엑서지 흐름을 이용한 해양 생물체 자원 이용 시스템의 포괄적인 평가

구로다 카나[†] · 나가타니 나오키 · 오쓰카 코지
일본 오사카부립대학 해양시스템공학과

Comprehensive Assessment of the Utilization System for Marine Biomass Resources Using Exergy Flows

Kana Kuroda[†], Naoki Nakatani and Koji Otsuka

Department of Marine System Engineering, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan

요 약

최근들어 육상의 인간 활동에 의한 다량의 오염물질 부하에 기인하여 연안에서 심각한 환경 문제가 발생하고 있다. 따라서 해양 생물체 이용 시스템이 육지와 해양간의 물질 순환을 시도하기 위하여 제안되었다. 포괄적인 평가는 제안된 시스템이 적절하고 지속가능한지를 밝힐 필요가 있다. 본 연구는 에너지의 질을 표현하고, 물질 순환 시스템에서 흐르는 물질과 에너지를 묘사하는 열역학적 개념의 엑서지를 도입하였다. 본 연구는 일본 오사카 중부에 위치한 사카이시의 물질 순환 시스템 내에서 물질, 에너지, 그리고 엑서지 흐름들을 제공한다. 엑서지는 엑서지 효율적인 물질 순환 시스템 내에서 무엇이 주요 역할인지 잘 이해하는데 도움을 주는 것으로 밝혀졌다.

Abstract – In recent years, serious environmental problems occur in coastal area due to high pollution loads from human activity in land. Marine biomass utilization system therefore has been proposed to prompt material circulation between land and sea. Comprehensive assessment is necessary to determine that the proposed system is suitable and sustainable. This study introduces thermodynamic concept exergy, which expresses energy quality, to describe material and energy flowing in the material circulation system. This study presents material, energy and exergy flows in the material circulation system at Sakai city located in the middle of Osaka in Japan. It is found that exergy helps a better understanding of what is a key role is in exergy-efficient material circulation system.

Keywords: Comprehensive assessment(포괄적인 평가), Energy(에너지), Exergy(엑서지), Marine biomass(해양 생물체), Material balance(물질 균형), Material circulation(물질 순환)

1. INTRODUCTION

Industrialized world is heavily dependent on fossil fuels, which are major sources of energy and related products. As a result, we face the shortage of energy resources. To overcome recent crisis, attention is increasing to marine biomasses as energy resources. In a land basis, human community has been recently shifting to a recycling society. On the other hand, discharged waste from land to sea such as carbon and nutrient (e.g., nitrogen and phosphorus) is not reused and stocked as a

sediment organic matter in an enclosed sea. Natural purification capacities, therefore, are overloaded and thus it causes serious environmental problems such as red tide, and “green tide”, which is similar to red tide and is a phenomenon that green algae propagate explosively. One of the proposed measures to solve these serious problems is to take them up from sea to land and to use them as energy resources in land. Green algae decrease nutrient concentration of seawater since they store carbon and nutrient. Marine biomass utilization system based on above concept has attracted recent attention since it would contribute to improve marine environment and lead to a sustainable society without relying on fossil fuels. From the environmental point of view, Otsuka [2010] mentioned that this

[†]Corresponding author: kuroda_k@marine.osakafu-u.ac.jp
This paper was selected and reviewed for publication from EAWOMEN2 2011

system has a high low-carbon effect and contributes to reduce food mileage.

