Bottlenecks in the Development of Bioethanol from Lignocellulosic Resources for the Circular Economy in Taiwan

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Abstract: Strategies and actions for mitigating the emissions of greenhouse gas (GHG) and air pollutants in the transportation sector are becoming more important and urgent due to concerns related to public health and climate change. As a result, the Taiwanese government has promulgated a number of regulatory measures and promotion plans (or programs) on bioethanol use, novel fermentation research projects and domestic production since the mid-2000s. The main aim of this paper was to present a trend analysis of the motor gasoline supply/consumption and bioethanol supply, and the regulatory system relevant to bioethanol production and gasohol use since 2007 based on the official database and the statistics. The motor gasoline supply has shown a decreasing trend in the last five years (2016–2020), especially in 2020, corresponding to the impact of the COVID-19 outbreak in 2020. Although the government provided a subsidy of NT$ 1.0–2.0 dollars per liter for refueling E3 gasohol based on the price of 95-unleaded gasoline, the bioethanol supply has shown decreasing demand since 2012. In addition, the plans for domestic bioethanol production from lignocellulosic residues or energy crops were ceased in 2011 due to non-profitability. To examine the obstacles to bioethanol promotion in Taiwan, the bottlenecks to bioethanol production and gasohol use were addressed from the perspectives of the producer (domestic enterprise), the seller (gas station) and the consumer (end user).

Keywords: gasohol; trend analysis; promotion policy; regulatory measure; bottleneck

1. Introduction

Taiwan, situated in East Asia, features a high population density (i.e., 650 people per km$^2$ based on a population of 23.4 million and a land area of 36,000 km$^2$) and dependence on imported energy (i.e., 97.56%) in 2020 [1]. Based on the official book of statistics [2], the total energy consumption in Taiwan increased from 76.84 million kiloliters of oil equivalent (KLOE) in 2005 to 84.91 million KLOE in 2019. When classified by sector, the transportation sector accounted for 15.78% of all energy consumption in 2019. When classified by the form of energy, petroleum-based products provided 46.18 million KLOE, accounting for 52.42%. It was indicated that petroleum-based products (e.g., gasoline) account for a significant proportion of greenhouse gas (GHG) emissions. On the other hand, the net GHG emissions in Taiwan have grown greatly, from 113 $\times 10^6$ metric tons of carbon dioxide equivalent (CO$_{2eq}$) in 1990 to 275 $\times 10^6$ metric tons of CO$_{2eq}$ in 2018 [3]. Since the Kyoto Protocol came into force in 2005, the Taiwan government has been seeking a balance between energy security, the green economy, and environmental sustainability, and for this reason, the “Guidelines on Energy Development in Taiwan” were first issued by the central competent authority (i.e., Ministry of Economic Affairs, MOEA) in 2012, and were recently revised in 2017 [4]. During the energy security phase, the energy supply side must achieve diversification, energy autonomy, and low carbon. One of the guiding principles...
is to promote the technological development and application of alternatives to fossil fuel energy in order to reduce dependency on fossil fuel energy.

Against the background mentioned above, the Taiwanese government decided to act in accordance with the direction concluded by the National Energy Conference in June 2005. A tentative policy was determined for the promotion of bioethanol [5–7], which was supplied by imports during the early stages, but which was mostly supplied by domestic producers during later stages. In 2007, the MOEA launched the Bioethanol Execution Plan with several development stages. To be able to enforce the policy, the Petroleum Management Act was revised in January 2008 to add new clauses describing fixed ratios for blends of fossil fuels with biofuels (i.e., E3 gasohol). In addition, the Taiwan Sugar Corporation (TSC, a state-owned enterprise) was encouraged to invest in the mass production of bioethanol in Taiwan in 2007, despite the fact that it had already terminated production of bioethanol from sugar-processing by-products (i.e., molasses) in 2003 due to the high costs and the low revenues. The fact that the establishment of a new bioethanol plant by the TSC was concluded to be unfeasible and unprofitable can be attributed to the high domestic production costs, insufficient support by end users, and the rapid increase in imported crude oil prices during the period of 2007–2009.

Although the technologies for the fermentation of bioethanol from various lignocellulosic sources [8–11], as well as its lifecycle analysis, have been studied by many Taiwanese scholars and researchers [12–16], few works have been devoted to a systematic description of the status of bioethanol use and its regulatory promotion, and the bottlenecks to domestic development from the perspectives of producers, sellers, and consumers in Taiwan [7]. Therefore, the main topics of this paper will cover the following subjects:

- Trend analysis of motor gasoline supply/consumption and bioethanol supply.
- Trend analysis of bioethanol supply during the period of 2007–2020.
- Regulatory systems relevant to bioethanol production and use.
- Official plans for bioethanol use and domestic production since 2007.
- Bottlenecks to domestic development of bioethanol.

