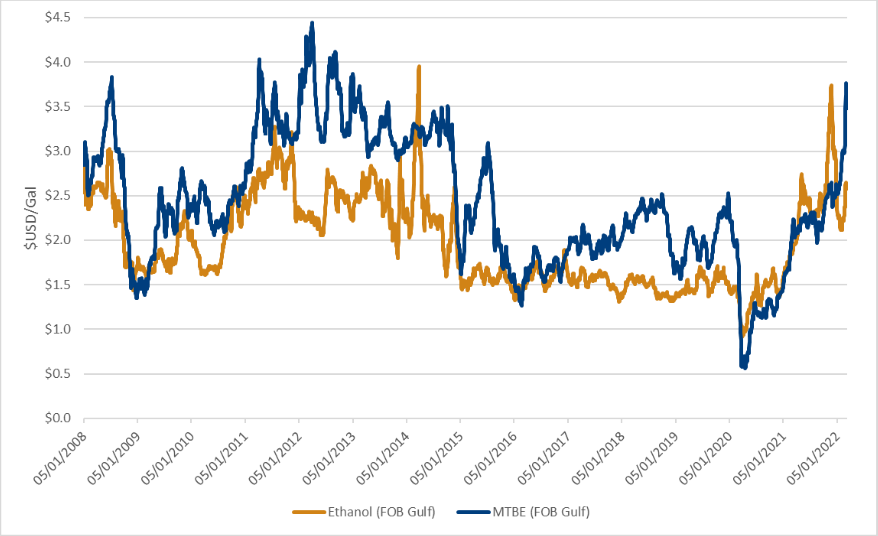


Figure 2. Daily prices of anhydrous ethanol and MTBE, 2008–2022. Source: own elaboration, data from US Grain Council, 2022 [26].

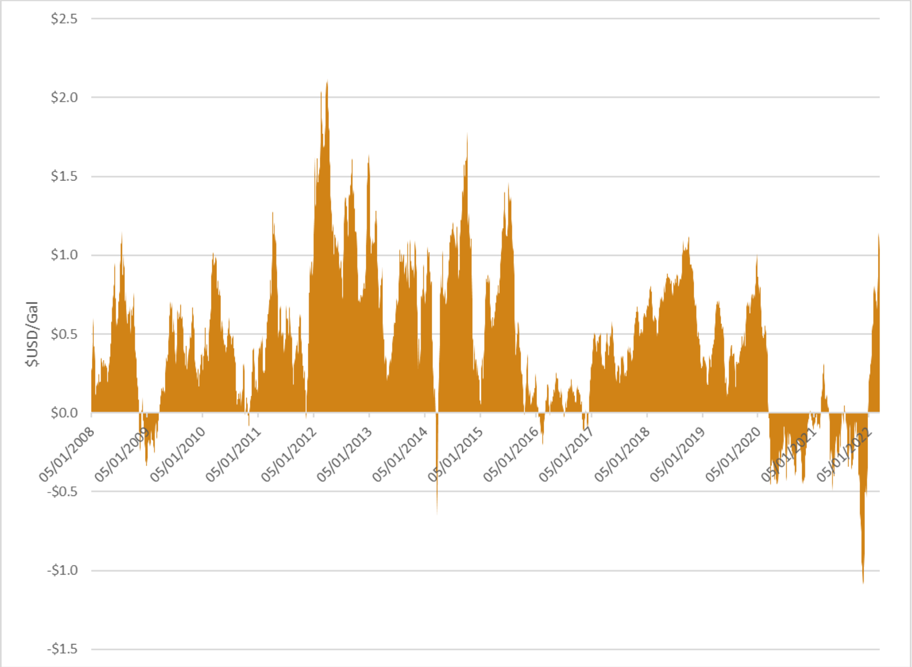


Figure 3. Daily price spread between MTBE and anhydrous ethanol, 2008–2022. Source: own elaboration, data from US Grain Council, 2022 [26].

2.2. Neoclassical Theory of the Firm

Assuming that the production of anhydrous ethanol is a supply problem, the neoclassical theory of the firm [27,28] can be applied. In addition, although the energy sector is far from both following the free market axiom and government intervention, the application of the postulates of cost minimization allows a profitability analysis [27]. Hence, it is assumed that a gasoline supplier will aim to maximize economic value and profitability while minimizing costs. Therefore, the use of MTBE as a gasoline oxygenate could be substituted by anhydrous ethanol (E) as long as it is economically convenient. From an economic perspective, the firm's decision problem of when to replace MTBE with E can be divided into two parts, the production function and cost minimization.

MTBE and E are assumed to be perfect substitute type inputs. A perfect substitute is an input that the company can use interchangeably to obtain a similar output. When the firm has only two factors available, the convenience to use one or the other can be analyzed through the isoquant curve, understood as "the set of possible combinations of factors 1 and 2 that are sufficient to obtain a given quantity of output" [27]. In other words, the isoquant curves show the technological constraints faced by a firm. When dealing with normal inputs (i.e., any product for which demand falls when its price rises), isoquant curves are strictly convex to the origin, while if they are perfect substitutes type inputs, the curves adopt a linear shape with a negative slope (see panel (a), Figure 4).