A comprehensive assessment, which addresses the sustainability and the best system in regional or global area, is required to design a suitable material circulation system. Unsuitable design would make the situation worse. In general, Life Cycle Assessment with carbon dioxide or other specific materials, material and energy balance have been used for quantitative analysis in a material circulation system, especially industrial system. Moriguchi [1999] used Material Flow Accounting (MFA), which focus on material mass flow based on weight unit, to examine the present state of recycling and waste management both in China and in Japan. Yamamoto *et al.* [2009] improved MFA by introducing the viewpoint of energy called virtual energy and calculated virtual energy of steel scrap and used cars between Japan and abroad. In order to assess whole circulation system, not only flows of material and energy but also their effect to the environment, in other words diffusion effect, should be considered. Therefore, the authors focus on thermodynamic concept exergy, one of the thermodynamic parameters. Exergy, which is called available energy, is defined as a maximum amount of work which can be produced by a flow of material or energy as it comes to equilibrium with a reference environment. Exergy analysis uses the conservation of mass and energy principles together with the second law of thermodynamics and has been widely used in various research fields. Jorgensen [1992] introduced exergy for ecological modeling to understand the function of ecosystem. In industrial system, Rosen [1995] examined the thermodynamic performance of a water-electrolysis process for producing hydrogen with energy and exergy analyses. From the viewpoint of resource accounting, Wall *et al.* [1994] applied an exergy concept to Italy society and described how exergy is consumed from the resource base to the consumers. As an example of applying the exergy concept to the material circulation in local area, Takahashi and Shukuya [1998] used an exergy analysis to garbage composting system in Tokyo and described various types of material and energy such as vegetables, water and LNG in terms of exergy. However, how exergy should be utilized has not been well examined.

The purpose of this study is to conduct a comprehensive assessment of marine biomass utilization system using exergy concept. The present situation in Sakai city, located in Osaka, Japan and the marine biomass utilization system are described by nitrogen and exergy and are examined from the viewpoint of food self-sufficient, dependence on fossil fuels and natural resources utilization.

2. MARINE BIOMASS UTILIZAION

2.1 Concept

In many Japanese eutrophic shallow water areas, green tide, a phenomenon of explosive propagation of green algae, often occurs in summer season. When a lot of green algae die and accumulate on the sea bottom or beach, large amount of their bodies are spoiled and cause destructive damages to benthic ecosystem. They are conventionally burned in a combustion plant consuming fossil fuels. However, green tide species, mostly *Ulva* sp. and *Enteromorpha* sp., have a very high growth rate, and effectively fix carbon and nutrient. Therefore, if we take them up from the sea and utilize them before their accumulation to sediment, we can reduce the nutrient concentration of seawater and also can expect low-carbon effects such as reduction of the supplementary fuels for combustion. Eutrophication is caused by loads of organic matter and nutrient due to our living activities. In other words, the utilization of biomasses of green tide species is a kind of recycle processes of these CNP (Carbon, Nitrogen and Phosphorus) wastes. Fig. 1 illustrates the proposed utilization system based on a CNP recycle using marine biomass. Marine biomass cultivation system is expected to effectively grow marine biomasses and reduce the nutrient concentration. The authors consider *Ulva* sp. called sea lettuce as a targeted marine biomass. Sea lettuce is cultivated in a pond, in which sea water is easily exchanged and sufficient nutrient is supplied to sea lettuce. A lot of marine biomass produced by green tide and cultivation are harvested before their accumulation and decomposition. Methane fermentation plant, which converts marine biomass to energy resources and residue, which can be used as liquid fertilizer. The plant is assumed to treat household garbage.

Fig. 1. Concept of marine biomass utilization system.

Fig. 2. Location of Sakai city and Sakaihama area.

2.2 Marine Biomass Utilization System Between Land and Sea

Sakai city, the secondly largest city (150 km²) in Osaka Prefecture, is located in the middle of Kinki area and Osaka bay is next to Sakai city shown in Fig. 2. Population is 0.84 million. Area for farming is 0.15 km², 10% of Sakai city, and most area is urban area. Sakai hama area, northeast part of Osaka bay is targeted for Marine biomass utilization system. Eutrophic water carried by Yamato river flows into Kitahakuchi, an enclosed area, and therefore its nutrient concentration remains very high.

Fig. 3 shows flow diagram, which describes material and energy flow on household in Sakai city. It consists of household, water supply, electricity generation facility, gas supply facility, rice field and crop land, waste water treatment and incineration

Fig. 3. Material and energy flow in the present system.

