A System Analysis of Greenhouse Gas Reduction for the Bio-Cycle Project in Kyoto

Kazuo Nakamura[1,2], Hiroaki Hori[1,2], Shingo Deguchi[2,3,*], Yasuhiro Hirai[4] and Shin-ichi Sakai[4]

[1] Kyoto City, Environmental Bureau
[2] Advanced Software Technology & Mechatronics Research Institute of Kyoto
[3] Urban System Integration, Inc., Osaka, Japan
[4] Kyoto University, Environment Preservation Center
[*] Corresponding author: deguchi@astem.or.jp (deguchi@ursin.co.jp)

Abstract: *The biomass available in Kyoto City was estimated to be 2.02 × 10^6 t-wet/yr (0.14 × 10^6 kL/yr oil equivalent), of which waste paper, waste timber, food waste, unused forest tree, and sewage sludge account for the largest amounts on an energy basis. Based on Kyoto's regionally specific biomass potential and its historic use of biomass, we started the "Kyoto-Bio-Cycle Project" in 2007. The objective of this project was to synergistically enhance the effects of greenhouse gas (GHG) countermeasures, through greening of necessary materials such as methanol and the cyclic use of byproducts, with "Kyoto City's project for the manufacture of biodiesel fuel from used cooking oil" as the core activity. Two technologies are being developed as part of the project. One is technology to synthesize methanol with the gas generated from the gasification of woody biomass. Through the use of this biomass-derived methanol ("green" methanol), totally carbon-neutral BDF can be manufactured from waste cooking oil and previously unused poor quality oils and fats. The other technology is a high efficiency biogasification system that treats food waste, waste paper, and waste glycerin. This system can improve the production rate of biogas and reduce the residue produced in fermentation tanks through the introduction of hyper-thermophilic hydrolysis in the thermophilic dry anaerobic fermentation process. Our system analysis indicated that, by collecting and recycling plastic packaging waste and introducing these new technologies in Kyoto City, GHG emissions would be reduced by 60% as compared to the current method of incinerating waste wood, cooking oil, and other combustibles such as plastics. Additionally, if these demonstration technologies were used throughout Japan, we estimated the reduction effect to be 3.5 X 10^6 t-CO_2/yr (equivalent to 1/20 of Japan's GHG emission reduction target of 6%).*

Keywords: biodiesel fuel, methanol synthesis, anaerobic fermentation, thermophilic hydrolysis, greenhouse gas reduction

1. INTRODUCTION

The city of Kyoto is an international tourist destination that attracts 50 million tourists annually. The many hotels, traditional inns and other lodgings in the city dispose of organic waste while there is abundant woody biomass from pruned branches at shrines, temples, homes, etc. and from the thinning of nearby mountain forests. The 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3) was held in Kyoto in 1997. The opportunity was taken to establish a sound material-cycle society to contribute to preventing global warming in the form of biodiesel fuel (BDF) production utilizing waste cooking oil and biogasification demonstration utilizing organic waste and other materials [1]. The Kyoto Bio-Cycle Project was started in 2007 to demonstrate these operations. An overview of the project and the results of a system analysis of the introduced technologies are reported here.

2. BIOMASS POTENTIAL IN KYOTO

In order to promote the use of regional biomass, the biomass resource available in the Kyoto City area was estimated based on a previous report [2]. Here resource refers to the "amount produced" and the "available supply". The "amount produced" is the amount collected and disposed annually for materials like biomass in waste streams as well as the annual growth of forest trees (plantations, bamboo) that can be sustainably harvested for use. "Available supply" is that portion of the "amount produced" that is not being utilized ("amount produced" – "amount currently used"). The material types, estimation method, and estimation results are shown in Table 1 and Fig. 1.

- The "amount produced" was estimated to be 2.42 million t-wet/year while the "available supply" was estimated to be 2.02 million t-wet/year (340 kt-dry/year).
- The largest material types in the available supply on a dry base were waste paper, waste timber, pruned branches, food waste, unused forest tree and sewage sludge.
- Energy conversion calculations assumed that low water content materials were used directly for heat while methane fermentation was assumed for high water content materials. The total energy for all materials was 5,454 TJ/year (T: 10^{12}). This is equivalent to crude oil of 154 million L/year (The amount of CO_2 emission reduced by substitute for the crude oil was 406 kt-CO_2/year). Waste paper, waste timber, food waste, unused forest tree and sewage sludge were significant contributors. These materials should receive priority in future utilization of biomass in the city area.

