Applied Energy 87 (2010) 2164–2168

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Net energy analysis of bioethanol production system from high-yield rice plant in Japan

Kiyotaka Saga [a], Kenji Imou [b], Shinya Yokoyama [b], Tomoaki Minowa [a,*]

[a] Biomass Technology Research Center, National Institute of Advanced Industrial Science and Technology, 2-2-2 Hiro-Suehiro, Kure, Hiroshima 737-0197, Japan
[b] Graduate School of Agricultural and Life Sciences, University of Tokyo, 1-1-1 Yayoi, Bunkyo, Tokyo 113-865, Japan

ARTICLE INFO

Article history:
Received 18 August 2009
Received in revised form 22 December 2009
Accepted 22 December 2009
Available online 13 January 2010

Keywords:
Bioethanol
High-yield rice
Net energy balance
Net energy ratio
I/O table

ABSTRACT

This study analyzes the energy balance of a bioethanol production system from high-yield rice plant in Japan. Two systems are considered in which rice is converted to ethanol: one in which cellulose feedstocks, straw and husk, are used for cogeneration (scenario 1), and the other in which they are converted to ethanol, and byproducts such as lignin and unreacted holocellulose are used for cogeneration (scenario 2). Energy input in the agricultural process including transportation is estimated to be 52.3 GJ/ha from an Input Output Table. The heating values of produced rice and cellulose feedstocks are 120.7 GJ/ha and 162.3 GJ/ha, respectively. The net energy balance (NEB) of scenario 1 is 129.2 GJ/ha, which produces 3.6 kL/ha of ethanol and 9420 kWh/ha of external electricity. On the other hand, NEB of scenario 1 is 11.7 GJ/ha, which produces 7.1 kL/ha of ethanol. Both NEBs are positive, but NEB of scenario 2 is much higher than that of scenario 1. An acid hydrolysis technology of cellulosic biomass applied to scenario 2 needs a large amount of heat energy for sulfuric acid recovery. If an enzyme hydrolysis of cellulosic biomass is developed, there is a possibility of improving NEB of scenario 2.

1. Introduction

The Biomass Nippon Strategy, an initiative of the Ministry of Agriculture, Forestry and Fisheries (MAFF) in cooperation with other ministries, was the first national strategy for biomass utilization. It was approved by the cabinet in 2002 and revised in 2006. In the 2006 version, biofuel were emphasized as a major product. The Biomass Nippon Strategy Promotion Council developed a roadmap entitled the Large Scale Expansion of Domestic Biofuel Production in February 2007. In the short-term until 2010, it says that ethanol production from currently available starch and waste materials can reach 50,000 kL. In the middle and long term, it seeks to resolve technical and institutional problems for bioethanol production from cellulosic biomass such as rice straw, unused timbers and energy crop. Estimated ethanol production could reach six million kL if successful [1].

From the point of view of global warming prevention, it is important whether the net GHG emission reduction for biofuel production is positive or not [2–4]. Life cycle assessment (LCA) is one method for such an evaluation, many LCA studies about biofuel production have been carried out [5–7]. The net energy ratio (NER) is also important indicator for analyzing the energy efficiency of biofuel production. NER is the ratio of total energy outputs to total energy inputs, and NER should be positive so that the net GHG emission reduction is positive. In Brazil, NER of sugar cane ethanol is clearly positive because of the byproduct bagasse, which is used to produce heat and power that are needed for ethanol conversion plants. It is reported that NER of sugar cane is 8.3–10.2 [8]. In USA, NERs of corn ethanol also are evaluated, and it is reported that NERs of corn ethanol are 0.71 [9] and 1.67 [10].

In Japan, uncropped agricultural land has been increasing because of decreasing population and rice consumption and increasing rice yields. The area of uncropped agricultural land in 2005 was 380,000 ha, and it is feared that this area may increase. When the uncropped agricultural land is left, it gradually becomes difficult to use the land as a productive farmland. It is effective in the maintenance of the farmland to make the bioethanol by using the uncropped agricultural, and the use of such a farmland becomes one choices from the viewpoint of the food security. This paper analyzes the energy balance of a bioethanol production system from high yielding rice plant in Japan. Two energy conversion technologies of cellulosic biomass are also considered.

2. Bioethanol production system from rice cropping

Fig. 1 shows the process flow of bioethanol production system from rice cropping. The system is divided into two processes: agricultural and conversion. The agricultural process includes not only

* Corresponding author. Address: AIST Chugoku, 2-2-2 Hiro-Suehiro, Kure, Hiroshima 737-0197, Japan. Tel./fax: +81 823 72 1953.
E-mail address: minowa.tom@aist.go.jp (T. Minowa).

0306-2619/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2009.12.014

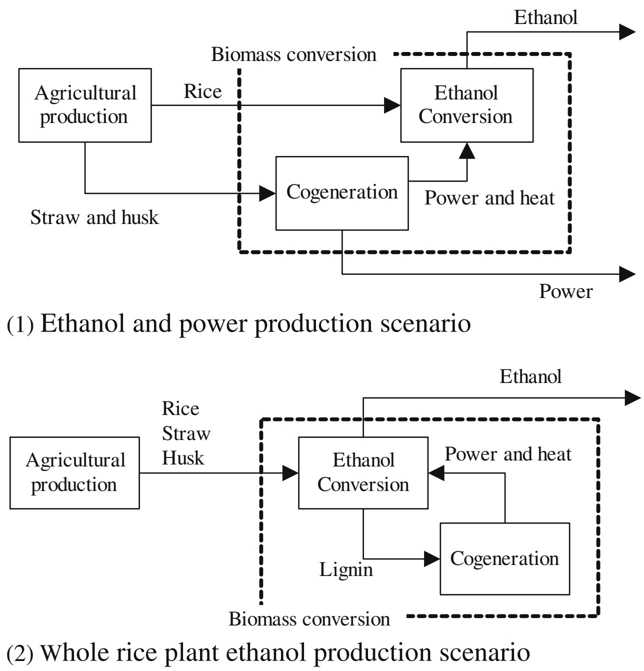

Fig. 1. Process flow of bioethanol production system from rice cropping.