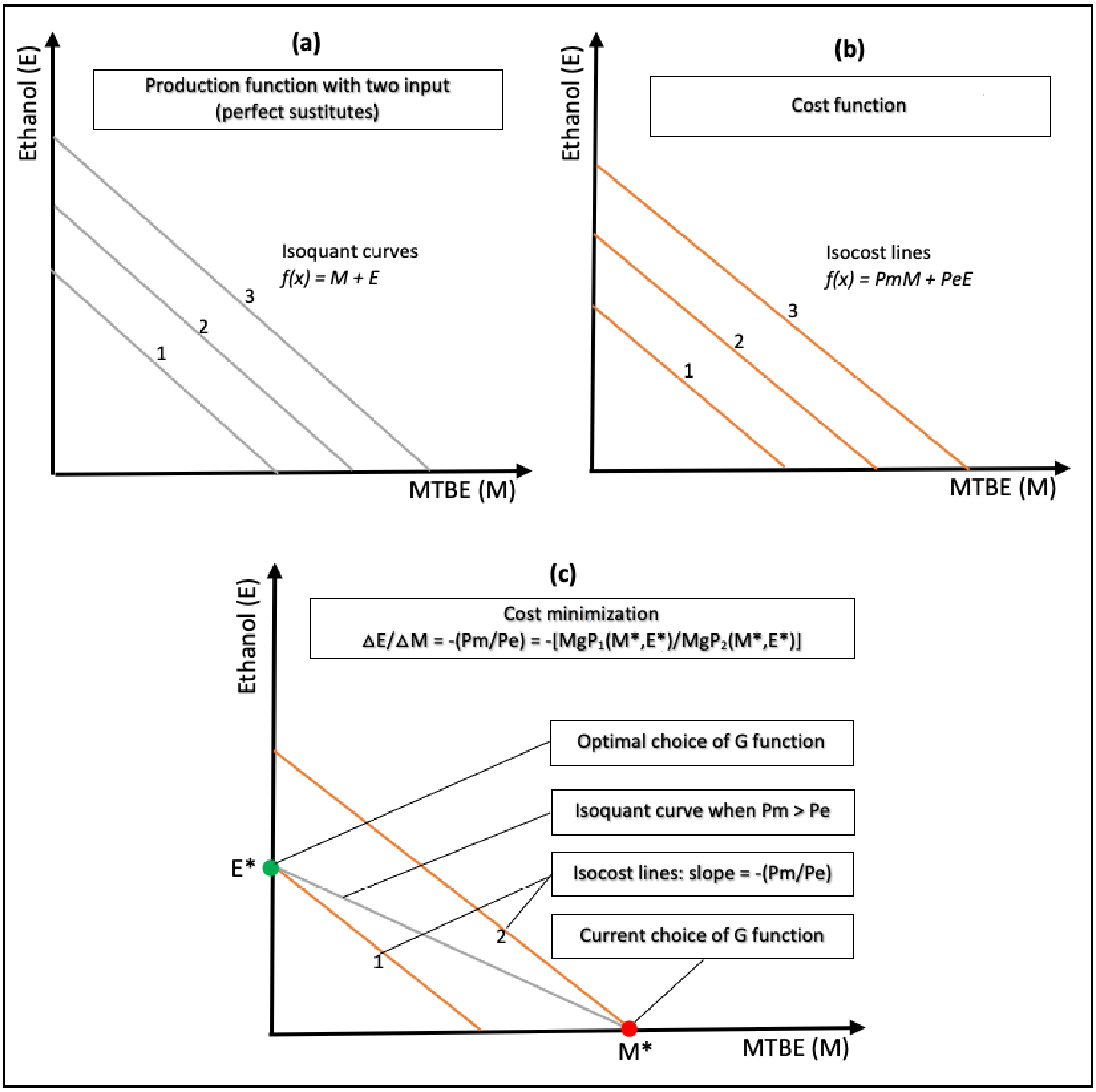


Figure 4. A firm's cost minimization for MTBE substitution by E according to the neoclassical theory of the firm. Panel (**a**): production function with two perfect substitutes, the isoquant curves show the possible combination of MTBE (M) and anhydrous ethanol (E) for a given amount of oxygenated gasoline (G). Panel (**b**): cost function, the isocost lines represent all possible combinations of minimum costs for a given quantity of G, [Pm = Price of M; Pe = Price of E]. Panel (**c**): cost minimization, it is the point of the isoquant curve that corresponds to the smallest isocost line; when Pm > Pe, this point is "E*" instead of "M*". Source: own elaboration, 2023.

Assuming that MTBE and E are perfect substitutes, a firm's production function is $f(x_1, x_2) = x_1 + x_2$, where the total amount of inputs used to oxygenate its gasolines is the sum of both products ($x_1 = MTBE$, y $x_2 =$ anhydrous ethanol).

For cost minimization, there is a tool defined by microeconomic theory. According to [27], the isocost line represents all combinations of production factors that have the same cost level; it can be derived from Equation (1):

$$C = w_1 x_1 + w_2 x_2 \tag{1}$$

of which, rearranging to extract the factor x_2 becomes

$$x_2 = \left(\frac{C}{w_2}\right) - \left(\frac{w_1}{w_2}\right) x_1 \tag{2}$$

where $C = firm's\ costs$; x_1 and x_2 are the factors of production; and $w_1$and w_2 are the prices of factors of production. In other words, the isocost line shows the cost constraints faced by the firm. Generally, isocosts take the form of a negatively sloped line (see panel (b), Figure 4).

Then we have a typical cost minimization problem, where the firm seeks the cheapest way to produce a given amount of output. Following Varian [27], the above can be expressed as follows:

$$\min w_1 x_1 + w_2 x_2 \tag{3}$$

$$subject\ to\ f(x_1,\ x_2) = y \tag{4}$$

where:

$$x_1 = MTBE,\ denoted\ by\ the\ letter\ M$$

$$x_2 = Anhydrous\ ethanol,\ designated\ with\ the\ letter\ E$$

$$w_1 = MTBE\ price,\ denoted\ by\ the\ letters\ P_m$$

$$w_2 = Anhydrous\ ethanol\ price,\ denoted\ by\ the\ letters\ P_e$$

$$y = desired\ production\ quantity\ of\ the\ company$$

Graphically, the solution to the problem consists of finding the point on the isoquant curve corresponding to the smallest isocost line. Since the firm's cost minimization considers perfect substitute inputs and assumes that the price of E is lower than the price of MTBE, the isoquant curve intersects two isocost lines. For the isocost lines, the farther away they are from the origin, the higher their cost is. Thus, the area where the firm minimizes its cost is where the isoquant curve intersects the smallest isocost line.

In our case, given that the isoquant curve has a lower slope than the isocost line, due to the existence in the market of a lower price of E compared to MTBE, the firm's cost minimization is at point "E*" (see panel (c), Figure 4). This means that the firm at that point will have lower costs by oxygenating gasoline with anhydrous ethanol instead of continuing to do so with MTBE.

Mathematically the solution to the cost minimization problem, with the above assumptions, is found when:

$$-\frac{MgP_1(x_1^*,\ x_2^*)}{MgP_2(x_1^*,\ x_2^*)} = TSR(x_1^*,\ x_2^*) = -\left(\frac{w_1}{w_2}\right) \tag{5}$$

where $MgP_1(x_1^*,\ x_2^*)$ is the derivative of the cost function (Equation (3)) with respect to factor 1 and interpreted as marginal product 1; $MgP_2(x_1^*,\ x_2^*)$ is the derivative of the cost function (Equation (3)) with respect to factor 2 and interpreted as marginal product 2; $TSR(x_1^*,\ x_2^*)$ is the technical substitution ratio, which must be equal to the quotient of the prices of factors 1 and 2 with a negative sign, and represents the slope of the function.

The same cost minimization problem, but now from a perspective of variation in the quantities of production factors 1 and 2 $(\Delta x_1,\ \Delta x_2)$, and keeping the same quantity of the firm's output "*y*" as the target, Equation (5) can be reformulated as follows:

$$\frac{\Delta x_2}{\Delta x_1} = -\left(\frac{w_1}{w_2}\right) = -\frac{MgP_1(x_1^*,\ x_2^*)}{MgP_2(x_1^*,\ x_2^*)} \tag{6}$$

3. Materials and Methods

3.1. Institutional Framework

Aware that research is a scientific activity that must follow a rigorous, procedural and systematic process to arrive at truthful results [29], a literature review was conducted to identify the efforts of the Mexican government to incorporate anhydrous ethanol as a gasoline oxygenate in the country's energy matrix. The legal framework of biofuels was consulted in the database of legal ordinances of the H. Chamber of Deputies and the DOF (official government gazette), for the period 2000–2022 [30,31]

For the analysis of the problem, according to Cronin et al. [32], a systematic process of deductive thinking was followed in the following order: (1) search for materials; (2) organization of the documents found; (3) interpretation and argumentation; (4) triangulation of information; (5) holistic analysis of the material reviewed. In all cases, we sought to identify the reason for inhibiting the commercial use of anhydrous ethanol as a gasoline oxygenate in Mexico.

A review of the different policies and actions that the Mexican government has promoted in favor of biofuels was also carried out, comparing their scope versus reality. For this purpose, the web pages and document databases of government agencies were consulted through specialized search engines. The period analyzed was 2000–2022 [33].

3.2. Indifference Price Methodology

Mexico is an economy open to international competition, where global behavior strongly influences local markets. Since the entry into force of NAFTA (North American Free Trade Agreement, 1 January 1994), now called USMCA (United States–Mexico–Canada Agreement, 1 July 2020), most Mexican markets have been liberalized.

An indifference price is a price at which the buyer (industrial company) is indifferent between acquiring the input from a local supplier (domestic company) or importing it from a foreign supplier (international company). In agriculture, the Mexican government continues to use the reference price mechanism to determine the subsidy amount by type of grain and producer, which in turn is estimated based on indifference prices. For the Ministry of Agriculture and Rural Development [34] the indifference price is the futures price of the Chicago Board of Trade (CBOT) plus the marketing basis and local market conditions prevailing in each region [35].

In the biofuels sector, domestic producers are the companies potentially interested in producing anhydrous ethanol, while PEMEX is the company that requires this input to produce oxygenated gasoline, which is then sold to the final consumer through its service stations and other gasoline distributors.

