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Utilization of Marine Biomass for Bioenergy: Fuel Cell Power Generation Driven by Biogas Derived from Seaweed (September 2006)

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Abstract *- This paper discusses the utilization of marine biomass as an energy resource in Japan. A marine biomass energy system in Japan was proposed consisting of seaweed cultivation (Laminaria japonica) at offshore marine farms, biogas production via methane fermentation of the seaweeds, and fuel cell power generation driven by the generated biogas. We estimated energy output, energy supply potential, and CO_2 mitigation in Japan on the basis of the proposed system. As a result, annual energy production was estimated to be 1.02×10^9 kWh/yr at nine available sites. Total CO_2 mitigation was estimated to be 1.04×10^6 tonnes per annum at the nine sites. However, the CO_2 emission for the construction of relevant facilities is not taken into account in this paper. The estimated CO_2 mitigation is equivalent to about 0.9% of the required CO_2 mitigation for Japan per annum under the Kyoto Protocol framework.*

Keywords **- CO_2 mitigation, fuel cell power generation, *laminaria japonica*, marine biomass, seaweed.**

1. INTRODUCTION

Global warming has become one of the most serious environmental problems. To cope with the problem, it is necessary to substitute renewable energy for nonrenewable fossil fuel. Biomass, which is one kind of renewable energy, is considered to be carbon-neutral, meaning that the net CO_2 concentration in the atmosphere remains unchanged provided the CO_2 emitted by biomass combustion and that fixed by photosynthesis are balanced. Biomass is also unique because it is the only organic matter among renewable energies. In other words, fuels and chemicals can be produced from biomass in addition to electricity and heat.

Marine biomass has attracted less attention than terrestrial biomass for energy utilization so far, but is worth considering especially for a country like Japan which has long available coastlines. Japan has an Exclusive Economic Zone of about 4.05×10^6 km^2, the sixth largest in the world. If the sea area is utilized efficiently, a vast amount of renewable energy could be made available. In addition, native seaweeds often form submarine forests that serve as habitats for fish and shellfish, and so if a marine biomass energy system is realized, it may boost the production of marine food and promote the marine energy industry leading to CO_2 mitigation.

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The use of marine biomass energy was investigated in the United States [1] and Japan [2] as an alternative energy in the 1970's after the oil crises, but the studies were discontinued when oil prices stabilized. However, now that global warming has become one of the most serious problems to be solved, we should reconsider the use of marine biomass energy as a means to mitigate CO_2 emissions.

The idea of using marine biomass for energy was first conceived by Howard Wilcox in 1968 [1]. At that time, the marine biomass energy program was conducted jointly among governmental organizations, universities, and private corporations in the United States until 1990 [1]. The program proposed using giant brown kelp (*Macrocystis pyrifera*) as a cultivation species, which is a kind of brown algae that grows rapidly and may reach up to 43 m long [1]. In Japan, research on energy production from marine biomass was conducted from 1981 to 1983 [2]. *Laminaria japonica*, one of the largest seaweeds in Japan, was proposed as a cultivation species and an energy production system using *Laminaria japonica* was designed. Figure 1 shows a schematic diagram of the marine biomass energy system that was designed and Fig. 2 illustrates the system. Seaweeds are cultivated at an offshore farm and then harvested and transported by vessels. Biogas is produced from seaweeds via methane fermentation. In order to supply nitrogen and phosphorus as main nutrients, several methods have been proposed, including using pumps to upwell deep-sea water rich in nutrients or fertilizing directly. Before methane fermentation, extraction of chemicals such as chlorophyll, carotene, poly-phenol, and vitamin was proposed in the research.

The income from by-products is so large that the system designed in the research would be economically unfeasible unless by-products were extracted, yet the by-product extraction consumes so much energy that the net energy produced was negative in the system [2].

In this study, we propose a new marine biomass system for providing energy. We estimate the energy output, seaweed production potential, and the amount of CO_2 mitigation.

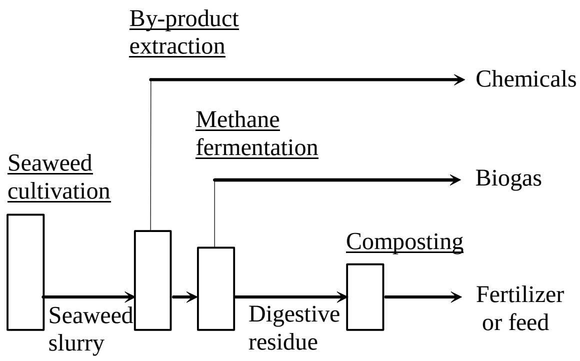

Fig. 1. Schematic of energy and chemicals production process from seaweed.

