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## System Efficiency and Economical Analysis of System for Producing Energy Material from Wooden Biomass (December 2006)

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**Abstract** - The ability of wooden biomass energy conversion system to produce energy material has been analyzed on the basis of the material and energy balances. In this study, as a first step towards analyzing the production of automobile fuels, we analyzed a zero-emission type biomass energy conversion system that produces methanol and methyl formate by biomass steam-reforming with a CO/H<sub>2</sub> ratio of ~1/(1.1-1.6). This system also produces ethanol, lactic acid, and propanediol from cellulose and it supplies electric power and steam to satisfy the internal requirements of the system (wood throughput capacity: 420 ton/day). Payback periods were calculated from the raw material costs of wooden biomass and the major equipment cost of the energy plant; it was found that the payback period was within 9 years. Economic analysis using IRR indicated that sawmill residue and building waste wood, which cost less than \$100/ton, were feasible in the proposed system. Furthermore, the subsidy of 1/3 of the fixed cost improved IRR approximately 10%. The effect of the feedstock composition on economics was small.

**Keywords**—Wooden biomass, Zero-emission, Methyl formate, Energy conversion, Renewable energy.

### 1. INTRODUCTION

It is very important to promote the effective utilization of the advantages offered by biomass technology in order to realize a reduction in the usage of fossil fuel resources; further, it is essential to create a society that promotes energy recycling in order to solve the global environmental problems [1]. In particular, in the case of societies that depend on fossil resources, which are carbon dioxide emission sources, the rate of emission has exceeded the rate at which natural cleaning occurs; consequently, various environmental problems such as global warming, waste, and toxic substance have become serious issues [2]. Therefore, it is important to actively exploit and utilize the regenerated biomass as long as life and solar energy exist. On the other hand, with regard to the global carbon circulation, the amount of carbon circulation by forests and soil bacteria is 10 times greater than the use of fossil resources caused due to human activity [3, 4]. The use of the biomass may be considered to be a part of forest carbon circulation and therefore, it is referred to as carbon neutral (the utilization of biomass is not considered as carbon dioxide exhaust: Kyoto Protocol).

We observed that several carbon fixation quantities exist in wood biomass; further, we expect an increase in the generation amount of the biomass resources in the future. We performed the basic examination of the conversion of the wood biomass to BTL (biomass to liquid) and ETBE (ethyl tertiary butyl ether), which are mainly used as transportation fuel. It is possible to reduce the global

energy consumption of fossil fuel by an order of 1% if the sawmill residue produced globally is utilized as a biomass resource [2]. In Japan, energy consumption can be reduced by 1% if sawmill residue, including the imported wood, can be utilized as a biomass resource [2]. As a first step in this study, we researched and developed the saccharification and separation of cellulose by hydrothermal treatment and mechanochemical powering; this was done in order to examine the economical and environment implications of various advantages offered by a wooden biomass utilization system. We examined the total system that comprised ethanol fermentation, gasification/liquid fuel synthesis, electric power generation, and heat utilization. We examined the material/heat balance of the system and constructed an independent system that did not require the supply of external energy such as electric power. In addition, we calculated the cost of the major equipment and performed an economical analysis by estimating the simple payback period and the internal rate of return (IRR).

### 2. EXAMINATION OF THE WOOD COMPOSITION

The average molecular structure of lignin, cellulose, and hemicellulose were modeled as a phenylpropane derivative (C<sub>18</sub>H<sub>24</sub>O<sub>11</sub>), the basic structure of D-glucose (C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>), and the basic structure of pentose (C<sub>5</sub>H<sub>8</sub>O<sub>4</sub>) [4], respectively. Further, the composition of lignin, cellulose, hemicellulose, and ash in wooden biomass were fixed at 27%, 50%, 20%, and 3%, respectively, and the average molecular structure model of wooden biomass for simulation was assumed to be C<sub>3.8</sub>H<sub>3.9</sub>O<sub>2.9</sub> (Table 1) as the base case. Additionally, based on literature, the representative carbon, hydrogen, and oxygen compositions in rice-sugar, cedar wood flour, rice straw, and rice hull were assumed to be 48-55wt%, 6-8wt%, and 37-45 wt%, respectively, and these compositions served as a reference [5].

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**Table 1. Research results of wood composition**

Name	Adopted Value			
	Lignin	Cellulose	Hemicellulose	Wood
element number				
C –	18	6	5	3.8
H –	24	10	8	5.9
O –	11	5	4	2.9
unit molecular weight	416	162	132	97
elemental composition				
C wt%	50.4	43.1	44.1	45.3
H wt%	5.6	6.0	5.9	5.9
O wt%	41	47.9	47	45.8
ash wt%	3	3	3	3
total	100	100	100	100

In order to consider the effect of feedstock composition on economics, the composition of lignin and cellulose was changed. In the proposed system, wooden biomass is used as feedstock. The composition was determined from reference [6]. The composition of lignin, cellulose were changed to 35% and 42% in case 2 and those were changed to 20% and 57% in case 3.