Fig. 4. Material and energy flow in marine biomass utilization system.

system. Water is supplied to household for drinking and waste water treatment. Rice and vegetable produced in the city are consumed in household and most of food is provided from outside Sakai city. Electricity and gas are consumed in household. Garbage is burned in Sakai city and its burned ash is filled in landfill. Household waste water flows to sea after treatment. Water for farming is supplied from irrigation system and rainfall. Fig. 4 shows flow diagram, which applies utilization system for marine biomass resources. Sea lettuce is effectively harvested in Kitahakuchi and is grown in artificial tidal flat to effectively absorb nutrient in discharged waste. It is mixed with garbage and is utilized at methane fermentation plant. They are decomposed into biogas, a mixture of methane and carbon dioxide. Methane gas is purified from biogas and is used for electricity, which is provided to the methane fermentation plant and other facilities. A digestive sludge from methane fermentation is utilized as a liquid fertilizer for farming and afforestation.

3. APPROACH AND HETHODOLOGY

3.1 Exergy

Exergy, which is called available energy, is the maximum amount of work which can be produced by a material or energy quantity as it is brought into equilibrium with a reference environment, and is therefore a measure of the usefulness or quality of energy. Following the second law of thermodynamics, exergy is consumed due to the generation of entropy in an irreversible process. Exergy, X , in a closed system is generally defined as

$$X = (H - H_0) - T_0 \cdot (S - S_0) \quad (1)$$

where H and S is enthalpy and entropy, respectively. The subscript '0' denotes conditions of the reference environment. T_0 is the environment temperature. Exergy can express different forms of energy and therefore it becomes possible to consider energy quality. This study uses fundamental exergy equations in a steady state presented as below.

Organic compound refers to Takahashi *et al.* [1998] and is expressed as

$$X = m \cdot H_i \cdot \left(1.0064 + 0.1519 \frac{\phi_H}{\phi_C} + 0.0616 \frac{\phi_O}{\phi_C} + 0.0429 \frac{\phi_N}{\phi_C} \right) + m \cdot R \cdot T_0 \left(\frac{\phi_C}{M_C} \ln \frac{1}{x_{CO}} + \frac{\phi_H}{2M_H} \ln \frac{1}{x_{vo}} + \frac{\phi_N}{2M_N} \ln \frac{1}{x_N} \right) - m \cdot R \cdot T_0 \left(\frac{\phi_C}{M_C} + \frac{\phi_H}{2M_H} - \frac{\phi_O}{2M_O} \right) \ln \frac{1}{x_{CO}} \quad (2)$$

where m is dry weight and H_i is lower heating value; ϕ , x and M are the composition ratio, molar fraction and molecular weight, respectively. Subscript H , C , O , N describes hydrogen, carbon, oxygen and nitrogen, while subscript co and vo are carbon dioxide and vapor, respectively. R is gas constant. The first term in right side means the exergy of solid fuels proposed by Nobusawa [1976] and second and third term express material diffusion.

Concentration is defined as

$$X = \frac{m}{M} R T_0 \ln \frac{x_i}{x_{i0}} \quad (3)$$

where x_i is the molar ratio of substances i .

Water for evaporation is defined as

$$X = \frac{m_w}{M_w} R T_0 \ln \frac{p_{vs(T_0)}}{p_{vo}} \quad (4)$$

where $p_{vs(T_0)}$ and p_{vo} describes saturated vapor pressure at temperature T_0 and vapor pressure at the reference environment, respectively. Subscript 'w' is water.

Kinetic exergy of water is defined as

$$X = \frac{1}{2} \rho v^2 q \quad (5)$$

where ρ , v and q are fluid density, mean velocity and flow volume, respectively.