Ethanol as an input is a "derived demand", meaning that its demand depends on the quantity that another company decides to offer in a different market from that of the input [28]. In this case, the total demand for anhydrous ethanol is "derived" from the amount of oxygenated gasoline that PEMEX decides to offer, which, depends on the final demand for gasoline.

Given that PEMEX behaves as a profit-maximizing competitive company, in the various attempts made to incorporate ethanol as a gasoline oxygenate, it has established the policy of not subsidizing the purchase of biofuel, since this would imply reducing its profit margins and the oil revenue for the State; a situation that goes against its legal and corporate objective. Therefore, it has implicitly adopted the criterion that the development of the national anhydrous ethanol industry in Mexico must be done at competitive prices in an open economy. In that sense, PEMEX has repeatedly stated that it will only purchase anhydrous ethanol at an indifference price [20].

Figure 5 exemplifies the supply alternatives that PEMEX has if it decides to substitute MTBE for anhydrous ethanol under a policy of indifference prices, which implies not subsidizing the incorporation of this biofuel into Mexico's energy matrix.

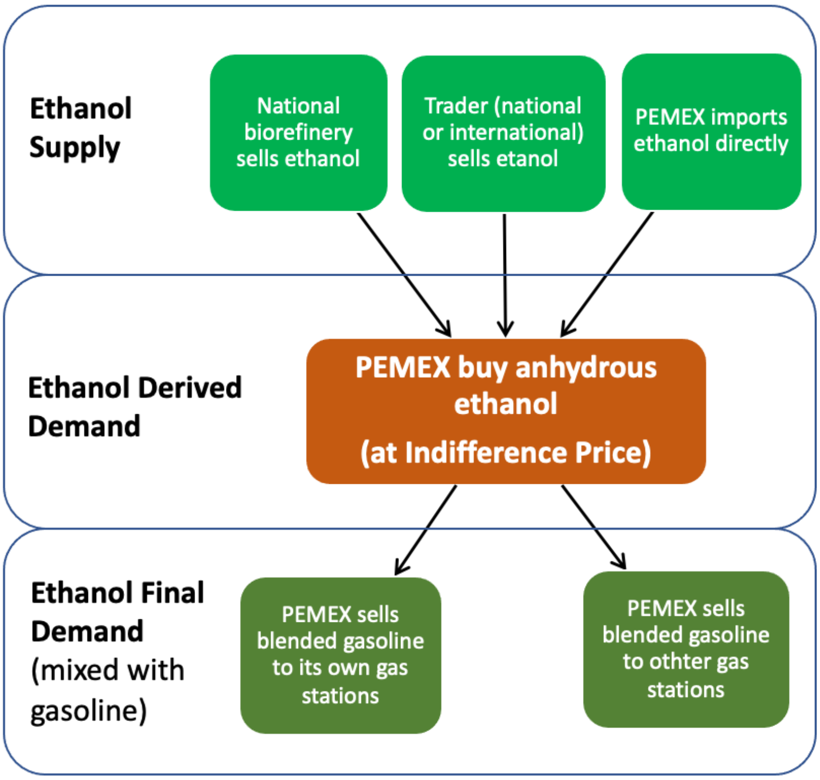


Figure 5. Anhydrous ethanol supply chain in Mexico through an indifference price policy without PEMEX subsidies. Source: own elaboration, 2023.

The Price-CEM uses the "indifference price of a product" methodology, which works in an open economy context and without subsidies. For its development, a database was integrated into a Microsoft® Excel 365 workbook, with daily data from January 2015 to January 2023. With official and specialized information (SENER, CBOT, US BUREAU OF LABOR STATISTICS, INEGI, PEMEX, BANXICO, SCT, among others) [20,36–38], a calculation process was followed through predefined routines using macros and formulas to estimate the indifference price (for more details, see Appendix A). The tool assumes that ethanol will be brought into the country through the Gulf of Mexico and delivered to PEMEX's TAD facilities. The tool is designed so that the user can enter his/her data and determine the indifference price for any other point in the country without local anhydrous ethanol prices, this calculator fills a gap in the emerging biofuel market in Mexico.

The estimated prices are valid only for the origin-destination segment defined by the user, and for the date indicated, which can be a specific day and/or period (month, year). The tool can also provide a price comparison between eight TADs and generate minimum, average and maximum prices. We must also remember that the price estimation includes the specific market conditions of anhydrous ethanol between the United States and Mexico.

The USMCA establishes that Mexican ethanol imports, under tariff items 22071001 and 22072001 from the United States, are duty-free [39].

In short, to estimate the indifference price of anhydrous ethanol in Mexico, the starting point is the international market price (United States) plus all import logistics costs, customs duties and services and internment costs to a specific PEMEX TAD, where it will be blended with base gasoline. The formulas developed for the method are a modified version of the PEMEX proposal [20], adapted by some logistics processes that incorporate updated information on costs, duties and customs services. The formulas are as follows:

$$PIEM_i = \left(\frac{FEP_i}{FC_1} + \frac{CLE_i}{FC_2}\right)TCP_i + CI_i + CLN_i \tag{7}$$

where:

$PIEM_i$: Indifference price of anhydrous ethanol in Mexico at PEMEX's TAD i, in USD and MXN, and in gallons and liters, at the user's choice.

FEP_i: Futures price; this is the average price of the ethanol futures contract on day i at the Chicago Board of Trade (CBOT) plus the cost of the basis of the contract corresponding to the State of Iowa, USA, including 21 previous days of quotes, to be applied on day 22. Alternatively, anhydrous ethanol prices FOB Houston, published by Platts, can also be used; in this case, which one was used, in USD/gallon.

CLE_i: Foreign logistics costs for month i; this is the maritime transportation of ethanol from the origin of shipment to the port of entry into Mexico, including sea freight, port storage and any other cost related to international ethanol transportation logistics, in USD/barrel.

TCP_i: Average exchange rate on day i; this is the exchange rate to settle obligations denominated in foreign currency, published by the Bank of Mexico, including 21 previous days of quotes, to be applied on day 22, in Mexican pesos/USD.

CI_i: Import costs for month; this is the formal import of ethanol, including customs clearance fees, customs import application cost, customs services and any other cost related to the legal and fiscal import process, in Mexican pesos/liter.

CLN_i: National logistics costs for month; this is the maritime transportation of ethanol from the port of entry into Mexico to TAD i, including land, toll and any other type of cost that allows the product to reach its final destination, in Mexican pesos/km.

FC_1: Conversion factor from gallons to liters; value used: 3.78541.

FC_2: Conversion factor from barrels to liters; value used: 158.9873.

$$CLE_i = FM_i + A_i \tag{8}$$

where:

FM_i: Sea freight for month i; this is the maritime transportation of ethanol from the origin of shipment to the port of entry into Mexico, costs reported by the specialized shipping companies, generally in metric tonnes, so it is necessary to convert to the unit USD/barrel.

A_i: Storage for month i; this is the cost for temporary storage at the destination port and use of port facilities, in USD/barrel.

$$CI_i = DTA_i + P_i + SA_i \tag{9}$$

where:

DTA_i: Customs duties for month i; these are the import duties for anhydrous ethanol, generally a percentage per thousand over the value of the product, in Mexican pesos/liter.

P_i: Pre-validation of month i; this is the value established by the customs law for customs import application, in Mexican pesos/liter.

SA_i: Customs service costs for month i; this is the tariff on the cost of the product including CLEs, in Mexican pesos/liter.

$$CLN_i = CT_i + Pe_i \tag{10}$$

where:

CT_i: Land cost for month i; this is the cost of the tanker truck from the Mexican port to TAD i; the tanker truck can be of different capacities, the one considered in this study is 30 thousand liters, in Mexican pesos/km.

Pe_i: Toll cost corresponding to month i; this depends on the route to be followed and the distance to be traveled; the tool used is the toll cost calculator of the Secretariat of Communications and Transportation of the Government of Mexico [29], in Mexican pesos/car (6 axles).