### 3. EXAMINATION OF THERMODYNAMIC DATA

#### Examination of Heat of Combustion and Standard Heat of Formation

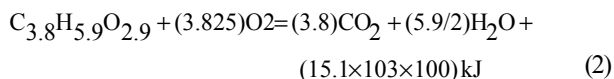
The standard heat of formation of the process configuration component is shown in Table 2. The pre-conditions for obtaining the standard heat of formation are as follows:

- The heat of combustion of lignin, hemicellulose, cellulose, and wood were estimated from Dulong's equation [7], shown in equation (1) and the standard heat of formation of wood was estimated as "830.4 kJ/mol (100 gwood) from the combustion reaction shown in equation (2).

$$\text{HHV} = (33.8)C + (144.2) \times (H - O/7.94) + (9.414)S \quad (1)$$

HHV: high heat value [MJ/kg]

C, H, O, S: elemental analysis values of carbon, hydrogen, oxygen, and sulfur.



- The thermophysical properties of water, carbon dioxide, carbon monoxide, methane, methanol, methyl formate, ethanol, and pentose (D-ribose was substituted) were obtained from NIST data (The National Institute of Standards and Technology, U.S.A) [8], and that of 1,3-propanediol was obtained from the DIPPR data (Design Institute for Physical Property Data, U.S.A) [9]. The thermophysical properties of

the carbon material (graphite), lactic acid, and hexose (D-glucose was substituted) were obtained from the Chemical Handbook [10].

**Table 2. Standard heats of formation (Hf) of the process configuration components**

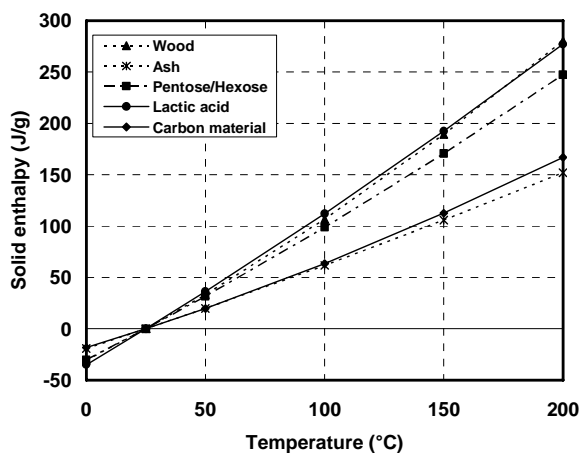
	Hf at 25°C, kJ/mol	phase
hydrogen	0	vapor
carbon monoxide	-110.5	vapor
oxygen	0	vapor
methane	-74.5	vapor
carbon dioxide	-393.3	vapor
methyl formate	-384.8	liquid
methanol	-239.4	liquid
ethanol	-277.1	liquid
water	-285.7	liquid
1,3-propanediol	-463.2	liquid
wood	-830.4	solid
cellulose	-1504.0	solid
hemicellulose	-1195.2	solid
lignin	-3352.3	solid
lactic acid	-694.0	solid
pentose	-1049.0	solid
hexose	-1273.3	solid
carbon material	0	solid

#### The Examination of Enthalpy and Vapor Pressure

The specific heat data on materials for which the enthalpy data was not available in literature, such as wood, ash, pentose, hexose, lactic acid, and carbon material was used to form a secondary temperature equation; which was then integrated and arranged as a tertiary temperature equation.

The assumptions made with regard to the enthalpy are mentioned as follows:

- Wood (cellulose, hemicellulose, and lignin), ash (SiO<sub>2</sub>), pentose, hexose, lactic acid, and carbon material: the enthalpy value of the solid at 25°C was assumed to be zero (Fig.1).

**Fig. 1 Enthalpy of the solid process configuration component.**

- Water, nitrogen, carbon monoxide, oxygen, carbon dioxide, hydrogen, methane, methanol, ethanol, methyl formate, and 1,3-propanediol (NIST data): the enthalpy value of the gas at 25 °C was assumed to be zero.

The vapor pressure required for the distillation calculation was evaluated by using the Antoine equation, shown in equation (3) and the Antoine constants for each material are given in Table 3.

$$\text{LOG}(P) = A1 - A2/(T + A3) \quad (3)$$

P: vapor pressure [mm Hg], T: temperature [°C]

A1, A2, A3: Antoine constants [-]

Temperature range: melting point ~ (critical temperature) × 0.9

**Table 3. Antoine constants for each component**

	Normal Boiling Point, °C	Critical Temperature, °C	Antoine Constants		
			A1	A2	A3
methyl formate	31.8	214.1	7.2043	1144.16	232.704
methanol	64.5	239.5	8.1509	1631.10	244.743
ethanol	78.3	240.8	8.2134	1652.05	231.480
water	100.0	374.2	8.0411	1722.45	233.526
1,3-propanediol	214.0	384.0	9.1703	3105.02	279.251
lactic acid	216.9	266.5	8.2803	2076.49	167.640

The pre-conditions for obtaining Antoine constants are as follows:

- The vapor pressures of the methyl formate, methanol, water, and 1,3-propanediol are obtained from the NIST data, and the vapor pressure of ethanol is obtained from the Chemical Handbook. The vapor pressure of lactic acid was estimated from the normal boiling point (obtained from the Chemical Handbook [11] data) and the critical temperature/pressure (estimated from the Lydersen method [12]).

#### 4. EXAMINATION OF SIMULATION MODEL

##### *Estimation of the Wood Throughput*

Sawmill residue was assumed to be a biomass resource, and a wood throughput of 420 ton/day, which corresponded to the throughput of a large-scale sawmill in Japan, was assumed; this wood throughput corresponds to an electric power generation of approximately 3500 kW when 50% of the sawmill residue (approximately 50% wood) is utilized (20% power generation efficiency, 15.1 MJ/kg heat value).