Chemical substance, which refers to Sciubba and Wall [2007],

is expressed with replacing the first term in Eq. (2) with the change of Gibbs free energy, ΔG , as follows:

$$X = -\frac{m}{M} \cdot \Delta G_{(T_0)} + m \cdot R \cdot T_0 \left(\frac{\phi_C}{M_C} \ln \frac{1}{x_{CO}} + \frac{\phi_H}{2M_H} \ln \frac{1}{x_{vo}} + \frac{\phi_N}{2M_N} \ln \frac{1}{x_{no}} \right) - m \cdot R \cdot T_0 \left(\frac{\phi_C}{M_C} + \frac{\phi_H}{2M_H} - \frac{\phi_O}{2M_O} \right) \ln \frac{1}{x_o} \quad (6)$$

Chemical exergy of organic matter in wastewater using *BOD* is presented by Takahashi *et al.* [2008]. Chemical exergy with *BOD* is calculated by

$$X = 0.0273 BOD \quad (7)$$

The exergy of light oil is given by Rant [1961] and is calculated with lower heating value as below.

$$X = 0.975 H_i \quad (8)$$

Direct solar radiation is followed by Kabelac and Drake [1992] and exergy and entropy of solar radiation are expressed as

$$X_{sun} = H_{sun} - S_{sun} \cdot T_0 \quad (9)$$

$$S_{sun} = 0.00046 H_{sun}^{0.9} \quad (10)$$

3.2 Assumptions of calculation

It is assumed that system is at steady state in a steady-flow process. Temperature and relative humidity for exergy calculation are 290 K and 63%, respectively, which are average temperature and relative humidity in Sakai city. Reference air environment for exergy calculation is presented in Table 1. Characteristics of sea lettuce, garbage and sludge are shown in Table 2. The characteristics of sea lettuce are based on the sample taken in 2004 at Rinku park, located in southern Osaka. Garbage and sludge are referred to Takahashi *et al.* [1998] and Oshita *et al.* [2008], respectively.

Material and energy that flow into household and the farming area refer to the statistics in Sakai city except below. Electricity consumed in household is assumed to be 300 kWh per month. Amount of food except rice and vegetable is deter-

Table 1. Reference environment of land in mole fraction

N ₂	O ₂	CO ₂	Ar
0.771	0.207	0.0003	0.00915

Table 2. Characteristics of sea lettuce, garbage and sludge

	TS [kg kg ⁻¹]	C [%-TS]	N [%-TS]	H [%-TS]	O [%-TS]	Lower heating value [MJ kg ⁻¹]
Sea lettuce	0.120	37.8	4.9	5.1	31.5	14.7
Garbage	0.202	50.3	4.7	7.2	37.7	17.7
Sludge	0.005	35.4	5.5	7.2	31.5	15.0

mined based on daily required amount of food for human. Required water for rice field is $1.5 \text{ million m}^3 \text{ ha}^{-1}$, which is partially supplied by rainfall. Water for crop land is assumed to be supplied by rainfall. Nitrogen required for fertilizer is 100 kg ha^{-1} for rice field, 265 kg ha^{-1} for crop land according to the fertilizer standard in Nara Prefecture in Japan. Marine biomass cultivation system in Kitahakuchi uses 44 ha areas, 80% of the area of Kitahakuchi. Sea lettuce is chosen as a cultivated species and is harvested with keeping its weight 1.0 kg m^{-2} , leading to be harvested $35,600 \text{ t y}^{-1}$. In the artificial mudflats, ecosystem model developed for an artificial lagoon (Otsuka and Natakani [2001]) estimates that 2,600 tons of sea lettuce are yearly available.

System with utilization system for marine biomass resources requires three methane fermentation plants, whose treatment capacity is 80 t d^{-1} , since it treats all household garbage in Sakai city with harvested sea lettuce. Required electricity for each facility is estimated to be $7,385 \text{ GJ y}^{-1}$ based on the plant in Hida city, Oita, which processes same amount of the assumed capacity. Biogas volume produced from garbage and sea lettuce is 122 and $52.4 \text{ Nm}^3 \text{ t-wet}^{-1}$, respectively. Methane concentration is 0.52. Lower heat value of biogas and methane is 21.6 and 36 MJ m^{-3} , respectively. Electricity generation efficiency is assumed to be 0.3.

