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Effect of local biomass projects on energy balance and GHG emission: a life cycle approach

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Abstract

Emerging attention has been given to the use of biomass in local areas for its contribution to reducing fossil fuel dependence and mitigating global warming. The objective of the present study is to develop a method that quantitatively assesses the effects of local biomass projects on fossil fuel consumption and greenhouse gas (GHG) emission. A practical method based on a life cycle approach is proposed and applied to a case of bioethanol project in Miyako Islands of Japan. The project is aiming to produce bioethanol from molasses within the islands, and to replace the entire gasoline consumed in the islands to E3 fuel (i.e. a mixture of 3% ethanol and 97% gasoline by volume). The assessment using the developed method revealed that, first, the complete shift from gasoline to E3 fuel allows for decreases in fossil fuel consumption and GHG emission. Second, the performance of the project is improved by the integration of the ethanol plant and the sugar factory. Moreover, the assessment found that, in small-scale bioethanol projects, the contribution of capital goods to life cycle fuel consumption and GHG emission is not negligible.

Keywords

bioethanol; energy; global warming; input-output table; LCA; life cycle approach; sugarcane

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1. INTRODUCTION

Emerging attention has been given to the use of biomass resources in local areas for its contribution to reducing fossil fuel dependence and mitigating global warming. Also in Japan, the use of local biomass resources for energy and materials has been supported by the government policies. Japanese government has promoted Biomass Town Concept to encourage the utilization of biomass resources in local areas. As of 31st April 2011, 318 of municipalities (MAFF, 2011) participate in the Concept to propose or carry out their biomass projects that aim to effectively use biomass resources in their local areas.

On the other hand, with increasing use of biomass for energy, questions arise about the validity of bioenergy as a means to reduce greenhouse gas (GHG) emissions and dependence on fossil fuels (Cherubini et al., 2009). Therefore, a lot of net energy analyses and life cycle greenhouse gas emission analyses about bioenergy, especially bioethanol and biodiesel, have been performed (e.g. Blottnitz et al., 2007, Gnansounou et al., 2009, Malça & Freire, 2009). While evaluation of a *product* such as bioethanol and biodiesel has been intensively carried out, few attempts to assess a local biomass *project* can be found. A practical and objective method is required to prospectively assess whether a local biomass project can help reduce fossil fuel consumption and GHG emission.

The present study is aiming to develop a method that quantitatively assesses the performance of a local biomass project as a way to reduce dependence on fossil fuels and GHG emissions. A practical and objective method based on the life cycle approach is proposed and applied to a case of bioethanol project in Miyako Islands of Japan.

2. BIOETHANOL PROJECT IN MIYAKO ISLANDS

Miyako Islands, which is a part of Okinawa Prefecture, is located in the southernmost region of Japan. Basic information of the islands is summarized in Table 1 (MC, 2011). The islands that has an area of 204.6 km^2 is flat like a low plateau, and consists of exposed coral and Ryukyu limestone filled by sandstone and clay. More than half of the total land area (about 11,500 hectare) is cultivated (MC, 2011). Out of the total cultivation area, sugarcane is cultivated in about 7,000 hectare (MC, 2011) because climate and soil of the islands are suitable for growing sugarcane. Thus, sugarcane is a local specialty of the islands, and sugarcane and sugar production forms the core industry of the islands.

In Miyako Islands, a project for the development and practical use of bioethanol derived from sugarcane, has been underway since 2004. The project, finally aiming to replace the entire gasoline consumed in the islands to E3 fuel (i.e. a mixture of 3% ethanol and 97% gasoline by volume), ranges from technical development and empirical study to actual car running tests via manufacturing, distributing and supplying E3 fuel within the islands. Bioethanol is produced from sticky dark syrup called molasses, which is a byproduct of sugar production in the islands.

The present study assesses the effects of a complete shift to E3 fuel on fossil fuel consumption and GHG emission using a method mentioned in the next section.