##### *Outline of the Process*

It was observed that the CO/H<sub>2</sub> ratio after the steam reforming reaction of wood (direct heating system is assumed), shown in equation (4), was 1/(1.1~1.6); further, the CO/H<sub>2</sub> ratios for methanol and methyl formate were 1/2 and 1/1, respectively. We constructed a zero-emission type biomass energy conversion system that produced both methanol and methyl formate according to equation (5,6),

and produced ethanol, lactic acid (biodegradable plastic raw material), 1,3-propanediol (resin raw material), carbon material, and methane according to equation (7–12). This system also generated electric power for the internal requirements of the system and steam for the reactions and distillation. Further, the surplus hot water could be supplied to the outside. The G/L/S represents the vapor/liquid/solid phase in equation (4–14), and the plus and minus symbols preceding the heat of reaction indicate the exothermic and endothermic reactions, respectively.

- steam reforming of cellulose (800°C)



Hemicellulose and lignin undergo a similar reaction.

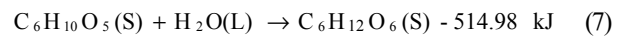
- methanol synthesis (210°C)



- methyl formate synthesis (60°C)

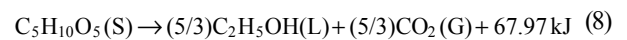


- enzymatic saccharification of hexose (45°C)

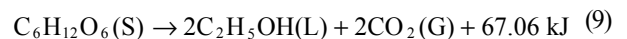


Pentose undergoes a similar reaction.

- pentose ethanol fermentation (30°C)



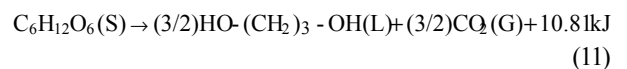
- hexose ethanol fermentation (30°C)



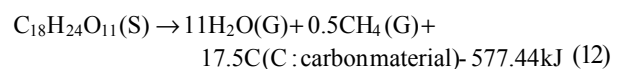
- lactic acid fermentation (37°C)



- 1,3-propanediol fermentation (30°C)

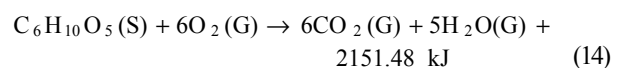
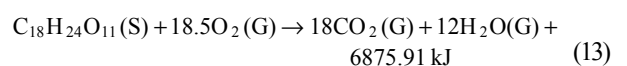


- carbonization of lignin (500°C)



Cellulose and hemicellulose undergo similar reaction.

- combustion reaction (1427°C or 1000°C)