cultivation but also transportation. Two technologies are considered in the conversion process of rice straw and husk. Rice is converted to ethanol in both systems: one in which cellulose feedstocks, straw and husk, are used for cogeneration and surplus power is exported (scenario 1: ethanol and power production scenario), and the other in which cellulose feedstocks are converted to ethanol, and byproduct lignin is used for cogeneration (scenario 2: whole rice plant ethanol production scenario).

3. Methodology

3.1. Agricultural process

3.1.1. Agricultural production process

In order to calculate energy inputs of agricultural production process, this study uses the statistical data of the expense for rice production published by the Ministry of Agriculture, Forestry, and Fisheries of Japan (MAFF) [11]. We classify the energy inputs of the agricultural production process into direct and indirect energy. Direct input energy is defined as fossil fuel and power used by agricultural machinery. On the other hand, indirect input energy is defined as fertilizer, herbicides, agricultural machinery, and so on.

The direct input energy includes petroleum products and power. At first, these consumptions are calculated by dividing the expense by its price. Next, the direct energy is calculated by multiplying consumption by energy unit per quantity (MJ/L or MJ/kWh) [12]. The direct energy, shown in Table 1, is calculated to be 13.2 GJ/ha.

Table 1
Direct input energy of agricultural production.

	Expense [11] (¥/ha)	Consumption	Energy unit [12]	Input energy (MJ/ha)
Diesel oil	10,680	123 L	43.1 MJ/L	5301
Kerosene	4870	73 L	39.9 MJ/L	2913
Gasoline	8850	72 L	43.3 MJ/L	3118
Motor oil	1770	4 L	41.3 MJ/L	165
Mixing oil	1590	10 L	43.3 MJ/L	433
Power	6250	120 kWh	10.9 MJ/kWh	1308
	34,010	–	–	13,238

This study considers the energy used for fertilizer or agricultural machine production defined as the indirect energy. This energy is calculated by multiplying expense for rice production by energy unit per expense (MJ/¥). This energy unit adopts data calculated from an input output table (I/O table) and an energy balance table for Japan [13]. The I/O table segment is adjusted to the appropriate segment of the MAFF statistics data. Expense of agricultural production is categorized as follows, together with an explanation of how the adopted energy units are calculated.

(1) Seedling: The "Seedling" segment of the I/O table (16.45 kJ/¥) is adopted.
(2) Fertilizer: Using the "Organic fertilizer" (35.13 kJ/¥) and "Chemical fertilizer" (104.43 kJ/¥) segments, the weighted average (84.11 kJ/¥) by expense ratio is adopted.
(3) Herbicides: The "Herbicides" segment of the I/O table (16.45 kJ/¥) is adopted.
(4) Other materials: Many kinds of small items are included in this category, such as vinyl sheet, polyethylene, string, soil for seedlings, and timber. Using the "Thermoplastic resin" (142.02 kJ/¥), "Organic fertilizer" (35.13 kJ/¥), and "Lumbering" (21.05 kJ/¥) segments, a weighted average (84.11 kJ/¥) by expense ratio is adopted.
(5) Land improvement and water supply: Using the "Agricultural service" (45.92 kJ/¥) and "Waterworks" (32.05 kJ/¥) segments, the weighted average (43.87 kJ/¥) by expense ratio is adopted.
(6) Agricultural service: This category includes such activities as cooperative herbicide application, agricultural machinery lending, and cooperative rice drying. Therefore, the "Agricultural service" segment of the I/O table (45.92 kJ/¥) is adopted.
(7) Facility: This category includes the depreciation and maintenance expense of drainage, concrete borders, soil dressing and so on. Therefore the "Agricultural public works" segment of the I/O table (38.36 kJ/¥) is adopted.
(8) Vehicle: The "Automobile" segment of the I/O table (39.69 kJ/¥) is adopted.
(9) Agricultural machinery: The "Agricultural machinery" segment of the I/O table (44.00 kJ/¥) is adopted.
(10) Production management: This category includes various items such as business supplies, personal computer, copier, fax, and telephone. Therefore, the "Information service" segment of the I/O table (12.43 kJ/¥) is adopted.

Table 2 shows that the indirect energy is 34.8 GJ/ha, and the input energy for agricultural production that includes direct and indirect energy is 48.0 GJ/ha. The indirect energy is larger than the direct energy, it becomes clear that the proportion of the agricultural machinery (28%), outsourcing (18%), fertilizers (19%), and herbicides (14%) in the indirect energy is large and these segments are very sensitive.

3.1.2. Biomass yield

In Japan, the average rice yield without husk is 5.3 t/ha (15 wt.% moisture) in 2006 [11]. If rice plant is cultivated as an energy crop, a high biomass yield is required. This study assumes that the high-yield rice developed for feed production is used for ethanol production. The yield of high-yield rice is set to be 8.3 t/ha (15 wt.% moisture) [14].

The amounts of straw and husk are calculated by the grain: byproduct ratio (dry basis). The ratios of straw and husk are 1.2