An Analysis of Supply and Demand Strategy of Bioethanol
Using an Agent-based Global Energy Model

Hiromi YAMAMOTO

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Bioethanol is an important transportation fuel but the resource is finite and unevenly distributed in the world. The purpose of this study is to evaluate strategies for export and import regions in the international bioethanol market. For that purpose, simulation studies using a global energy model to which an agent technique was applied were conducted, and the following results were obtained. (1) If bioethanol importer regions adopt a strategy of a rigid mixture ratio of bioethanol to gasoline-type fuel, and if only a dominant bioethanol exporter region can control the price premium of exported bioethanol in the case of high cost cellulosic ethanol production, the international bioethanol price would converge at a high price. This is because of the high production cost of the cellulosic bioethanol and the high price premium of the exported ethanol. (2) If the bioethanol importer regions adopt a strategy of flexible mixture ratios, the regions could avoid the high price premium. (3) If cellulosic bioethanol is commercialized at a low cost, approximately the cost of starch biomass, the simulation results converge at high mixture ratios and low price premiums. In this case, bioethanol could be one of the major transportation fuels in the future.

1. Introduction

Production and consumption of biofuels such as bioethanol for transportation are increasing. The global production of fuel bioethanol in 2015 was estimated at 97 × 10⁶ m³, 85% of which is accounted for by production in two countries: the United States at 56 × 10⁶ m³ and Brazil at 27 × 10⁶ m³. The production cost of bioethanol in Brazil is about 0.7 times the cost in the US, and Brazil could be a major exporter in the global bioethanol market by around 2020.

Meanwhile, the Japanese Government has promoted the use of bioethanol for automobile fuel since 2005, to reduce emissions of greenhouse gases. The national target for bioethanol introduction is 500 × 10⁶ m³ of oil equivalent in 2017. However, meeting the national target of biofuel would heavily depend on imports because of the high production cost of biofuel in Japan. In addition, countries such as Australia, Belgium, Canada, Italy, Norway, and the United States have already implemented biofuel blend mandates. However, if many countries implement ambitious standards for bioethanol, it may cause high prices of bioethanol and could affect the prices of food in the international market.
The purpose of this study was to analyze problems and measures about bioethanol implementation policies assuming the condition that a monopolistic exporter would exist in the international bioethanol market. The problems of monopoly and oligopoly have been studied analytically \textsuperscript{7).} However, complex problems such as international trade of bioethanol in the global energy system, and bioethanol use in the national electricity markets are too difficult to obtain typical analytical solutions. Instead, these are analyzed using simulation, such as agent-based techniques \textsuperscript{8) 9).} In this study, an agent-based technique was applied to a global energy systems model to analyze the bioethanol implementation policies numerically.

This study consists of four sections. In Section 2, the methodologies of this study are described. These include an agent-based technique and a global energy systems model. The results from using this methodology, in relation to international policies of bioethanol implementation, are described in Section 3. The conclusions drawn from this study are presented in Section 4.

2. Global Energy Systems Model and an Agent Technique

This section explains the tools of the global energy systems model and the agent-based technique used to analyze the international bioethanol policies.

2.1 Outline of Global Land Use and Energy Systems Model

The global energy systems model used in the study is the Global Land-Use and Energy (GLUE) model \textsuperscript{10) 112).} The model minimizes the global energy systems cost, including production costs of primary energy, conversion costs from primary energy to final energy, and inter-regional trade costs using a linear optimization technique. The global energy systems cost is the summation of the regional energy systems costs (see Formula 1, 2, and 3)\textsuperscript{11 12)}.

For this analysis, the world was divided into 11 regions: 1) North America, 2) West Europe, 3) Japan, 4) ANZ (Australia and New Zealand), 5) China etc., 6) MENA (Middle East and North America), 7) Sub-Sahara Africa, 8) Latin America, 9) FSU (Former Soviet Union) and Eastern Europe, 10) Southeast Asia, 11) South Asia. It is defined that the developed regions in the study include North America, Western Europe, Japan, ANZ, and FSU and Eastern Europe (see Sub-Section 2.2). The analysis covers a single year: 2020.

The model consists of two sub-models that are the energy sub-model and the land-use sub-model.