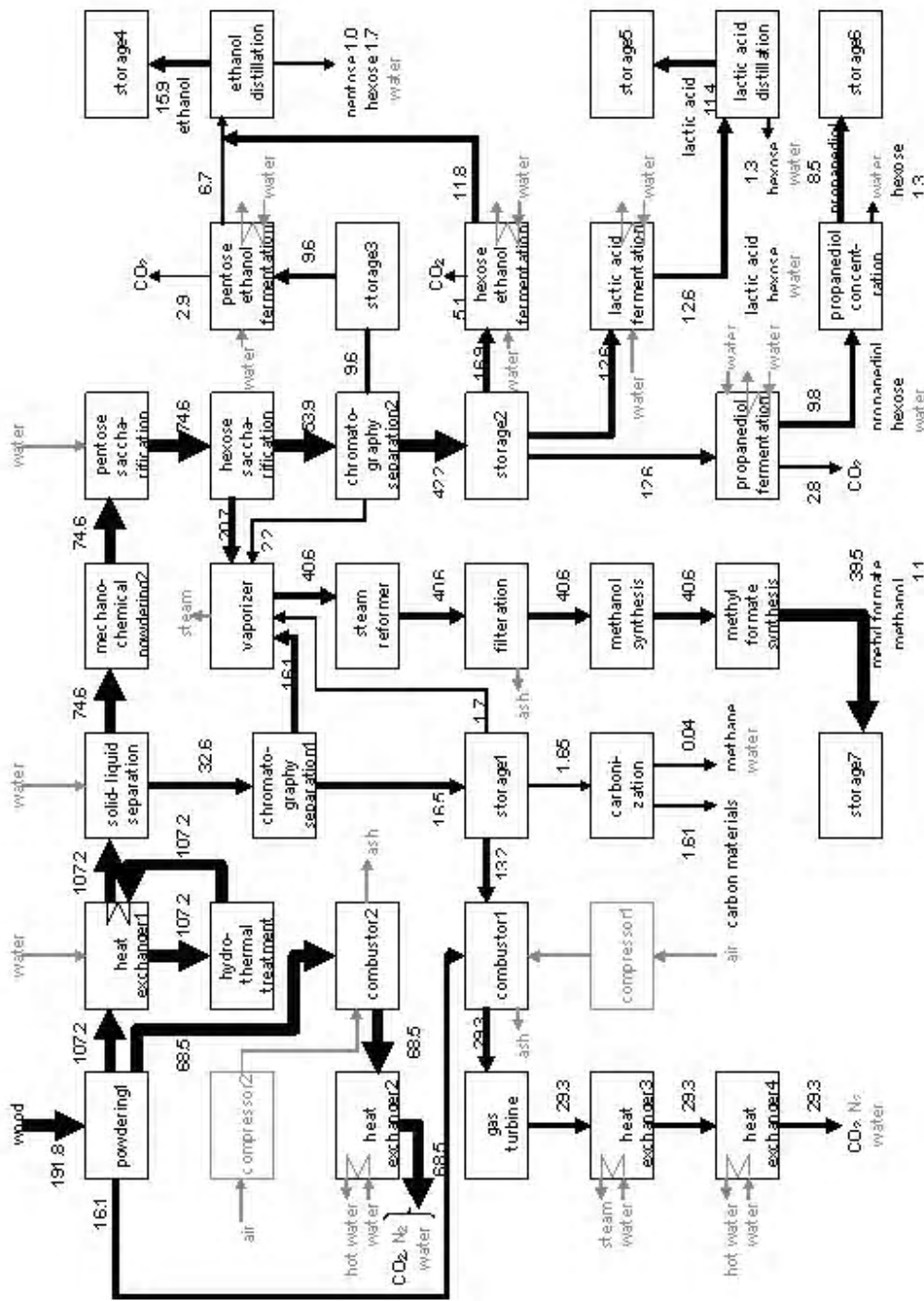


Fig. 2. Carbon balance of the whole process

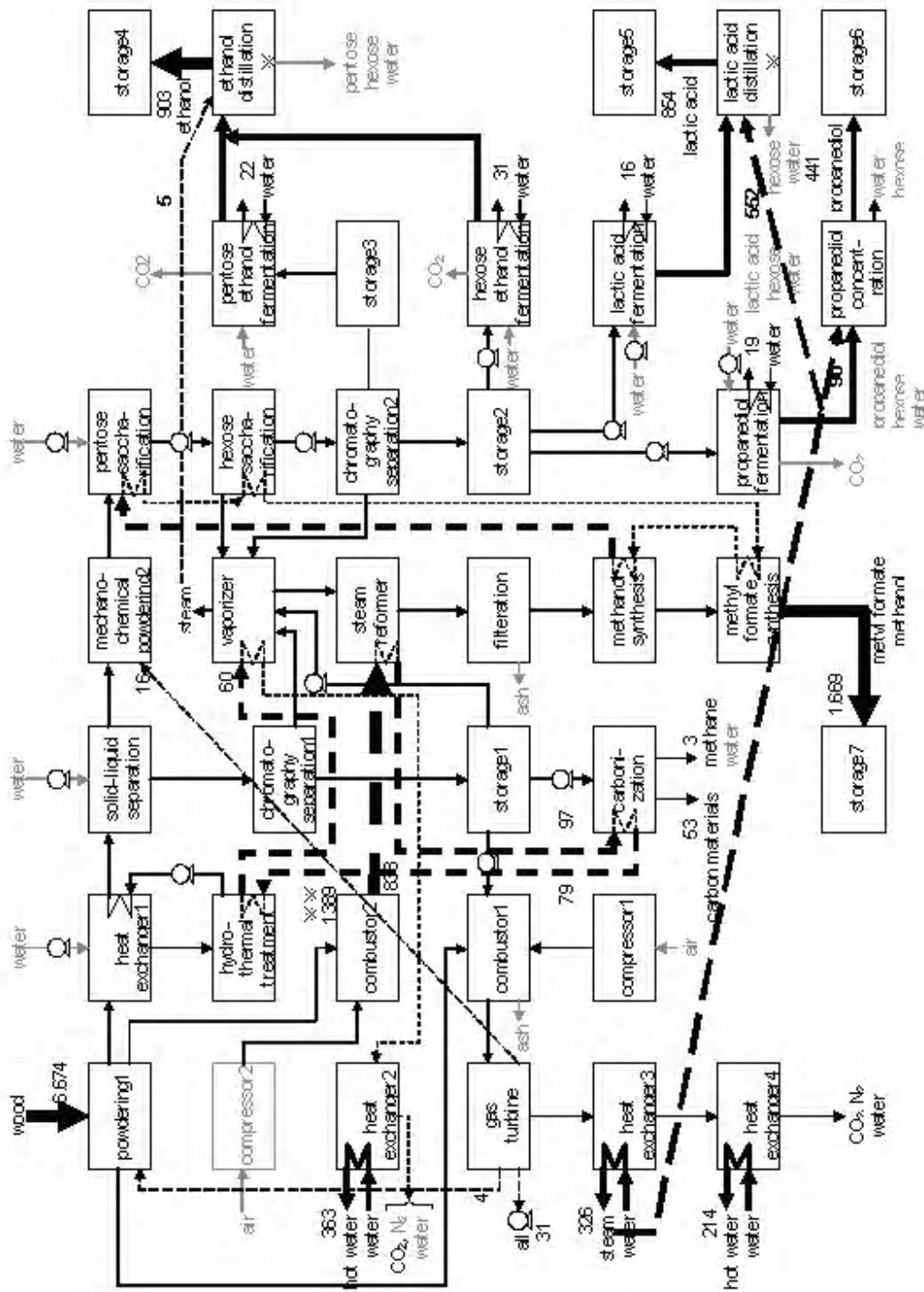


Fig. 3. Heat balance of the whole process

**Table 4. Pre-conditions for the material balance**

process	Parameter	Ratio, %
heat exchange1	water addition ratio	10
solid-liquid separation/blasting	rinse water addition ratio	10
	hemicellulose solubilization ratio of hot water	50
	lignin solubilization ratio of hot water	50
	cellulose solubilization ratio of hot water	90
chromatography separation1	cellulose separation ratio for the vaporization process	90
	hemicellulose separation ratio for the vaporization process	90
	lignin separation ratio for the storage1 process	90
storage1	lignin, etc. distribution ratio for the vaporization process (for the gasification)	10
	lignin, etc. distribution ratio for the carbonization process (for the carbonization)	10
	lignin, etc. distribution ratio for the combustion1 process (for the power generation)	80
powdering2 (mechanochemical)	water content in the solid (cellulose mainly)	10
pentose enzymatic saccharification	sugar concentration (pentose and hexose)	40
hexose enzymatic saccharification	lignin separation ratio for the vaporization process	90
	pentose separation ratio for the chromatography separation2 process	90
	hexose separation ratio for the chromatography separation2 process	90
chromatography separation2	hexose separation ratio for the hexose fermentation process	99
	pentose separation ratio for the storage2 process	99
pentose ethanol fermentation	Pentose-derived ethanol concentration	12
	Pentose-derived ethanol fermentation ratio	90
storage2	Hexose-derived ratio (for ethanol fermentation)	40
	Hexose-derived ratio (for lactic acid fermentation)	30
	hexose-derived ratio (for 1,3-propanediol fermentation)	30
hexose ethanol fermentation	hexose-derived ethanol concentration	12
	hexose-derived ethanol fermentation ratio	90
lactic acid fermentation	lactic acid concentration	5
	lactic acid fermentation ratio	90
1,3-propanediol fermentation	1,3-propanediol concentration	10
	1,3-propanediol fermentation ratio	90

#### **Examination of Overall Material (Carbon)/Heat Balance**

The reaction and separation ratios of each process, which are related to process construction, were assumed based on basic experimental results and literature data, as shown in Table 4, and the material balance (Table 5)/heat balance calculations were performed. The wood used for the simulation was assumed to have 10% water content under the condition that it was sunlight dried. In the first powdering process, it was assumed that wood was reduced to wood flour with particle sizes of several centimeters (the powdering power corresponded to the catalog value). In the second powdering process (mechanochemical powdering), it was assumed that the particle size of the wood flour was of the order of several ten micrometers (the powdering power is assumed to be four times that used in the first powdering process). It was assumed that the hydrothermal treatment was conducted at 200°C. The