2. Data Mining and Methodology

In this work, an analytical description of trends related to Taiwan’s registered vehicles, motor gasoline supply/consumption, and bioethanol supply during the period of 2007–2020 is carried out using the latest databases of the relevant central government agencies (i.e., Bureau of Energy under of the MOEA, and Directorate General of Highways under the Ministry of Transportation and Communications) [1,2,17]. In addition, information regarding the regulatory measures for the promotion of bioethanol use and the standards for E3 gasohol was accessed through official websites [18,19]. On the basis of these background data, accessed through official and open websites, the bottlenecks to domestic development of bioethanol were compiled and correlated with the official plans for bioethanol use since 2007. These plans included domestic production using the large local lignocellulosic resources (i.e., second-generation bioethanol feedstock such as rice straw and sorghum stalk) and research and development (R&D) for pretreatment and fermentation technologies by the universities and national institutes under the sponsorship of the National Energy Programs [7].

3. Results and Discussion

3.1. Status of Motor Gasoline Supply/Consumption and Bioethanol Supply

3.1.1. Trend Analysis of Motor Gasoline Supply/Consumption during 2000–2020

According to the statistical database by the Bureau of Energy (BOE) under the MOEA [1], the data on motor gasoline supply and consumption in Taiwan during the period of 2005–2020 are listed in Table 1 and also shown in Figure 1. The trend analysis was further addressed as follows:
1. In Taiwan, about 10 million kiloliters (KL) of motor gasoline per year were consumed over the past fifteen years. However, it indicated a V-type fluctuation during the period of 2005–2011, which should be attributed to the soaring oil prices (gasoline price thus increased) and economic recession due to the financial crisis of 2007–2008. By contrast, the data on motor gasoline supply indicated an up-and-down trend from 15.1 million KL in 2005 to 12.5 million KL in 2020. However, the motor gasoline supply showed a decreasing variation (i.e., 16.6 million KL in 2016, 15.5 million KL in 2017, 15.3 million KL in 2018, 14.7 million KL in 2019, and 12.5 million KL in 2020). There was no doubt that the impact of COVID-19 on motor gasoline supply was very obvious during the year 2020.

2. The ratio of motor gasoline consumption in the transportation sector to domestic gasoline consumption accounted for over 99%. Further, the trend of gasoline fuel consumption in the transportation sector was in accordance with the data on the amounts of registered gasoline motors during the period. For example, the amounts of newly registered passenger cars were 337,886 vehicles in 2015, as compared to 340,349 vehicles in 2020 [9]. In addition, the significant increase in fuel-efficient cars, diesel passenger cars, hybrid electric cars and electric vehicles in recent years also resulted in the suppression of gasoline motors growth [10], suggesting that the consumption of petroleum-based fuels will be on decreasing trend in the near future.

Table 1. Motor gasoline supply and consumption in Taiwan during the period of 2005–2020 1.

| Item               | 2005   | 2010   | 2015   | 2020   |
|--------------------|--------|--------|--------|--------|
| Total supply       | 15,109.4 | 14,869.3 | 15,790.8 | 12,502.8 |
| Production         | 15,058.9 | 14,869.3 | 15,591.8 | 12,257.6 |
| Export             | 4811.4  | 4947.0  | 5512.2  | 2324.9  |
| Import             | 50.5    | 0.0     | 199.0   | 245.2   |
| Domestic consumption | 10,578.5    | 9784.5    | 10,155.5    | 10,170.5    |
| Transportation     | 10,501.8 | 9713.3  | 10,097.1 | 10,105.9 |
| Others 2           | 76.7    | 71.2    | 58.4    | 64.6    |
| Change in stocks   | –280.5  | 137.8   | 123.1   | 7.4     |

1 Source [3]; unit: 10^3 kiloliter (KL). 2 Including the energy (own use), industrial, agricultural, and service sectors.

Figure 1. Variations of motor gasoline consumption during 2015–2020.
3.1.2. Trend Analysis of Bioethanol Supply during the Period of 2007–2020

