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LONG-TERM FEASIBILITY OF TIMBER AND FOREST BIOMASS RESOURCES AT A MOUNTAINOUS AREA IN JAPAN – DISCUSSION ON ECONOMY AND ENERGY BALANCES

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Abstract: *In this study, economy and energy balances of a power-generating plant were discussed on the model area. Forest resource, slope, public and forest road layers of Geographic Information System (GIS) were obtained from a prefecture, where a model area was located, in order to calculate harvesting costs of timber and forest biomass resources. Future forest resources at each stand were predicted using Richard's growth curves. Then, stand harvesting schedules were planned by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing harvesting costs.*

First, the optimum scales of a direct combustion power plant and a small-scale gasification power plant were discussed. Small scale gasification is under developing technology. With regard to the direct combustion power generation, the optimum scale of a power-generation plant was more than 3 MW of generation capacity and more than 18% of energy-conversion efficiency. Its electricity cost was 23-24 yen/kWh (US$1=115 yen). On the other hand, the optimum scale of a small-scale gasification power plant was 1.3 MW of generation capacity and 27% of energy-conversion efficiency. Its electricity cost was 10.7 yen/kWh. As the average electricity price in Japan, 2005 is 22.2 yen/kWh, it is important to develop the small-scale gasification technology.

Then, the energy balance and the carbon dioxide (CO2) emission from energy utilizations of forest biomass resources were analyzed using the method of a life cycle inventory (LCI). Energy consumption involved materials, construction, and the repair and maintenance of forestry machines as well as an energy-conversion plant. With regard to the direct combustion power generation with a generation capacity of 5 MW, energy consumption was 16,348 GJ/year. On the other hand, energy consumption of a small-scale gasification power plant with a generation capacity of 1.3 MW was 4,162 GJ/year. As a result on both types of power generation, the ratio of energy output to input was calculated to be 18.1, indicating that the system examined in this study could be feasible as an energy production system.

Lastly, the CO2 emission of the direct combustion power generation with a generation capacity of 5 MW was 913.3 t CO2/year. On the other hand, the CO2 emission of a small-scale gasification power plant with a generation capacity of 1.3 MW was 486.2 t CO2/year. However, the reductions in the amount of CO2 emission that would result from replacing fossil fuel were 15,913 t CO2/year and 3,040 t CO2/year, respectively. If 100 direct combustion power generation plants with 3-MW generation capacity assumed to be established based on the potential of forest biomass resources in Japan, CO2 emission was reduced by 1.11 million t CO2/year, corresponding to 1.5% of the 74 million t CO2 which Japan pledged to reduce in the Kyoto Protocol.

1. Introduction

The Japanese forest industries have been depressed for a long time. There are so many regions where forestry is not mechanized and the logging cost cannot be reduced. On the other hand, forest biomass attracts a great deal of attention in such regions. This is because the energy utilization of forest biomass is expected to contribute to revitalizing the forest industries as well as to maintaining the relevant ecological, economic, and social functions of man-made forests, but many of which are behind in tending. In order to utilize forest biomass as energy in a region where forestry is the major source of income, it is crucial to find out the relationship between the annual available amount and the procurement (harvesting and transporting) cost of forest biomass in the region. Kuboyama et al. (2004) estimated potential supply using timber production and processing statistics and forest biomass yield tables. Yoshioka and Sakai (2005) have carried out detailed analyses of potential supply based on a geographic information system (GIS). However, these studies have used current status of timber production and processing statistics, forest biomass yield tables, stocks and growth rates in the forests. Nord-Larsen and Talbot (2004) have already assessed long-term availability of forest fuel resources in Denmark.

In this study, long-term feasibility of the energy utilization of forest biomass in a mountainous region in Japan is discussed. A model region was the same with the study area of Yoshioka and Sakai (2005). They defined logging residues, thinned trees, and broad-leaved forests as forest biomass. Then, they analyzed the relationship between the mass and the procurement cost of biomass in the region with the aid of the GIS. In this study, growth rates were used to find out the future situation of the region for the energy utilization of forest biomass. Then, the long-term relationship between the mass and the procurement cost of biomass was discussed while minimizing procurement cost and balancing the mass using random search. Finally, the optimum scale of a power-generation plant was discussed for the model area using statistical data on a direct combustion power plant and a small-scale gasification power plant from the viewpoints of economic and energy balances.

2. Material and methods

2.1 Study site

The model area was Hikami County in Hyogo Prefecture, the middle part of Japan (Figure 1). The gross area of the county is 49,328 ha, the population is 72,862, and the number of households is 21,769. Its climate belongs to the inland and basin type, the annual average temperature is 13-14 degrees Celsius, and the annual precipitation is 1,500-1,600 mm/year. Its forest belongs to the lucidphyllous forest zone, the forest area is 37,202 ha (the percentage to the gross area is 75%), and man-made forest covers 58% of the forest area. The number of sawmills is 43, and the annual consumption of logs for timber is 78,992 m^3/year. Hikami County is a leading region in forestry and timber business in Hyogo Prefecture. However, in the region, the annual cut volume of logs has dropped almost by 50% in the past five years, and the forest stands behind in tending are increasing. Delay in mechanization in forestry is one of the major reasons for such a situation.

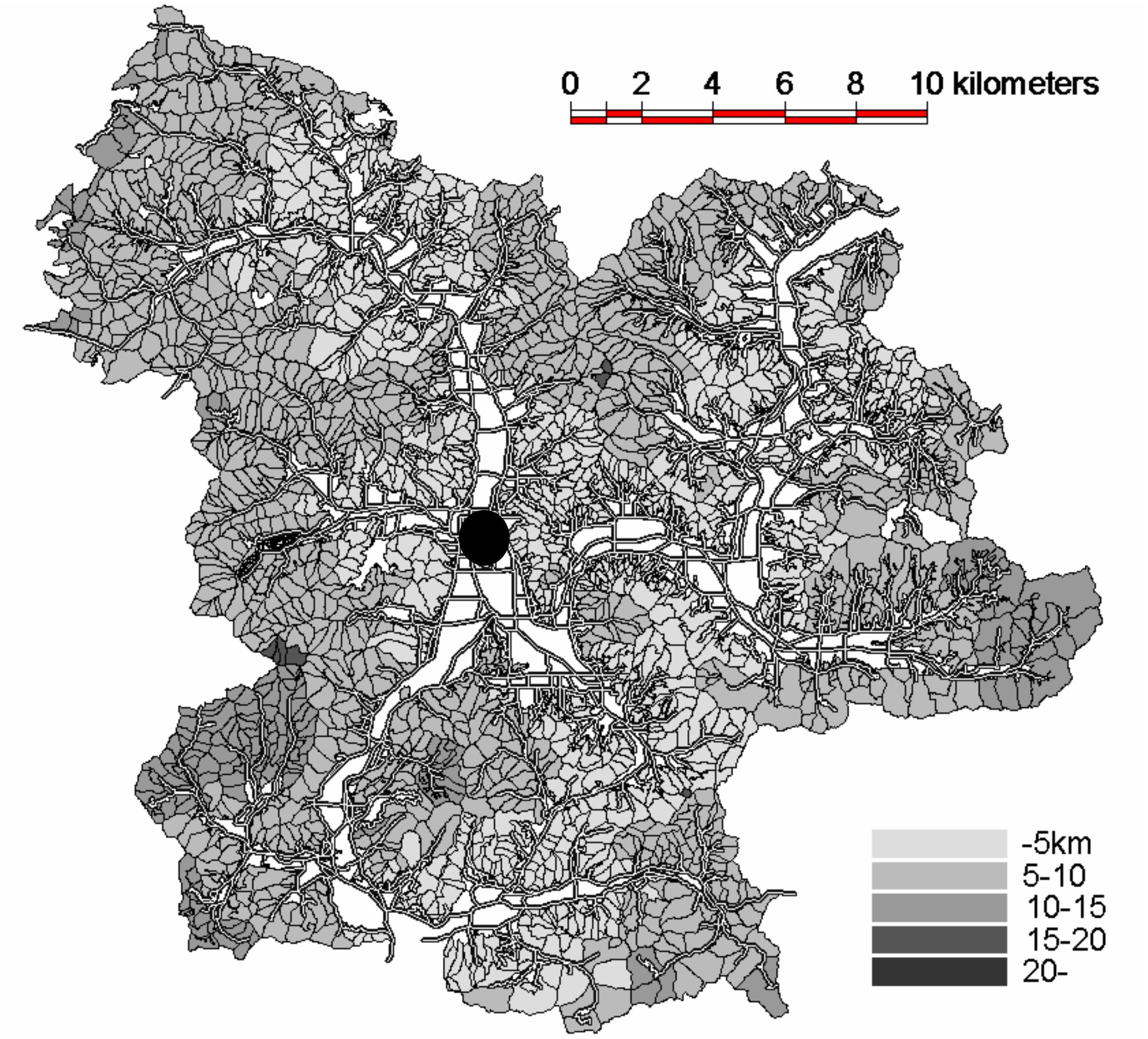


Figure 1: Transporting distance to energy-conversion plants (● is the location of a direct combustion power plant or a small-scale gasification plant)

