Evaluation of Biofuel Production Using Energy and Exergy Analyses
—Introduction of a System Design Concept for Achieving Final Benefits—

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Abstract

Evaluation functions for minimizing the disparity between energy supply and demand and reducing the field area for biomass production, which are based on energy benefits, were proposed in a system design for biofuel production. An Exergy Profit Ratio (ExPR) and an extended the Energy Profit Ratio (EPR) were also proposed to measure the quality and availability of energy for the biofuel plant in Utsunomiya City in Tochigi Prefecture, Japan. In the calculation of minimum field area of biomass production based on societal demand in household of Utsunomiya City, 17,500 ha was the minimum value by the evaluation function by energy ($E_{\text{system}}$) and 29,500 ha was the minimum value by the evaluation function by exergy ($E_{\text{system}}^{EX}$) under the case of lighting: 100% electricity; heating: 89% electricity and 11% of vapor. On the other hand, 17,000 ha was the minimum value by $E_{\text{system}}$ and 29,000 ha was the minimum value by $E_{\text{system}}^{EX}$ under the case of lighting: 100% electricity; heating: 100% electricity and 100% of vapor. Thus, if EPR and $E_{\text{system}}^{EX}$ of bio-ethanol & electricity production were underestimated for a minimum field area, then ExPR and $E_{\text{system}}^{EX}$ could be used to maintain the results of introducing biofuel production to prevent field area shortages for biofuel production.

Keywords

biofuel, energy profit ratio, exergy, system

Introduction

Due to a significant increase in the cost of fossil fuels, biofuel has begun to gain acceptance as a viable resource of alternative energy. Fossil fuel is valuable because it can produce significant amounts of energy per unit weight, it is abundant, and it is easy to transport, extract and process as a liquid. However, some uncertainty exists regarding its availability, effect on the environment, cost in the world market and the shortage of existing supplies (United Nation 2012). The substitution of fossil fuel with biofuel aims to reduce environmental impacts and the cost of imported fossil fuels, such as coal, petroleum and natural gas (Shen et al. 2011, Sawangphol and Pharino 2011). Biofuel is considered a feasible approach for reducing fossil fuel consumption and CO₂ emissions. Moreover, the promotion of biofuel can add high value to biomass.

There exists concern that the expansion of biofuel crop production will threaten food security around the world by affecting food supply and cost (International Union of Food Science and Technology (IUFoST) 2010). For example, bio-ethanol production in the USA requires vast amounts of edible maize (Farrell et al. 2006). Mitchell (2008) reported that more than 70% of increases in food costs were attributable to biofuel demand. According to Tollens (2009), the increasing cost of maize in the US from 2007–2008 was highly related to biofuel production. The impact on food security will depend upon the biofuel crop grown. Therefore, a new evaluation method is required to minimize the disparity between energy supply and energy demand and reduce field biomass production.

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Field area of biomass production, variety of biomass and conversion efficiency of biofuel plants were used in the evaluation of total energy efficiency for biofuel production (Noguchi and Misumi 2007). The evaluation method of total energy efficiency for biofuel production can be utilized in field production and lead to a more effective production of biofuel energy. Furthermore, the Energy Profit Ratio (EPR), which is a ratio of output energy to input energy in biofuel production, is a very popular and standard method of evaluation for decision making (Nomura Research Institute Ltd. 2007, Pimentel and Patzek 2005, Silalertruksa and Gheewala 2009). Energy consumers who are interested in biofuel production seek final benefits such as heating, lighting, and mileage (Hamamatsu 2010, Central Research Institute of Electric Power Industry 2011).

From the viewpoint of quality of life, environmental protection, and sustainable development, “backcasting” should be utilized to identify policies and programs that connect the future with the present for defining a desirable future (Oliver and Brooks 2005). Forecasting is an estimation of future impact. To achieve established objectives, both should be followed by an explicit manifestation of future target goals and an evaluation of required policies. Backcasting involves setting policy goals and determining how those goals can be achieved. In addition, the measurement of precise physical quantities of energy for biofuel production is indispensable for determining the total amount of social benefit (Noguchi and Koyama 2010).

Evaluation functions, which are based on energy benefits, were developed in this research to minimize the disparity between energy supply and demand and to reduce the field area of biomass production in biofuel production. An Exergy Profit Ratio (ExPR) which is extended EPR was also proposed to measure the quality and availability of energy. To validate the system design model, Utsunomiya City in the Tochigi Prefecture of Japan was selected as an example and studied to assess the credibility of the evaluation functions.