The energy sub-model includes energy flows from primary energy to final energy (Fig. 1). The biomass considered was divided into five kinds that are cellulosic biomass, starch-and-sugar, fat-and-oil, waste biomass (such as kitchen refuse and paper waste), and high water-content biomass. For example, cellulosic biomass can be used in processes that include biomass solid fuel production, cellulosic bioethanol fermentation, gasification and liquefaction, and power generation.

Bioethanol can be produced from cellulosic biomass as well as from starch and sugar sources. Bioethanol can substitute for gasoline to reduce the use of petroleum-based transportation fuel.

The land-use sub-model consists of a wood sector...
and a food sector \(^{10}{-}^{12}\). The sub-model contains the wood biomass flow and the food biomass flow shown in Figs. 2 and 3, respectively. Five kinds of demand for biomass, which are timber, particle board, paper, vegetable food, and animal food, are set exogenously following references \(^{10}{-}^{12}\). The other data concerning the biomass flows, such as land productivity, biomass conversion efficiency, and discharge rates of biomass residues; are based on the same references \(^{10}{-}^{12}\).

The land-use sub-model is a simple material balance model that does not consider biomass prices. In order to determine the biomass flow without considering biomass prices, reference values and priorities of biomass supply and demand were assumed \(^{10}{-}^{12}\).

The following principles of the reference value of inter-regional biomass trade were assumed. (1) The reference values of the biomass imports in the future are set on the assumption that the ratios of the imports to biomass consumption will be constant at those in the reference year 2000. (2) The reference values of the biomass exports in the future are set on the assumption that the ratios of the exports to the global exports of the traded biomass will be constant at those in the reference year 2000. (3) The reference values of the rates of biomass uses such as for food, feed, and seed are assumed to be constant at those in the reference year 2000. In addition, the priorities of biomass supply and demand were assumed. The principles of food supply and demand are explained hereinafter. (1) The 1st priority is assumed for food supply over energy crop supply. In other words, energy crops are produced on surplus arable lands. (2) The 2nd priority is assumed for domestic food supply over food for export. (3) The 3rd priority is assumed for vegetable food supply over animal food supply. The priority of wood biomass supply and demand is assumed for domestic wood supply over wood for export. These priorities were implemented in the cost minimization model using the penalty costs of the adjustments from the reference values. The model minimizes the energy systems cost, including the penalty costs, while it determines the supply and demand in the biomass flows \(^{11}{-}^{12}\).

The major data of energy and energy utilization technologies are explained below. The data of primary energy were developed from the data in reference \(^{13}\) (Table 1). The major data on energy utilization technologies are shown in Fig. 4 \(^{11}\). The five kinds of final energy demand, which are solid, liquid excluding transportation, liquid for transportation, gaseous, and electricity, are exogenously determined based on the IPCC SRES B2 scenario (Fig. 5). It is assumed that each kind of final energy demand does not substitute for the other kinds of demand. The final energy demand is satisfied by primary energy production and

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**Fig. 2** Wood biomass flow in the GLUE model
Table 1 Data of primary energy in the model

| Resource | Grade 1 | Grade 2 | Grade 3 | Grade 4 | Grade 5 |
|----------|---------|---------|---------|---------|---------|
| Natural gas (EJ) | 1171 | 3971 | 1996 | 3533 | 4756 |
| Oil (EJ) | 4812 | 1307 | 1074 | 501 | 6646 |
| Coal (EJ) | 22931 | 28109 | 39943 | 54738 | 18034 |

| Cost (USD/GJ) | Grade 1 | Grade 2 | Grade 3 | Grade 4 | Grade 5 |
|--------------|---------|---------|---------|---------|---------|
| Natural gas | 3.4 | 4.2 | 4.7 | 5.2 | 23.2 |
| Oil | 3.9 | 4.8 | 6.0 | 12.1 | 30.0 |
| Coal | 21 | 22 | 66 | 16.0 | 31.0 |

a) The costs include royalty and subsidy for resource production. The costs (in year 2000 USD) of natural gas and oil are those in Middle East and North Africa. The costs of coal are those in North America.

Fig. 3 Food biomass flow in the GLUE model

Fig. 4 Capital costs of energy conversion technologies in the model: The cost of oil refinery is in Year 2000 USD kW⁻¹ thermal-feed. It is assumed that the annual expense rates of power generation and oil refinery are 17% and 25%, respectively.

Fig. 5 Final energy demand in the world in 2020.
energy conversion such as power generation, the amounts of which are calculated endogenously in the model.

The details of the energy data are explained in reference 11.