2.2 Data

The forest register, the statistics on the forest industries, and the guides to forestry practice were offered from the prefectural office. Using these materials and the GIS, the annual available amount of biomass resources was calculated, and the distribution map was made based on sub-compartments. With regard to the GIS software, TNTmips® (MicroImages, Inc., the U.S.) is used in this study. The number of sub-compartments in the region was 2,168. Among these sub-compartments, there were 1,113 man-made coniferous stands and 398 naturally regenerated broad-leaved stands. The DEM of the region (50 m mesh, the Geographical Survey Institute, Japan) is input into the software to calculate the slope of each sub-compartment and to judge the skidding/yarding direction (uphill or downhill). The digital topographic map of the region (1:25,000 scales, the Geographical Survey Institute, Japan) is input into the software, and forest and public roads whose width is greater than 3 m are traced and converted to vector data.

2.3 Procurement costs

Harvesting and transporting systems for forest biomass were classified depending on the parts of a tree for energy and the topographical conditions, and the equations for calculating costs are made. Table 1 lists the operation patterns of sub-compartments to be felled. According to the parts of a tree for energy (logging residues or the whole tree), harvesting and transporting systems for forest biomass are classified into two types (Figure 2). Logging residues are considered as a by-product of conventional forestry. Therefore, the system boundary of logging residues starts with comminuting logging residues at the landing of the logging site by a mobile chipper.

Table 1: Operation patterns of sub-compartments to be felled

Forest	Age (y)	Operation pattern
Man-made and coniferous[1]	31-60	[Biomass resources: Thinned trees] Thinning is carried out in the stands of which stocks are more than Richard's growth curves with a 20% or more thinning rate so that stocks are below Richard's growth curves, and the whole trees are used as energy sources.[2]
	Over 61	[Biomass resources: Logging residues] Clearcutting is carried out to all the stands. Trees are limbed and bucked, logs are harvested, and tops and branches are used as energy sources.
Naturally regenerated and broad-leaved[1]	Over 31	[Biomass resources: Broad-leaved forests] Clearcutting is carried out at 30-year interval cycle, and the whole trees are used as energy sources.

[1] The representative tree species in the region are "hinoki" which is a cypress (*Chamaecyparis obtusa*) for coniferous and "keyaki" which is a zelkova (*Zelkova serrata*) for broad-leaved.

[2] It is supposed in this study that all of the cut material at thinnings can be used as an energy source in consideration of the actual Japanese market value.

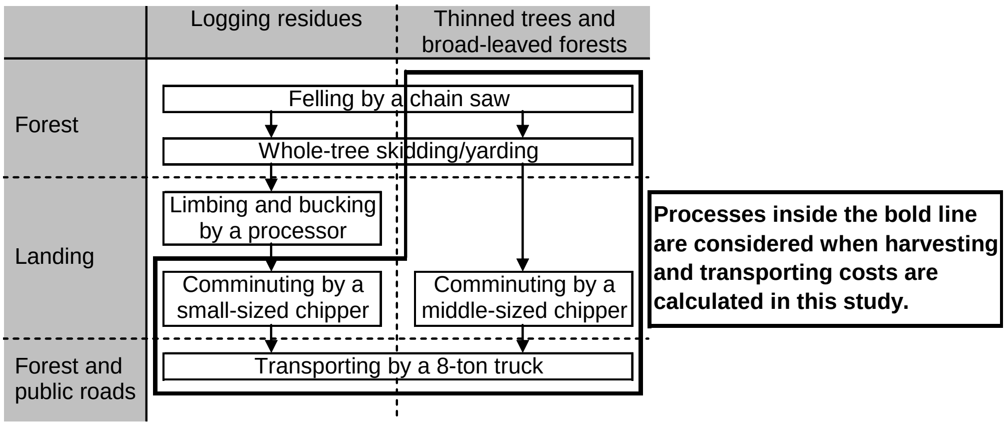
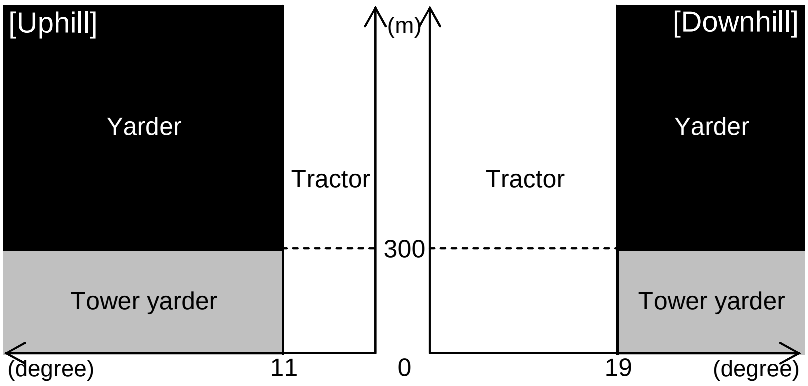


Figure 2: Classification of systems according to the parts of a tree for energy

The machine for skidding/yarding is usually decided according to the topographical conditions, *i.e.*, slope, skidding/yarding distance, and skidding/yarding direction (uphill or downhill). In this study, tractors (skidders), tower yarders (mobile yarders), and yarders are to be used for the skidding/yarding process, and Figure 3 shows the classification of skidding/yarding machines according to the topographical conditions of sub-compartments. Table 2 shows the machine specification and Table 3 shows the equations for calculating the harvesting and transporting costs of forest biomass whose variables are slope θ (degree), harvesting volumes per ha V (m^3/ha), skidding/yarding distance L_Y (m), and transporting distance L_T (m). In addition to the direct costs of labor, machine, and fuel, the indirect costs of labor (55% of the direct cost of labor), machine moving cost (50,000 yen/each), and overhead costs (20% of the total direct cost) are considered here.



[X axis: Slope; Y axis: Skidding/yarding distance]

Figure 3: Classification of machines according to the topographical conditions

Table 2: Machine specification

Machine	Remark	Mass (kg)	Duration (hour)	Efficiency (m^3/hour)	Fuel consumption (L/hour)
Chain saw	Conifer	6	2,700	2.2	2.8
	Broadleaf	6	2,700	2.0	2.8
Tractor	Whole tree	6,000	6,480	$5{,}440/L_Y$	4.3
Tower yarder	Whole tree	7,425	5,400	$4{,}860/(2L_Y+243)$	3.0
Yarder	Whole tree	3,000	6,300	$12.06L_Y^{-0.2142}$	2.8
Processor	Whole tree	6,770	6,480	7.0	2.0
Chipper		7,802	5,000	13.0	28.0
Truck(8t)	Cut-to-length	7,960	5,500	$247{,}422/L_T$	8.2
	Chip	7,960	5,500	$199{,}500/L_T$	8.2
Backhoe	Forest road cutting	16,400	6,300	29.73	18.0
Bulldozer	Forest road filling	11,000	5,390	38.33	14.0
	Strip road bulldozing	3,000	3,420	454m/h	5.0

Finally, the following items on topography are processed on the GIS software. The average angle of inclination of each sub-compartment is calculated. To determine skidding/yarding distance of each sub-compartment, the distance between the center of gravity of a sub-compartment and the nearest road from the sub-compartment is calculated. A landing is to be arranged at the point on the nearest road from the sub-compartment. The skidding/yarding direction (uphill or downhill) is judged by comparing the altitudes of the center of gravity with the landing. Transporting distance from landings to energy-conversion plant is calculated by the shortest path function of GIS software (Figure 1). By applying the topographical data on each sub-compartment to the equations listed in Table 3, the procurement costs of forest biomass from all sub-compartments in the region can be calculated.