**Methodology**

**System design for evaluation functions**

In a conventional system design for biofuel production, final benefit is considered after calculating field area, type of biomass, type of biofuel plant and type of biofuel, which are systematically based on single energy and single benefit (Fig. 1). In this research, the final benefit of specific area is considered at the beginning of system design for biofuel production via the backcasting method. Type of biofuel, type of biofuel plant, type of biomass and field area were systematically based on multiple types of energy. Subsequently, societal acceptance was also considered for introducing biofuel production, as shown in Fig. 1. If a shortage of energy results from achieving final benefits, biofuel production should be modified to increase the amount of energy. Conversely, if there is a surplus in field area during biomass production, surplus energy production should be reduced. Therefore, the purpose of proposing an evaluation function is to ensure adequate proportions of energy supply and demand with regards to the final benefit.

To obtain a greater evaluation when the difference between energy supply and demand is near zero, the evaluation function by energy $E_{\text{system}} [\text{J}]$, energy consumption $E_{\text{cons}} [\text{J}]$, and energy production $E_{\text{pro}} [\text{J}]$ were used in the evaluation function (Nakamizo 1988) as follows:

$$E_{\text{system}} = (E_{\text{cons}} - E_{\text{pro}})^2$$  \hfill (1)

Additionally, there is extensive variation in final benefit and energy in biofuel production. $E_{\text{system}}$ can be expressed using a variety of energy $f$, energy consumption $E'_{\text{cons}} [\text{J}]$, and energy production $E'_{\text{pro}} [\text{J}]$ as follows:

$$E_{\text{system}} = \sum_f (E'_{\text{cons}} - E'_{\text{pro}})^2$$  \hfill (2)
After defining field area of biomass production $S$ [ha], biomass yield per unit area $Y$ [t/ha], variety of energy $j$, energy conversion efficiency including biofuel plant $\eta'$ [J/t], and $E_{prev}$, which is proportional to $S$, $E_{system}$ can be expressed as follows:

$$E_{system} = \sum_j \left( E'_{cons} - SY\eta' \right)^2$$

(3)

Generally, the field area of biomass production for converting biofuel is limited. Minimizing the field area of biomass production could satisfy the energy demand for final benefit. This objective function needs to incorporate the most appropriate strategies for reducing environmental impact and maintaining agricultural production.

Therefore, the most efficient system design of biofuel production can be achieved by minimizing field area, which can be obtained by differentiating Eq. (3) as follows:

$$\frac{dE_{system}}{dS} = \frac{d}{dS} \left\{ \sum_j \left( E'_{cons} - SY\eta' \right)^2 \right\} = 0$$

(4)

### System design based on final benefit

$E_{system}$ for biofuel production was examined using direct energy flow, which can be easily evaluated with clear numerical values. As illustrated by Fig. 2, a biofuel plant not only can produce biofuel but can also produce electricity. The final benefit could be achieved through mileage and heating. In this case, biofuel can be used for gasoline vehicles or direct combustion boilers. Electricity is used for electric vehicles or heat pumps. Biofuel & electricity are also used to satisfy the energy demand of biomass production in field and biofuel plants. Biofuel is used as an alternative to gasoline in automobiles. Because electricity and gasoline are primarily used for energy in the civilian sector, including households, the household is considered the smallest unit in this research.

A number of variables of biofuel production comprises the annual cycle of biomass production. The amount of final benefit was also based on one year. Annual mileage per household $M$ [km], annual heating per household $H$ [J], number of households with gasoline vehicles $n_{GV}$ [–], number of households with boilers (heating equipment by combustion) $n_{BL}$ [–], number of households with electric vehicles $n_{EV}$ [–] and number of households with heat pumps $n_{HP}$ [–] were used in the system design. In addition, mileage from gasoline vehicles using biofuel $\eta_{GV}$ [km/L], mileage from electric vehicles $\eta_{EV}$ [km/kWh], amount of heat energy produced by boilers using biofuel $\eta_{BL}$ [J/L], and amount of heat energy produced by heat pumps $\eta_{HP}$ [J/kWh] were also used in the system design.