Table 1. Basic information of Miyako Islands, Japan

3. METHODOLOGY

3.1. Life cycle approach: LCA in a broad sense

Life cycle assessment (LCA), which is standardized in ISO 14040 series, is recognized to be a powerful tool to assess the environmental impacts of products and services. On the other hand, analyses/assessments based on a life cycle approach, which do not exactly follow ISO 14040 series, has extensively been performed such as energy analysis (e.g. Nguyen et al., 2008), life cycle GHG emission analysis (e.g. Hondo, 2005), and life cycle sustainability assessment (e.g. Moriizumi et al., 2010). Although such analyses/assessments based on life cycle approach may be not LCA in a narrow sense, it can be called LCA in a broad sense. Especially in the field of energy technology assessment including bioenergy, a great deal of LCA studies in broad sense has been performed from the viewpoint of energy and climate change policies (e.g. Searcy & Flynn, 2008, Varun et al., 2010). A method developed in the present study is based on a life cycle approach.

3.2. Definition of system boundary and functional unit

The developed method assesses the performance of a local biomass project by comparing annual fossil fuel consumptions or GHG emissions before and after the implementation of the project. Two systems that present the situations “before” and “after” the project are defined. In order to appropriately evaluate the performance of the project, first, it is required to draw a system boundary by thoroughly considering indirect effects caused by the project based on a life cycle approach. Second, the two compared systems have to be defined so that their functions are identical. A functional unit is one year’s operation of a system, and the two systems provide the same amount of goods and services for a year.

The present case study, which aims to assess the effects of a complete shift to E3 fuel, defines and compares two systems shown in Figure 1: Base System where gasoline is used as fuels of all gasoline-engined cars driven on the islands, and E3 System where E3 fuel is used. The two systems have the same function, and provide the same amount of products for one year as shown in Table 2.

(1) Base System

Gasoline that is required for cars within the islands is produced outside and shipped to the island. Raw sugar is produced from sugarcane cultivated in the islands and is shipped outside the islands. In the sugar production process some byproducts are left behind. Molasses that is one of the byproducts is shipped outside the islands and is used as raw materials of nutrient media for baker’s yeast etc. Other byproducts such as surplus bagasse are converted into organic matters and returned to sugarcane farms.

(2) E3 System

E3 fuel is used for all gasoline-engined cars within the islands. E3 fuel is produced by blending gasoline and bioethanol derived from molasses. While raw sugar is produced and shipped outside the island like Base System, molasses is used as the raw material of bioethanol within the islands. Vinasse that generates in the ethanol production is returned to sugarcane farms. Vinasse is potassium-rich and substitutes for potassium of chemical fertilizers.

Figure 1. Base System (before the project) and E3 System (after the project).

Table 2. Products delivered by one year’s operation of Base or E3 Systems.

3.3. Estimation of fossil fuel consumption and GHG emission

The present study focuses on fossil fuel consumption and GHG emission. CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 are included as contributors to global warming, and the 100-year time horizon global warming potentials (GWP) are used (IPCC, 2001). Carbon contents in biomass resources, biofuels produced and other byproducts (e.g. bagasse) are not accounted.

In general, there are two basic methods to estimate resource uses and environmental releases over the whole life cycle, namely, process analysis and input-output analysis. In addition, various hybrid methods that combine both merits of process analysis and input-output analysis have been developed (e.g. Bullard et al., 1978, Suh et al., 2004). Process analysis allows for more accurate estimation because of compiling process-specific data for each process in a system to be studied. On the other hand, process analysis often requires considerable efforts for data collection due to the size or complexity of a system to be studied. In general, input-output analysis has characteristics opposite to those of process analysis. In order to estimate fossil fuel consumptions and GHG emissions as accurately as we can within reasonable constraints of time and cost, the present study proposes a practical hybrid method as mentioned below.