Table 3: Procurement cost (yen/m^3)

Machine	Remark	Cost
Chain saw	Conifer	1,308
	Broadleaf	1,472
Tractor	Whole tree	$0.972L_Y+27{,}510e^{0.117\theta}/V+1{,}771$
Tower yarder	Whole tree	$5.397L_Y+5{,}870{,}250/L_YV+747$
Yarder	Whole tree	$991.644L_Y^{0.2142}+5{,}071{,}896/L_YV+161{,}236/V+196$
Processor	Whole tree	1,906
Chipper		1,093
Truck(8t)	Cut-to-length	$0.027L_T+778$
	Chip	$0.033L_T+778$

2.4 Amount of available forest biomass

The amount of available biomass resources can be calculated from the stem volume and the coefficient. The total stem volume of each sub-compartment is recorded in the forest register. The coefficients listed in Table 4 are used to calculate the amount of biomass resources. Consequently, by applying Tables 1 and 4 to the forest register and considering the cutting cycles of coniferous and broad-leaved forests, the annual available amount of forest biomass in the region can be calculated. To find out the future available amount of forest biomass V (m^3/ha), Richard's growth curves with the year t are applied to the forest register (Figure 4 and 5):

conifer: $$V=377(1-\exp(-0.047t))^{2.26} \quad (1)$$

broad-leaves: $$V=281(1-\exp(0.032t))^{1.82} \quad (2)$$

Table 4: Methods for calculating the amount of biomass resources

Biomass resources	Equation (s.v.: Stem volume)	Note
Logging residues[1]	Amount (tDM) = s.v. · 15/92 · 0.40	· 15/92: Ratio of tops and branches' volume to stem volume · 0.40: Density of a coniferous tree
Thinned trees	Amount (tDM) = s.v. · 20/100 · 100/92 · 0.40	· 20/100: Thinning rate · 100/92: Ratio of the whole tree's volume to stem volume · 0.40: Density of a coniferous tree
Broad-leaved forests	Amount (tDM) = s.v. · 100/80 · 0.56	· 100/80: Ratio of the whole tree's volume to stem volume · 0.56: Density of a broad-leaved tree

[1] The method for calculating the cut volume of logs in clearcutting is as follows:
Volume of logs (m^3) = s.v. · 85/92 (85/92: Ratio of logs' volume to stem volume)

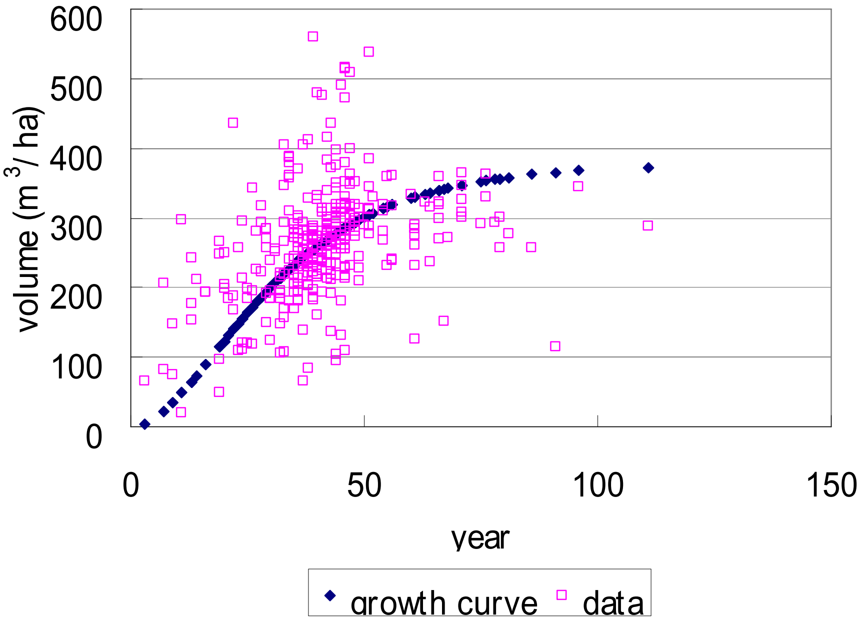


Figure 4: Richard's growth curve for conifer

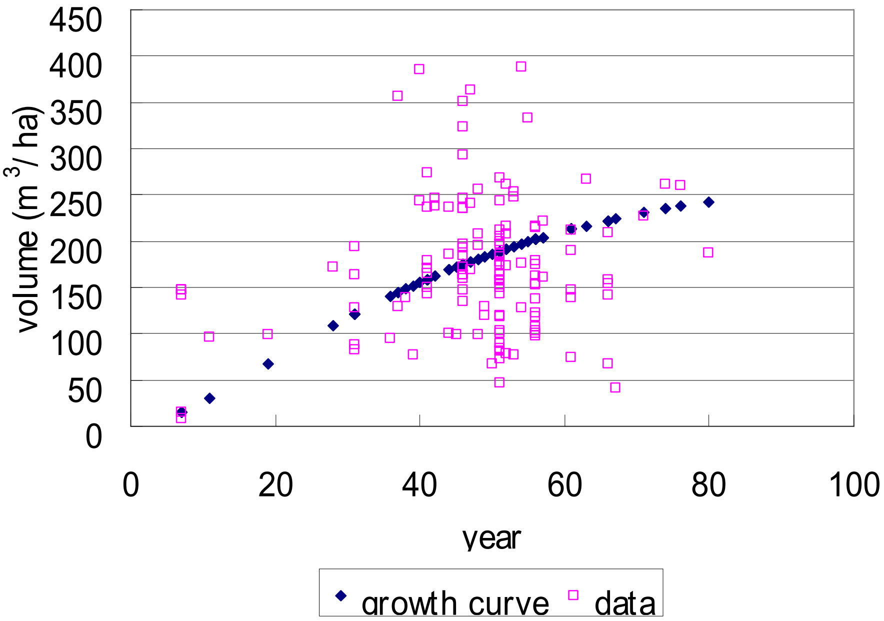


Figure 5: Richard's growth curve for broad-leaves

In order for energy-conversion plant to work stably, forest biomass resources should be provided to the plant stably. In this study, stand harvesting schedules were planned by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing harvesting costs.

2.5 Energy-conversion plant

Two types of an energy-conversion are considered in this study. One is a direct combustion and another is small-scale gasification. A direct combustion plant or a small-scale gasification plant is assumed to be located on the center of this region (Figure 1). Table 5 shows basic specifications on power generation plants. Net power output and steam flow changes in relation with plant scale. Yagi and Nakata (2006) reported the energy-conversion efficiency, E (%) of direct combustion and small-scale gasification is expressed by the following equations with the generation capacity C (kW) (Figure 6);

Direct combustion power-generation: $E=5.35\mathrm{xLN}(C)-24.59$ (3)

Small-scale gasification power-generation: $E=3.14\mathrm{xLN}(C)+5.10$ (4)

Table 5: Power generation plant specifications

Item	Direct combustion	Small-scale gasification
Plant scale (dry-t/day)	202	6.8
Operating rate (%)	72	87
Net power output (kW)	2,663	208
Steam flow (t/h)	24	6
Initial cost (million yen)	1,464	68
Subsidy ratio (%)	50	50
Interest rate (%)	3.5	3.5
The number of operator	7	1
Labor cost (yen/year/person)	7,000,000	7,000,000
Land tenancy cost (yen/year)	8,400,000	0
Overhead rate to initial cost (%)	5	5
Surplus power ratio (%)	79	75
Surplus steam ratio (%)	83	100
Power selling price (yen/kWh)	8	8
Steam selling price (yen/kg)	0.5	0.5
Duration (year)	30	30

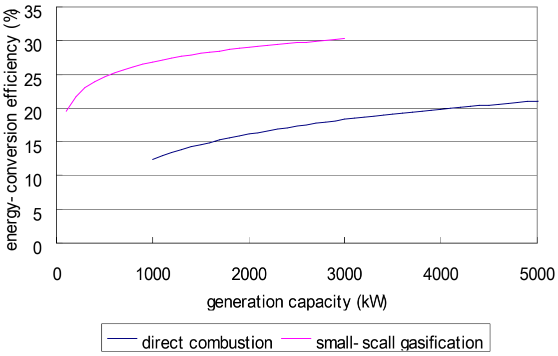


Figure 6: Generation capacity and energy-conversion efficiency

Figure 7 shows the relationship between generation capacity and harvesting volumes. The costs are assumed to be proportional to the 0.7 power of the net power output of the plant. A half of initial costs are assumed to be subsidized and another half of initial costs are assumed to be borrowed with interest. A part of generated power and steam are assumed to be used in the plant and surplus power and steam are assumed to be sold.