The method here described can be adjusted to include other—and more detailed—costs not yet considered, such as type of land transportation (tanker truck), distances between ports and TADs (in km), land routes costs (e.g., tolls), cargo insurance, changes in commercial and customs legislation. The user can use their own data and define the anhydrous ethanol delivery point, as well as dates, costs, or discounts, among other variables. The objective of the tool is that, in the absence of a market price for ethanol in Mexico, it is possible to estimate a price for any point in the national territory, which can serve as a basis for purchase/sale operations between PEMEX and potential national producers of this biofuel.

4. Results and Discussion

4.1. Institutional Framework and Actions Carried out by Mexico in the Area of Biofuels

The institutional framework for biofuels in Mexico is made up of the Sustainable Rural Development Law [40]; Law for the Sustainable Development of Sugarcane [41]; Law for the Promotion and Development of Bioenergy [42]; Decree reforming and adding various provisions of the Political Constitution of the United Mexican States, in energy matters [43]; PEMEX Law [44]; Law of the Energy Regulatory Bodies [45]; Official Mexican Standard NOM-016-CRE-2016, quality specifications for petroleum products, based on Article 51 of the Federal Law on Metrology and Standardization [46]; Agreement by which the SENER and the CRE issue criteria for the application of permitted activities in the area of bioenergy [47]; Agreement in compliance with the resolution of the Second Chamber of the Supreme Court of Justice of the Nation (A. R.610 /2019), derived from the Judgment of Indirect Amparo 1118//2017, filed against agreement A/028/2017, amending NOM-016-CRE-2016 [48]; Decree amending and adding various provisions of the Electricity Industry Law [49].

In the last decade, Mexico supported and carried out some actions aimed at using anhydrous ethanol, but still needs to achieve its objective. For example, The Inter-Secretarial Commission on Bioenergy (2008), a high-level Mexican government body, was formed to define a strategy for introducing ethanol. Some laws and programs were also approved, but these failed and are therefore no longer in force. These are the cases of the Law for the Use of Renewable Energies and the Financing of the Energy Transition (2008); Program for the Sustainable Production of Bioenergy Inputs and Scientific and Technological Development (2009); Program for the Introduction of Bioenergy (2009), Program for the Introduction of Anhydrous Ethanol (2011), Analysis and Proposal for the Introduction of Anhydrous Ethanol in the Gasoline Commercialized by PEMEX (2014), economic support given to specific private projects (e.g., Sinaloa ethanol plant, etc.), among other actions.

The following is a summary of the main actions taken by the Mexican government, specifically in the area of anhydrous ethanol as an oxygenate for the gasoline produced by PEMEX:

(1) Pilot test of oxygenated gasoline with 6% by volume (v/v) of anhydrous ethanol, carried out at the end of 2008 and beginning of 2009.

(2) PEMEX public bidding process to purchase between 658 and 823 million liters of anhydrous ethanol, carried out in 2009—declared void after the winning companies declined to sign the contracts, alleging cost problems concerning the purchase price proposed by PEMEX.

(3) PEMEX public tender to purchase 425 to 520 million liters of anhydrous ethanol, executed in 2012—declared deserted due to disagreements between potential participants and PEMEX on the purchase price.

(4) PEMEX public tender to purchase 1550 to 2215 million liters of anhydrous ethanol, executed in 2014, to be blended with base gasoline at 5.8% by volume (v/v) in eight PEMEX TADs. Four companies were winners for six TADs, but they still need to deliver the product, again, due to price problems.

(5) A financial fund was created in 2008 to support R&D, called the CONACYT-SENER-Sustainability Energy Sectorial Fund, which disappeared at the end of 2021.

(6) Creation of a research network in 2015 on different types of bioenergy, called the Mexican Center for Innovation in Bioenergy (CEMIEBio, for its acronym in Spanish). This network was formed through clusters, with the participation of several universities and national and foreign institutions. In the case of ethanol, the bio-alcohols cluster was formed to achieve technological development through four lines of research: (a) characteristics and national availability of sugarcane bagasse, agave bagasse, wheat straw and corn stover; (b) production of biohydrogen and butanol with native microbial consortia; (c) sustainability and life cycle analysis (LCA); (d) human resources training. The R&D work undertaken by the different clusters advanced the state of the art significantly, but with the disappearance of funding these efforts also gradually faded away, although in some cases certain initiatives remain due to economic support from other calls for proposals and/or participating institutions.

(7) In 2014, the Bioenergy Thematic Network (RTB) of CONACYT was created to promote scientific research and technological development. In this case, knowledge exchange has been promoted, but again, economic resources are the main limitation.

(8) In addition to the above, since at least 2015, certain institutional funds have been supporting R&D projects, validation of inputs and processes, innovation in private companies, consulting and sectoral diagnosis, among others, but positive results have been scarce due to insufficient economic resources, bureaucratic problems, continuity, and above all, the lack of a biofuels policy that integrates production chains aimed at solving structural and social problems of a regional/local nature.

4.2. Tool to Estimate Anhydrous Ethanol Price

The Price-CEM tool calculates anhydrous ethanol indifference prices on a daily frequency (2015–2022), referring to a specific point in the national territory. The tool estimates two types of prices, one with default data and one with user-supplied data. With default data, prices are estimated for eight TADs: (1) Cd. Madero; (2) Cd. Valles; (3) Cd. Mante; (4) Pajaritos; (5) Veracruz; (6) Xalapa; (7) Perote; (8) San Luis Potosí. Due to the available port infrastructure and distances, we assume that TADs 1, 2, 3 and 8 can be supplied by the port of Altamira (P2); TADs 5, 6 and 7 can be supplied by the port of Veracruz (P1); and TAD 4 can be supplied by the port of Coatzacoalcos (P3) (see Figure 6).

The tool results are concentrated in a "Dashboard", divided into two parts, which are explained below.

In the first part (see Figure 7), the user defines the TAD for which he/she wishes to estimate the price (from the eight available), then the currency (USD or MXN), and then the unit of measurement (gallons or liters). Immediately afterward, the calculator displays three graphs. The graph called "historical data" (upper left corner), is the historical (daily) indifference price of the selected TAD, for the entire period that the calculator has data (2015–2022); at the bottom of this graph, the minimum, maximum and average historical prices of the selected TAD are shown. The graph called "PIEM from 2021 onwards" (upper right corner), is the indifference price (daily) of the selected TAD, but from the selected year to the present; the user enters the desired year at the bottom of the figure. The third graph, labeled "Mexican Ethanol Indifference Price (PIEM) per TAD" (bottom), is the indifference price of the eight TADs, with two options that can be set at the bottom of the figure: a specific date that the user defines or the last date for which the calculator has data. This graph presents three types of price for each of the eight TADs: (a) minimum price of the selected month/year; (b) maximum price of the selected month/year; (c) price of the selected day. The purpose of this figure is to compare the minimum and maximum prices for a given month.