4. RESULTS AND DISCUSSION

Estimated results of yearly nitrogen flows at present Sakai city are shown in Fig. 5. Nitrogen input into household is $3,808 \text{ t y}^{-1}$ in total as food. Sakai city can produce 64 t y^{-1} , which is 1.7% of nitrogen in consumed food. This indicates that Sakai city is far from local production for local consumption. Nitrogen in garbage is 476 t y^{-1} and $1,111 \text{ t y}^{-1}$ are diffused into sea after waste water treatment. It is noted that there are no way to take nitrogen from sea to land, and therefore nitrogen keeps storing in sea. Figure 6 shows the estimated exergy flow at present Sakai city. Compared to nitrogen flow, it expresses natural exergy such as sun and rainfall, exergy originated from fossil fuels, water exergy and exergy related to biomass in the same unit, TJ y^{-1} . This means that exergy can offer a comprehensive assessment with expressing various material and energy. Household receives various resources $6,360 \text{ TJ y}^{-1}$ in total and consumes $5,890 \text{ TJ y}^{-1}$. Since most food and chemical fertilizer are transported from the outside the city, light oil for transportation is consumed proportional to the amount of food and fertilizer. It is noted that garbage has 210 TJ y^{-1} , indicating that it

Fig. 5. Nitrogen flow in present Sakai city [t y^{-1}].

Fig. 6. Exergy flow in present Sakai city [TJ y^{-1}].

has an ability to work to the environment even if it is generally considered as a waste. However, present system does not have a way to use garbage as resources. Waste water treatment system decreases exergy of waste water in household from 390 TJ y^{-1} to 10 TJ y^{-1} as treatment water.

Figure 7 presents the results of yearly nitrogen flows in the marine biomass utilization system. Digestive water contains 453 t y^{-1} , which can be provided 130 t y^{-1} as a liquid fertilizer to rice field and cropland. If rice field and cropland not be used at present are assumed to be available, additionally 75 t y^{-1} can be supplied as a fertilizer. Fertilizer for mountain and forest is also possible and available area is 4 km^2 , requiring 60 t y^{-1} . However, still 187 t y^{-1} are available even if as much as nitrogen can be assumed to be used in land. If remaining nitrogen is assumed to be all used in cropland, it requires 7 km^2 , which is 4.6% of Sakai city. Since Sakai city does not have enough area at present, it needs to increase the area of cropland. Additional option is that

Fig. 7. Nitrogen flow in marine biomass utilization system [$t\ y^{-1}$].

remaining nitrogen can be provided to the cities around Sakai city, which afford enough area for cropland. If remaining nitrogen, 187 $t\ y^{-1}$, is provided to the cities within 20 km distance from Sakai city, 91 $t\ y^{-1}$ of nitrogen contained in vegetables can be back to the household. This implies that it is necessary to carefully determine the amount of garbage to be processed in methane fermentation and the cultivation area of sea lettuce since Sakai city does not have enough area to use a liquid fertilizer. The estimated exergy flow of the system with utilization system for marine resources is presented in Fig. 8. Produced electricity in methane fermentation can be used in the methane fermentation plant and is provided to waste water treatment facility, where 23% of the required electricity can be supplied. Compared to present system, the results show that utilization system is effective in reducing LNG and light oil by 220TJ y^{-1} and 8.2TJ y^{-1} , respectively.

Fig. 8. Exergy flow in marine biomass utilization system [$TJ\ y^{-1}$].

Attention will now be given to the food exergy self-sufficiency ratio and LNG exergy reduction one. The food exergy self-sufficiency ratio is determined by dividing the food exergy produced in inside the city by food exergy required for household, while LNG exergy reduction ratio is calculated by dividing the reduction amount of LNG by LNG required in Sakai city at present. Food exergy self-sufficiency ratio of present and the utilization system is 0.05% and 6.6%, respectively. LNG exergy reduction rate is 1.8%. Since the utilization system prompts nitrogen circulation by increasing the nitrogen circulation path, it improves food exergy self-sufficiency ratio. An additional remark is that seaweed has higher natural exergy utilization ratio per unit area than biomass produced in land. Natural exergy utilization ratio is defined by dividing produced biomass by natural exergy such as sun and water. Seaweed and food produced in land are 8.7 and 0.06, respectively. This indicates that marine biomass can be more effectively produced from the viewpoint of land area use.