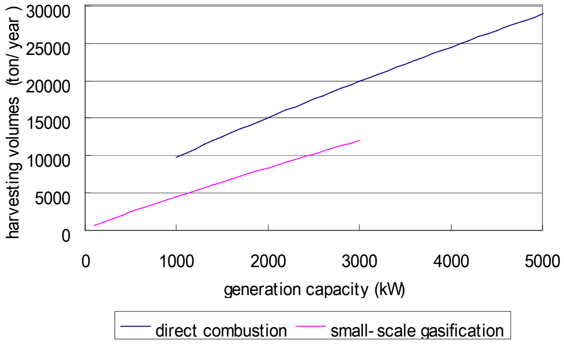


Figure 7: Generation capacity and harvesting volumes

2.6 Energy balance

The energy input into the system consists of the equipment and operation energies over the entire life cycle of the plant (Yoshioka et al 2005). Equipment energy is defined as the energy necessary for manufacturing equipment, which constitutes a system, i.e., forestry machines and a forest biomass power generation plant in this study, and is composed of the “material,” “production,” “transportation,” and “construction” energies. On the other hand, operation energy is defined as the energy necessary for operating a system and is composed of the fuel consumption of forestry machines and the “repair and maintenance” energy of a power generation plant.

The material energies are calculated using the weight of each kind of necessary material and the energy density of each necessary material. On the basis of the analysis by Hondo et al. (2000), all the parts of each forestry machine are assumed to be made of steel in this study. The weight of the required material for each machine is calculated from the mass, the durable hours of each machine, the productivity of each machine, and the annual required amount of logging residues for the plant. The quantity of required materials for a power generation plant is reported to be proportional to the 0.7 power of the net power output of the plant (Tahara et al. 1998). In this study, the required materials for a forest biomass power generation plant are calculated with reference to a 1000-MW coal-fired power generation plant (Uchiyama and Yamamoto 1991). A forest biomass power generation plant is assumed to be made of steel, aluminum, and concrete. The quantity of required material for the 3-MW forest biomass power generation plant is 1,519.6-t steel, 15.3-t aluminum, and 4,356-t concrete. Energy density of steel is 4,709-MJ/t (500-kWh) electricity and 20,930-MJ/t coal. Energy density of aluminum is 164,826-MJ/t (17,500-kWh) electricity and 46,047-MJ/t oil. Energy density of concrete is 184-MJ/t (20-kWh) electricity, 435-MJ/t oil, and 255-MJ/t coal. The sum of the production, transportation, and construction energies is assumed to be equivalent to 20% of the total material energy according to Uchiyama and Yamamoto (1991).

The quantity of required fuel is calculated from the fuel consumption of each machine, the productivity of each machine, and the annual required amount of logging residues for the plant. The gasoline is used for fuel of chainsaw and light oil is used for fuel of other machines. Energy densities of gasoline and light oil are 34.6 MJ/L and 38.2 MJ/L, respectively. The repair and maintenance energy of a power generation plant is assumed to be equivalent to 5% of the equipment energy over the life cycle of the plant based on the condition that the repair and maintenance of the plant is supposed to be performed every year so that all parts of the plant may be updated in 20 years (Uchiyama and Yamamoto 1991).

The goal of this study is to investigate the following two environmental load profiles of the defined biomass procurement and bioenergy supply chain. First, the energy balance factor (EBF) is the ratio of energy output to input, which is used to confirm whether the system is feasible as an energy production system. Second, the energy payback time (EPT) is the index that accounts, by energy production, for the number of years required to recover the total energy input into the system over an entire life cycle. Forest biomass power generation is compared with fossil and renewable resources from the perspectives of EBF and EPT, respectively. The basic theoretical equations for the two environmental load profiles defined in this study (EBF and EPT) are based on the rule made by Uchiyama and Yamamoto (1991). In addition, the CO_2 emissions from all the processes of the system are examined. The CO_2 emissions are calculated from energy input into each process and the CO_2 emission per unit energy of each energy resource. The CO_2 emissions from electricity, coal, oil, and light oil per unit energy are 392.33 $kgCO_2$/MWhe, 90.61 $kgCO_2$/GJ, 67.10 $kgCO_2$/GJ, and 68.70 $kgCO_2$/GJ, respectively (Uchiyama and Yamamoto 1992; Ministry of the Environment 2005).

3. Results

3.1 Economic balance

The maximum available amount of forest biomass is 30,106 ton/year with which about 5MW direct combustion power plant works (Figure 7 and 8). This plant will be sufficient to supply electricity to 41.3% of houses in the model area. According to harvesting volumes of forest biomass resources, logging residues were harvested based on the schedule. If the forest biomass resources are not sufficient, broad-leaved forests and thinned trees are harvested to meet sufficient volumes (Figure 9). According to harvesting costs of forest biomass resources, logging residues were the cheapest, 7,147 yen/ton, followed by broad-leaved forests, 15,404 yen/ton; thinned trees were the most costly, 23,097 yen/ton (Figure 10). As target volume of forest biomass decrease, harvesting costs of forest biomass resources decrease as well due to the reduction of harvesting volumes of thinned trees and broad-leaved trees of which harvesting costs are high (Figure 8).