The data on biomass and biomass utilization technologies are explained below. The unused lands in Latin America are $10^6$ Mha $^{10}$ and half of this land area is assumed to be converted to arable land by 2020. The other data about biomass flows are based on the data in earlier work $^{10} - 12$. Figs. 6 and 7 show the supply potentials of energy crops and cellulosic biomass, respectively, calculated by the GLUE model.

The feedstock costs of biomass are based on the references $^{2} - 12$ (Fig. 8 and Table 2). The production costs of cellulosic bioethanol were considered in three scenarios: low, middle, and high (Fig. 9). The low cost is based on the cost of starch bioethanol in the US $^{2}$. The middle cost and the high cost are assumed about 14 times and 27 times as much as the low cost, respectively.

Most countries currently impose taxes on transportation fuels such as gasoline and diesel fuel and

| Table 2 | Costs of bioenergy resources of carbohydrate and cellulosic biomass in the GLUE model $^{4}$ |
|------------------|---------------------------------|------------------|
|                  | Relative cost (1st grade cost is 1.0) | Resource amount (total resource is 1.0) |
|                  | Grade 1 Grade 2 Grade 3 Grade 4 Grade 5 | Grade 1 Grade 2 Grade 3 Grade 4 Grade 5 |
| Sugar crops      | 1.00 1.47 1.93 2.39 2.85          | 0.20 0.20 0.20 0.20 0.20 |
| Starch crops     | 1.00 1.47 1.93 2.39 2.85          | 0.20 0.20 0.20 0.20 0.20 |
| Fuelwood         | 1.00 1.50 2.00 2.50 3.00          | 0.20 0.20 0.20 0.20 0.20 |
| Roundwood residues | 1.00 1.33 1.67 2.00 -             | 0.13 0.13 0.13 0.13 - |
| Sawmill residues | 0.00 (0.86) - - -                | 0.13 0.63 - - -         |
| Wood waste       | 0.00 (0.86) - - -                | 0.13 0.63 - - -         |
| Crop harvest residues | 1.00 - - - - -                | 0.25 - - - - -         |
| Sugarcane harv. residues | 1.00 - - - - -                | 0.67 - - - - -         |
| Bagasse          | 0.00 - - - - - -                | 1.00 - - - - -         |

a) The values in the parentheses are absolute values at year 2000 price. The costs of bioenergy resources are assumed on stair-like functions in the model and the data are based on $^{11} - 12$. 

Fig. 6 Ultimate supply potential of energy crops and cellulosic biomass residues calculated by the GLUE model: The ultimate supply potential of energy crops is defined as energy crops produced from all surplus arable land calculated by the GLUE model $^{10} - 11$. The ultimate supply potential of energy wood is defined as sustainable production of energy wood from all mature forest areas calculated by the GLUE model $^{10} - 11$. The potentials of energy wood in Sub-Saharan Africa and Latin America are 64 and 173 EJ per year, respectively.

Fig. 7 Ultimate supply potential of cellulosic biomass residues calculated by the GLUE model: The ultimate supply potential of cellulosic biomass is defined as all discharged cellulosic biomass excluding material-recycled biomass calculated by the GLUE model $^{10}$.

Fig. 8 Costs of bioenergy resources of carbohydrate and cellulosic biomass in the GLUE model: The costs are at the year 2000 price. It is assumed that the cost of sawmill residues, wood waste, and bagasse are zero. The figure shows the lowest costs of the cost functions. The shapes of the cost functions are shown in Table 2. ‘W. Europe etc.’ includes W. Europe and Japan. ‘N. America’ includes all the regions except L. America, W. Europe, and Japan.
subsides on bioethanol. However, it is assumed the taxes and subsidies on transportation fuels in 2020 are zero in the model. This is because it is difficult to describe the current country-level taxes and subsidies in the GLUE model with 11 world regions, and to predict the future policy in them all about taxes and subsidies. If the current taxes and subsidies exist in 2020, the economy of bioethanol will be improved and the price premium of the bioethanol would be reduced compared with the results in this study (see Figs. 10 and 12). In future work it is necessary to develop a high-resolution multi-region model and to conduct numerical analysis that includes taxes and subsidies on bioethanol.

2.2 Simple Agent Techniques

Simple agent techniques are those used to realize agent-based calculations in cost minimization models such as the GLUE model. Two techniques are explained below (i.e., the one-agent technique and two-agent technique).