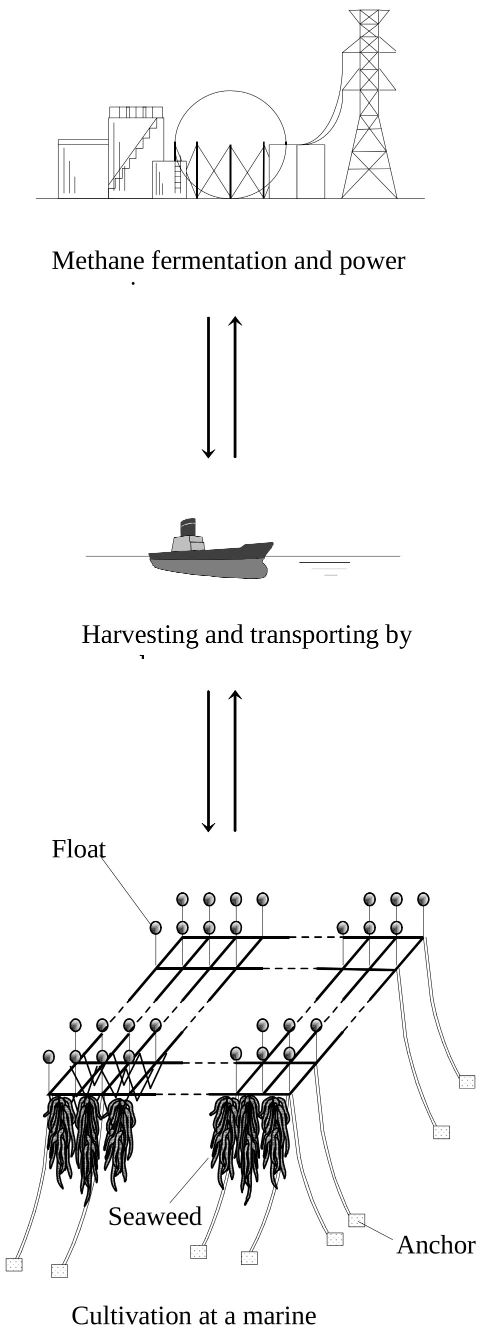

Fig. 2. Illustration of energy production from marine biomass.

2. MARINE BIOMASS ENERGY SYSTEM

In this paper, we propose the marine biomass energy system shown in Fig. 3. A fuel cell power generator was installed and the extracted by-product was eliminated in spite of its economical advantage. The previous study assumed that biogas would be used for city gas not as a fuel for power generation [2]. Fuel cells are now widely known as a clean and potentially efficient source of power generation and the technology will continue to progress, accelerating introduction. In this study, an energy system equipped with a fuel cell power generator is proposed.

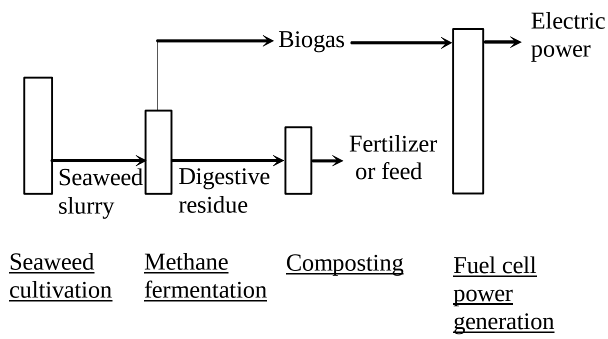

Fig. 3. Schematic of energy production process assumed in this study.

3. SEAWEED CULTIVATION

Seaweed Species for Energy Production

Various seaweeds have been considered to be potential energy crops: *Macrocystis pyrifera*, *Laminaria*, *Gracilaria*, *Sargassum*, *Ulva*, etc. These seaweeds have a high productivity which is required for energy production. *Macrocystis pyrifera* may be the most appropriate species among them because it grows quickly to large sizes, and can be harvested several times a year. In addition, its biochemical methane potential is larger than that of other seaweeds like *Laminaria* or *Sargassum* [3]. However, *Macrocystis pyrifera* does not grow in Japan. Among the seaweeds indigenous to Japan, the best species for energy production is considered to be *Laminaria japonica*, as it grows faster than any other seaweed in Japan. Table 1 shows data on the productivity of *Laminaria japonica* and *Macrocystis pyrifera* for reference. *Laminaria japonica* was chosen as the species for energy utilization in this study; it consists of volatile solids (VS), ash, and moisture. Figure 4 shows a typical example of the composition.