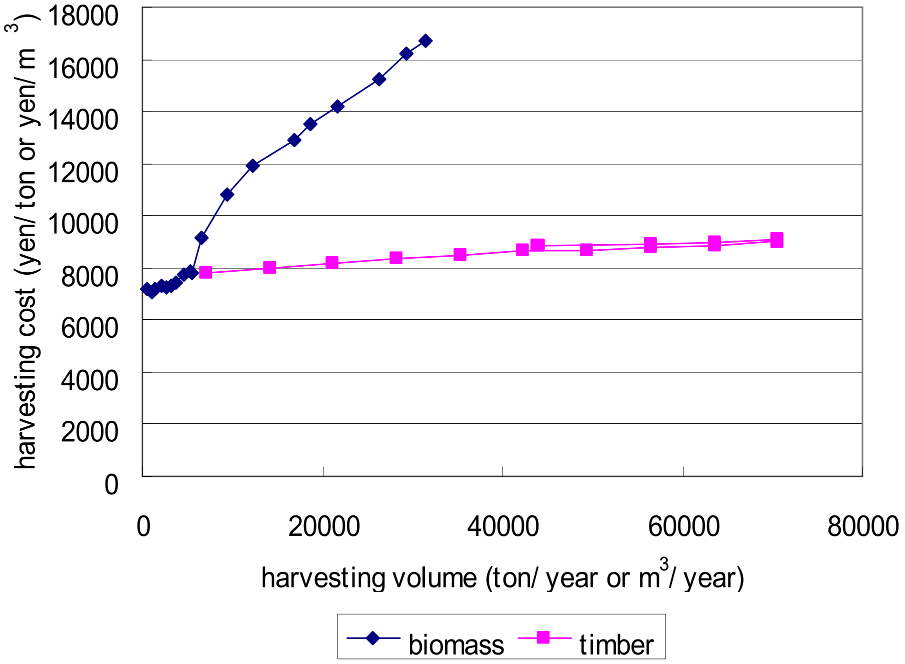


Figure 8: Harvesting volumes and costs

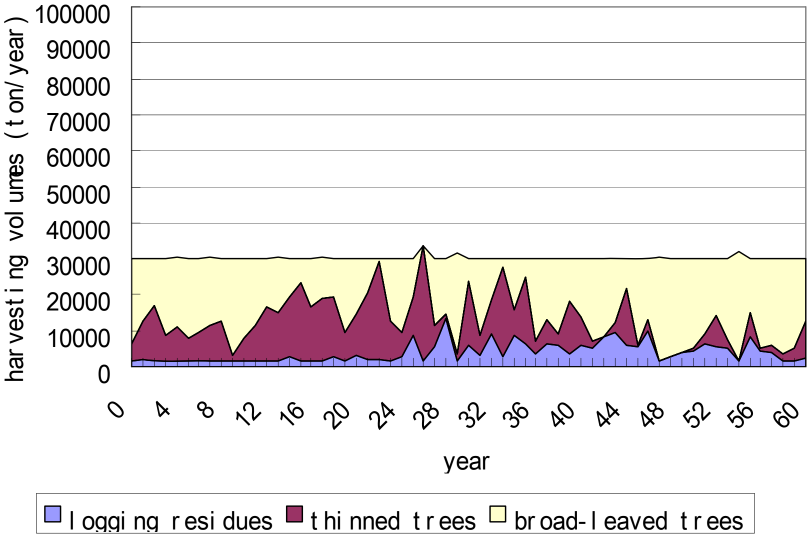


Figure 9: Harvesting volumes

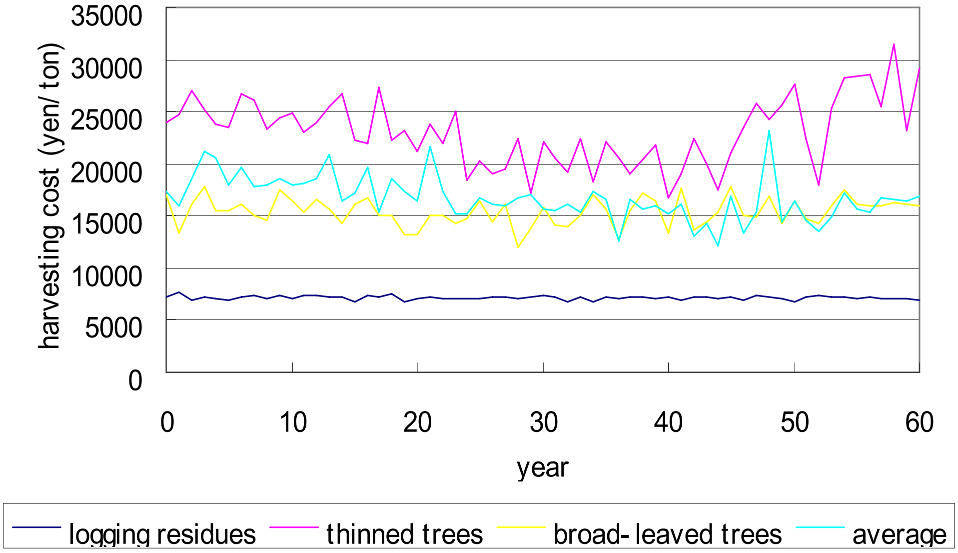


Figure 10: Harvesting costs

Then, the optimum scale of a power-generation plant was discussed on the model area using Figure 7 and Figure 8 on a direct combustion power plant and a small-scale gasification power plant. With regard to the direct combustion power generation, the optimum scale of a power-generation plant was a generation capacity of more than 3 MW and an energy-conversion efficiency of more than 18% (Figure 11). Its minimum fuel (harvesting) cost of electricity was 14.6 yen/kWh on 3-MW generation capacity. However, other costs were reduced as generation capacity increased. Therefore, total costs were almost constant, 23-24 yen/kWh over 3-MW generation capacity. On the other hand, the optimum scale of a small-scale gasification power plant was 1.3-MW generation capacity and 27% energy-conversion efficiency. Its fuel cost was 5.5 yen/kWh. Fuel costs were almost constant below 1.3-MW generation capacity and fuel costs increase over 1.3-MW generation capacity. However, other costs were reduced as generation capacity increased. Then, the minimum total cost was 10.7 yen/kWh on 1.3-MW generation capacity (Figure 12).

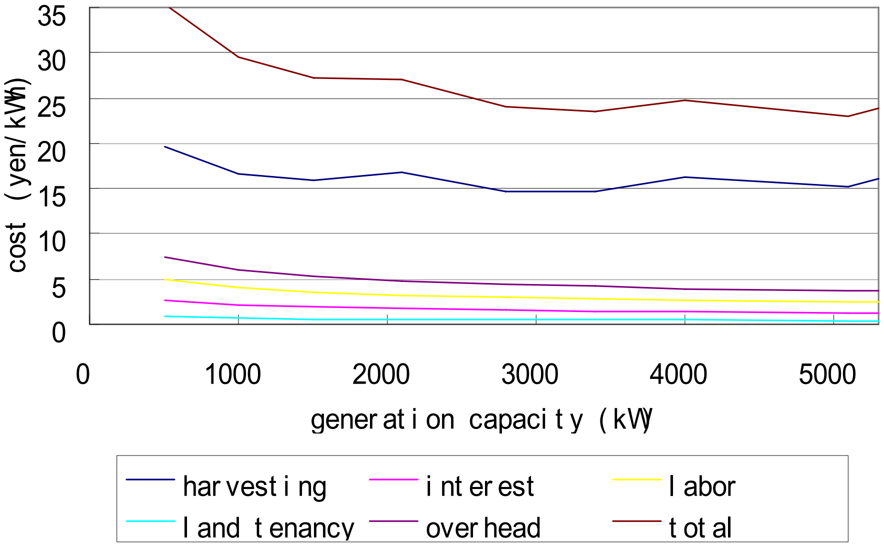


Figure 11: Relationship between generation capacity and costs on a direct combustion

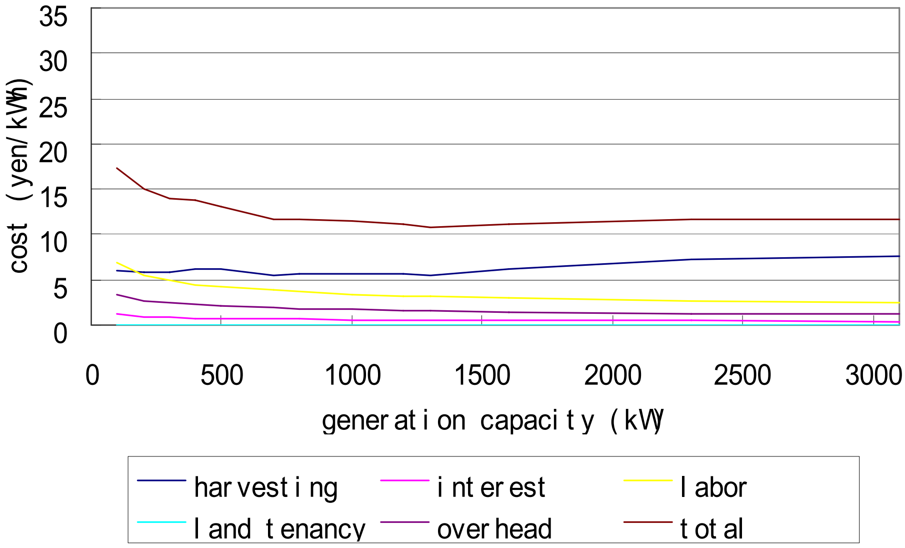


Figure 12: Relationship between generation capacity and costs on a small scale gasification

As the average electricity price in Japan, 2005 is 22.2 yen/kWh, the electricity generated from the small-scale gasification power-generation plant can be used in houses on the model area. Selling the electricity to grids at the price of 8 yen/kWh is not a good option even for small scale gasification. If the steam can be sold to houses on the model area at the price of 0.5 yen/kg, economic balance of small scale gasification is positive while economic balance of direct combustion is still negative (Figure 13). In this case, half of initial costs which are supposed to be borrowed for constructing 1.3-MW small scale gasification power-generation plant would be payback during 2.5 years (Figure 14).