After entering the World Trade Organization (WTO) on 1 January 2002, the production of bioethanol from sugar processing by-products (i.e., molasses) in Taiwan has been temporarily stopped by the Taiwan Sugar Corporation (TSC, one of the state-owned enterprises) since then [7]. However, the crude oil price has risen by the mid-2000s, becoming an unstable factor for economic development. The Taiwan government was facing pressure to reform the industrial structure and raise energy-saving technologies. Meanwhile, the Kyoto Protocol—put into force on 16 February 2005—pushed the government to mitigate greenhouse gas (GHG) emissions and also develop a renewable energy industry. Although Taiwan is not a signatory to the Protocol, this treaty, which is relevant to the environmental, economic, and energy issues, played a vital role in leading the national development because of its high dependence on imported energy (over 97%) [2]. A green policy was determined for promoting bioethanol in accordance with the direction concluded by the National Energy Conference in June 2005 [7]. The bioethanol in the E3 gasohol was supplied by imports in the early stage and mostly supplied by domestic producers in the later stage. In 2007, the MOEA launched the Bioethanol Execution Plan with several development stages, which will be described in Section 3.3. Furthermore, the Petroleum Management Act was subsequently revised in January 2008 to add new clauses concerning the blends of fossil fuels with biofuels at a fixed ratio (i.e., E3 gasohol, as addressed in Section 3.2.1). Figure 2 depicts the variations of bioethanol supply imported during the period of 2007–2020 [1]. Although the government provided a subsidy of NT$ 1.0–2.0 per liter based on the price of 95-unleaded gasoline, the bioethanol supply has indicated a decreasing demand since 2012.

Figure 2. Variations of bioethanol supply during the period of 2007–2020 in Taiwan.

3.2. Regulations Relevant to Bioethanol Production and Use

3.2.1. Petroleum Management Act

For the main purposes of promoting the sound development (production, supply, sale, etc.) of the domestic oil industry and giving equal consideration to environmental protection, the Petroleum Management Act was initially promulgated on 11 October 2001 and recently revised on 4 June 2014. According to Article 29 of the Act, petroleum-based fuels can be imported or sold in the domestic market if they meet national standards. Therefore, the central competent authority (i.e., Bureau of Standards, Metrology, and Inspection, BSMI) of the MOEA established the national standard, which entitled “Unleaded Gasoline for Automobile” in the Chinese National Standards (CNS) code by CNS 12614. Table 2 lists the specifications of unleaded gasoline for automobiles based on the code of CNS 12,614 [19]. Table 3 shows the further specifications of bioethanol-E3 (95E3 gasohol),
which was accessed on the website of the only gasohol supplier (i.e., Chinese Petroleum Corporation) [20]. In addition, the central competent agency (i.e., BOE) of the MOEA will stipulate the relevant measures for the businesses engaging in the production of the renewable energies of alcohol gasoline, biodiesel, or renewable oil products under Article 38 of the Act. The regulation ("Business Management Measures Governing the Production, Import, Blending and Sale of Alcohol Gasoline, Biodiesel, or Renewable Oil Products") was first announced on 12 December 2001 and recently revised on 3 March 2019. Based on the definitions by the regulation, alcohol gasoline (gasohol) is a fuel, which is prepared by blending fuel ethanol with fossil gasoline, or direct use of denatured fuel ethanol without blending fossil gasoline. Herein, the fuel ethanol means the pure ethanol (i.e., E100) with less than 0.5 vol% of water content, which is manufactured from the processing steps (i.e., fermentation, distillation, and dehydration) of biomass materials containing sugar, starch, or lignocellulosic residues.

Table 2. Specifications of unleaded gasoline for automobiles in Taiwan ¹.

| Property                        | Limit             | Unit       |
|---------------------------------|-------------------|------------|
|                                 | Minimal | Maximal |
| Appearance and color            | Bright and clear  |           |
| Density (at 15 °C)              | 0.720     | 0.775  | g/mL |
| Copper strip corrosion          | No. 1    | Level  |           |
| Oxidation stability (Induction period method, 100 °C) | 240 | - | min |
| Cleaning glue solvent content   | -        | 4       | mg/100 mL |
| Benzene content                 | -        | 0.9     | vol% |
| Sulfur content                  | -        | 10.0    | mg/kg |
| Oxygen content                  | Ethanol not contained | - | 2.7 | wt% |
|                                 | Ethanol contained | - | 3.24 | wt% |
| Ethanol content                 | -        | 3.0     | vol% |
| Lead content                    | -        | 5       | mg/L  |
| Aromatics content               | -        | 35.0    | vol%  |
| Olefins content                 | -        | 18.0    | vol%  |
| Vapor pressure (at 37.8 °C)     | Ethanol not contained | 45 | 60 | kPa |
|                                 | Ethanol contained | 45 | 66.9 | |
| Distillation temperature        | 10 vol% vaporized (T₁₀) | - | 70 | °C |
|                                 | 50 vol% vaporized (T₅₀) | - | 121 | |
|                                 | 90 vol% vaporized (T₉₀) | - | 190 | |
|                                 | Final boiling point | - | 225 | |
| Distillation residue            | -        | 2.0     | vol%  |
| Drivability index (DI)          | -        | 597     | °C    |

¹ Based on the code of CNS 12614. ² Unit free.
Table 3. Specifications of denatured ethanol fuel for blending with gasoline for use in an automotive spark-ignition fuel engine in Taiwan.