Japan is an island country surrounded by the sea, consisting of four main islands: Honshu, Hokkaido, Kyushu, and Shikoku. In general, the coast of southern Japan is influenced by the Kuroshio Current and the Tsushima Current, both of which are warm currents. Northern Japan is influenced mainly by the Oyashio Current, a cold current. Figure 5 shows the drifts of ocean currents around Japan. In general, seaweeds are larger in colder sea areas than warmer ones. *Laminaria japonica* grows along the coast of southern Hokkaido and the Pacific coast of the northeastern part of Honshu, where the sea temperature is cold due to the influence of the cold current.

Table 1. Productivity of Laminaria Japonica and Macrocystis Pyrifera

Species	VS yield (kg-VS/m^2/yr)	Methane yield (Nm^3/kg-VS)
Laminaria japonica	2.7[a]	0.25-0.28[b]
Macrocystis pyrifera	3.7[a]	0.39-0.41[c]

[a]Source:Investigation into fuel production from marine biomass[2].
[b]Source: [2] and Biochemical methane potential of biomass and waste feedstocks, Biomass and Bioenergy 5(1): 95-111[3].
[c]Source: [3].

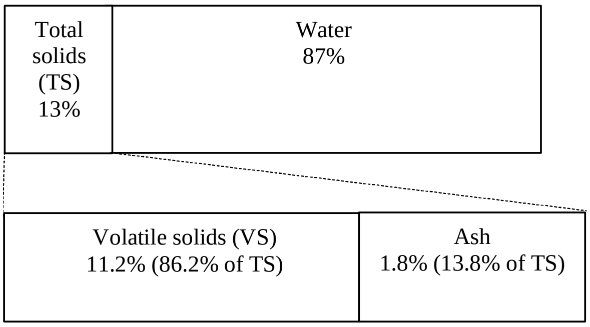

Fig. 4. Composition of Laminaria Japonica [2].

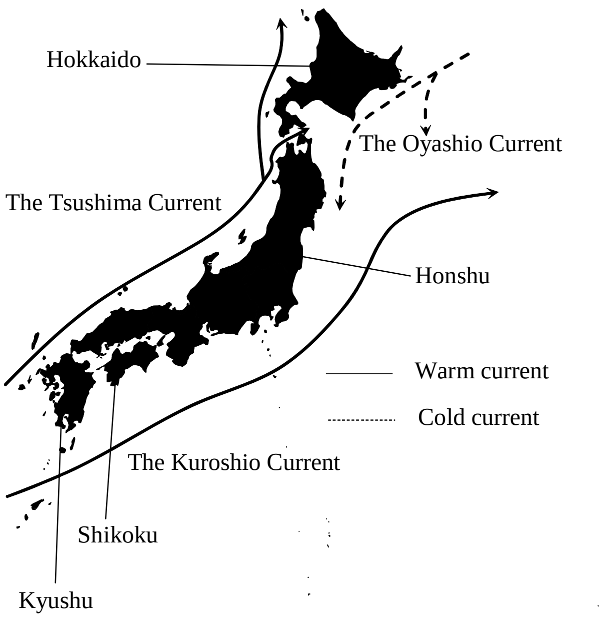

Fig. 5. Ocean currents around Japan.

Production of Laminaria japonica

It was assumed that *Laminaria japonica* is cultivated at offshore marine farms. As already shown in Fig. 2, the marine farm is anchored in position and floats on the surface of the sea. A marine farm of 41.2 km^2 area, 5120 m wide and 8050 m long, was designed at a distance of 8 km from the coast in the previous study [2].

Two methods of artificial cultivation of *Laminaria japonica* as food are practiced in Hokkaido: biennial cultivation and forced cultivation [4]. It takes two years from seeding to harvesting by the former method whereas the forced cultivation takes one year for harvesting. It is desirable that harvesting can be done all year round with a view to producing energy, to enable the harvesting ships to be operated continuously and to reduce the kelp storage time, thus reducing cost. In the previous study, one-year cultivation was proposed and the cultivation was scheduled on the assumption that year-round harvesting was possible. Table 2 shows the yield of *Laminaria japonica* estimated in the previous study taking account of the above conditions [2]. It was estimated that 1.00×10^6 tonnes of *Laminaria japonica* was produced per annum at one site, consisting of 0.112×10^6 tonnes of volatile solids, 0.0180×10^6 tonnes of ash, and 0.870×10^6 tonnes of moisture.