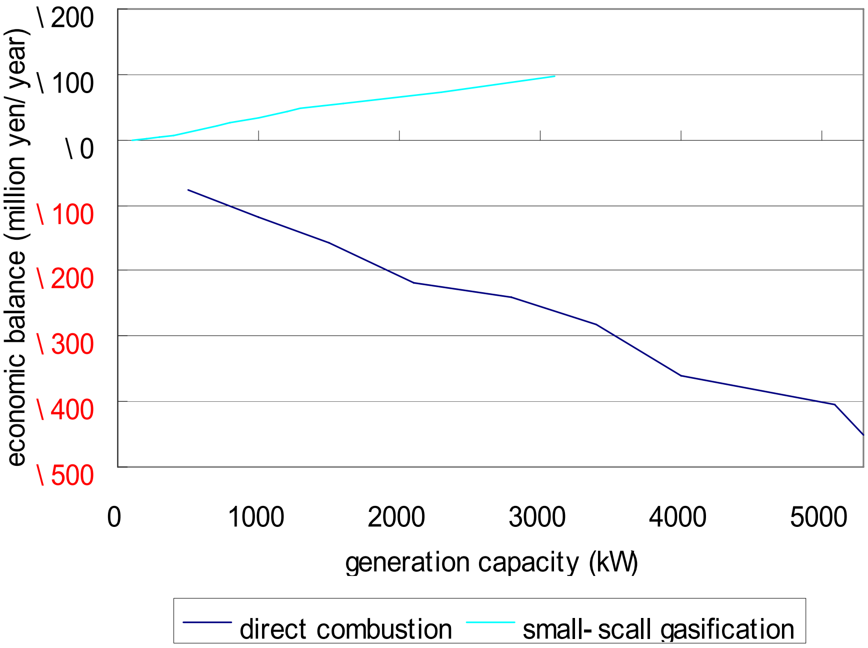


Figure 13: Relationship between generation capacity and economic balance

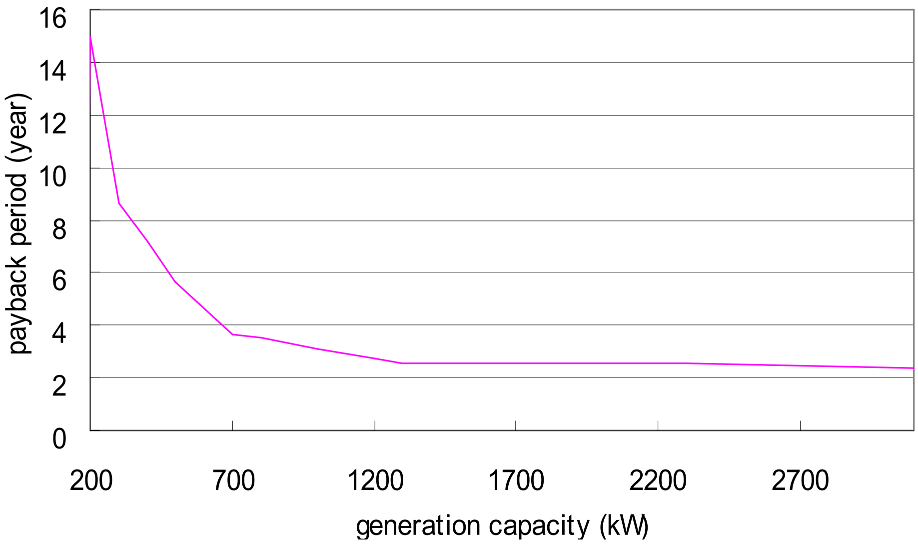


Figure 14: Relationship between generation capacity and payback period of a small scale gasification

3.2 Energy balance

Energy input increases as generation capacity increases. With the regard to direct combustion of 5-MW generation capacity, harvesting equipment and operation energy input are 536 GJ/year and 9,128 GJ/year while plant equipment and operation energy input are 2,673 GJ/year and 4,010 GJ/year (Figure 15). On the other hand, with the regard to small-scale gasification of 1.3-MW generation capacity, harvesting equipment and operation energy input are 98 GJ/year and 1,497 GJ/year while plant equipment and operation energy input are 1,027 GJ/year and 1.540 GJ/year (Figure 16).

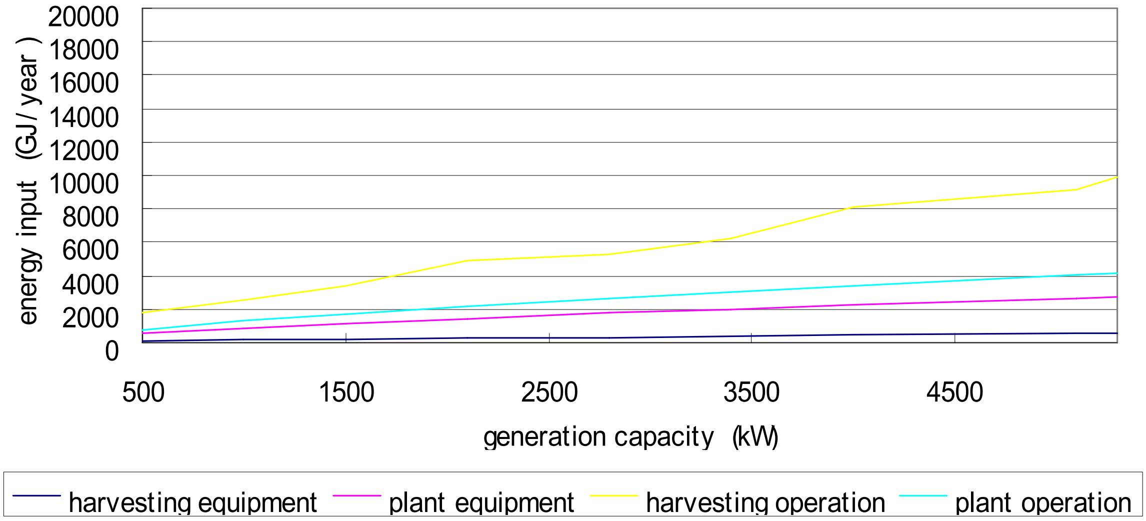


Figure 15: Relationship between generation capacity and energy input of direct combustion

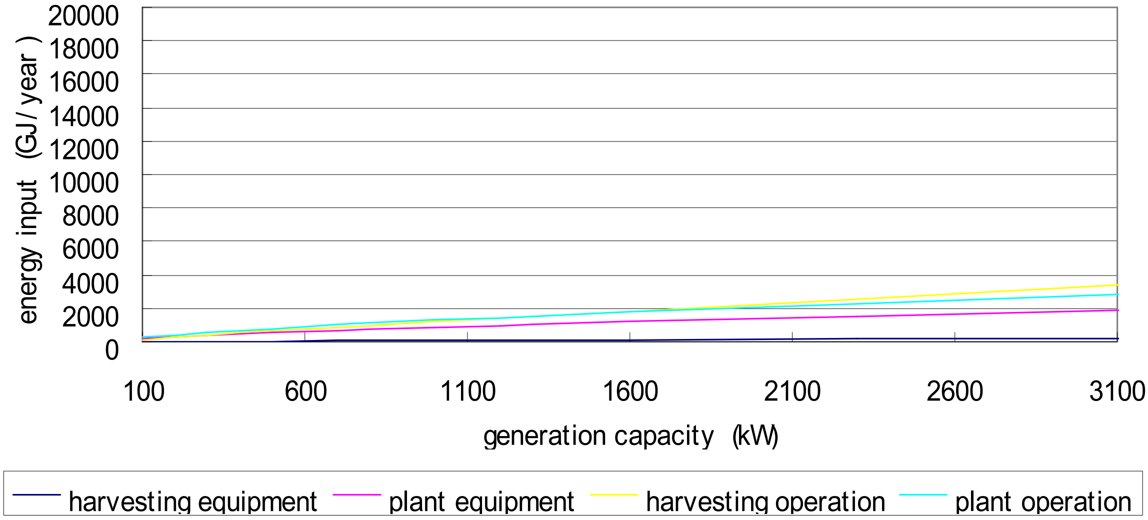


Figure 16: Relationship between generation capacity and energy input of small scale gasification

The energy balance factors both of direct combustion with 5-MW generation capacity and small scale gasification with 1.3-MW generation capacity are 18.1 (Figure 17). The energy balance factors of 1,000-MW generation capacity, a large-scale power generation system with coal and oil are 17.2 and 20.8, respectively (Uchiyama and Yamamoto 1991). The energy payback time of direct combustion with 5-MW generation capacity and small scale gasification with 3-MW generation capacity are 0.34 and 0.47 years, respectively (Figure 18). The energy payback time of wind power-generation and solar power-generation are 1.99 and 10.00 years, respectively (Uchiyama and Yamamoto 1999). Therefore, forest biomass power-generation was relatively superior to other renewable energy resources from the perspective of the energy payback time and it was similar to fossil energy resources from the perspective of the energy balance factor.