In the proposed method, process analysis is used to estimate fossil fuel consumptions and GHG emissions associated with the following three activities: (a) combustion of fuels that are directly input to each process, (b) generation of electricity that is directly input to each process, (c) application of fertilizers (N_2O emission). These consumptions and emissions (E) are estimated according the following equation:

$$E = q \times f \qquad (1)$$

q is the amount (e.g. kl/year, kWh/year, kg/year) of fuels, electricity or fertilizers required for one year; f is higher heating values or GHG emission factors. The values of q are obtained from field surveys and statistics (See Section 4). Higher heating values and GHG emission factors of fuels and fertilizers are obtained from Japan GHG Inventory Report (CGER, 2009). As for electricity, higher heating value and GHG emission factor are estimated reflecting the actual situation of a local electric power company. In the present case study (case of Miyako Islands), a local electric power company generates 85% of electricity by coal-fired and the remaining 15% using internal combustion engines or gas turbines (OEPC, 2007-2010).

Input-output analysis is used to estimate fossil fuel consumptions and GHG emissions associated with all activities except for the three activities above mentioned. The consumptions and emissions (E) are estimated according the following equation:

$$E = \mathbf{e}^{T}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{d} \qquad (2)$$

$\mathbf{e}$ is a vector with elements representing the direct consumption/emission per output of each sector; $\mathbf{I}$ is the identity matrix; $\mathbf{A}$ is a coefficient matrix; $\mathbf{d}$ is a vector with elements representing the final demand for each sector; T indicates transposition. The vector $\mathbf{e}$ is based on Nansai et al., 2009. The matrix $\mathbf{A}$ is obtained from the latest Japanese input-output table, which has about 400 industrial sectors (MIC, 2009). Thus, even if the vector $\mathbf{d}$, that is, the amount (Japanese Yen/year) of products and services directly required for processes within a system to be studied is given, the direct and indirect consumptions/emissions are easily calculated according to Eq. (2). The amount of products and services are obtained from statistics and field surveys (See Section 4).

It should be noted that the present study also considers the construction of new plants required for E3 System, that is, plants to produce ethanol and blend gasoline with ethanol. Land preparation, building construction and equipment production are included. The lifetime of these capital goods is assumed to be 15 years. Fossil fuel consumption and GHG emission caused by the capital goods are evenly allocated over the lifetime (15 years), because the functional unit is one year’s operation of a system.

3.4. Assessment of project performance

The performance of a local biomass project is assessed by the differences of annual fossil fuel consumption (or annual GHG emission) between before and after the implementation of the project according to the following equation:

$$E = E_{before} - E_{after} \qquad (3)$$

E_{before} and E_{after} indicate annual fossil fuel consumptions (or annual GHG emissions) before and after implementing the project, respectively. They are calculated using the equation (1) and (2). In the present case study, E_{before} and E_{after} corresponds to fossil fuel consumptions (or GHG emissions) of Base System and E3 System, respectively.

4. PROCESS DATA AND DESCRIPTION

4.1. Direct inputs and outputs in each process

Table 3 summarizes direct inputs and outputs of materials and energy in each process shown in Figure 1. These data is obtained mainly from field surveys, and partially from official statistics. The inputs in sugarcane cultivation process are based on statistics published by Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF, 2011) and Okinawa Prefecture (OP, 2011). The outputs in sugarcane cultivation process and the inputs/outputs in all the other processes are provided from related companies through interview and questionnaire surveys. Although costs of ‘Others’ in sugarcane cultivation, and “Land preparation”, “Building construction” and “Equipment” in ethanol production are aggregated in Table 3, actual calculation is performed based on the more detailed cost data.

Table 3. Direct inputs and outputs in each process.

4.2. Process description

Basic information and assumptions of each process in Base and E3 Systems (Figure 1 and Table 3) are as follows:

(1) Sugarcane cultivation includes land preparation, planting, crop maintenance (fertilizing, weeding), and harvesting. In Miyako Islands, generally, the harvest is made about 18 months after planting on summer (from August to September), and the average annual productivity is 71.0 t of cane per hectare (OP, 2011). N_2O emissions associated with fertilizing are considered based on Japan GHG Inventory Report (CGER, 2009). Fertilizer required in E3 System is less than Base System because vinasse is used as fertilizer (see (6)).

(2) Sugar production includes cutting, shredding, milling, clarification, evaporation, crystallization, and centrifugation. Since raw sugar produced (17080 t per yr) is shipped outside the islands, raw sugar refining is excluded. In addition to 17080 t of raw sugar, 3269 t of molasses and 35342 t of bagasse are generated.