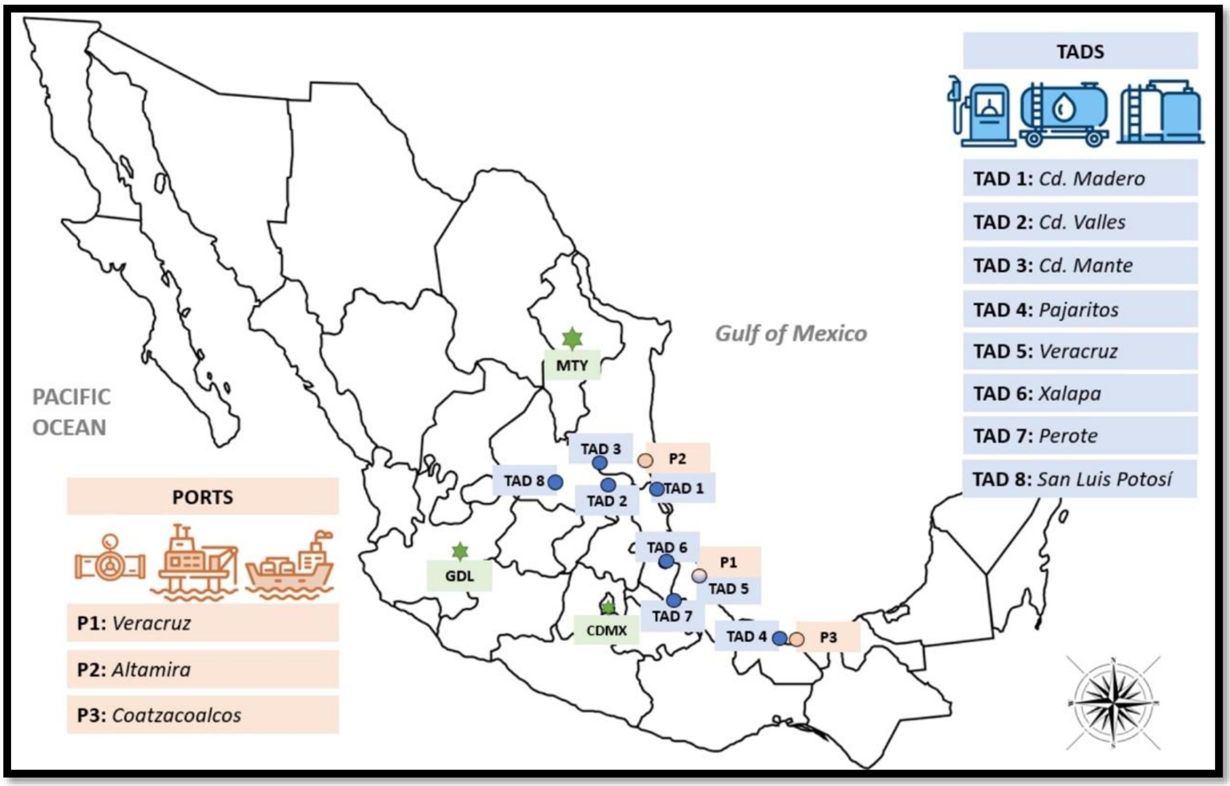
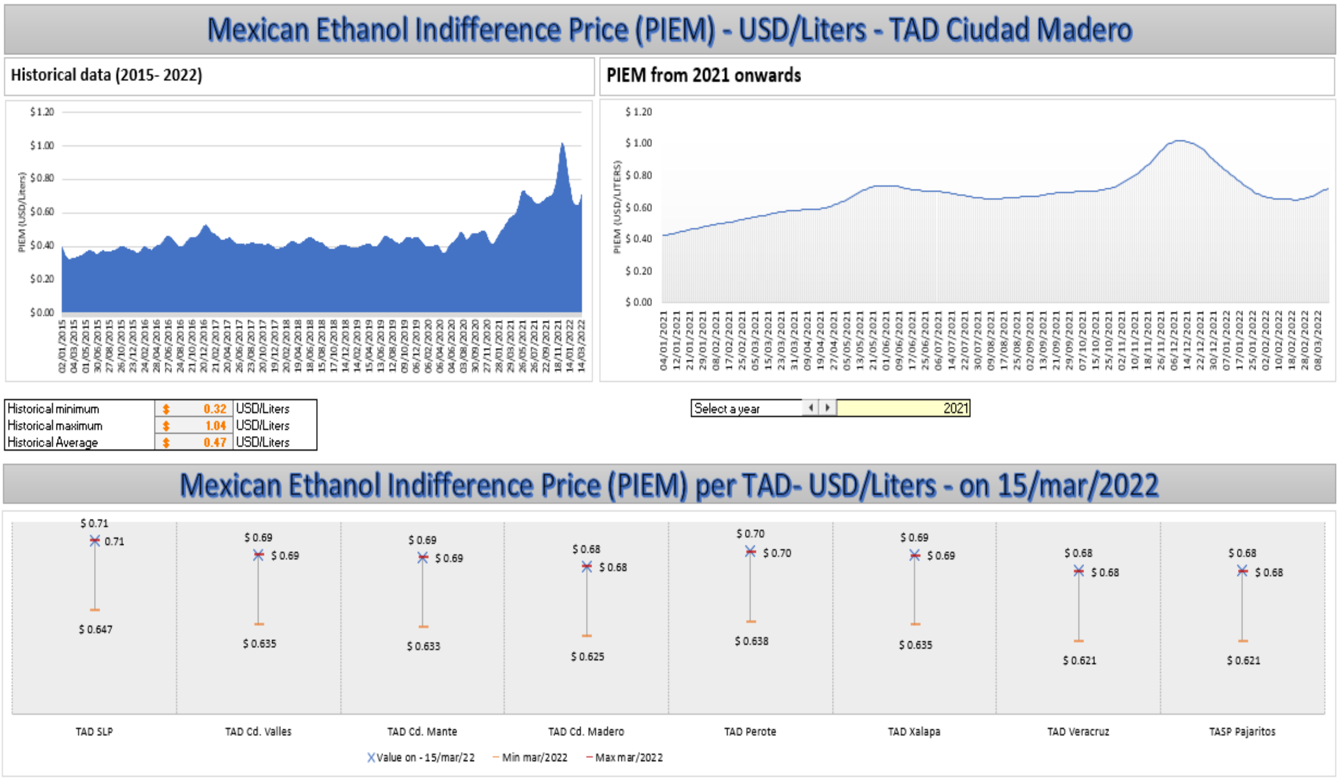


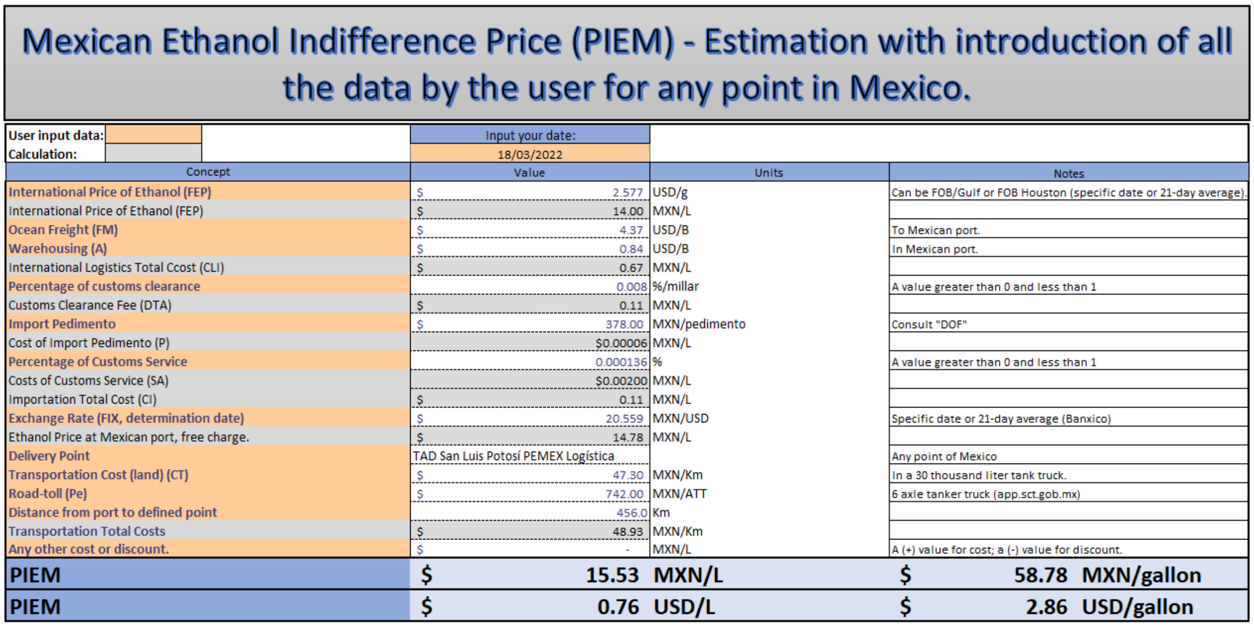
Figure 6. Map of Mexico with eight TADs and three ports of arrival for anhydrous ethanol. Source: own elaboration, 2022 [50–52].