The simple-one-agent technique is a technique in which only one agent can control its own strategic parameter. The strategic agent adjusts the strategic parameter and minimizes its energy system cost.

It is assumed that the strategic agent is Latin America, which has great potential for the export of bioethanol and its strategic parameter is the premium on exported bioethanol.

The constraints about energy flows and biomass flows in the GLUE model are described in Formula (1).

$$AA^s \cdot xx^s - \sum_{ri} \text{ATX}_{ri} \cdot xt_{ki} + \sum_{ri} \text{ATM}_{ri} \cdot xt_{ki} = YY,$$

where $k$ is an iteration number (that is not used in the original GLUE model and is used in the agent technique); $r$ is a region; $xx$ is an energy export region; $rm$ is an energy import region; $AA$ is a parameter matrix regarding energy flows and biomass flows; $ATM$ is a parameter matrix regarding energy export, $ATX$ is a parameter matrix regarding energy import; $xt$ is a variable matrix about energy trade; $YY$ is a parameter vector regarding demand of energy and biomass.

The energy systems cost in a region (OBR) in the GLUE model is defined in Formula (2).

$$OBR = \text{CAA} \cdot xx^s + \sum_{ri} \text{CAX}_{ri} \cdot xt_{ki} + \sum_{ri} \text{CAM}_{ri} \cdot xt_{ki},$$

where $CAA$ is a cost parameter matrix regarding energy and biomass flows; $CAX$ is a cost parameter matrix regarding energy export; and $CAM$ is a cost parameter matrix regarding energy import.

The objective value ($OBJ$), which is the global summation of the OBR, is minimized in the GLUE model.

$$OBJ = \sum_r OBR.$$

(3)

The calculation procedure of the simple-one-agent technique is explained below.

(1) The bioethanol price premium exported from Latin America is added to the inter-regional trade cost. The price premium of exported bioethanol tends to raise the import price of bioethanol.

$$OBR = \text{CAA} \cdot xx^s + \sum_{ri} \text{CAX}_{ri} \cdot xt_{ki} + \sum_{ri} \text{CAM}_{ri} \cdot xt_{ki},$$

where $CAX$ is the matrix that explains the price premium of bioethanol exported from Latin America.

Then, the GLUE model solves Formulas (1), (3), and (4) and minimizes the global energy systems cost including the price premium of exported bioethanol.

(2) Using the calculation results in Procedure (1), the model calculates the energy systems cost in Latin America in Formula (5). The $xx$ and the $xt$ are fixed at the calculation results in Procedure (1). The prices of bioethanol as well as the other fuels in the $CAXM$ are assumed to be the marginal fuel prices in Procedure (1). When the marginal price of bioethanol is raised by the price premium, the raised marginal price decreases the energy systems cost in Latin America in Formula (5). The $CAXP$ in Formula (4) is the virtual cost to calculate the marginal bioethanol price including the price premium and is not included in the calculation of the $OBR$ in Formula (5).

$$OBR = \text{CAA} \cdot xx^s + \sum_{ri} \text{CAX}_{ri} \cdot xt_{ki} + \sum_{ri} \text{CAM}_{ri} \cdot xt_{ki},$$

where $CAXM$ is the matrix of traded prices of fuels that are the marginal fuel prices calculated in Procedure (1).

(3) It is assumed that the agent of Latin America can conduct a full search of the candidate price premiums.
The price premium is changed in Formula (4), and then Procedures (1) and (2), are repeated. After all the calculations regarding the candidate price premiums are finished, the minimum value of the energy system cost in Latin America is chosen in Formula (5) and the price premium to minimize the energy system cost is found.

The price premium of bioethanol exported from Latin America is assumed to fall within the range of USD (0.0 to 25) GJ$^{-1}$ with steps of USD 0.025 GJ$^{-1}$. In this study, the price is shown at the real price for year 2000.

In the calculations of the one-agent-technique, constraints of mixture ratios of bioethanol in the developed regions are added to Formula (1). The mixture ratios of bioethanol to gasoline-type fuel in the developed regions considered were (0, 3, 5, 10, and 20) % of their heating value. The wide range of mixture ratios (up to 20%) enables a wide range of analysis about bioethanol as fuel to be conducted. The cost of CO₂ discharge in all the cases with the one-agent technique is assumed to be zero.

The developed regions in the study include North America, Western Europe, Japan, ANZ, and FSU and Eastern Europe. The developed regions were the biomass importer regions in the calculation.