Bagasses is mainly burned as boiler fuel to generate electricity and steam, and surplus bagasse (6862 t) is used to make organic matters.

(3) Organic matter is made of surplus bagasse, filtercake, trash, and bagasse ash on the site near the sugar factory, and is distributed to sugarcane farms.

(4) Base System has the molasses transportation process. In the case of Base System, molasses generated at the sugar production within the islands is shipped outsides the islands.

(5) Gasoline is produced outside the islands and is shipped to the islands using oil tankers.

(6) Ethanol production includes yeast propagation, fermentation, distillation, and dehydration using zeolite membrane. Since the ethanol plant is located away from the sugar factory, heavy oil and electricity required for the ethanol production are supplied from local energy companies. When ethanol is produced, vinasse is generated together. Vinasse is distributed to sugarcane farms and replaces a part of chemical fertilizer for sugarcane cultivation. Therefore, the amount of fertilizer required for E3 System is less than that for Base System.

(7) E3 fuel is produced by blending gasoline (97%) and bioethanol (3%), and distributed to 21 gas stations within the islands using tank lorries and/or ferries.

(8) E3 System has the molasses production & transportation process. In the case of E3 System, molasses is imported from southeastern Asian countries, because molasses used for nutrient media for baker’s yeast etc. outside the islands is not supplied from the islands.

(9) Although transportation is not explicitly shown in Figure 1 (except for molasses transportation), fuels required for the transportation (e.g. trucks, tankers) are included in inputs of each process in Table 3. These fuels are calculated using energy intensity (MJ/tkm) (MLIT, 2011, OPRF, 2001), transport distance (km), and freight weight (t).

5. RESULTS AND DISCUSSION

5.1. Performance of the project

Figures 2 and 3 show the differences of fossil fuel consumptions and GHG emissions between the two systems, respectively. A complete shift to E3 fuel results in decreases in fossil fuel consumption (5.3 TJ/yr) and GHG emission (505 t-CO_2 equiv./yr.).

In the two processes of gasoline production and fuel use, 23.2 TJ/yr of fossil fuel consumption and 1733 t-CO_2 equiv./yr of GHG emission are reduced. This is because the production and consumption of gasoline decrease due to the 3% reduction of gasoline consumed for cars. Moreover, in the sugarcane cultivation process, 2.9 TJ/yr of fossil fuel consumption and 421 t-CO_2 equiv./yr of GHG emission are reduced. Since vinasse that generates at the production of ethanol is returned to the sugarcane field, the use of chemical fertilizers is reduced. Consequently, the decrease in the production of chemical fertilizers results in the reduction of fossil fuel consumption and GHG emission. On the contrary, fossil fuel consumption and GHG emission from the ethanol production process greatly increases associated with the construction and operation of bioethanol and E3 fuel plants.

Table 4 shows the breakdown of increases in fossil fuel consumption and GHG emission in the ethanol production process. About 70% of the fossil fuel consumption and GHG emission is caused by energy required for the operation of ethanol production equipment. The consumption and emission from building construction and equipment production accounts for more than 25%, which includes indirect emissions associated with product manufacturing (e.g. boilers, tanks), material production (e.g. steel, concrete), resource extraction (e.g. crude oil, iron ore) etc. Although few previous LCA studies for biofuels have considered the effects of plant construction and equipment production, it should be noted that the effects cannot be neglected. It is conjectured that since the project is a small scale in a local level, the contribution of capital goods to life cycle fuel consumption and GHG emission are relatively large.

Figure 2. Performance of the bioethanol project: fossil fuel consumption.

Figure 3. Performance of the bioethanol project: GHG emission.

Table 4. Breakdown of the increase in fossil fuel consumption and GHG emission in the ethanol production process.