In this case, total amount of mileage for final benefit in society $M_0$ [km] and total amount of heat $H_0$ [J] were expressed as follows:

$$M_0 = M \left( n_{GV} + n_{EV} \right)$$

(5)

$$H_0 = H \left( n_{BL} + n_{HP} \right)$$

(6)

The amount of biofuel expected from the final benefit $e_{BF}$ [L/–] and amount of electricity expected from the final benefit $e_{EL}$ [kWh] were expressed as follows:

$$e_{BF} = \frac{Mn_{GV}}{\eta_{GV}} + \frac{Hn_{BL}}{\eta_{BL}}$$

(7)

$$e_{EL} = \frac{Mn_{EV}}{\eta_{EV}} + \frac{Hn_{HP}}{\eta_{HP}}$$

(8)

Thus, conversion efficiency from biomass to biofuel in the plant $\eta_{BF}$ [L/t], conversion efficiency from biomass to electricity $\eta_{EL}$ [kWh/t], lower quantity of heat for biofuel $e_{BF}$ [J/L] and conversion efficiency from electricity to heat $e_{EL}$ [J/kWh] were used to calculate the evaluation function, which can be expressed as follows:
Moreover, liquid fossil fuels used for biomass production including transportation \(E_{\text{BBF}}\) [L], electricity used for biomass production including transportation \(E_{\text{hel}}\) [kWh] and the proportional relationship between these two variables and the amount of biomass \(\eta_{\text{BBF}}, \eta_{\text{hel}}\) were used for \(E_{\text{system}}\) as follows:

\[
E_{\text{system}} = \left( \frac{Mn_{\text{EL}}}{\eta_{\text{EV}}} + \frac{Hn_{\text{HP}}}{\eta_{\text{EV}}} - SY\eta_{\text{EF}} \right) e_{\text{BF}}^2 + \left( \frac{Mn_{\text{EV}}}{\eta_{\text{EV}}} + \frac{Hn_{\text{HP}}}{\eta_{\text{HP}}} - SY\eta_{\text{EL}} \right) e_{\text{EL}}^2 \tag{9}
\]

Therefore, \(E_{\text{system}}\) was expressed using a variety of energy conversion equipment \(i\), number of energy conversion equipment \(n_i\), efficiency of energy conversion equipment \(\eta_i\), type of energy produced in the plant \(k\), conversion factor of heat \(c_k\) and amount of final benefit per unit for type of energy \(j\) \(F_j\) as follows:

\[
E_{\text{system}} = \sum_k \left( \sum_{i,j} \left( \frac{F_j}{\eta_i} \right) + SY(\eta_{\text{BF}} - \eta_k) \right) e_k^2 \tag{11}
\]

**Evaluation function for energy conversion to other type of energy**

If one type of energy is converted to another type of energy, as in excess and deficiency of biofuel energy or electricity, as shown in Eq. (10), \(E_{\text{system}}\) should be adjusted. If a shortage of electricity and surplus of biofuel occurs, \(E_{\text{system}}\) can be minimized by producing electricity from biofuel using power generators. Then, \(E_{\text{system}}\) can be expressed using amount of electricity produced from biofuel \(E_{\text{biofuel}}\) [L] and efficiency of power generator \(\eta_{\text{G}}\) [kWh/L] as follows:

\[
E_{\text{system}} = \left( \frac{Mn_{\text{EL}}}{\eta_{\text{EV}}} + \frac{Hn_{\text{HP}}}{\eta_{\text{EV}}} + SY(\eta_{\text{BBF}} - \eta_{\text{EF}} - E_{\text{biofuel}}) \right) e_{\text{BF}}^2 + \left( \frac{Mn_{\text{EV}}}{\eta_{\text{EV}}} + \frac{Hn_{\text{HP}}}{\eta_{\text{HP}}} + SY(\eta_{\text{hel}} - \eta_{\text{EL}} + E_{\text{biofuel}}) \right) e_{\text{EL}}^2 \tag{12}
\]

Therefore, based on energy conversion of all types of energy, \(E_{\text{system}}\) can be expressed as follows:

\[
E_{\text{system}} = \sum_k \left( \sum_{i,j} \left( \frac{F_j}{\eta_i} \right) + SY(\eta_{\text{BF}} - \eta_k) - \sum_{i,j} E_{\text{el}i} \right) e_k^2 \tag{13}
\]