The simple-two-agent technique is one in which two strategic agents can control their own strategic parameters. The strategic agents are not only Latin America but also the agent of all developed regions. It was assumed that all developed regions in the study were considered a single agent.

The first agent, which is assumed to be Latin America, can control one strategic parameter; in this case, the price premium of the traded bioethanol. The strategic parameter was assumed to be within the range of USD (0.0 to 25) GJ$^{-1}$ with steps of USD 1.2 GJ$^{-1}$.

The second agent, which is assumed to be the agent of all developed regions, can control a second strategic parameter; in this case, the mixture ratio of bioethanol to gasoline-type fuel. The range of this strategic parameter was assumed to be within the range E0 (0% ratio (no ethanol in gasoline) based on the heating value standard) to E20 (20%), with steps of 1%.

The first and second agents are assumed to be uncooperative and to conduct sequential events. The calculation procedure for each ratio is explained below.

(0) It was assumed that the initial values were the strategic parameters of the first and the second agent. The strategic parameter of the price premium is described in Formula (4) and that of the mixture ratio is added to Formula (1), which is the aggregate of the constraints on energy flows and biomass flows.

(1)-(3) Procedures (1), (2) and (3) here, are the same as Procedures (1), (2) and (3) of the simple-one-agent technique.

(4) Using an assumed mixture ratio, the GLUE model solves Formulas (1), (3), and (4) and minimizes the global energy system cost including the price premium of the exported bioethanol.

(5) Using the calculation results from Procedure (4), the model calculates the energy system cost in the agent of all developed regions. The cost is the summation of OBR in Formula (5) in the agent of all developed regions.

(6) It is assumed that the second agent in the agent of all developed region can conduct a full search of the candidate bioethanol mixture ratios. The bioethanol mixture ratio is changed in Formula (1), and Procedures (4) and (5) are repeated. After all the calculations regarding the candidates of the mixture ratio are finished, the mixture ratio that minimizes the energy system cost in the agent of all developed region is found.

(7) Procedures (1)-(6) are repeated until the two strategic parameters reach convergence. After they reach convergence, the two strategic parameters are reported.

The CO₂ discharge costs in the cases with the simple-two-agent technique are assumed to fall between USD (0 and 31) t$^{-1}$ CO₂.

It is assumed that the agent all developed regions adopts its own strategy to control the mixture ratio of the bioethanol to gasoline in order to minimize its energy system cost. In reality, it is almost impossible that the parts of the developed regions behave as a single agent. However, the author supposes that it is not unrealistic that the developed countries might co-operate to adjust bioethanol consumption using the price signals of bioethanol in the future. There is a supporting example of a coordinated scheme regarding oil consumption in IEA member countries in the case of supply disruptions of oil, called as the Co-ordinated Emergency Response Measures (CERM)³⁶.

3. Simulation Results

Simulations were conducted using the GLUE model and the agent-based techniques and the following results were obtained.

3.1 Simulation results with the simple-one-agent technique

First shown are the simulation results from the simple-one-agent technique (see Sub-Section 2.2).

In the high-cost case of cellulosic bioethanol production, the bioethanol prices in the developed regions increase, according to increase in the mixture ratios of bioethanol in the developed regions (Fig. 10). The bioethanol
prices, including the price premium of the traded bioethanol, are high; even in the cases with low mixture ratios (i.e., E3 and E5). The price premium of the bioethanol traded from Latin America is between USD (7 and 9) GJ⁻¹ (Fig. 10). The reason for the high premium in the above case is explained below. When Latin America raises the price premium, the bioethanol price (including the price premium) tends to increase, but the export of bioethanol from Latin America tends to decrease. The increase in the bioethanol price is an advantage for Latin America but the decrease in the export of bioethanol is a disadvantage. When Latin America produces bioethanol exclusively and raises the price premium, it tends to keep the export volume of bioethanol and to increase the profit by raising the price premium. However, when Latin America produces bioethanol competitively, it tends to reduce the export of bioethanol and not to increase the profit by raising the price premium.

In cases E3 and E5, Latin America would produce about 95% of the global bioethanol production (Fig. 11). However, in cases E10 and E20, Latin America would produce about (84 and 74) %, respectively, of the global bioethanol (Fig. 11). Thus, the price premium does not increase monotonically, as the mixture ratio increases (Fig. 10). However, the bioethanol price, including the price premium, increases monotonically, as the mixture ratio increases. This is because the expansion of bioethanol production forces the utilization of more expensive bioenergy resources to make ethanol.