5.2. Improvement of the project

The results mentioned above (Figures 2 and 3) indicate that the ethanol production is a key to improve the bioethanol project from the viewpoints of fossil fuel consumption and GHG emission. Since the ethanol plant is built away from the existing sugar factory, heavy oil and electricity required for the operation of the ethanol plant are supplied from local energy companies. However, if the ethanol plant was located near the sugar factory, it could use electricity and steam that are generated from bagasse in the sugar factory. This subsection analyzes the influences of integration of the ethanol plant and the sugar factory on fossil fuel consumption and GHG emission by comparing the following two systems: E3 System where the ethanol plant is located away from the sugar factory and Integrated E3 System where the ethanol plant is integrated with the sugar factory.

5.2.1. Assumptions

In the ethanol production of E3 System, energy is always supplied shown as Type A in Figure 4. In Integrated E3 System, Type B is employed as energy supply of the ethanol plant within the period of sugar production (73 days/yr), while energy is supplied shown as Type A when the sugar factory is not operated (127 days/yr). Electricity and steam required for the ethanol production in Integrated E3 System within the period of sugar production are 6.4% and 2.1% of those generated in the sugar factory, respectively (Table 5). Since steam is generated about 10% more than consumed in the sugar factory, it is possible to supply energy from the sugar factory to the ethanol plant. Although it may be actually necessary to enhance the equipment in the sugar factory, the effects are not considered.

Figure 4. Energy flows of sugar and ethanol production processes.

Table 5. Energy supply potential in the sugar factory.

5.2.2. Results.

Table 6 shows results of the improvement analysis. The integration of the ethanol plant and the sugar factory allows for decreases in heavy oil and electricity required for the ethanol production. As a result, fossil fuel consumption and GHG emission in the ethanol production process of Integrated E3 System are 34% and 32 % smaller, respectively, compared to those of E3 System. Consequently, the integration improves the performance of the project, and the implementation of the project can reduce 11.7 TJ/yr of fossil fuel consumption and 992 t-CO_2 equiv./yr of GHG emission (Table 7).

Table 6. Effects of the integration on energy consumptions and GHG emissions in ethanol production process.

Table 7 Effects of the integration on performances of the bioethanol project.

6. CONCLUSIONS

The present study developed a practical method to assess the effects of local biomass projects on fossil fuel consumption and GHG emission. The developed method allows for comprehensive evaluation considering not only direct but also indirect effects from the life cycle perspective.

The bioethanol project in Miyako Islands of Japan was assessed as a case study using the developed method. The project is aiming to produce bioethanol from molasses within the islands and to replace the entire gasoline consumed in the islands to E3 fuel (i.e. a mixture of 3% ethanol and 97% gasoline by volume). The assessment using the developed method revealed the following: (1) The complete shift from gasoline to E3 fuel contributes to reducing fossil fuel consumption (5.3 TJ/yr) and GHG emission (505 t-CO_2 equiv./yr). (2) There is potential to improve the performance of the project. The integration of the ethanol plant and the sugar factory allows for more reduction of fossil fuel consumption (11.7 TJ/yr) and GHG emission (992 t-CO_2 equiv./yr). Moreover, the assessment found that, in small-scale bioethanol projects, the impacts of plant construction and equipment production on life cycle fuel consumption and GHG emission cannot be neglected, which has not received enough consideration in previous LCA studies for biofuels.

Although the present study focuses on fossil fuel consumption and GHG emission, other environmental impacts (e.g. water consumption, land use change, biodiversity) and socio-economic impacts are also important to assess the sustainability of local biomass projects. In the future, the development of a more comprehensive method that also considers these impacts is required.