Historical minimum	$	0.32	USD/Liters
Historical maximum	$	1.04	USD/Liters
Historical Average	$	0.47	USD/Liters

Figure 7. Dashboard (1st part) for TAD San Luis Potosí. Top left graph: daily ethanol prices, 2015–2022. Upper right graph: daily ethanol prices, 2021–2022. Lower graph: ethanol price in 8 PEMEX TADs, 15 March 2022 (includes minimum and maximum price per TAD for the month of March 2022). Source: own elaboration, 2022.

In the second part (see Figure 8), the tool calculates the indifference price for any date and country destination. This figure represents the greatest degree of freedom that the tool has since the user enters almost all the input data. The significance of "Price-CEM" is not the fact that it estimates a historical ethanol price (2015–2022) for Mexico, but that it can estimate the ethanol price for any PEMEX TAD, even for a future date, as long as the user has reliable data for the required variables. This leads to the user being able to calculate prices adjusted to their specific needs (research, profitability analysis and public policies).



Mexican Ethanol Indifference Price (PIEM) - Estimation with introduction of all the data by the user for any point in Mexico.

User input data: 🟧
Calculation: ▨

Input your date:
18/03/2022

Concept	Value	Units	Notes
International Price of Ethanol (FEP)	$ 2.577	USD/g	Can be FOB/Gulf or FOB Houston (specific date or 21-day average).
International Price of Ethanol (FEP)	$ 14.00	MXN/L	
Ocean Freight (FM)	$ 4.37	USD/B	To Mexican port.
Warehousing (A)	$ 0.84	USD/B	In Mexican port.
International Logistics Total Ccost (CLI)	$ 0.67	MXN/L	
Percentage of customs clearance	0.008	%/millar	A value greater than 0 and less than 1
Customs Clearance Fee (DTA)	$ 0.11	MXN/L	
Import Pedimento	$ 378.00	MXN/pedimento	Consult "DOF"
Cost of Import Pedimento (P)	$0.00006	MXN/L	
Percentage of Customs Service	0.000136	%	A value greater than 0 and less than 1
Costs of Customs Service (SA)	$0.00200	MXN/L	
Importation Total Cost (CI)	$ 0.11	MXN/L	
Exchange Rate (FIX, determination date)	$ 20.559	MXN/USD	Specific date or 21-day average (Banxico)
Ethanol Price at Mexican port, free charge.	$ 14.78	MXN/L	
Delivery Point	TAD San Luis Potosí PEMEX Logística		Any point of Mexico
Transportation Cost (land) (CT)	$ 47.30	MXN/Km	In a 30 thousand liter tank truck.
Road-toll (Pe)	$ 742.00	MXN/ATT	6 axle tanker truck (app.sct.gob.mx)
Distance from port to defined point	456.0	Km	
Transportation Total Costs	$ 48.93	MXN/Km	
Any other cost or discount.	$ -	MXN/L	A (+) value for cost; a (-) value for discount.
PIEM	**$ 15.53**	**MXN/L**	**$ 58.78 MXN/gallon**
PIEM	**$ 0.76**	**USD/L**	**$ 2.86 USD/gallon**

Figure 8. Dashboard (2nd part) with anhydrous ethanol indifference price exercise, TAD San Luis Potosí PEMEX Logística, for 18 March 2022. Source: own elaboration, 2022.

To elaborate, an exercise is presented below. Suppose we want to estimate the price of ethanol for 18 March 2022 at the "TAD San Luis Potosi PEMEX Logistics", located at Observatorio s/n, Españita C.P. 78395, San Luis Potosi, Mexico; and that the ethanol will arrive in the country through the port of Altamira, Tamaulipas. First, the date is set and sequentially entered the information requested in Figure 8. Note that the data that can be entered are indicated with a colored label. If some data inputs are unavailable, they can be left "by default". It is recommended to see the units and the corresponding notes to avoid incorporating inconsistent information and generating estimation errors. In this case, the FOB/Gulf ethanol price of 18 March 2022 [26] is used and the FIX exchange rate of 17 March 2022 is applied [38]. The Apps of the Ministry of Communications and Transportation [53] were used to determine the distance and cost of toll booths. After entering the rest of the data, the estimated results are: 0.76 USD/liter (15.53 MXN/liter) and 2.86 USD/gallon (58.78 MXN/gallon) (see Figure 8).

In order to have a medium-term view of the behavior of the anhydrous ethanol market, the daily and monthly prices of eight TADs from PEMEX have been summarized. Figure 9 shows daily prices from 2 January 2020 to 2 January 2023, while Table 2 shows monthly prices from January 2021 to December 2022. The estimated prices have several readings: (a) consistently the lowest prices are in the Veracruz and Pajaritos TADs, while the highest are in the SLP TAD; a situation caused by the difference in distance and toll booths. (b) The October–December 2021 quarter prices increased as a result of an imbalance between supply and demand due to the expectations of corn harvest, the main raw material in the USA. (c) In general, ethanol prices reflect an upward trend due to the post-pandemic inflationary process. (d) From June 2022 onwards, there is a downward trend in Mexico's ethanol prices, reflecting the Mexican peso's revaluation process against the US dollar. This makes potential ethanol imports and their price cheaper. (e) The price at which PEMEX has expressed interest in buying anhydrous ethanol (indifference price) is highly volatile given the behavior of the international price, in addition to the exchange rate effect, without a compensation mechanism to smooth these ups and downs.