Table 1 Biomass Supply Estimation Method and Results (per annum)

Sector	Item	Amount Produced		Available Supply				
		Estimation Method	10^3t-wet	10^3t-wet	10^3t-dry	TJ	kL-oil	10^3t-CO_2
Agriculture	Rice straw	Amount harvested X residue output ratio	7.0	0.21	0.19	2.6	72	0.19
	Rice husks		1.4	0.17	0.15	2.4	67	0.18
	Agricultural residues		2.3	0.45	0.09	0.6	18	0.05
Forestry	Timber residues in forests	Amount material wood produced X remaining timber production rate	2.3	2.3	0.92	16.5	464	1.2
	Thinning wood	Thinning area X thinning wood production ratio	9.1	9.1	3.6	64.8	1,825	4.8
	Unused forest tree (Trees not yet harvested for wood)	Private plantation area X (50 year cycle final cutting + 3 times thinning)	88.9	88.9	35.6	635.8	17,909	47.3
	Bamboo	Bamboo grove area X amount annual growth	9.3	9.3	4.6	83.1	2,341	6.2
Livestock	Excreta	Number raised X excretion rate per animal	7.4	7.4	0.88	6.2	174	0.46
Waste	Food waste	Municipal solid waste collection/carry-in X composition ratio + private sector recycling amount + industrial waste	222.1	211.9	42.4	648.4	18,265	48.2
	Organic sludge	Industrial waste amount	30.8	30.8	3.1	41.7	1,174	3.1
	Pruned branches, construction waste, factory waste wood	Municipal solid waste collection/carry-in X composition ratio + industrial waste	75.6	64.4	47.5	849.9	23,940	63.2
	Waste paper	Municipal solid waste collection/carry-in X composition ratio + community group collection + private sector recycling amount + industrial waste	251.9	186.1	171.2	2,738.3	77,134	203.6
	Waste cooking oil	Domestic: cooking oil purchases X waste disposal ratio + commercial: allocated based on number of business sites from national food service waste cooking oil volume	5.3	2.1	2.0	77.2	2,174	5.7
	Sewage sludge (from night soil treatment facility)	City sewage treatment results	38.0	0	0	0	0	0
	Sewage sludge (from urban sewage disposal plant)	City sewage treatment results (Calculated from amounts solids assuming 98% water content)	1,668.4	1,405.6	28.1	286.7	8,077	21.3
Total			2,420	2,019	340	5,454	153,633	406

Note) After methane fermentation of livestock waste and sewage sludge, use of the residues as compost was assumed, thus almost 100% of amount produced could be used. Conversion coefficients were as follows: 35.5 MJ-LHV/L-oil, 2.64 kg-CO_2/L-oil.

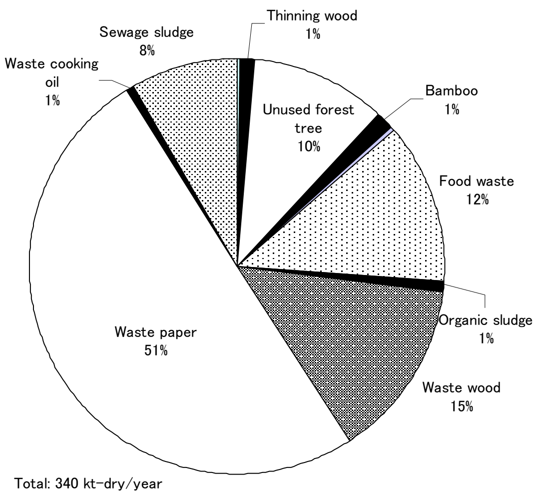

Fig. 1 Available supply amount (dry weight)

3. BIO-CYCLE PROJECT IN KYOTO

3.1 Objective and frame of project

Building on previous initiatives and regional characteristics, the Kyoto Bio-Cycle Project was started in 2007 to green necessary raw materials (methanol) and addresses the recycling of by-products (waste glycerin), with the core activity "Kyoto City's project for the manufacture of biodiesel fuel from used cooking oil" that has been conducted with citizen involvement. The objectives of the project are to improve the efficiency of material and energy recovery technologies for utilizing biomass (forestry and urban biomass) and building a stable integrated system in order to achieve effective control measures for global warming. The overall image of the project and its component systems are shown in Fig. 2.