When the agent of all developed regions increases the mixture ratios of bioethanol, not only the world, but also Latin America increases bioethanol production (Fig. 11 a). However, Latin America consumes a constant amount of bioethanol at all mixture ratios and allocates all the increases of bioethanol production to increase bioethanol export in order to get a profit from the exports, and to minimize the energy system cost in its own region (Fig. 11 b). These results imply that a policy of inflexible mixture ratio of bioethanol in the developed regions may cause high bioethanol price (including the price premium) if the cellulosic bioethanol production is expensive.

Next explained are the simulation results for low-cost cellulosic bioethanol production. In this case, the bioethanol price in the developed regions increases, according to the

![Graph](image1)

**Fig. 10** Import prices (at year 2000 price) of bioethanol in the developed regions calculated by the simple-one-agent technique (for high-cost cellulosic bioethanol production): The prices are the weighted averages in the developed regions. Base means no constraints about bioethanol mixture ratio. It was assumed that no subsidies were provided for bioethanol and no gasoline taxes were levied in 2020, and that the calculated mixture ratio in the developed regions was zero. The calculated price of petroleum fuel for transportation is about USD 6.6 GJ⁻¹

![Graph](image2)

**Fig. 11** Bioethanol production (a) and bioethanol consumption (b) in Latin America and the Rest of the World (ROW) calculated by the simple-one-agent technique (for high-cost bioethanol production): Base means no constraints on the bioethanol mixture ratio. It was assumed that no subsidies for bioethanol were paid and no gasoline taxes were levied in 2020, and that the calculated mixture ratio in the developed regions was zero
increase in the mixture ratios of bioethanol in the developed regions (Fig. 12). However, the bioethanol prices in the low-cost case are still lower than those in the high-cost case, assuming the same mixture ratio. This is because the low-cost cellulosic bioethanol production decreases not only the bioethanol production costs but also the price premium of the bioethanol exported from Latin America. For example, the total prices of the imported bioethanol in the low-cost case and the high-cost case, with mixture ratio E3, are about USD (11 and 24) GJ$^{-1}$, respectively. The price premiums included in the total prices in the two cases are USD (0 and 9) GJ$^{-1}$, respectively (Figs. 10 and 12). The cost of the cellulosic bioethanol production affects both the bioethanol price and the price premium of the bioethanol.

The cost reduction of cellulosic bioethanol production does not affect the structure of the bioethanol consumption of Latin America and the ROW (Fig. 11 and 13). However, the cost reduction does affect the structure of bioethanol production. As the mixture ratio increases, the ROW increases production of cellulosic bioethanol (Fig. 13). The cost reduction of the bioethanol production decreases the global share of the bioethanol production in Latin America and lessens both the price premium and the total price of bioethanol (Fig. 12).

3.2 Simulation result of the simple-two-agent technique

The simple-two-agent technique is assumed to allow a strategy not only for Latin America, but also the agent of all developed regions (see Sub-Section 2.2). It is assumed that Latin America controls the price premium of the export of bioethanol and the agent of all developed regions controls the mixture ratio of bioethanol to gasoline-type fuel.

When the CO$_2$ discharge cost is zero in all the cases with the one-agent technique, the price premium of bioethanol converges at a positive value (Figs. 10 and 12). However, when CO$_2$ discharge cost is zero in the cases with the two-agent technique, the calculation results converge at zero price premium and zero mixture ratio regardless of the costs of the cellulosic ethanol production (Fig. 14).

Thus, the author added cases with positive CO$_2$ discharge costs in the agent of all developed regions that minimizes the energy system cost with the CO$_2$ discharge cost, by changing the strategic parameter of the mixture ratio of bioethanol to gasoline-type fuel. The CO$_2$ discharge costs were assumed to be between USD (0 and 31) t$^{-1}$ CO$_2$.

![Fig. 12](image1.png)

**Fig. 12** Import prices (at year 2000 price) of bioethanol calculated by the simple-one-agent technique (for low-cost cellulosic bioethanol production): The prices are the weighted averages in the developed regions. Base means no constraints on the bioethanol mixture ratio. It was assumed that no subsidies for bioethanol were paid and that no taxes for transportation petroleum fuel were levied in 2020; and that the calculated mixture ratio in the developed regions was zero. The calculated price of liquid fuel for transportation is about USD 6.6 GJ$^{-1}$.