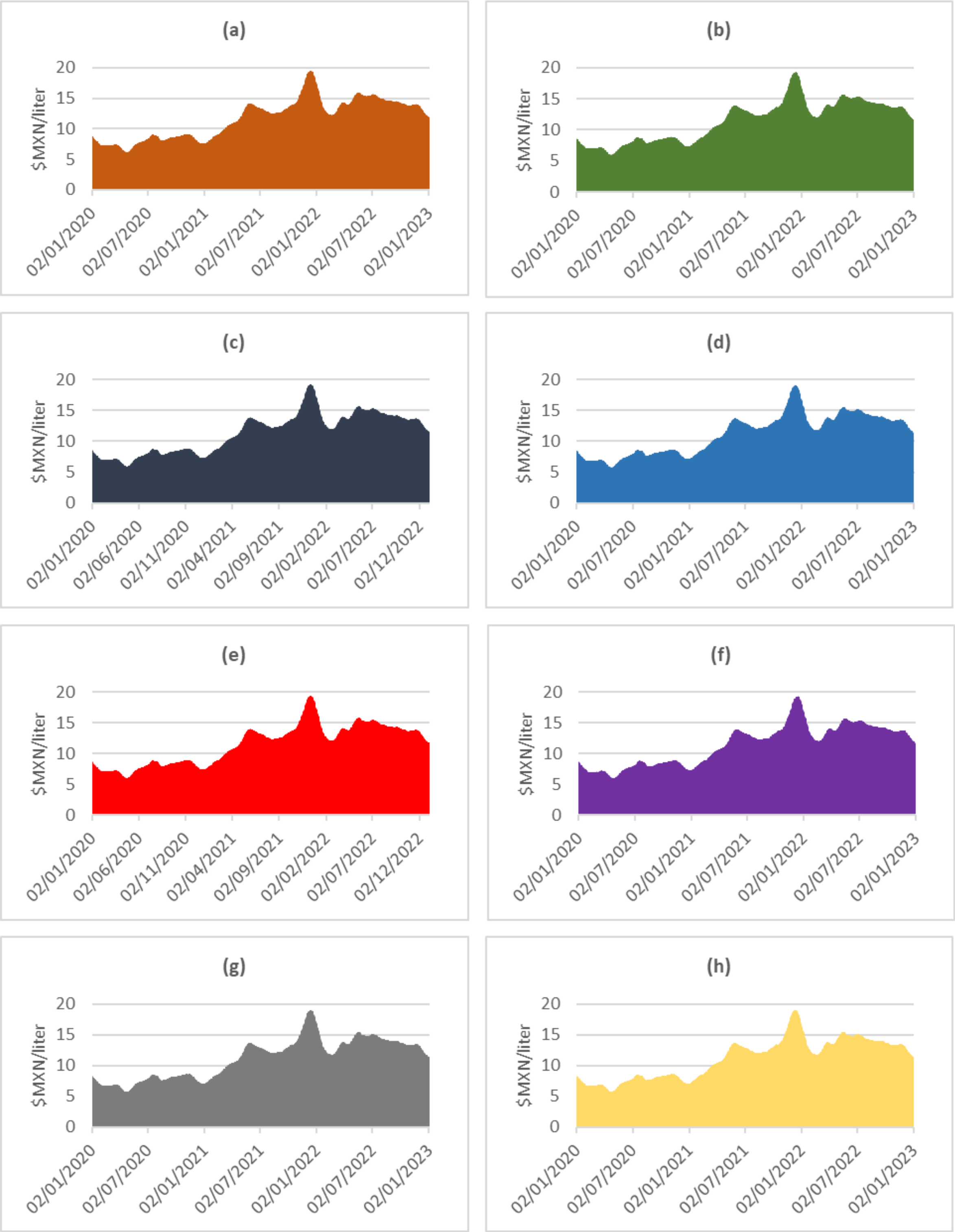


Figure 9. Indifference Price of Ethanol in Mexico by Storage and Distribution Terminal (TAD) from PEMEX (Mexican oil company): (**a**) TAD San Luis Potosí; (**b**) TAD Cd. Valles, (**c**) TAD Cd. Mante; (**d**) TAD Madero; (**e**) TAD Perote; (**f**) TAD Xalapa; (**g**) TAD Veracruz, (**h**) TAD Pajaritos. Source: own elaboration, 2023.

Table 2. Indifference price of ethanol in Mexico, 2021–2022.

Date	**PEMEX Storage and Distribution Terminal ($MXN/liter) ***							
	SLP	**Cd. Valles**	**Cd. Mante**	**Cd. Madero**	**Perote**	**Xalapa**	**Veracruz**	**Pajaritos**
January 2021	$8.60	$8.37	$8.33	$8.18	$8.42	$8.36	$8.11	$8.11
February 2021	$9.54	$9.31	$9.27	$9.12	$9.36	$9.30	$9.05	$9.05
March 2021	$10.88	$10.65	$10.61	$10.45	$10.69	$10.64	$10.38	$10.38
April 2021	$12.05	$11.82	$11.78	$11.62	$11.87	$11.81	$11.55	$11.55
May 2021	$14.13	$13.90	$13.86	$13.70	$13.95	$13.89	$13.63	$13.63
June 2021	$13.41	$13.18	$13.14	$12.99	$13.23	$13.17	$12.91	$12.91
July 2021	$12.70	$12.47	$12.43	$12.27	$12.52	$12.46	$12.20	$12.20
August 2021	$12.71	$12.47	$12.43	$12.28	$12.52	$12.47	$12.20	$12.20
September 2021	$13.46	$13.23	$13.19	$13.03	$13.28	$13.22	$12.96	$12.96
October 2021	$14.53	$14.29	$14.25	$14.09	$14.34	$14.28	$14.01	$14.01
November 2021	$18.80	$18.56	$18.51	$18.36	$18.61	$18.55	$18.28	$18.28
December 2021	$17.52	$17.28	$17.24	$17.08	$17.33	$17.27	$17.00	$17.00
January 2022	$12.98	$12.73	$12.69	$12.53	$12.79	$12.73	$12.45	$12.45
February 2022	$12.38	$12.14	$12.10	$11.93	$12.19	$12.13	$11.86	$11.86
March 2022	$14.29	$14.04	$14.00	$13.83	$14.09	$14.03	$13.76	$13.76
April 2022	$14.93	$14.68	$14.64	$14.47	$14.73	$14.67	$14.39	$14.39
May 2022	$15.55	$15.30	$15.26	$15.09	$15.35	$15.29	$15.01	$15.01
June 2022	$15.61	$15.36	$15.32	$15.15	$15.42	$15.35	$15.07	$15.07
July 2022	$14.93	$14.68	$14.64	$14.47	$14.74	$14.67	$14.39	$14.39
August 2022	$14.55	$14.30	$14.25	$14.08	$14.35	$14.29	$14.00	$14.00
September 2022	$14.26	$14.00	$13.96	$13.79	$14.06	$13.99	$13.71	$13.71
October 2022	$13.84	$13.58	$13.54	$13.37	$13.64	$13.57	$13.29	$13.29
November 2022	$13.85	$13.59	$13.54	$13.37	$13.65	$13.58	$13.29	$13.29
December 2022	$11.99	$11.72	$11.68	$11.51	$11.78	$11.72	$11.42	$11.42

* Price on the last day of each month. Source: own estimation, 2023.

In order to make the incorporation of anhydrous ethanol into the energy matrix a reality, this requires a public policy of fiscal support for R&D, agricultural waste logistics and ethanol production, as well as a new regulatory framework that gradually eliminates MTBE. Institutional efforts are also required to integrate all links in the biofuel production chain, including primary input producers. The prices estimated here are a valuable input contributing to the development of a domestic ethanol market.

4.3. Policy Recommendations

Based on the above account, and after three failed public tenders (2009, 2012, 2014) aimed at the purchase of anhydrous ethanol by the Mexican government, it is evident that there are problems in two areas:

1. production costs and ethanol price (microeconomic level).
2. legal and governmental decisions (macroeconomic level).

The first has to do with the type of raw material, technology, operating cost, financial cost and market price; while the second refers to an inadequate legal and regulatory framework that obliges PEMEX to use anhydrous ethanol as an oxygenate in the gasoline it produces, as well as to establish blending targets, financial support, infrastructure adjustments, R&D, etc. For example, if we think of 1G ethanol, for which there is a mature technology and standard efficiency at the international level, Mexico should have no problem producing ethanol from sugarcane, sorghum-grain and sorghum-sweet. If we think of 2G ethanol, other problems are associated with the disposal of lignocellulosic biomass, its logistics, pretreatment technology and enzyme production (in situ), among others.

Therefore, institutional efforts have been insufficient and there has been a lack of a comprehensive public policy that includes actions in the regulatory, fiscal, financial, promotional, commercial, input production, research, etc.

The policy of acquiring anhydrous ethanol at a price that does not consider the national reality, such as the support demanded by all the new subsectors (ethanol industry), has been a "straitjacket" that has inhibited progress on the issue. The decision not to prohibit using MTBE as a gasoline oxygenate is a strong bottleneck that inhibits the incorporation of anhydrous ethanol into the energy matrix. The fact that NOM-016-CRE-2016 does not allow the blending of anhydrous ethanol in the three main metropolitan areas of the country (Mexico City, Guadalajara and Monterrey), and limits its blending in the rest of Mexico to 5.8% by volume (v/v), is another strong restriction. In fact, the greatest environmental benefits occur in ethanol-gasoline blends equal to or greater than 10% [54]. From this point of view, it was a mistake to deactivate the modification of NOM-016 that allowed the blend to be increased up to 10% by volume (v/v).