**Exergy evaluation**

The conventional EPR is calculated using thermal unit [J] for energy production and energy consumption as follows:

\[
EPR = \frac{\sum_j E_j^{\prime}_{\text{pro}}}{\sum_j E_j^{\prime}_{\text{cons}}} \tag{14}
\]

The thermal unit [J] in EPR is not satisfied from an evaluation standpoint of available energy because its unit is not expressed for quality of available energy. Thus, \(E_{\text{system}}\) which is \(E_{\text{system}}\) based on exergy instead of energy, was proposed by considering exergy theory (Nobusawa 1980, Oshida 1986) in the evaluation function \(E_{\text{system}}\). Because electricity has 100% efficiency of exergy virtually 100% of electricity can be converted to energy for mechanical work. However, 15°C water in 15°C environmental temperature has 0% efficiency of exergy; thus, it is impossible to produce work energy from 15°C water because of the theory of the Carnot cycle. On the other hand, ExPR, which is expressed as a ratio of output exergy to input exergy, can be expressed by establishing the type of energy \(j\), exergy consumption for the type of energy \(E'_{\text{exo}}\) [J] and exergy production for the type of energy \(E'_{\text{exo}}\) [J] as follows:

\[
\text{ExPR} = \frac{\sum_j E_j^{\prime}_{\text{pro}}}{\sum_j E_j^{\prime}_{\text{cons}}} \tag{15}
\]

**Simulation**

Mileage, heating, and lighting of all households in Utsunomiya City, as shown in Table 1, were used in the simulation. Mileage energy consumption was calculated using annual mileage of vehicles (Ministry of Land, Infrastructure, Transport and Tourism 2008), fuel consumption of gasoline vehicles (Ministry of Land, Infrastructure, Transport and Tourism 2005), and quantity of heat for gasoline.

The diffusion rate for heat pumps in households was 89% (Council on Competitiveness-Nippon (COCN) 2010, The Institute of Energy Economics, Japan 2008). Thus, vapor produced by biofuel plants not equipped with heat pump facilities can take advantage of the heat energy of households. A 100% diffusion rate of heat pumps in households was also considered in the simulation. The energy consumption of lighting was estimated for a household equipped with average lighting, such as fluorescent light, incandescent light and LED light (Environmental Pollution Control Center, Osaka Prefecture 2002). The energy flow of specialized bio-ethanol production and the bio-ethanol & electricity production (Saga et al. 2007) was utilized in the simulation. Energy consumption for biomass
production was also included for the trial calculation in this simulation. Electricity, fuel (bio-ethanol, gasoline), vapor and heat were considered energy flows of biofuel production.

90% of fuel energy was used for the value of exergy based on the estimation by Rant’s approximation (Nobusawa 1980). 41% of vapor energy which revealed a temperature of 500°C and a pressure of 1,960 kPa in the cogeneration of biofuel plants (The Institute of Applied Energy 2002, Nobusawa 1980) was used for the value of exergy. 10% of heat energy was used for the value of exergy, because 0.107 of the availability ratio for heat was observed for a waste heat temperature of 80°C and an environmental temperature of 10°C (Nobusawa 1980).

Results and Discussion

Energy profit ratio and exergy profit ratio

Direct energy for agricultural production, collection and transportation, biofuel plant, and final benefit was calculated in this research (Table 2). In agricultural production, collection and transportation, fuel and electricity were used. In biofuel plant, the bio-ethanol and electricity production doesn’t use energy supply from outside, and produces not only bio-ethanol but also electricity, vapor, and heat. On the other hand, the specialized bio-ethanol production uses energy supply of electricity and vapor from outside. Accordingly, total amount of bio-ethanol is increased, but a vapor is not able to be utilized in outside of the biofuel plant. Because all vapor is used in the biofuel plant. Furthermore, total amount of heat also is also decreased.

Two types of biofuel production were evaluated from the standpoint of EPR and ExPR, as shown in Table 2. EPR and ExPR of bio-ethanol & electricity production were 10.4 and 7.14, respectively. The bio-ethanol and electricity production does not need the input energy, because of using rice straw and rice husk for energy supply to the biofuel plant. Thus, 10.4 of EPR and 7.14 of ExPR were very high compared with the normal value of EPR and ExPR for biofuel production. Because, input energy is very small, and all kinds of energy including bio-ethanol were used for calculation of EPR.