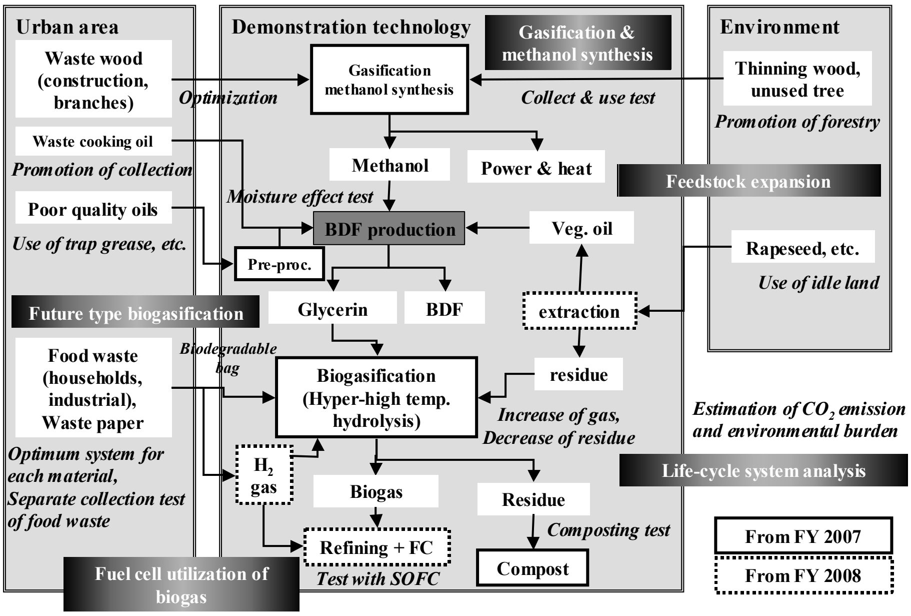

Fig. 2 Overview of Kyoto Bio-Cycle project

3.2 Goal and progress of project

The features of the 5 demonstration technologies being introduced by this project, final targets and the progress during FY2007 are shown in Table 2. Also, the flow diagrams for the main demonstration technologies are shown in Figs. 3 and 4.

Table 2 Features, targets and progress of demonstration technologies

Technology	Features	Final Targets	Progress
Gasification and methanol synthesis technology	Renewable "green methanol" is synthesized and used to produce "carbon free BDF". Development of thermal decomposition gasification methanol synthesis technology that can use construction waste, pruned branches, forest thinning wood and other feedstocks. Feedstock is gasified in circulating fluidized bed gasifier (atmospheric pressure, air blown), and high efficiency methanol synthesis is conducted using a new type energy conserving reaction vessel (low temperature, low pressure, one path type). Independent distributed system due to off gas power generation.	◆ Demonstration unit is 1/20 scale of a commercial unit. ◆ Achievement of carbon conversion ratio 95%, cold gas efficiency 65%, 30 L/day methanol production.	Construction and test operation of gasifier unit has been conducted and performance targets have been reached. Operating conditions are being optimized using simulation calculations. Methanol synthesis unit is being designed.
BDF feedstock expansion technology	Establishment of domestic waste cooking oil collection system, and assessment of available supply of unused poor quality oils and fats as preparation for spreading and expansion of domestic BDF production. Development of pretreatment and fuel production technology capable of handling free fatty acids, trap grease from restaurants, etc. and other unused poor quality feedstocks that are difficult to convert to fuel with conventional technology.	◆ Establishment of a collection system for domestic waste cooking oil and other unused feedstocks. ◆ Establishment of fuel conversion technology for unused feedstocks containing impurities.	The properties, amount generated and management situation for unused poor quality feedstocks have been comprehended. Development of pretreatment technology for poor quality feedstocks and production methods for BDF from extracted oils and fats are being considered.