Table 2. Yield of Laminaria Japonica per Annum at One Site and Its Composition [2]

Kelp yield (10^6 kg wet wt)	Volatile solids (10^6 kg)	Ash (10^6 kg)	Water (10^6 kg)
1 000	112	18	870

4. METHANE FERMENTATION

Harvested raw kelp is dried, stored, and then sent to the methane fermentation process. The extracted by-product is ignored in the marine biomass energy system in this study, so all kelp is sent to the methane fermentation process.

Table 3 shows the basic parameters of the methane fermentation process [2]. One-phase methane fermentation was planned in the previous study. The energy produced at one site per annum is estimated to be 1.02×10^{15} J/yr (LHV) on the basis of the parameters. H_2S included in the biogas must be eliminated before it is sent to the fuel cell power generation process.

Table 3. Basic Parameters of the Methane Fermentation Process [2]

Biogas yield	0.49 Nm^3/kg-VS
Methane yield	0.25 Nm^3/kg-VS
Loading rate	4 kg-VS/m^3/day
Temperature	35°C
Biogas composition	CH_4 52 vol% CO_2 43 vol% H_2S 0.6 vol%
Product biogas output at one site	5.49×10^7 Nm^3/yr
Heating value of the biogas (LHV)	1.86×10^7 J/Nm^3
Energy output at one site (LHV)	1.02×10^{15} J/yr

5. FUEL CELL POEWR GENERATION

System

In this marine biomass energy system, we propose that a fuel cell is used for the power generation process.

Figure 6 shows the energy and materials flow of the fuel cell power generation system operated by biogas. Biogas is reformed before being sent to the stack where CH_4 is converted into H_2. Reaction (1) and the water gas shift reaction (2) occur in the steam reforming process (3).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (3)$$

Then the reformed gas is sent to the stack, where heat and power are generated. The heat can be used for steam generation or maintaining the temperature of the methane fermentation reactor.

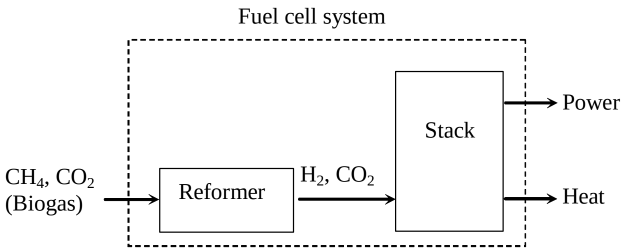

Fig. 6. Schematic of fuel cell power generation fueled with biogas.

Different Types of Fuel Cells

Table 4 shows the characteristics of major fuel cells. As the operating temperature is relatively low, Pt is used as a catalyst in PAFC (phosphoric acid fuel cells) and PEFC (proton electrolyte fuel cells). Since CO poisons Pt, the CO content must be reduced to its tolerable level via reaction (2). On the other hand, in MCFC (molten carbonate fuel cells) or SOFC (solid oxide fuel cells), an expensive metal catalyst like Pt is not necessary because the operating temperature is higher than that of PAFC or PEFC. In addition, CO can be used as fuel for them. MCFC or SOFC are, therefore, desirable for the power generation fed with biogas. Although many 200 kW class PAFC generation systems driven by biogas are operating in Japan, MCFC and SOFC are desirable as they are suitable for MW class systems while PAFC and PEFC are not suitable for such large-scale systems. SOFC is the most suitable fuel cell for the marine biomass energy system because the amount of generated biogas is very large (1.02×10^{15} J/yr). For these reasons, SOFC was selected as the fuel cell of the marine biomass energy system.

Electric Energy Output

The electric power generated by SOFC was estimated. SOFC systems running on biogas derived from agricultural residue, sewage sludge, landfill sites, etc. have been studied [6]-[10]. J. Van herle et al. reported that electric efficiency was 33.8% (LHV) in a 3.1 kW_{el} SOFC cogenerator fed with biogas derived from livestock [8]. Higher electric efficiency will be achieved in the future as technology progresses, so a power generating efficiency of 40% is used in this paper. Electric energy generated at one site per annum was estimated as follows:

Electric energy generated at one site per annum:
$= 1.02\times10^{15}$ J/yr × 0.40
$= 4.08\times10^{14}$ J/yr
$= 1.13\times10^{8}$ kWh/yr

The marine biomass system should be considered in the long term, so this rough estimation is adequate.