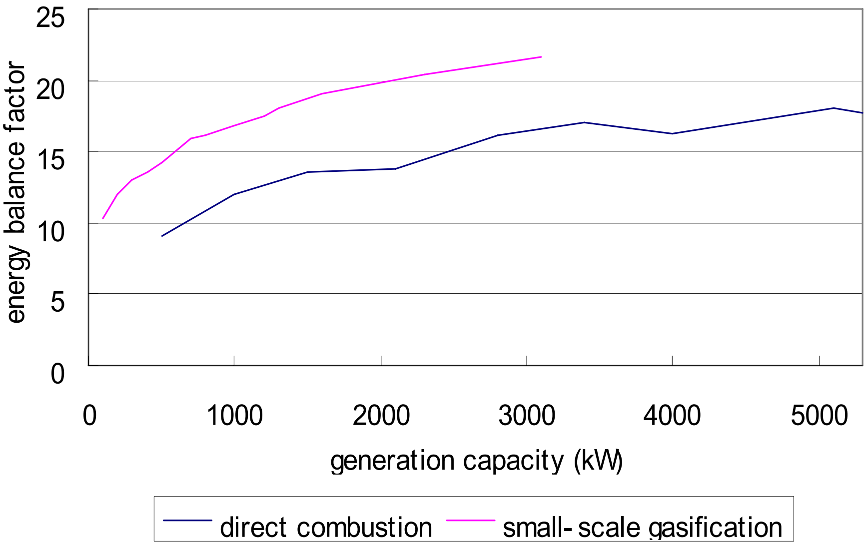


Figure 17: Relationship between generation capacity and energy balance factor

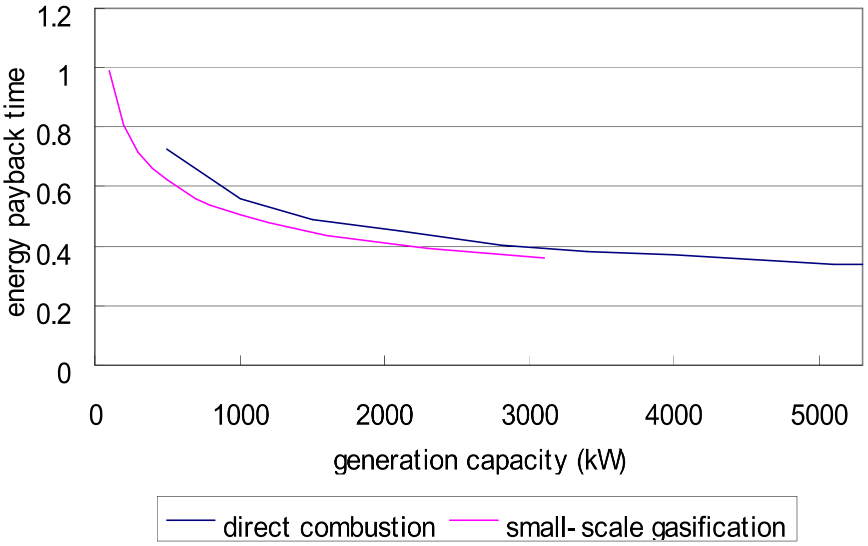


Figure 18: Relationship between generation capacity and energy payback time

Same with energy input, CO_2 emission increases as generation capacity increases (Figure 19). With the regard to direct combustion of 5-MW generation capacity, harvesting equipment and operation CO_2 emission are 43.7 t CO_2/year and 302.4 t CO_2/year while plant equipment and operation CO_2 emission are 209.3 t CO_2/year and 314.0 t CO_2/year. On the other hand, with the regard to small-scale gasification of 1.3-MW generation capacity, harvesting equipment and operation CO_2 emission are 16.6 t CO_2/year and 100.1 t CO_2/year while plant equipment and operation CO_2 emission are 147.8 t CO_2/year and 221.7 t CO_2/year.

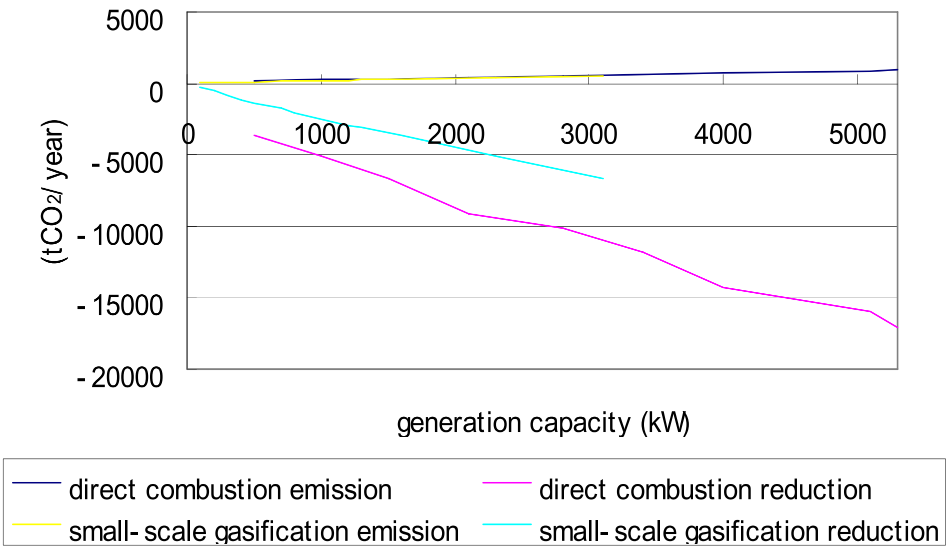


Figure 19: Relationship between generation capacity and CO_2 emission

However, using surplus electricity and steam reduces CO_2 emissions from fossil energy resources. CO_2 reduction of direct combustion with 5-MW generation capacity and small-scale gasification with 1.3-MW generation capacity are 15,913 t CO_2/year and 3,040 t CO_2/year, respectively. These reductions are much larger than CO_2 emission from forest biomass power generation. These reductions can contribute to achieving the goals of the Kyoto Protocol in the first period of commitment starting in the year 2008, when Japan must reduce its greenhouse gas emissions by 6% of the amount recorded in the year 1990. Yoshioka et al. (2005) assumed that Japan has the potential for forest biomass resources to construct 100 direct combustion power-generation plants with 3-MW generation capacity. CO_2 emission and reduction of a direct combustion with 3-MW generation capacity are 11,769 t CO_2/year and 623 t CO_2/year. Therefore, 100 power-generation plants reduce CO_2 emission by 1,114,600 t CO_2/year. This figure is 1.5% of the 74,000,000 tCO_2/year which amount of greenhouse gas emission Japan must reduce.

4. Discussion

4.1 Forest road construction

In order to reduce costs of direct combustion power generation, it is necessary to reduce harvesting costs remarkably by developing forest road network and machines for harvesting and transporting forest biomass resources efficiently. In this study, the effect of forest road construction on harvesting costs is discussed. Forest roads are assumed to be constructed so that skidding/yarding distances were reduced by 100 m, 200 m, or 300 m each skidding/yarding operation constantly. Forest road construction cost, *r* (yen/m) are expressed by the following equations;

$$r = 18{,}270 \times \exp(0.027\theta') \qquad (5)$$

where θ' is slope (%).