Technology	Features	Final Targets	Progress
High efficiency biogasification technology	Development of dry methane fermentation technology (urban biogasification system) incorporating hyper-thermophillic hydrolysis technology (80°C, waste heat utilizing, chemicals not required) to increase biogas generation while reducing fermentation residue and waste liquid generation. The by-product waste glycerin from BDF production will be utilized. Recovery of ammonia from the fermentation liquid reduces wastewater treatment burden and the recovered ammonia is effectively used as a process chemical for incinerator NOx emission control. Laboratory experiments are being conducted to select the optimum raw material for hydrogen fermentation in two-stage fermentation. Biodegradable plastic fermentation experiments will be conducted.	◆ Demonstration unit is 1/10 the scale of a commercial unit (dry thermophillic methane fermentation technology incorporating hyper-thermophillic hydrolysis). ◆ 20% increase in biogas production, 50% reduction of residues, 70% reduction of wastewater treatment burden.	Hyper-thermophillic hydrolysis tank, waste glycerin feed equipment and residue composing unit have been added to existing methane fermentation unit and a test run is being conducted. Laboratory experiments are being conducted to collect the data necessary for optimizing the operation of the hyper-thermophillic hydrolysis tank.
Fuel cell utilization of biogas	Development of gas refining, reforming and fuel cell system (optimum combination utilizing SOFC) for high efficiency generation and heat recovery utilizing methane fermentation gas for clean use.	◆ Proposal for a biogas refining and reforming system for connection to a fuel cell system.	(Initiated from FY2008)
Life-cycle System analysis of cyclic utilization technology	Modeling and analytical assessment of technology according to the integrated system and expanding feedstock for each technology will be conducted. Proposals for optimal feedstock collection methods will be developed based on local experiments.	◆ Establishment of a forest industry biomass collection system. ◆ Establishment of a system analysis model for feedstock expansion.	Understanding of Kyoto City forest industry biomass discharge situation and resource abundance. Proposal for basic framework for collection and utilization experiments has been developed.

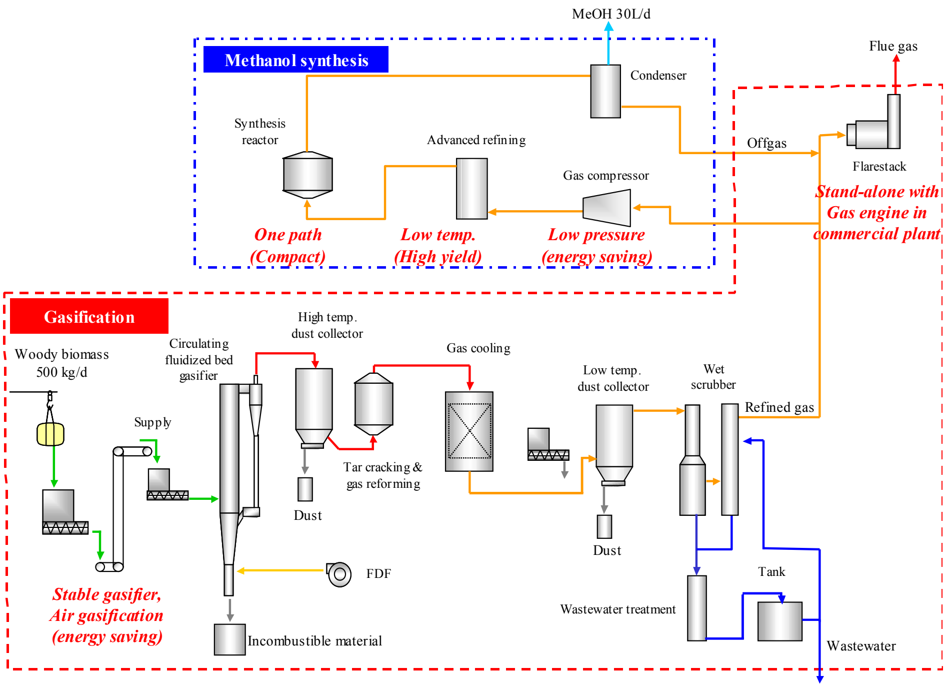

Fig. 3 Flow diagram of gasification and methanol synthesis demonstration

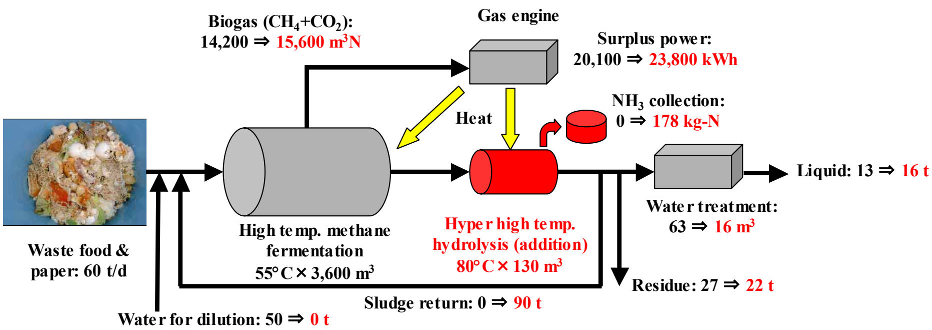

Fig. 4 Flow diagram of dry thermophilic methane fermentation incorporating hyper-thermophilic hydrolysis (prospect in commercial plant, without → with hydrolysis tank)