Table 4. Characteristics of Major Fuel Cells

Type	Operating temperature*	Fuel	Applications*
PAFC	About 220°C	H_2	Widely used for 200 kW class CHP systems
PEFC	30-100°C	H_2	Small capacity systems like Motor vehicles, mobile devices
MCFC	About 650°C	H_2, CO	Middle to large CHP systems, MW class CHP systems
SOFC	500-1000°C	H_2, CO, CH_4	2 kW to several MW class CHP systems, covering the widest range of capacity

*Source: Fuel cell systems explained [5].

6. ENERGY POTENTIAL

The energy potential of this system in Japan was calculated. We considered how many plants are feasible in Japan taking account of biological restrictions of *Laminaria japonica*, restrictions on infrastructures, and on the state of sea areas. First, seaweeds should be cultivated in the sea areas where the native seaweeds grow, namely off the coast of Hokkaido and the Pacific coast of the northeastern part of Honshu. This is because in such sea areas, the nutrient concentration in the sea water and the water temperature are suitable for the growth of the seaweed growth, but this restriction will be eased by breed improvements.

Second, the restriction of infrastructures must be considered as an absolute prerequisite for realization of the marine biomass energy system. It is not economically realistic to construct a new large-scale port that has facilities capable of landing 1.00×10^{6} tonnes of seaweed per annum. Hence, it was decided that existing large-scale ports would be used for the landing.

Third, the cultivation should not be done along coastlines that are reached by drift ice, because in such areas transplanting and harvesting would be difficult and a large amount of energy would be required for maintaining the temperature of the fermentation reactor.

Judging from the data from the website of the Ministry of Land, Infrastructure and Transport, Hokkaido Regional Development Bureau [11] etc., nine ports satisfy the above conditions: Port of Nemuro, Kushiro, Tokachi, Tomakomai, Muroran, Otaru, Ishikari, Rumoi, and Hachinohe. One plant is assumed to be constructed near each respective port.

The amount of seaweed produced is assumed to be the same all over the sea area. Table 5 shows the potential of *Laminaria*, biogas, and electricity estimated on the basis of the above assumptions. The calculation was made by simple multiplication of the figures in Tables 2 and 3 by nine.

Table 5. Potential of Laminaria, Biogas, and Electricity at One Site of the Marine Biomass Energy System

Laminaria (10^6 kg wet wt/yr)	Biogas (Nm^3/yr)	Electricity (kWh/yr)
9 000	4.94×10^8	1.02×10^9

7. CO_2 MITIGATION

The amount of CO_2 mitigation was calculated on the assumption that the marine biomass energy system replaces coal-fired power generation systems.

We defined x_0 [kg-CO_2] as the amount of CO_2 emitted by burning coal, x_0' [kg-CO_2] as the amount of CO_2 emitted by transporting coal, running the facilities, and constructing the power generation plant, and y_0 [kWh/yr] as the power supply of the coal-fired power generation. Then, x_1' [kg-CO_2] as the amount of CO_2 emitted by running the facilities of the marine biomass energy system, and y_1 [kWh/yr] as the power supplied by the system, were defined. Accordingly, the amount of CO_2 mitigation is estimated by the following calculation.

The amount of net CO_2 mitigation by employing the marine biomass energy system instead of coal-fired power generation:

$$= y_1 \times (x_0 + x_0') / y_0 - x_1' \text{ [kg-CO}_2\text{/yr]}$$

Figure 7 shows the flow of CO_2 and energy in a coal-fired power generation and a marine biomass energy system. CO_2 emission for the construction of the relevant facilities was not taken into account in this paper.

Table 5 shows that the electricity potential is 1.02×10^9 kWh/yr. Table 6 shows the electricity and fuel required for running the facilities of the marine biomass energy system. The amount of electricity for running one plant is 23.38 kWh/yr, so y_1 was calculated as follows:

$$y_1 = 1.02\times10^9 \text{ kWh/yr} - 23.38\times10^6 \text{ kWh/yr}\times9$$
$$= 0.810\times10^9 \text{kWh/yr}$$

$(x_0 + x_0') / y_0$ [kg-CO_2/kWh] is the amount of CO_2 emission for coal-fired power generation. We used 1.02097 kg-CO_2/kWh [12] as its value in Japan.