EPR and ExPR for the specialized bio-ethanol production were 1.31 and 1.86, respectively. The energy and exergy analysis revealed that the bio-ethanol & electricity production had a higher advantage than the specialized bio-ethanol production, if produced electricity could be used for final benefit, with the exception of mileage. Both values of EPR and ExPR of bio-ethanol & electricity production were higher than EPR and ExPR of the specialized bio-ethanol production because produced energy, except for bio-ethanol, was used for making bio-ethanol in the specialized bio-ethanol production. EPR was higher than ExPR in the bio-ethanol & electricity production. However, in contrast, ExPR was higher than EPR in the specialized bio-ethanol production. Because high-efficiency exergy, such as electricity, was used as input energy in the specialized bio-ethanol production, biofuel as a high-efficiency exergy was also produced.

The method of converting low-efficiency exergy, such as vapor, from other type of energy to usable energy was crucial for improving EPR and ExPR in biofuel production. Evaluation by EPR and ExPR can be used to ascertain improvement points

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
<th>Reference, Calculation basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of city</td>
<td>416.84</td>
<td>km(^2)</td>
<td>Utsunomiya City (2011)</td>
</tr>
<tr>
<td>Population</td>
<td>510,898</td>
<td>person</td>
<td>Utsunomiya City (2011)</td>
</tr>
<tr>
<td>Number of households</td>
<td>212,430</td>
<td>—</td>
<td>Utsunomiya City (2011)</td>
</tr>
<tr>
<td>Area of rice field</td>
<td>5,851</td>
<td>ha</td>
<td>Tochigi Prefecture (2010)</td>
</tr>
<tr>
<td>Area of rice field in unpractical use</td>
<td>763</td>
<td>ha</td>
<td>Tochigi Prefecture (2010)</td>
</tr>
<tr>
<td>Number of automobiles (passenger cars)</td>
<td>101,981</td>
<td>—</td>
<td>Utsunomiya City (2011)</td>
</tr>
<tr>
<td>Annual mileage of automobile per person</td>
<td>4,989</td>
<td>km</td>
<td>Ministry of Land, Infrastructure, Transport and Tourism (2008)</td>
</tr>
<tr>
<td>Fuel efficiency of gasoline vehicle</td>
<td>10</td>
<td>km/L</td>
<td>Ministry of Land, Infrastructure, Transport and Tourism (2005)</td>
</tr>
<tr>
<td>Quantity of heat: gasoline</td>
<td>34.6</td>
<td>MJ/L</td>
<td>Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy (2007)</td>
</tr>
<tr>
<td>Diffusion rate of heat pump for household</td>
<td>89</td>
<td>%</td>
<td>Council on Competitiveness-Nippon (COCN) (2010)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mileage</td>
<td>2,395</td>
<td>km</td>
</tr>
<tr>
<td>Lighting: Energy consumption</td>
<td>573</td>
<td>kWh</td>
</tr>
</tbody>
</table>
which are not clearly identified through only a conventional evaluation of EPR.

**Minimizing field area of biomass production using the evaluation function**

Minimum field area of biomass production based on societal demand was calculated by Eq. (4) in the case of introduction of the bio-ethanol and electricity production. Relationships between $E_{\text{system}}$ for energy and field area of biomass production is shown in Fig. 3. Relationships between $E_{\text{system}}^{\text{Ex}}$ for exergy and field area of biomass production is depicted in Fig. 4. $E_{\text{system}}$ and $E_{\text{system}}^{\text{Ex}}$ were calculated from 0 ha to 50,000 ha in 500 ha increments and based on several factors, such as mileage: 100% biofuel; lighting: 100% electricity; and heating: 100% electricity. As a result, 28,193 ha were required to satisfy the biofuel demand. When the field area of biomass production was 17,000 ha, the minimum value of $E_{\text{system}}^{\text{Ex}}$ was 0.289 PJ. The field area was 1,307 ha greater compared with the 28,193 ha that satisfies the biofuel demand, as shown in Fig. 4. The total value of $E_{\text{system}}^{\text{Ex}}$ was less than the total value of $E_{\text{system}}$ because the value of exergy was calculated by multiplying efficiency of exergy with energy.