4. GHG REDUCTION EFFECT OF PROJECT

4.1 Method of system analysis

The CO_2 reduction effect of this project was estimated based on the available supply of biomass. The calculation method and calculation conditions were basically the same as previously reported [3,4]. The range of the assessment was from the collection and transport of waste wood, waste cooking oil and combustible waste (food waste, waste paper, plastic, etc.) through the conversion process, use of the recovered material (substitution effects for existing products) and the transport and disposal of residues. Also, only the operation stage of facilities was covered and the construction stage was not included in the analysis. Table 3 shows the estimation scenario.

The amount of each material handled in calculation was based on the demand for recovered material to build the material-cycle system for BDF production (5 kL-BDF/day). BDF production requirements were used to set the amount of waste cooking oil and waste wood (raw material for methanol) required. In addition, combustible waste from households and large businesses in the city were combined for processing.

Table 3 Scenarios for biomass recycling

Scenario			Waste wood	Waste cooking oil	Combustible waste (food waste, paper, plastics)
			6,000 t (20 t/day)	Household: 125 kL +Business: 1,425 kL (5 kL/day)	Household: 280 kt + Business: 160 kt (1,500 t/day), including food waste: 140 kt, Businesses which each generate at least 100 t/yr
0	Landfill (Current Asia)		Landfill	Landfill	Landfill
1	Incineration (Average in Japan, low efficiency: 5.7%)		Incineration	Incineration (mixed refuse collection)	Incineration (mixed refuse collection)
	(Average in advanced plant, high efficiency: 10.5%)				
2	Waste plastic collection (recycle of plastic packaging)				
3	Kyoto Bio-Cycle project	I		BDF + incineration of waste glycerin	
		II		BDF + biogasification of waste glycerin	Mixed refuse collection + mechanical separation + biogasification
		III	Pyrolytic gasification + methanol synthesis		
		IV			Introduction of biodegradable plastic bags as refuse collection bags

The outline and parameters for the main processes were as follows:

- Landfill scenario: CH_4 emissions from the decomposition of food waste, waste paper, waste cooking oil, and waste wood were assessed. The decomposition rate for the carbon content was 0.77, the CH_4 proportion of the decomposition gas was assumed to be 0.5.
- Separate collection scenario for plastic: Separate collection of plastic packaging and recycling was assumed. The proportion of plastic packaging in combustible waste is about 14% and the cooperation rate for separate collection was assumed to be 50%. Reduction of CO_2 emissions due to avoidance of incinerating plastic and the increase in CO_2 emissions due to the reduction of power generation were assessed on the assumption that plastic packaging collected by source separation will be effectively recycled (the CO_2 emissions reduction effect of plastic recycling was not assessed).
- Biodegradable plastic introduction scenario: Replacement of 10% of the residual plastic in combustible waste after implementation of separate collection was assumed. The heat content of biodegradable plastic was taken to be one half that of plastic produced from petroleum, the CO_2 emissions during combustion was taken to be zero, and the increase in CO_2 emissions due to the reduction of power generation was assessed (the CO_2 emissions from manufacture of biodegradable plastic was not assessed).
- Incineration process: The electric power required for incineration is 100 kWh/t-wet. The power generation efficiency for the low case was 5.7% (Japan nationwide average) and that for the high case was 10.5% (average for urban incineration plants with generation facilities). The CO_2 emission reduction of surplus electric power was assessed as 0.353 kg-CO_2/kWh (average for all power generation sources in Japan).

4.2 Results of system analysis

The calculated results are shown in Fig. 5.

- Assuming all waste is landfilled "Landfill scenario", the methane emissions from organic material were equivalent to 440 kt-CO_2 emissions, by weight methane has 21 times the global warming potential of CO_2. For incineration of all waste "Incineration scenario", plastic combustion has a large impact with 181-203 kt-CO_2 being emitted (including CO_2 emission reduction effect of power generation).
- Introduction of separate collection of waste plastic reduces emissions by 93 kt-CO_2 compared to "Incineration scenario". Reduction of use of fossil resource derived plastics and expanding 3R initiative are important.