saccharification ratio of cellulose to glucose was assumed to be 90% and it was assumed that the enzyme for the saccharification of the cellulose was supplied by cultivating microorganisms. Consequently, in the zero-emission type process construction, approximately 43% of the total carbon contained in the wooden biomass was effectively converted into energy materials/chemicals such as methanol, methyl formate, ethanol, etc., and the remaining 57% was released as carbon dioxide as a result of the combustion to produce steam; this steam was used for the conversions and distillations. (Fig.2 and Table 7)

It was estimated that approximately 62% of the total energy produced by wooden biomass was used in the formation of energy materials/chemicals such as methanol, methyl formate, and ethanol; approximately 0.8% and 27% were converted into electric power and steam, respectively, for satisfying the internal system requirements; and approximately 8.6% was used for heating the external water

supply to 95°C; and around 1.7% was used for cooling in the fermentation processes, etc. (Fig.3 and Table 7).

**Table 5. Overall material balance**

Input		Output	
Material	Weight, ton	Material	Weight, ton
wood	423.20	Methanol	2.92
water	1017.13	methyl formate	98.84
air	1255.65	Ethanol	30.41
		lactic acid	28.46
		1,3-propanediol	18.02
		carbon material	1.61
		Methane	0.06
		unfermented pentose	2.40
		unfermented hexose	10.54
		carbon dioxide	398.21
		water	1075.40
		steam(0.3 MPa)	24.45
		nitrogen	991.96
		ash	12.70
Total input	2695.98	Total output	2695.98

**Table 6. Overall carbon balance of the process**

Material	Carbon, ton	Ratio, %
Input		
Wood	191.85	100
Total input	191.85	100
Output		
Methanol	1.10	0.60
methyl formate	39.54	20.60
ethanol	15.87	8.30
lactic acid	11.38	5.90
1,3-propanediol	8.54	4.40
carbon material	1.61	0.80
Methane	0.04	0.02
unfermented pentose	0.96	0.50
unfermented hexose	4.22	2.20
carbon dioxide	108.60	56.60
Total output	191.85	100.00

### Economical Analysis

#### (i) Examination of proportional cost

From the simulation results, the proportional cost of wood for a transportation distance of 40 km was estimated to be approximately \$114/ton wood (lumbermill residue cost is \$90/ton wood and delivery cost is \$0.6/km/ton [13]), the wood throughput is 127,000 ton/year (300 workday/year), and the annual wood material cost was estimated to be \$14.47 million. Typically, the water supplied to the fermentor is the recycled type; therefore, the water cost was neglected because it was considerably lower than the fixed cost.