As shown in Figs. 5 and 6, 100% heat demand was estimated to satisfy the heat pump in this simulation, based on factors such as mileage: 100% biofuel; lighting: 100% electricity; and heating: 100% electricity. A result, 28,193 ha were required to satisfy the biofuel demand, and 53,000 ha were required to satisfy the electricity demand. When the field area of biomass production was 17,000 ha, the minimum value of the evaluation function by energy $E_{\text{system}}$ was 2.172 PJ, as depicted in Fig. 5. The field area was 11,193 ha less compared with the 28,193 ha that satisfied the biofuel demand. When the field area of biomass production was 29,000 ha, as shown in Fig. 6, the minimum value of the evaluation function by energy $E_{\text{system}}^{\text{Ex}}$ was 0.560 PJ. The field area was 807 ha greater compared with the 28,193 ha that satisfied the biofuel demand.

When vapor produced in the plant was used effectively, a 0.315 PJ (from 2.172 PJ to 1.857 PJ) reduction in $E_{\text{system}}$ and a 0.271 PJ (from 0.560 PJ to 0.289 PJ) reduction in $E_{\text{system}}^{\text{Ex}}$ were achieved in the case of total heat gained by the heat pump.

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**Table 2  Comparison of EPR and ExPR for two different types of biofuel production systems**

<table>
<thead>
<tr>
<th>Reference data</th>
<th>Bio-ethanol and electricity production&lt;sup&gt;1)&lt;/sup&gt;</th>
<th>Specialized bio-ethanol production&lt;sup&gt;1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of biomass</td>
<td>Unmilled rice, Rice straw, Rice husk</td>
<td>Unmilled rice, Rice straw, Rice husk</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>Exergy&lt;sup&gt;2)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Input (MJ/10a) for agricultural production, collection and transportation</td>
<td>131</td>
<td>131</td>
</tr>
<tr>
<td>Electricity</td>
<td>1,672</td>
<td>1,505</td>
</tr>
<tr>
<td>Fuel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Input (MJ/10a) for biofuel plant</td>
<td>2,367</td>
<td>2,366</td>
</tr>
<tr>
<td>Electricity</td>
<td>7,916</td>
<td>7,124</td>
</tr>
<tr>
<td>Fuel</td>
<td>4,303</td>
<td>1,764</td>
</tr>
<tr>
<td>Vapor</td>
<td>4,220</td>
<td>422</td>
</tr>
<tr>
<td>Output (MJ/10a) from biofuel plant</td>
<td>358 L/10a</td>
<td>707 L/10a</td>
</tr>
<tr>
<td>Electricity</td>
<td>10.4</td>
<td>7.14</td>
</tr>
<tr>
<td>Fuel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vapor</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

1) Saga et al. (2007) (The data regarding water is not included in this table because the type of energy is unclear.)
2) Exergy efficiency: Electricity (100%), Fuel (90%), Vapor (41%), Heat (10%): Nobusawa (1980),
3) EPR: Energy Profit Ratio, ExPR: Exergy Profit Ratio
Thus, using the waste energy of vapor in the bioenergy systems was effectively accepted by society. In particular, $E_{\text{system}}^\text{EX}$ was reduced to 48.6%. Therefore, an effective use of waste heat could contribute to a reduction in energy consumption from the viewpoint of exergy.

In the case of vapor use for heat, minimum values of $E_{\text{system}}$ and $E_{\text{system}}^\text{EX}$ were lower than the case of heating: electricity 100%. On the other hand, a minimum field area of 500 ha, which was higher than the field area for total heat gained through the heat pump, was obtained. The tendency for minimizing the value of field area and minimizing the values of $E_{\text{system}}$ and $E_{\text{system}}^\text{EX}$ differed when different types of energy and/or final benefit were demanded. In this case, selection based on similarity in energy demand for final benefit and energy demand for production, or based on minimization of field area is required. In addition, a difference of approximately 12,000 ha was observed between minimum field area in $E_{\text{system}}$ by exergy and minimum field area in $E_{\text{system}}$ by energy. The minimum value of $E_{\text{system}}^\text{EX}$ is less than half the minimum value of $E_{\text{system}}$. 