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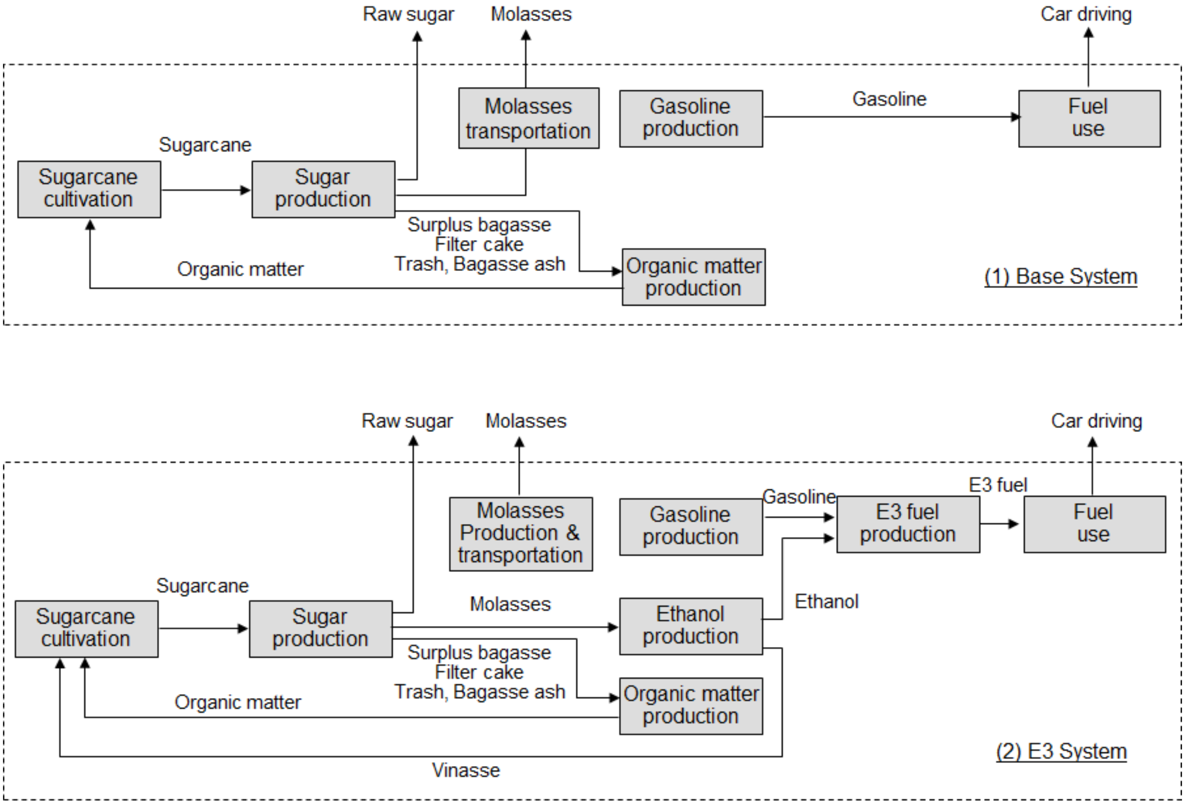

Fig. 1. Base System (before the project) and E3 System (after the project).

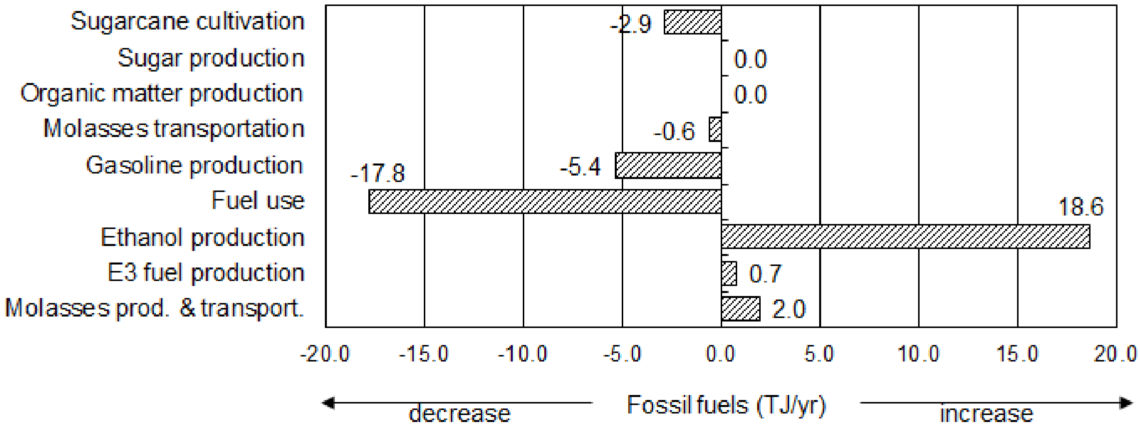

Fig. 2. Performance of the bioethanol project: fossil fuel consumption.