| Property                              | Performance Range | Unit  |
|---------------------------------------|-------------------|-------|
| Appearance and color                  | Bright and clear  |       |
| Density (at 25 °C)                    | 0.720             | 0.775 | g/mL |
| Ethanol content                       | 99.5              | -     | vol% |
| Methanol content                      | -                 | 0.3   | vol% |
| Water content                         | -                 | 0.5   | mg/kg|
| Copper content                        | -                 | 0.07  | mg/kg|
| Sulfur content                        | -                 | 30.0  | mg/kg|
| Acidity (as acetic acid)              | -                 | 30    | mg/L |
| pH                                    | 6.5               | 9.0   |      |
| Conductivity                          | -                 | 500   | µS/m |
| Denaturants content                   | 2                 | 5     | vol% |

1 Based on the code of CNS 15109. 2 Unit free.

3.2.2. Renewable Energy Development Act

Regarding the policy and promotion for biomass energy, the Renewable Energy Development Act (REDA) should be the most important regulation [21], which was passed on 8 July 2009 and revised on 1 May 2019. According to the definition of biomass energy in the Act, it refers to the energy generated from direct use or treatment of vegetation, marsh gas (biogas), and domestic organic waste. Although the promotion incentives, such as feed-in-tariff (FIT), and support or subsidies played a determining role in the installation of renewable power system [18], these incentive measures in the Act are not beneficial for the industry development of biomass fuels, such as bioethanol and biodiesel. However, the REDA also provides the relevant measures concerning the biomass fuel, which were addressed as follows:

1. According to Article 6 of the Act, the central competent authority (i.e., MOEA) shall take into account the development potential of renewable energy and its impact on the domestic economy and stable power supply in order to set the promotion goals for renewable energy and the percentage of each category, and formulate and announce the development plans and initiatives for the next two years and by 2025. Based on the economic benefits, technological developments, relevant factors, and the promotion goals and schedules for heat utilization of renewable energy have been stipulated by the MOEA. However, biomass fuels are not included by the MOEA in the current promotion goals for renewable energy in Taiwan by 2025.

2. According to Article 6 of the Act, the MOEA shall consider reasonable costs and profits for the heat utilization of renewable energy (including biomass fuels and solar energy) and shall prescribe regulations on subsidies and rewards for heat utilization according to the effectiveness of their energy contribution. For the heat utilization in the biomass fuels, such subsidy expenses for the substituted portions of petroleum energy may be financed by the Petroleum Fund under the Petroleum Management Act. Furthermore, the reward expenses for the exploitation of fallow land or idle land for agriculture, forestry, animal husbandry to plant energy crops for producing biomass fuels will be financed by the Agricultural Development Fund. The regulations governing such reward eligibility, conditions and subsidy methods, and schedule shall be prescribed by the MOEA in conjunction with the Council of Agriculture (i.e., COA).
3.2.3. Air Pollution Control Act

In 1975, the Air Pollution Control Act (APCA) was initially enacted. With the progressive development of air pollution control and prevention measures, the Act was revised several times and recently amended on 1 August 2018. Under the authorization of the Act, there are two important regulations concerning the exhaust emissions from vehicles or motors and the composition/property standards for the use of bioethanol fuel.

1. “Exhaust Emission Standards of mobile Sources”

According to Article 36 of the Act, air pollutants emitted from mobile sources (e.g., vehicles or motors) should meet the exhaust emissions standards, which shall be stipulated by the central competent authority (i.e., EPA). Therefore, the regulation, named “Exhaust Emission Standards of mobile Sources”, was first promulgated on 5 June 1980 and recently amended on 27 July 2020. In Provision 3 of the regulation, the exhaust emissions from motors or vehicles using gasoline and alternative clean fuel must comply with the Standards of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NOx), particulate matter (PM) and particulate number (PN) [18], as listed in Table 4. In view of the standards based on the driving cycle testing, the emission standards of new vehicles in Table 4 were implemented from 1 September 2019. In order to improve ambient air quality, the Standards will be further revised to reduce the emissions of HC and NOx from passenger cars in the future. In this regard, more energy-saving cars, hybrid motors, electric vehicles or electronic tolling devices entered the market in Taiwan [22, 23].

2. “Standards for the Compositions of Fuels in Mobile Sources”

Under the authorization (i.e., Article 39) of the Act, the manufacture, import, sale, or use of fuel supplied to vehicles (or motors) shall comply with the composition standards for fuel types determined by the central competent authority (i.e., EPA). The standards (as listed in Table 5), named “Standards for the Compositions of Fuels in Mobile Sources” [18], were first promulgated on 15 December 1999 and recently amended on 20 March 2021. In Provision 3 of the regulation, the composition standards for vehicles (or motors) with gasoline (including E3 gasohol) cover the properties (or contents) of benzene, sulfur, oxygen, aromatics and olefins, and vapor pressure. It is noted that the benzene content in gasoline fuel has been reduced from 0.9 vol% in 2020 to 0.8 vol% in 2024. The stringent regulation will be expected to reduce the content of aromatics in motor engine fuels by adding clean fuels such as bioethanol or biobutanol, thus improving air quality due to the reduction in the air pollutants emitted from mobile sources [24].