![Fig. 13](image2.png)

**Fig. 13** Bioethanol production (a) and bioethanol consumption (b) in Latin America and the Rest of the World (ROW) calculated by the simple-one-agent technique (for low-cost bioethanol production): Base means no constraints on the bioethanol mixture ratio. It was assumed that no subsidies were paid for bioethanol and no taxes levied for transportation petroleum fuel in 2020 and that the calculated mixture ratio in the developed regions was zero.
In the case with high-cost cellulosic bioethanol production, the mixture ratio converged to zero regardless of the CO₂ discharge cost (Fig. 14). This is because bioethanol production in the high-cost case is not economical even if a high CO₂ discharge cost is applied. The result in the two-agent case contrasts with the result in the one-agent case for high-cost cellulosic bioethanol production: the price premium converged at a high level (see Fig. 10).

In the cases with low-cost and middle-cost cellulosic bioethanol production, the mixture ratio converges at zero when the CO₂ discharge cost is USD 0 GJ⁻¹ (Fig. 14). As the CO₂ discharge cost increases, the price premium and the mixture ratio converge at a high level. When the CO₂ discharge cost is high (USD 31 t⁻¹ CO₂), it converges at about USD 4 GJ⁻¹ of the price premium and at the mixture ratio E20.

When the results in the two-agent case (Fig. 14) are compared to those in the one-agent case (Fig. 10 and 12), the price premium of bioethanol in the one-agent case is more expensive than that in the two-agent case. This shows that the developed regions could avoid a high price premium of bioethanol if it implements flexible mixture ratio targets in the two-agent case.

Regarding the feasibility of a flexible mixture ratio of bioethanol, in general, the specifications of bioethanol mixture ratios for automobiles and distribution infrastructure are the specifications of maximum mixture ratios. Automobiles and gas stations usually could accept flexible mixture ratios lower than the maximum ratios. For example, E3 vehicles can operate over the range from pure gasoline to E3 fuel, and Flex-Fuel Vehicles (FFVs) can operate using any mixture ratio of bioethanol [17]. In Brazil, the legal maximum mixture ratio is 26% as of 1999. However, the gas stations in Brazil change the mixture ratio of ethanol-blend gasoline flexibly between (19 and 26) %, following Government determinations [18].

4. Conclusions

In this study, numerical analyses about the introduction of bioethanol in the world energy system were conducted for various cases regarding the cost of cellulosic bioethanol production, and regarding policies regulating the mixture ratios of bioethanol to gasoline. The simulation analyses were conducted and the following results obtained. (1) It is assumed that cellulosic bioethanol is commercialized at a high cost in 2020, and that Latin America can adopt its own strategy of changing the price premium of exported bioethanol to minimize the energy system cost, including the surplus, from the bioethanol price premium. In the case that the bioethanol importer regions, as typified by the developed countries in this study, adopt rigid targets for bioethanol mixture ratios without a strategy for controlling the mixture ratios, the bioethanol price premium would converge at a high price. In the case that Latin America is the dominant producer of bioethanol in the world, it can control the strategic parameter of the price premium of exported bioethanol. (2) If it is assumed that cellulosic bioethanol is commercialized at a low cost (equal to the cost of the starch ethanol production), the price premium of the traded bioethanol would be low, even if the bioethanol importer regions adopt rigid targets of high mixture ratios of bioethanol. In this case, cellulosic bioethanol fuel will be produced in most regions and Latin America will not remain a dominant producer of bioethanol. If Latin America tries to spike the price premium, it will lose market share and decrease its export of bioethanol. Thus, the price premium will not run up in this case. (3) If it is assumed that not only Latin America, but also the bioethanol importer region can apply separate strategies, and that the latter controls the mixture ratios and minimizes its energy system cost; if Latin America raises the price premium, the bioethanol importer regions can adopt the strategy of decreasing the mixture ratio. Thus, in this case, the price premium would converge at a low price.

From these results, the following conclusions were drawn. If the bioethanol importer regions adopt a policy of mixture of bioethanol with gasoline fuel in the present situation (expensive cellulosic ethanol production), they
should apply a strategy of flexible targets for the mixture ratio. For example, the target mixture ratio should be adjusted flexibly, when bioethanol hits higher or lower prices.

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