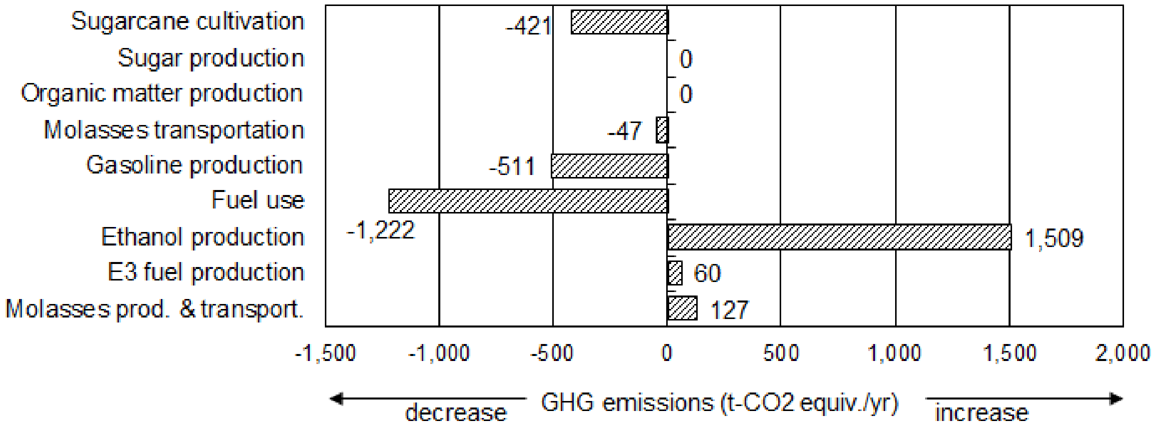

Fig. 3. Performance of the bioethanol project: GHG emission.

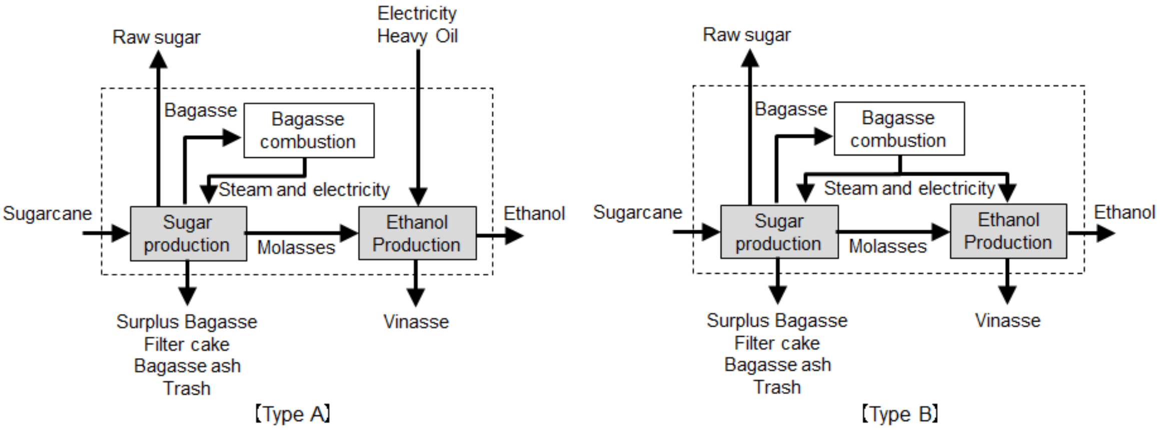

Fig. 4. Energy flows of sugar and ethanol production processes.

Table 1. Basic information of Miyako Islands, Japan

Location	24-25 degrees North latitude, 125-126 degrees East latitude
Area	204.6 km^2
Population	55036
Average Temperature	23.8 degree C
Average Humidity	75%
Average annual Precipitation	2008.8 mm
Climate	Subtropical

Table 2. Products delivered by one year's operation of Base or E3 systems.