### Table 4. The standards of engine exhaust emissions from gasoline and clean alternative fuel in Taiwan

| Vehicle Classification | Emission Standards (Based on Driving Cycle Testing) |
|------------------------|-----------------------------------------------------|
|                        | CO (mg/km) | THC (mg/km) | NMHC (mg/km) | NOx (mg/km) | PM (mg/km) | PN (p/km) |
| Sedans and station Wagons | 1000 | 100 | 68 | 60 | |
| Reference mass ≤1305 kg | 1000 | 100 | 68 | 60 | |
| Reference mass >1305, ≤1760 kg | 1000 | 130 | 90 | 75 | |
| Reference mass >1760 kg | 2270 | 160 | 108 | 82 | |

1 The standards are applied to new vehicles since the promulgation date on 1 September 2019. 2 Notations: Carbon monoxide (CO), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), nitrogen oxides (NOx), particulate matter (PM), and particulate number (PN).
Table 5. The standards for the composition of gasoline (including E3 gasohol) in Taiwan.

| Property                        | Limit (Maximal)               |
|---------------------------------|-------------------------------|
|                                 | Starting from 1 July 2020     | Starting from 1 January 2024 |
| Benzene content                | 0.9 vol%                      | 0.8 vol%                      |
| Sulfur content                 | 10 mg/kg                      | 10 mg/kg                      |
| Vapor pressure (37.8 °C)       | 60 kPa                        | 60 kPa                        |
| Oxygen content                 | 2.7 wt%                       | 2.7 wt%                       |
| Aromatics content              | 35 vol%                       | 35 vol%                       |
| Olefins content                | 18 vol%                       | 18 vol%                       |

1 Prior to the promulgation of E3 gasohol for all vehicles in Taiwan area, the maximal limits of vapor pressure and oxygen content are 66.9 kPa and 3.24 wt%, respectively.

3.3. Official Plans for Bioethanol Use and Domestic Production Since 2007

As described above, the policy for promoting the use of bioethanol and its domestic production was adopted in 2007 under the considerations of energy security, environmental sustainability and green economy. In February 2007, the MOEA launched the Bioethanol Execution Plan with three development stages (listed in Table 6), aiming at supplying E3 gasohol in all gas stations since 1 January 2011. Furthermore, the Petroleum Management Act was subsequently revised in January 2008. According to the Plan, the first stage was based on the “Green Public Vehicle Pilot Plan” that public vehicles in Taipei City must refuel E3 gasohol at eight designated gas stations. During the period, these gas stations also provided E3 gasohol for all private vehicles volunteering to refuel by subsidizing a discount rate at NT$ 1.0–2.0 per liter. The second stage was to promote the use of E3 gasohol for all public and private vehicles, which were refueled in Taipei City at eight designated gas stations and in Kaohsiung City at six designated gas stations. During the promotion period from July 2009 to September 2011, the total E3 gasohol supply amounted to about 11,400 KL, which was equivalent to the use of E100 bioethanol by 340 KL. Due to the insufficient supply of domestic production, the source of bioethanol in the E3 gasohol came from Asian countries such as Thailand during the first and second stage promotion period.

Table 6. Various stages of development plans for bioethanol in Taiwan.

| Implementation Period | Promotion Plan                  | Promotion Measure                                |
|-----------------------|---------------------------------|-------------------------------------------------|
| 2007/9–2008/12        | Pilot plan for green public vehicles | Public vehicles in Taipei City (capital city in Taiwan) must refuel E3 gasohol. |
| 2009/1–2010/12        | E3 gasohol plan in metropolitan area | E3 gasohol was supplied for all vehicles in Taipei City and Kaohsiung City. |
| 2011/1–                | E3 gasohol plan in all gas stations | E3 gasohol was supplied for all vehicles in Taiwan area. |
| 2015/1 (or 2020/1)–    | E5 gasohol plan in all gas stations |                                                |
| 2025/1–                | E10 gasohol plan in all gas stations |                                                |

1 The bioethanol production plans have been halted by the Taiwan government, but the E3 gasohol plan still ran up to now. 2 E3 gasohol was only supplied by 14 gas stations in Taipei City and Kaohsiung City.