International experience, especially in the United States and Brazil, shows that the public policies of promotion and support made it possible to integrate the ethanol production chain. To develop the market, these countries designed production subsidies, granted financial support, encouraged research, promoted partnership schemes between agricultural producers and investors, supported the production of inputs, and limited and later banned MTBE. In addition, these countries raised awareness among end consumers about the benefits of biofuel consumption and, in general, institutionally decided to incorporate anhydrous ethanol as an oxygenate in gasoline.

Based on the above, it can be deduced that in Mexico there has been no political will to incorporate anhydrous ethanol into the energy matrix, and, at least in the short term, this is not expected to happen. However, given the global environmental pressure, and the need for more jobs in rural areas, anhydrous ethanol production will sooner or later become a reality in Mexico.

5. Conclusions

Governmental efforts to incorporate anhydrous ethanol into Mexico's energy matrix need to be increased. The existing regulatory framework, comprising a Bioenergy Promotion and Development Law (approved in 2008) and other legal and promotional regulations, has so far proven to be insufficient to substitute the use of MTBE and other fossil fuel derivatives as gasoline oxygenates despite their proven effects on contamination and to human health. The development of a bioethanol market in Mexico would require an integrated vision that considers fiscal policies to support R&D actions, agricultural waste management, and local production of anhydrous ethanol while taking advantage of available resources and capacities. Such a vision deserves prompt attention and action. Additionally, a new regulatory framework is necessary to transition from the use of MTBE to only bioethanol/gasoline blends. Furthermore, the method and tool developed for the indifference price calculations, for any PEMEX TAD, help to provide greater certainty in the incipient negotiations and purchase/sale intentions between private companies and the government since there is no formal ethanol market in the country. This is the first tool to estimate the price of anhydrous ethanol at the local level under Mexican conditions, which contributes to the development of the biofuel market in Mexico. However, the values calculated with the indifference price method and tool should be prudently used since different databases and currency factors have been used.

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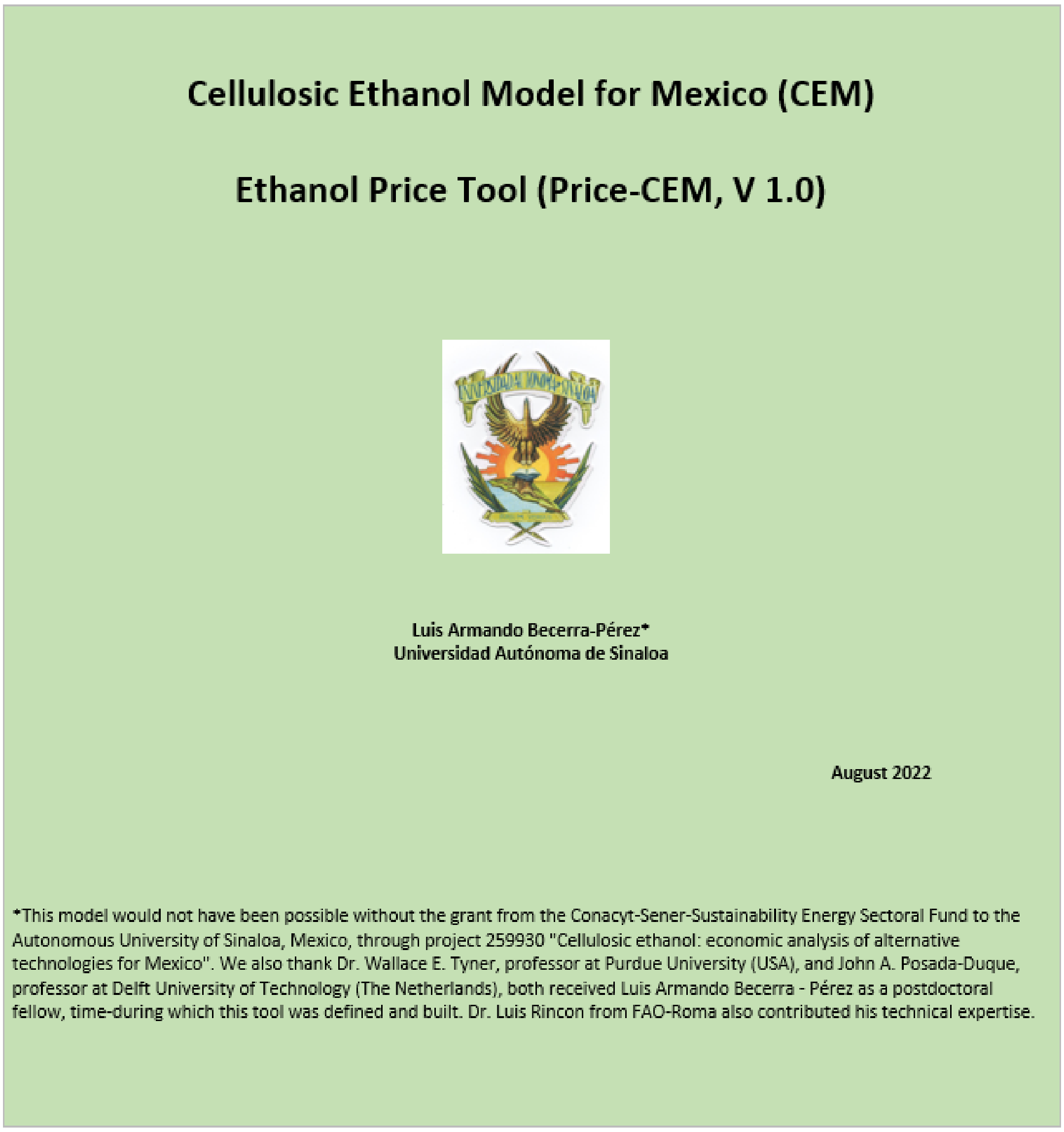
Appendix A. Ethanol Price Tool (Price-CEM, V 1.0)

The "Ethanol Price Tool" (Price-CEM, V 1.0) calculator, which was developed by Luis Armando Becerra-Pérez from the Autonomous University of Sinaloa in 2022, is part of the "Cellulosic Ethanol Model for Mexico" (CEM) and is aimed at estimating the indifference price of ethanol in Mexico. The calculator, which is composed of a Microsoft® Excel 365 workbook, comprises five sheets, some of which are linked to each other.

The cover page of the calculator simply displays "Price-CEM", while the instruction sheet provides general guidelines on the calculator as well as a detailed explanation of the contents of the workbook. The model sheet contains a brief description of the model, the methodology used in developing the calculator, and the assumptions that are utilized. The dashboard sheet presents the estimates of the Indifference Price of Ethanol in Mexico (PIEM) and it allows users to estimate several price options. For instance, the user can consult the price of ethanol for eight TADs of Pemex historically and/or over a defined period, check the price for the last date that the tool has data and modify some parameters, or calculate the indifference price of ethanol for any other delivery point by inputting all their data. The references sheet describes the main sources that the calculator uses.

Note that certain sheets that contain the database and technical instructions have been intentionally hidden, as they are not required. However, it is essential to follow a particular order of the sheets, starting from the lowest to the highest, to arrive at the market ethanol balance. It is important to note that the estimates of the Indifference Price of Ethanol in Mexico (PIEM) presented by the calculator are only indicative, and the authors and the institutions for which they work bear no legal responsibility, either present or future, for the use and/or decisions that may be made based on said estimates.

The tool is available on request and can be obtained by contacting Luis Armando Becerra Pérez, Ph.D., via email (becerra@uas.edu.mx).



Cellulosic Ethanol Model for Mexico (CEM)

Ethanol Price Tool (Price-CEM, V 1.0)

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August 2022

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Figure A1. Cover page "Ethanol Price Tool" (Price-CEM, V 1.0) calculator. Source: own elaboration, 2023.

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