According to table 6, the fuel energy for running the whole system is 3.23×10^{15} J/yr. The fuel was considered to be heavy oil, whose CO_2 emission is 0.069×10^{-6} kg-CO^2/J. Accordingly, x_1' was calculated as follows:

x_1' (construction not considered)
$$= 3.23\times10^{15} \text{ J/yr} \times 0.069\times10^{-6} \text{ kg-CO}_2\text{/J}$$
$$= 0.222\times10^9 \text{ kg-CO}_2\text{/yr}$$

Consequently, the amount of CO_2 mitigated at the nine sites except for CO_2 emission for the construction was calculated as follows:

The amount of CO_2 mitigation at nine sites:
$$= 0.810\times10^9 \text{ kWh/yr} \times 1.02097 \text{ kg-CO}_2\text{/kWh} - 0.222\times10^9 \text{ kg-CO}_2\text{/yr}$$
$$= 0.827\times10^9 \text{ kg-CO}_2\text{/yr} - 0.222\times10^9 \text{ kg-CO}_2\text{/yr}$$
$$= 0.605\times10^9 \text{ kg-CO}_2\text{/yr}$$

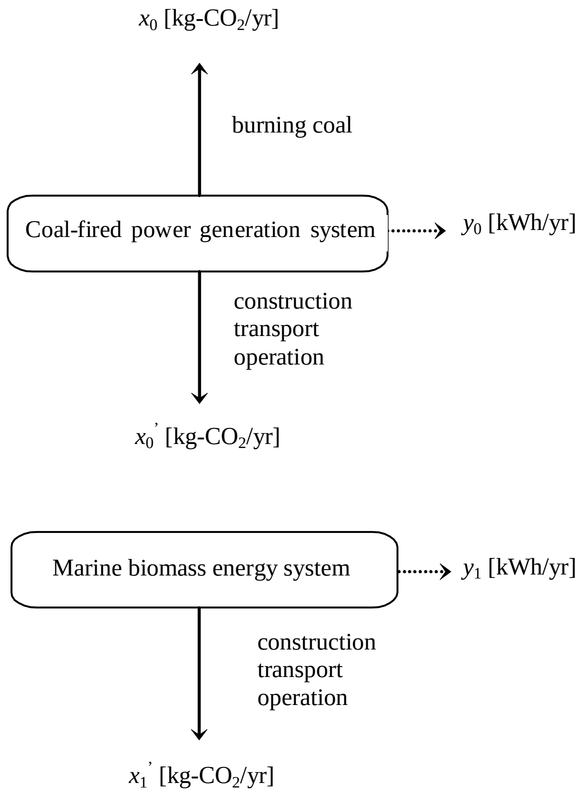

Fig. 7. Flow of CO_2 and energy in the coal-fired power generation system and the marine biomass energy system.

Table 6. Electricity and Fuel Required For the Marine Biomass Energy System

Electric power required for the marine biomass energy system (10^6 kWh/yr)	1 site	23.4*
	Total (9sites)	210
Fuel required for the marine biomass energy system (10^{15} J/yr)	1 site	0.359
	Total (9 sites)	3.23

*Source: [2].

8. RIPPLE EFFECTS

The marine biomass energy system has some ripple effects. Submarine forests which native seaweeds often form provide important shelters for fish and shellfish. In addition, planktons will flourish by upwelling deep-sea water rich in nutrients for the growth of seaweeds, leading to the formation of some ecosystems including fish and shellfish.

For these reasons, the sea area around marine farms will become a good fishery. The marine biomass energy system will, therefore, improve fisheries and increase the production of marine food. The marine production of Japan has decreased recently, so the utilization of marine biomass is a potential way to boost production. Seaweed growth is not restricted by water supply, so a marine industry that produces not only energy but also food may counteract the impending shortage of fresh water resources.

9. CONCLUSIONS

CO_2 mitigation was estimated to be 605,000 tonnes per annum on the assumption that the nine sites are feasible in Japan. Under the Kyoto Protocol, Japan is required to reduce its greenhouse gas emissions by 6% compared with the level in 1990, during the first commitment period from 2008 to 2012. The estimated CO_2 mitigation is equivalent to about 0.9% of the required CO_2 mitigation. The marine biomass energy system is, therefore, one of the potential countermeasures for global warming. The use of marine biomass for energy may also have the advantage of providing good fisheries. However, problems remain to be solved. Although the by-product extraction process was not considered in this paper, its necessity is apparent in terms of cost. An economical and energy-saving by-product extraction process should be considered in future studies. Cultivation techniques for rapid growth of seaweeds and an energy-saving drying process are also important. Since methane fermentation fed with *Laminaria japonica* slurry has not been thoroughly studied, research on highly efficient methane fermentation fed with *Laminaria* spp. is also required.

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