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![Evaluation by energy: $E_{\text{system}}$ and field area of biomass production](image1)

**Fig. 3** Evaluation by energy: $E_{\text{system}}$ and field area of biomass production (mileage: 100% biofuel; lighting: 100% electricity; and heating: 89% electricity and 11% vapor) in the case of introduction of the bio-ethanol and electricity production

![Evaluation by exergy: $E_{\text{system}}^\text{EX}$ and field area of biomass production](image2)

**Fig. 4** Evaluation by exergy: $E_{\text{system}}^\text{EX}$ and field area of biomass production (mileage: 100% biofuel; lighting: 100% electricity; and heating: 89% electricity and 11% vapor) in the case of introduction of the bio-ethanol and electricity production
These results indicate that if EPR and $E_{\text{system}}$ of bio-ethanol & electricity production were underestimated for minimum field area, $E_{\text{system}}^{\text{Ex}}$ can be used to maintain the result of introducing biofuel production to prevent a field area shortage for biofuel production because EPR and $E_{\text{system}}$ are categorized as quantity evaluations of energy, and ExPR and $E_{\text{system}}^{\text{Ex}}$ are categorized as quality evaluations of energy. Thus, the values of ExPR and $E_{\text{system}}^{\text{Ex}}$ should be examined when more than two types of energy must be considered in the design of biofuel production. The effect on system design of introducing a biofuel plant may have been completely different if the analysis method from the viewpoints of energy and exergy was used. The results of $E_{\text{system}}$ and $E_{\text{system}}^{\text{Ex}}$ can highlight improvements in the system, and it is easy to work with different types of energy, as shown in Eqs. (12) and (13). Therefore, $E_{\text{system}}^{\text{Ex}}$, which contain physical quantities of exergy and $E_{\text{system}}$, was suitable for the evaluation method using a system design approach.

In this simulation, 28,193 ha, which significantly exceeds 5,851 ha of the current field area of Utsunomiya City, was required to satisfy the biofuel demand of the final benefit.
53,000 ha, which exceeds 41,684 ha of Utsunomiya City, was required to satisfy the electricity demand. Therefore, there is significant variation between current field areas and future expected field areas. If the biofuel production field areas are unable to satisfy the energy demand, an energy shortage may occur. Suitable management, such as an agricultural extension for promoting the highest yield production in similar cultivation areas, and the introduction of an energy import system from outside of Utsunomiya City should be considered. If fuel production areas were strongly promoted, they might cause a deficit of food in Utsunomiya City. The production of biomass energy crops for the purpose of fuel production may deplete land areas that are designated for agricultural production. Potential areas for biofuel production and food production should be evaluated to avoid a food shortage in Utsunomiya City. In this simulation, a reduction in final benefit is needed to introduce biofuel production in Utsunomiya City. A more stable and efficient system design of biofuel production can be achieved by employing the proposed evaluation function and conventional flow diagram of system design.

Conclusions

1) The evaluation function by energy $E_{\text{system}}$ of the energy concept and $E_{\text{system}}^{\text{EX}}$ of the exergy concept were proposed for biofuel production to analyze the consistency between energy production and energy consumption, to achieve final benefits, and to analyze available energy. The Exergy Profit Ratio (ExPR) was also proposed instead of the Energy Profit Ratio (EPR) from an exergy analysis standpoint.

2) In the calculation of minimum field area of biomass production based on societal demand in household of Utsunomiya City, 17,500 ha was the minimum value by $E_{\text{system}}$ and 29,500 ha was the minimum value by $E_{\text{system}}^{\text{EX}}$ under the case of lighting: 100% electricity; heating: 89% electricity and 11% of vapor. On the other hand, 17,000 ha was the minimum value by $E_{\text{system}}$ and 29,000 ha was the minimum value by $E_{\text{system}}^{\text{EX}}$ under the case of lighting: 100% electricity; and heating: 100% electricity and 100% of vapor.

3) If EPR and $E_{\text{system}}$ of bioethanol & electricity production were underestimated for a minimum field area, ExPR and $E_{\text{system}}^{\text{EX}}$ can be used to maintain the results of introducing biofuel production to prevent a field area shortage for biofuel production. EPR and $E_{\text{system}}$ are categorized as quantity evaluations of energy, and ExPR and $E_{\text{system}}^{\text{EX}}$ are categorized as quality evaluations of energy. Thus, the values of ExPR and $E_{\text{system}}^{\text{EX}}$ should be examined when more than two types of energy are considered in the design of biofuel production.

4) The results of $E_{\text{system}}$ and $E_{\text{system}}^{\text{EX}}$, in particular, can reveal improvements in the system. Therefore, $E_{\text{system}}^{\text{EX}}$, which contains physical quantities of exergy, and $E_{\text{system}}$ were suitable for the evaluation method using a system design approach.

References


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