**Table 7. Overall heat balance of the process**

Heat	Heat Capacity, GJ	Ratio, %
input		
wood	6673.52	100.0
Total input	6673.52	100.0
output		
Methanol	3.08	0.05
methyl formate	52.80	0.80
Ethanol	1603.13	24.00
lactic acid	66.25	1.00
1,3-propanediol	903.40	13.50
carbon material	853.95	12.80
Methane	37.46	0.60
unfermented pentose	163.97	2.50
unfermented hexose	440.92	6.60
fermentation cooling	88.72	1.30
other cooling	27.59	0.40
supply electric power.	51.09	0.80
supply steam (0.3 MPa)	1804.38	27.00
supply hot water (95 °C)	576.77	8.60
Total output	6673.52	100.00

#### (ii) Examination of fixed cost

From material and heat balance, the material throughput and heat exchange quantity in each constituent equipment of the system were determined, and the major equipment costs of the system was calculated on the basis of equipment cost, basic data obtained from AIST Biomass Technology Research Center, and this cost added up to approximately \$85 million (Table 8). In the literature [14], the fixed cost of instrumentation, buildings, and piping, etc., has been estimated to be around 3.6 times the major equipment cost. The fixed cost was changed at 3 times the major equipment cost by using the experimental rule that considers the recent trend, and it was estimated to be \$255 million. The dimensions of the site were estimated to be 60 m × 40 m (maximum height 20 m) including the raw material wood storage tank (3 days) and the product tank.

The specifications of the major equipment are as follows:

- Distillation column design (minimum theoretical stages and minimum reflux ratio, etc.) using Fenske, Underwood, and Gilliland equations [7].
- Overall heat transfer coefficients of the heat exchanger and condenser/reboiler of the distillation column were 1.67 MJ/m<sup>2</sup>/°C and 2.51 MJ/m<sup>2</sup>/°C, respectively.
- A water adsorption system that employs molecular series was adopted for removing water (3 wt%) from ethanol after the azeotropic distillation of ethanol/water.
- The power generating efficiency of gas turbine is 20%, the adiabatic efficiency of the compressor is 85%, and the efficiency of a five effect evaporator used for 1,3- propanediol concentration is 80%.

**Table 8. Estimation result of the major equipment cost**

Major Equipment	Major Specification	Unit Cost, \$100	Quantity	Amount, \$ 100
powdering1	466 ton wood/day	4,655	1	4,655
hydrothermal treatment + solid-liquid separation/blasting high pressure vessel	450m <sup>3</sup> (SUS304)	46,455	2	92,910
compressor2 (output pressure: 0.25 MPa)	28300 Nm <sup>3</sup> /h	8,746	1	8,746
combustor2	87.1 GJ/h	29,239	1	29,239
heat exchanger2 (supply 95°C hot water)	449 m <sup>3</sup> (SUS304)	31,444	1	31,444
chromatography separator1	67.4 ton charge/day	19,062	1	19,062
storage1 (SCS13correspondent)	196 m <sup>3</sup> (SUS304)	6,196	1	6,196
carbonization reaction vessel	9.42 m <sup>3</sup>	848	1	848
gas turbine	2043 kWh	40,854	1	40,854
heat exchanger3 (supply 0.3 MPa steam)	37.3 m <sup>3</sup> (SUS304)	2,611	1	2,611
heat exchanger4 (supply 95°C hot water)	285 m <sup>3</sup> (SUS304)	18,571	1	18,571
Vaporizer (supply 0.3 MPa steam)	150 m <sup>3</sup> (SUS304)	5,420	1	5,420
steam reformer + methanol synthesis equipment	55.6 ton methanol/day	60,300	1	60,300
methyl formate synthesis equipment	3.18 m <sup>3</sup> (SUS304)	37,010	1	37,010
powdering2 (mechanochemical powdering)	177 ton wood/day	2,655	1	2,655
pentose enzymatic saccharification equipment	519 m <sup>3</sup> (SUS304)	16,395	2	32,790
hexose enzymatic saccharification equipment	519 m <sup>3</sup> (SUS304)	16,102	2	32,204
chromatography separator2	134 ton charge/day	30,804	1	30,804
storage3 (pentose)	81.6 m <sup>3</sup> (SUS304)	2,449	1	2,449
pentose ethanol fermentation equipment	143 m <sup>3</sup> (SUS304)	4,543	1	4,543
storage2	754 m <sup>3</sup> (SUS304)	23,472	1	23,472
hexose ethanol fermentation equipment	254 m <sup>3</sup> (SUS304)	8,003	1	8,003
ethanol distillation/adsorption column	11.0 m <sup>3</sup> (SUS304)	68,617	1	68,617
lactic acid fermentation equipment	822 m <sup>3</sup> (SUS304)	25,884	1	25,884
lactic acid distillation column	30.0 m <sup>3</sup> (SUS304)	227,179	1	227,179
1,3-propanediol fermentation/five effect evaporator	268 m <sup>3</sup> (SUS304)	29,945	1	29,945
total major equipment cost				846,411

**(iii) Examination of the operating cost**

The operating cost is divided into direct operating cost (personnel expenses), fixed property tax/insurance, and general administrative cost.

Personnel expenses and other costs are as follows:

- Personnel expenses: the operation of a plant by 3 person's × 4 groups costs \$0.08 million/person/year, the maintenance cost is 1% of fixed cost, and test and inspection costs are 20% of the plant operation cost.
- Other costs: fixed property tax and insurance cost are 1.5% and 0.4% of the fixed cost and general administrative cost is 25% of the personnel expenses.
- Personnel expenses, fixed property tax/insurance cost, and general administrative cost are \$3.7, \$4.85, and \$0.93 million/year, respectively.

**Examination of Payback Period**

Pre-conditions for the payback period are as follows:

- Based on the adjustment of the current market price, unit price of the energy materials was assumed, and the output and sales of the energy materials/chemicals are shown in Table 9.