Car fuel (Gassoline or E3 fuel)	GJ	864550
Molasses (Domestic or Impoted)	t	3269
Raw sugar	t	17080

Table 3. Direct inputs and outputs in each process.

Process	Unit	
Sugarcane cultivation		
Input		
Material		
Seedlings	million yen/year	7
Fertilizer (Base system)	million yen/year	92
Fertilizer (E3 system)	million yen/year	66
Pesticide	million yen/year	39
Agricultual machinery	million yen/year	60
Others	million yen/year	190
Energy		
Diesel	kl/year	271
Output		
Sugarcane	t/year	122,434
Sugar production		
Input		
Material		
Sugarcane	t/year	122,434
Chemicals et.al	million yen/year	15
Energy		
Heavy Oil (type A)	kl/year	19
Output		
Raw sugar	t/year	17,080
Molasses	t/year	3,269
Surplus bagasse	t/year	6,862
Trash	t/year	3,647
Filter cake & Bagasse ash	t/year	6,537
Organic matter production		
Input		
Material		
Surplus bagasse	t/year	6,862
Trash	t/year	3,647
Filter cake & Bagasse ash	t/year	6,537
Energy		
Diesel	kl/year	5
Output		
Organic matter	t/year	17,047
Molasses transportation		
Input		
Energy		
Diesel	kl/year	1
Heavy Oil (type C)	kl/year	13
Output		
Molasses	t/year	3,269
Gasoline production		
Output		
Gasoline (Base system)	kl/year	25,000
Gasoline (E3 system)	kl/year	24,485
Ethanol production		
Input		
Material		
Molasses	t/year	3,269
Water	million yen/year	23
Chemicals et al.	million yen/year	3
Energy		
Electricity	MWh/year	454
Heavy oil (type A)	kl/year	174
Diesel	kl/year	3
Land preparation	million yen	43
Building construction	million yen	342
Equipment	million yen	1,579
Output		
Ethanol	kl/year	757
Vinasse	kl/year	9,087
E3 fuel production		
Input		
Material		
Gasoline	kl/year	24,485
Ethanol	kl/year	757
Energy		
Electricity	MWh/year	7
Diesel	kl/year	3
Heavy oil (type C)	kl/year	3
Equipment	million yen	184
Output		
E3 fuel	kl/year	25,243
Molasses production & transportaion		
Input		
Material		
Sugarcane	t/year	10,701
Chemicals et.al	million yen/year	1
Energy		
Heavy Oil (type A)	kl/year	2
Heavy Oil (type C)	kl/year	39
Output		
Molasses	t/year	3,269

Table 4. Breakdown of the increase in fossil fuel consumption and GHG emission of the ethanol production process.

	Fossil fuel consumption		GHG emission	
	TJ/year	%	t-CO_2 eq./year	%
Heavy oil (Type A)	7.7	41%	556	37%
Diesel	0.2	1%	12	1%
Electricity	5.4	29%	454	30%
Water	0.5	3%	35	2%
Chemicals et al.	0.3	2%	36	2%
Building construction	0.9	5%	86	6%
Equipment production	3.7	20%	329	22%
Total	18.6	100%	1,509	100%

Table 5. Energy supply potential in the sugar factory.

		Real production in sugar factory (a)	Assumed consumption in ethanol plant (b)	ratio (b/a)
Steam	TJ/73 days	158.7	3.3	2.1%
Electricity	MWh/73 days	3,428.9	219.0	6.4%

Table 6. Effects of the integration on energy consumptions and GHG emissions in ethanol production process.

		E3 System	Integrated E3 System	Difference
Electricity consumption	MWh/year	454	235	-48%
Heavy oil consumption	kl/year	174	90	-48%
Fossil fuel consumption	TJ/year	19	12	-34%
GHG emission	CO_2 eq./year	1,509	1,022	-32%

Table 7. Effects of the integration on performances of the bioethanol project.

		E3 System	Integrated E3 System
Fossil fuel consumption	TJ/yr	-5.3	-11.7
GHG emission	CO_2 eq./yr	-505	-992