5. CONCLUSIONS

This study applied exergy concept and attempted comprehensive assessment of material circulation in Sakai city. Nitrogen and exergy flow in present Sakai city and the utilization system for marine biomass resources were presented. As shown in Figs. 6 and 8, various resources including natural resources, fossil fuels and biomasses are expressed in a same unit and are therefore evaluated together. It was found that proposed utilization system takes up more nitrogen from sea to land and is slightly more effective in reducing LNG consumption and improving food self-sufficiency ratio. On the other hand, it requires more land to use nitrogen as liquid fertilizer. When nitrogen can be provided to the cities around Sakai city, transportation exergy is required and therefore the areas should be chosen with the light oil consumption minimized as possible. Natural exergy utilization ratio indicates that marine biomass has higher productivity than biomass in land. Expected necessary steps are therefore to find marine biomasses with higher productivity. These considerations showed that assessment with exergy concept provides useful viewpoint for designing a suitable material circulation system.

REFERENCES

- [1] Jorgensen SE., 1992, "Exergy and ecology", Ecological Modelling, 63, 185-214.

- [2] Kabelac, S. and Drake, F.D., 1992, "The entropy of terrestrial solar radiation, Solar Energy", Vol 48, No 4, 239-248.
- [3] Moriguchi Y., 1999, "Recycling and waste management from the viewpoint of material flow accounting", J Mater Cycles Waste Manag, 1, 2-9.
- [4] Nobusawa, T., 1976, "Exergy calculation applied method, Fuel and Combustion", Vol 43, No 11, 49-79 (in Japanese).
- [5] Oshita, K., Mori, A., Takaoka, M., Takeda, N., Matsumoto, T. and Kitayama, A., 2008, "Fundamental study on the composition and heating value of char, tar and gas from sewage sludge pyrolysis", Japan Society of Civil Engineers, Vol 64, No 3, 221-230 (in Japanese).
- [6] Otsuka, K. and Nakatani, N., 2001, "Estimation of Carbon and Nutrient Fixation Effects of an Artificial Lagoon in Osaka Bay", Proc of 20th International Conference on Offshore Mechanics and Arctic Engineering, OMAE01/OMS-5036, 1-8.
- [7] Otsuka, K., 2010, "A feasibility study of marine biomass utilization system in Osaka bay", Proc Renewable Energy 2010.
- [8] Rant, Z., 1961, Warmetechn, 10, 172.
- [9] Rosen, MA., 1995, "Energy and exergy analyses of electrolytic hydrogen production", Int. J. Hydrogen Energy, Vol 20, No 7, 547-553.
- [10] Sciubba, E. and Wall, G., 2007, "A brief Commented History of Exergy From the Beginning to 2004", Int. J. of Thermodynamics, Vol 10, No 1, 1-26.
- [11] Takahashi, I. and Shukuya, M., 1998, "An exergy analysis of the circulation of matter obtained from composting garbage in urban area", J Archit. Plann. Environ. Eng., No 510, 23-29 (in Japanese).
- [12] Takahashi, I., Shiino, W., Torikai, M. and Fuse, Y., 2008, "A field measurement of a residential plumbing system recycling rainwater and greywater and its exergy analysis", J. Environ. Eng., Vol 73, No 623, 39-45 (in Japanese).
- [13] Wall, G., Sciubba, E. and Naso, V., 1994, "Exergy use in the Italian society", Energy, Vol 19, No 12, 1267-1274.
- [14] Yamamoto, H., Yada, T., Nakamura, M. and Yamaji, K., 2009, "Material Flow Analysis Using a Concept of Virtual Energy", J Japan Society Energy Resources, Vol 31, No 1, 1-9 (in Japanese).

2012년 3월 2일 원고접수

2012년 5월 8일 심사수정일자

2012년 5월 18일 게재확정일자