In order to be in accordance with the policy for promoting the use of bioethanol and its domestic production, the COA, in cooperation with the MOEA, subsidized a state-owned enterprise (i.e., Taiwan Tobacco and Liquor Corporation) to supply initial domestic demands by producing a small amount of bioethanol from the fermentation of...
sweet potatoes. It was planned that E3 gasohol would be gradually supplied by domestic production at the third and further promotion stages. The TSC (a state-owned enterprise that once produced bioethanol from molasses) and other private enterprises were also planning to establish the commercial bioethanol plants or bio-refineries using sugarcane juice, processing by-products (i.e., molasses, bagasse), or lignocellulosic residues (e.g., rice straw, sorghum stalk) in the fermentation process. According to the financial analysis by Liang and Jheng [25], the domestic oil price will rise 0.363–1.292% with the use of gasohol instead of gasoline at all gas stations, thus causing a fall by 0.009–0.03% in the gross domestic product (GDP) and a rise by 0.024–0.085% in consumer price index (CPI). Although the investment project for the mass production of bioethanol has been completed by the TSC and submitted to the central competent authority (i.e., MOEA) for approval in 2011 [7], the feasibility of establishing a new bioethanol plant seemed to be not profitable. This project withdrawn by the TSC can be attributed to the high domestic production cost (as compared to the imported price of bioethanol), insufficient support by the gasoline end users (E3 gasohol consumption not expected during the promotion period), and the imported crude oil price inclined significantly. Other private enterprises involving the domestic production of bioethanol also encountered similar bottlenecks. Finally, the MOEA decided to halt the mass production of bioethanol from lignocellulosic residues or agricultural by-products in Taiwan. Alternatively, the bioethanol supply must be dependent on the imports because the E3 gasohol plan still ran up to now.

3.4. Bottlenecks to Domestic Development of Bioethanol

3.4.1. Producer Side

With the international oil prices soaring and increasing threat of global warming during the early 2000s, the efforts to find clean energy sources to reduce GHG emissions became an urgent issue for government and industry. Under the policy support by the Taiwan government, a state-own company (i.e., Taiwan Sugar Corp.) and several private enterprises planned to invest local production of bioethanol from imported molasses, or sweet sorghum and other energy crops (e.g., napier grass) planted in fallow land. However, the domestic production of bioethanol from lignocellulosic residues (e.g., rice straw, sorghum stalk) or agricultural by-products (e.g., molasses, bagasse) in Taiwan still posed a higher cost as compared to the imported bioethanol. It was reported that the production cost of cellulosic ethanol will be as high as NT$35–38 (US$1.2–1.3) per liter [11]. This bottleneck was inherently caused by several economic factors, including interest rate, imported crude oil price, imported bioethanol price, labor cost, land cost (or land rent), harvesting and transporting cost for lignocellulosic materials, and capital cost for purchasing production machines and equipment. Among these factors, the international oil price may be the most significant one that indicated violet fluctuations decreasing from US$130 a barrel in July 2008 to US$80 a barrel in July 2009. Although the domestic bioethanol production would contribute to the reduction in GHG emissions and the reactivation in agricultural fallow lands by planting energy crops [7], the government also provided some subsidies under the Renewable Energy Development Act. Obviously, there are no enterprises willing to invest in the domestic bioethanol production from local mass non-food feedstocks such as rice straw and bagasse. During the past decade (2009–2018), the universities and research institutions were funded by the MOEA and the Ministry of Science and Technology (MOST) through the National Energy Program in the lab- and pilot-scale bioethanol production projects [7]. However, the research and development (R&D) and regulatory policies were not implemented in a complementary direction for commercial bioethanol production in Taiwan because it currently seemed not to be economically profitable. This situation was also reflected in the research publications and their corresponding project grants by the government based on the survey through the academic database such as the Web of Science.
3.4.2. Supply (Storage) Side

Although the use of E3 gasohol contributed to mitigate GHG emissions and improve urban air quality, its stability in the storage tank was relatively lower than gasoline due to the hygroscopic properties of ethanol [26]. This gasohol will be liable for absorbing moisture from the atmosphere or humid environments, thus causing phase separation. As Taiwan’s climate features the tropical zone with high humidity, this situation will be more serious, forming distinct layers in the storage pool or tank, where a thicker layer of gasoline mixed with a little ethanol appears on top, and a thinner layer of water and more ethanol appears on the bottom. This process is unavoidable, and it can also be triggered by a drop in temperature. In addition, it is better to reduce the storage time in the E3 gasohol tank or pool at the gas stations because this biofuel could cause corrosion and rust inside the tanks and pipelines in the presence of water [27–29]. Because of this potential for phase separation at any ethanol level such as E3 gasohol, it is imperative that motor gasoline containing bioethanol is not exposed to water during its supply chain (distribution and storage) at the service stations for the purpose of preventing water contamination.

3.4.3. Consumer Side

Concerning the reasons for ceasing bioethanol promotion in Taiwan, the insufficient support by the motor fuel consumers should be the most important one. The author addressed the following viewpoints from the consumer side.