- The annual total sales were estimated to be \$53.05 million/year (300 workday/year and all the chemicals were sold).

- Based on the abovementioned condition, the payback period was estimated to be 8.8 years, and this value is greater than the period of several years presently required for the development of the energy-saving techniques. Recently, it was reported that the development process of energy-saving technologies lasts for around 10 years, whereas the development process of new energy technologies such as photovoltaic power generation lasts for several decades [15]. Therefore, the feasibility of the proposed system appears to be high.

Payback money

$$= (\text{total sales}) - (\text{cost of biomass}) - (\text{personnel expenses}) - (\text{other expenses})$$

$$= 53.05 - 14.47 - 3.70 - 5.77 = \$29.11 \text{ million/year}$$

Initial cost (= fixed cost) = \$255 million/year

$$\text{Simple payback period} = (\text{initial cost}) / (\text{payback money})$$

$$= 255 / 29.11 = 8.8 \text{ years}$$



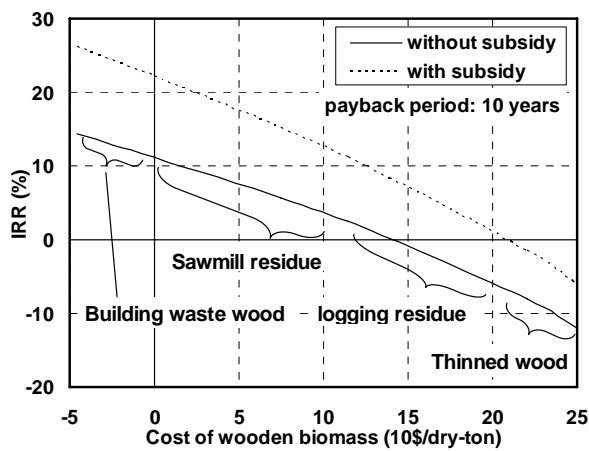
**Table 9. Result of estimation annual sales**

Manufactured Goods	Output, ton/day	Unit Cost, \$0.01/kg	Sales, \$ million
methanol	2.9	40	0.35
methyl formate	98.8	80	23.71
ethanol	30.4	50	4.56
lactic acid	28.5	200	17.10
1,3-propanediol	18.0	100	5.40
carbon material	1.6	400	1.92
methane	0.1	20	0.01
total			53.05

**Examination of Wooden Biomass Cost**

Although the cost of sawmill residue was assumed to be \$90/ton wood in the calculation of item (4.4), the actual cost of sawmill residue is \$0–100/ton wood. If building waste wood can be utilized, the treatment costs of 35\$/ton will be obtained. On the other hand, when thinned wood is utilized, the cost increases to \$125–300/ton wood because the cost depends on the collection of wood [16]. The economic analysis using IRR was performed, considering that the wooden biomass cost was a variable. The payback period was fixed at 10 years.

Figure 4 shows the relationship between the cost of wooden biomass and IRR. In this case, IRR for \$140/ton was 0%. When thinned wood (\$300/ton) and unused wood (\$125/ton) were used as the feedstock, the proposed system was unprofitable. On the other hand, logging residue (\$125/ton), sawmill residue (\$0–100/ton) and building waste wood (\$–35/ton) were feasible as the feedstock. However, IRR for \$100/ton was 3.64% and even that for \$50/ton was 7.55%. It is considered that the values were relatively low from the viewpoint of investment. The subsidy of 1/3 for the fixed cost was taken account of. The result was also shown in Fig. 4. It was found that the feasibility of the proposed system was improved. IRR for the biomass cost of \$ 208/ton was 0%. IRRs for \$ 100/ton and \$ 50/ton increased to 12.64% and 17.55% respectively. It was found that the subsidy increased IRR approximately 10%.



**Fig. 4. Economical analysis of the wooden biomass utilization system**

It was indicated that the subsidy was one of the effective options in order to realize the proposed system. Political supports were desired.

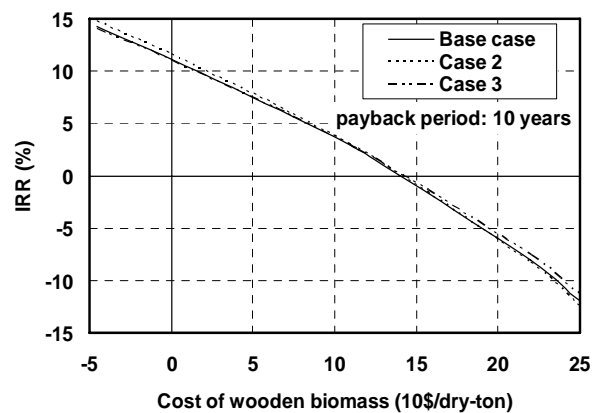
**Effects of Feedstock Composition on Economics**

The product amounts, the initial cost and the running cost with the change of the feedstock composition were shown in Table 10. The product amount and total sales changed with the change of the feedstock composition. Therefore the equipment size also changed. Accordingly the personnel expenses (including the maintenance cost), the fixed cost and the other expenses varied. It is found that although the increase of cellulose amount increased the total sales, it also increased the initial and running costs.

Figure 5 shows the relationship between the cost of wooden biomass and IRR in this case. The payback period was assumed as 10 years. In the biomass cost of less than \$115/ton, IRR of case 2 was higher. In that of more than \$140, IRR of case 3 was higher though IRR was negative in all the case. However, the difference were very small. It was confirmed that the effect of the feedstock composition on economics was small.