- Implementation of "Kyoto Bio-Cycle project" would result in reduction of 36 kt-CO_2 emissions. The breakdown was (1) Conversion to BDF 3 kt, (2) methane fermentation 15 kt, (3) no major increase or reduction from gasification methanol synthesis (about the same CO_2 emission reduction effect as incinerator power generation), (4) a 18 kt-CO_2 emission reduction effect from introduction of biodegradable plastic bags.
- Separate collection of plastic and the implementation of this project would results in an 110-130 kt reduction in CO_2 emissions. This would be about a 60% reduction compared to incineration scenario with current average generation efficiency.

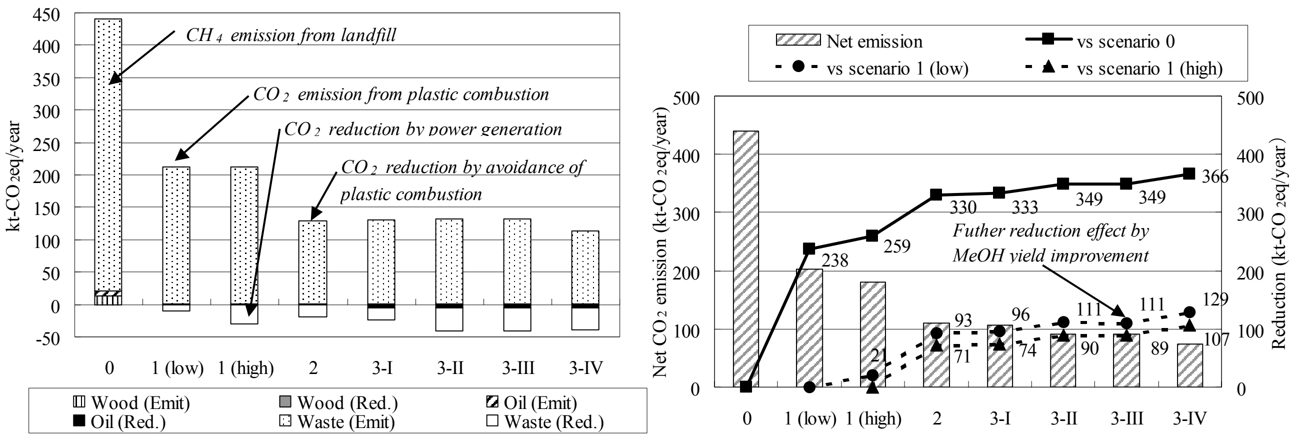

Fig. 5 Calculated results

As the handling of plastic and other wastes were included in addition to biomass, the CO_2 emissions per unit amount handled were calculated to be 20 kg-CO_2/t-wet, a plus value (the CO_2 emission assessment for biomass only is minus). Also, as the calculation conditions did not include use of all of the biomass available supply within the city, achievement of further reductions in CO_2 emissions could be expected from use of the remaining waste wood and trees, sludge, etc. Further technology development and planning of systems to meet the regional demand of recovered material and energy will be necessary.

The calculated results for CO_2 emission reduction for each biomass material were waste wood 54 kg-CO_2/t-wet, waste cooking oil 2.4 t-CO_2/kL, and only food waste 205 kg-CO_2/t-wet. Based on these results, if 47 (one per prefecture) gasification methanol synthesis plants and BDF production plants were built throughout Japan and if 16 million t-wet/year of food waste were used to produce methane, about 3.5 million tons of reduction in CO_2 emission could be expected. This is equivalent to about 1/20 of the Japan's 6% greenhouse gas reduction target (75 million t-CO_2).

5. CONCLUSIONS AND PROSPECTS

We estimated the biomass available in Kyoto city area with statistics and revealed those characteristics. "Kyoto-Bio-Cycle Project" from 2007, which utilizing the waste biomass, was proposed and indicated the features of demonstration system and consisting technologies. In addition the implementation effect of project, reducing CO_2 emission by utilizing waste biomass, was calculated. In 2008', we will proceed with program for realizing a vision and goal of the project by operating demonstration plants. Additionally, introducing the application to the Solid Oxide Fuel Cell (SOFC) of biogas, we are going to develop the highly effective and synergetic integrated system for the further CO_2 reduction effect.

6. ACKNOWLEDGMENTS

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