1. Although the government encouraged the use of E3 gasohol by subsidizing NT$ 1.0–2.0 per liter fueled, this price was still high when compared to that of 95-unleaded gasoline.
2. There are only 14 gas stations with the supply of E3 gasohol in metropolitan areas (one is Taipei City located in northern Taiwan, another is Kaohsiung City situated in southern Taiwan), indicating that it is very inconvenient to refuel the green motor gasoline.
3. As described above, the property of E3 gasohol is hygroscopic, easily causing corrosion and rust inside the pipelines and tending to clog fuel filters and lines. Sometimes, there are increased risks of detonation and engine durability due to the phase separation that occurred in the fuel tank [30,31].

4. Conclusions and Future Perspectives

Since the Kyoto Protocol came into force in 2005, the coupling of renewable energy development with GHG emission mitigation has become a sustainable development goal in government governance. In Taiwan, this challenge is extra important because it highly depends on imported energy. Since the early 2000s, the Taiwan government promulgated some regulatory measures and promotion plans (or programs) on bioethanol use and domestic production. Obviously, these efforts on E3 gasohol use were not successful during the period of 2007–2020. In addition, the plan for domestic bioethanol production from local lignocellulosic residues (i.e., rice straw and bagasse) or energy crops has decreased since 2011. It was concluded that the feasibility of establishing a new bioethanol plant seemed to be not currently profitable. It can be attributed to the high domestic production cost, insufficient support by the end users, and imported crude oil price inclined rapidly during the period of 2007–2009. On the other hand, the bottlenecks to gasohol use in Taiwan have been addressed from the sides of producer, seller, and consumer.

In Taiwan, domestic bioethanol production from lignocellulosic residues or energy crops currently seemed not to be highly profitable by international crude oil prices. However, with renewable energy sources for generating electricity and biofuels expanding rapidly and economically, reducing GHG emissions from our transportation system will be the next major hurdle we must overcome in order to meet the zero-emission target under the Paris Climate Agreement by 2050. In this regard, it is necessary to promote gasohol use as a transitional stage from clean fuel to the electric vehicle. In order to expand the gasohol consumption for reducing GHG emissions and criteria air pollutants in urban areas, the Taiwan government should subsidize more discounts for newer car owners (consumers) of fueling E3 gasohol. In response to the government’s energy transformation
policy, the CPC Corporation (one of the state-owned companies focusing on petroleum refinery and petroleum-based products) should take more corporate social responsibility (CSR) for providing this clean fuel at more gas stations.