**Table 10. Results of estimation product amount, sales, initial cost and running cost**

	Base Case	Case 2	Case 3
<i>Manufactured Goods</i>			
methanol, ton/day	2.9	3.8	2.2
methyl formate, ton/day	98.8	108.7	90.2
ethanol, ton/day	30.4	27.3	33.1
lactic acid, ton/day	28.5	23.9	32.4
1,3-propanediol, ton/day	18.0	15.1	20.5
carbon material, ton/day	1.6	2.0	1.2
methane, ton/day	0.1	0.1	0.0
<i>Annual Sales, Initial And Running Costs</i>			
total sales, million \$/y	53.05	51.96	54.01
personnel expenses, million \$/y	3.70	3.61	3.76
other expenses, million \$/y	5.77	5.60	5.88
fixed cost, million \$	255.0	246.0	261.0



**Fig. 5. Economical analysis of the wooden biomass utilization system**

## 5. CONCLUSIONS

We observed that wooden biomass such as wood can reduce the energy consumption due to utilization of fossil fuel by 1% globally and in particular, in Japan. In this study, wooden biomass was converted into BTL/ETBE, which is transportation fuel. In the first step, a system that comprised ethanol fermentation, gasification/liquid fuel synthesis, power generation, and heat utilization was constructed in order to examine the environmental and economical implications of the various advantages offered by wooden biomass utilization systems. From material and heat balances, the major equipment costs were calculated, and an economical analysis was performed in terms of the simple payback period and IRR. The following conclusions were obtained:

- (1) The total system has a payback period of 8.8 years, which is feasible for a reversible energy plant.
- (2) 43% of the total carbon is converted into energy materials and chemicals, and the remaining 57% is released as carbon dioxide; and the efficiency of energy conversion is 63%.
- (3) Thinned wood and logging residues have negative value of IRR for payback period of 10 years due to the high gathering cost involved. Sawmill residue and building waste wood, which cost less than \$100/ton, are feasible in the proposed system.
- (4) The subsidy of 1/3 of the fixed cost increases IRR approximately 10%. IRR for \$100/ton and that for \$50/ton were 12.64% and 17.55% respectively.
- (5) The effect of the feedstock composition on economics is small.

## NOMENCLATURE

A1, A2, A3 = Antoine constants [-]  
 C, H, O, S = elemental analysis values of carbon, hydrogen, oxygen and sulfur [-]  
 P = vapor pressure [mm Hg]  
 T = temperature [°C]  
 HHV = high heat value [MJ/kg]

## Subscripts

L = liquid  
 S = solid  
 V = vapor

## REFERENCES

- [1] Sakoda, A, Mochidzuki, K, Abe, I, Katayama, Y, Kawai, S, Sawada, T, Tanada, S, Nakasaki, K, Nakamura, Y, Fujita, S, Funaoka, M, Miura, M and Yoshida, T. 2001. Material Conversion of Unutilized Plant Biomass for Zero Emissions. *Society of Environmental Science* (in Japanese). 14: 383–390.
- [2] The essential part of Biomass Japan genetic strategy. 2002. <http://www.maff.go.jp/biomass/senryaku/senryaku.pdf>. Retrieved October 10, 2004.
- [3] Biomass handbook (The Japan Institute of Energy edition). 2002. pp.12–13, 20–21. Tokyo, Japan: Ohmsha.
- [4] Janzen H. H. 2004. Carbon cycling in earth systems—a soil science perspective. *Agriculture Ecosystems & Environment*. 104: 399–417.
- [5] Nakagawa, H, Sakai, M, Harada, T, Kitamura, Y, Taniwaki, K and Hashimoto, A. 2000. *Proceedings of the 4th ecology balance international conference*. pp.405–408 (2000).
- [6] Wood industry handbook revision 4 editions (The Forestry and Forest Products Research Institute edition). 2004. pp.139, 199–202. Tokyo, Japan: Maruzen.
- [7] Chemical engineering handbook revision 6 editions (The Society of Chemical Engineers, Japan edition). 1999. pp.17, 23, 528, 972. Tokyo, Japan: Maruzen.
- [8] NIST Chemistry WebBook. The National Institute of Standards and Technology (U.S.A.), <http://webbook.nist.gov/chemistry/>.
- [9] DIPPR; Design Institute for Physical Property Data (U.S.A.)
- [10] Chemical handbook revision 3 base edition II (Chemical Society of Japan edition). 1984. pp.306, 315, 317. Tokyo, Japan: Maruzen.
- [11] Chemical handbook revision 3 base edition I (Chemical Society of Japan edition). 1984. pp.325. Tokyo, Japan: Maruzen.
- [12] Reid, RC, Prausnitz, J M and Sherwood, T K. 1985. Physical property prediction handbook of gas and liquid. pp.10–14. Tokyo, Japan: McGraw-Hill Book Company.
- [13] Biomass Japan genetic strategy decision urgent research report. 2002. The Japan Institute of Energy.
- [14] Takaoka, S. 1973. Evaluation method of chemical process. pp.156. Tokyo, Japan: Maruzen.
- [15] Uchiyama, Y. 1996. Our energy. pp.96. Tokyo, Japan: Baifukan.
- [16] Kitani, O. 2004. Biomass (Bioresources and Environment). pp.157. Tokyo, Japan: Corona Publishing Co., Ltd.