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**References**

1. Energy Statistics Database (Ministry of Economic Affairs, Taiwan). Available online: http://www.esist.org.tw/database (accessed on 24 June 2021).
2. Ministry of Economic Affairs (MOEA). Energy Statistics Handbook; MOEA: Taipei, Taiwan, 2020.
3. Environmental Protection Administration (EPA). Taiwan Greenhouse Gases Inventory; EPA: Taipei, Taiwan, 2020.
4. Ministry of Economic Affairs (MOEA). Guidelines on Energy Development; MOEA: Taipei, Taiwan, 2017.
5. Tsai, W.T.; Lan, H.F.; Lin, D.T. An analysis of bioethanol utilized as renewable energy in the transportation sector in Taiwan. Renew. Sustain. Energy Rev. 2008, 12, 1364–1382. [CrossRef]
6. Liou, H.M. Policies and legislation driving Taiwan’s development of renewable energy. Renew. Sustain. Energy Rev. 2010, 14, 1763–1781. [CrossRef]
7. Chung, C.C.; Yang, S.V. The emergence and challenging growth of the bio-ethanol innovation system in Taiwan (1949–2015). Int. J. Environ. Res. Public Health 2016, 13, 230. [CrossRef] [PubMed]
8. Liu, S.Y.; Lin, C.Y. Development and perspective of promising energy plants for bioethanol production in Taiwan. Renew. Energy 2009, 34, 1902–1907. [CrossRef]
9. Su, M.Y.; Tseng, W.S.; Shyu, Y.T. An analysis of feasibility of bioethanol production from Taiwan sorghum liquor waste. Bioresour. Technol. 2010, 101, 6669–6675. [CrossRef]
10. Ko, C.H.; Wang, Y.N.; Chang, F.C.; Chen, J.J.; Chen, W.H.; Hwang, W.S. Potentials of lignocellulosic bioethanols produced from hardwood in Taiwan. Energy 2012, 44, 329–334. [CrossRef]
11. Wen, P.L.; Lin, J.X.; Lin, S.M.; Feng, C.C.; Ko, F.K. Optimal production of cellulosic ethanol from Taiwan’s agricultural waste. Energy 2015, 89, 294–304. [CrossRef]
12. Su, M.H.; Tso, C.T. Life cycle assessment of environmental and economic benefits of bio-ethanol in Taiwan. Int. J. Green Energy 2011, 3, 339–354. [CrossRef]
13. Su, M.H.; Huang, C.H.; Lin, W.Y.; Tso, C.T.; Lur, H.S. A multi-years analysis on the energy balance, green gas emissions, and production costs of the first and second generation bioethanol. Int. J. Green Energy 2014, 12, 168–184.
14. Su, M.H.; Huang, C.H.; Li, W.Y.; Tso, C.T. Water footprint analysis of bioethanol energy crops in Taiwan. J. Clean. Prod. 2015, 88, 132–138. [CrossRef]
15. Chiu, C.C.; Shiang, W.J.; Lin, C.J.; Wang, C.H.; Chang, D.M. Water footprint analysis of second-generation bioethanol in Taiwan. J. Clean. Prod. 2015, 101, 271–277. [CrossRef]
16. Chang, F.C.; Lin, L.D.; Ko, C.H.; Hsieh, H.C.; Yang, B.Y.; Chen, W.H.; Hwang, W.S. Life cycle assessment of bioethanol production from three feedstocks and two fermentation waste reutilization schemes. J. Clean. Prod. 2017, 143, 973–979. [CrossRef]
17. Highway Statistical Data Query (Directorate General of Highways, Ministry of Transportation and Communications, Taiwan). Available online: https://stat.thb.gov.tw/hb01/webMain.aspx?sys=100&funid=e11100 (accessed on 27 June 2021).
18. Laws and Regulation Retrieving System (Ministry of Justice, Taiwan). Available online: https://law.moj.gov.tw/Eng/index.aspx (accessed on 24 June 2021).
19. CNS Online Service (Bureau of Standards, Metrology and Inspection, MOEA, Taiwan). Available online: https://www.cnsonline.com.tw/?locale=en_US (accessed on 21 June 2021).
20. Specifications for Motor Unleaded Gasoline (CPC Corporation, Taiwan). Available online: https://www.cpc.com.tw/cl.aspx?n=37 (accessed on 21 June 2021).
21. Gao, A.M.Z. Taiwan’s recent efforts to promote renewable energy development: Policy measures, legal measures, challenges, and solutions in the post-Fukushima era. Renew. Energy Law Policy Rev. 2012, 3, 263–279.
22. Tsai, W.T. Trend analysis of Taiwan’s greenhouse gas emissions from the energy sector and its mitigation strategies and promotion actions. Atmosphere 2021, 12. (in press) [CrossRef]
23. Lu, S.M. A low-carbon transport infrastructure in Taiwan based on the implementation of energy-saving measures. *Renew. Sustain. Energy Rev.* 2016, 58, 499–509. [CrossRef]

24. Tsai, J.H.; Ko, Y.L.; Huang, C.M.; Chiang, H.L. Effects of blending ethanol with gasoline on the performance of motorcycle catalysts and airborne pollutant emissions. *Aerosol Air Qual. Res.* 2019, 19, 2781–2792. [CrossRef]

25. Liang, C.Y.; Jheng, R.H. Long-term policy and strategies for bioethanol development in Taiwan. *Qual. Bank Taiwan* 2010, 61, 68–107. (In Chinese)

26. Spitzer, P.; Fisicaro, P.; Seitz, S.; Champion, R. pH and electrolytic conductivity as parameters to characterize bioethanol. *Accred. Qual. Assur.* 2009, 14, 671–676. [CrossRef]

27. Thomson, J.K.; Pawel, S.J.; Wilson, D.F. Susceptibility of aluminum alloys to corrosion in simulated fuel blends containing ethanol. *Fuel* 2013, 111, 592–597. [CrossRef]

28. Rocabruno-Valdes, C.I.; Escobar-Jimenez, R.F.; Diaz-Blanco, Y.; Gomez-Aguilar, J.F.; Astorga-Zaragoza, C.M.; Uruchurtu-Chavarin, J. Corrosion evaluation of Aluminum 6061-T6 exposed to sugarcane bioethanol-gasoline blends using the Stockwell transform. *J. Electroanal. Chem.* 2020, 878, 114667. [CrossRef]

29. Thangavelu, S.K.; Ahmed, A.; Ani, F.N. Corrosive characteristics of bioethanol and gasoline blends for metals. *Int. J. Energy Res.* 2016, 40, 1704–1711. [CrossRef]

30. Yusoff, M.N.A.M.; Zulkifli, N.W.M.; Masum, B.M.; Masjuki, H.H. Feasibility of bioethanol and biobutanol as transportation fuel in spark-ignition engine: A review. *RSC Adv.* 2015, 5, 100184–100211. [CrossRef]

31. Thangavelu, S.K.; Ahmed, A.S.; Ani, F.N. Review on bioethanol as alternative fuel for spark ignition engines. *Renew. Sustain. Energy Rev.* 2016, 56, 820–835. [CrossRef]