As a result, forest road construction reduced costs of electricity from 23.0 yen/kWh to 20.0 yen/kWh (Figure 20). However, the total cost including the cost of harvesting and forest road construction in the case of reducing each skidding/yarding distance by 100 m was increased to 947 million yen/year from 915 million yen/year without forest road construction. As the total cost excluding the cost of forest road construction was reduced to 862 million yen/year, forest road construction is a good option to reduce forest biomass harvesting costs if forest road could be constructed in public projects. Energy input without forest road construction is 16,348 GJ/year while harvesting and plant energy input is 15,754 GJ/year and energy input of forest road construction is 444 GJ/year. Therefore, total energy input was reduced.

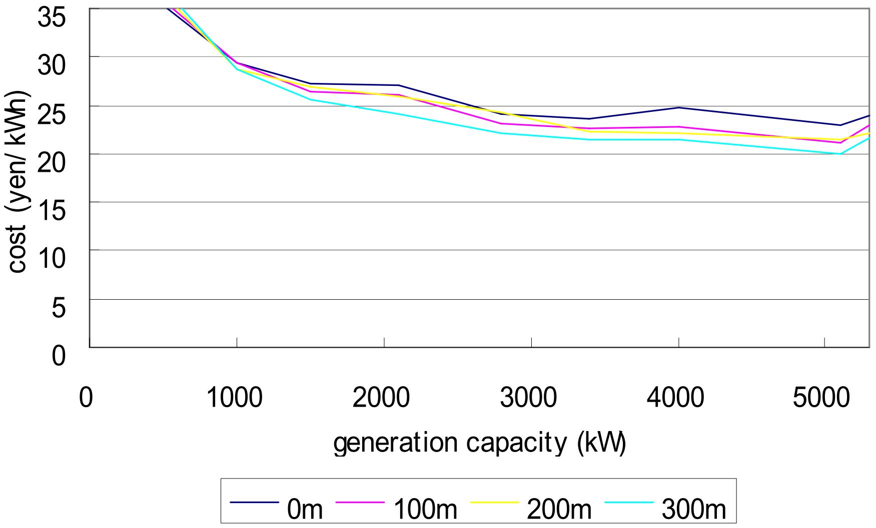


Figure 20: Relationship between generation capacity and costs of direct combustion after forest road construction

4.2 Skidding/yarding machine selection with minimizing operation costs

In this study, the machine for skidding/yarding is selected according to the topographical conditions of sub-compartments (Figure 3). In this section, skidding/yarding machine selection is conducted so that skidding/yarding costs are minimized within the topographical conditions of sub-compartments. Although the harvesting costs of logging residues were a little bit increased from 7,147 yen/ton to 7,165 yen, the harvesting costs of broad-leaved forests and thinned trees were much reduced from 15,404 yen/ton and 23,097 yen/ton to 14,376 yen/ton and 21,682 yen/ton, respectively. Therefore, the cost of electricity was reduced from 23.0 yen/kWh to 21.3 yen/kWh (Figure 22). Furthermore, forest road construction reduced the cost of electricity from 21.3 yen/kWh to 18.3 yen/kWh with minimizing skidding/yarding costs of each sub-compartment. The usage of appropriate machines is crucial to reduce the harvesting cost. In Japan, an excavator-based swing yarder has been spread out because it can be used for both excavator and yarder (Goto 2002). Monorail system has been developed for harvesting timber and forest biomass resources on steep terrains (Aruga 2004). In Nordic countries, chip-harvester (Talbot and Suadicani, 2005) and bundler (Johansson et al. 2006) has been used for harvesting whole trees and logging residues. Future study will examine appropriate usage of these machines from the economic and energetic points within applicable topographical conditions.

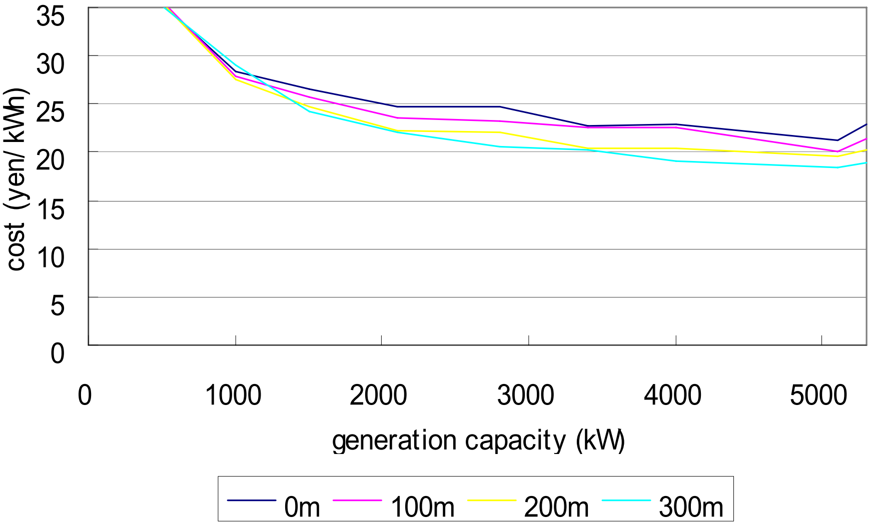


Figure 22: Relationship between generation capacity and costs of direct combustion after forest road construction and changing machine selection with minimizing skidding/yarding costs on each sub-compartment

5. References

Aruga K (2004) Precision forestry operations and equipment in Japan. Proc. of 2nd Precision Forestry Symposium: 31-36.

Goto, M. (2002) Thinning production systems with a swing yarder. Tokushima Pref. Forest Exp. Stn., Tokushima 9p.

Hondo H, Uchiyama Y, Moriizumi Y (2000) Evaluation of power generation technologies based on life cycle CO_2 emissions: reestimation using the latest data and effects of the difference of conditions (in Japanese with English abstract). Socioeconomic Research Center Report No. Y99009, Central Research Institute of Electric Power Industry, Tokyo

The Institute of Applied Energy (2005) Study on Biomass Energy Introduction Systems and Development Strategy, 255pp, New Energy and Industrial Technology Development Organization, Tokyo.

Johansson, J., Liss, J.E., Gullberg, T., Bjorheden, R. (2006) Transport and handling of forest energy bundles—advantages and problems. Biomass and Bioenergy 30(4):334–341.

Kuboyama, H., T. Nishizono, T. Iehara, and H. Okuda. 2004. Feasibility of Wood-biomass Utilization as an Energy Source: Case Study in Tohno City, Iwate Prefecture. J. Jpn. For. Soc. 86(2): 112-120p. (in Japanese with English summary).

Ministry of the Environment (2005) Guideline for the method to calculate GHG emissions from organizations. 83pp, Ministry of the Environment, Tokyo.

Nord-Larsen, T. and B. Talbot. 2004. Assessment of forest-fuel resources in Denmark: technical and economic availability. Biomass and Bioenergy 27: 97-109.

Tahara K, Kojima T, Inaba A, Ogi T, Yokoyama S (1998) Reduction in CO_2 emission by biomass power generation with sustainable afforestation: evaluation by LCA (in Japanese with English abstract). J Jpn. Inst. Energy 77:403–409

Talbot, B. and Suadicani, K. (2005) Analysis of Two Simulated In-field Chipping and Extraction Systems in Spruce Thinnings. Biosystems Engineering 91(3): 283–292.

Uchiyama Y, Yamamoto H (1991) Energy analysis on power generation plants (in Japanese with English abstract). Economic Research Center Report No. Y90015, Central Research Institute of Electric Power Industry, Tokyo

Uchiyama Y, Yamamoto H (1992) Greenhouse effect analysis of power generation plants (in Japanese with English abstract). Economic Research Center Report No. Y91005, Central Research Institute of Electric Power Industry, Tokyo

Yagi, K. and T. Nakata. 2007. Economic analysis on small-scale forest biomass gasification considering regional resource distribution and technical characteristics (in Japanese with English abstract). J. Jpn. Inst. Energy 86(2):109-118p.

Yoshioka, T. and H. Sakai. 2005. Amount and availability of forest biomass as an energy resource in a mountain region in Japan: A GIS-based analysis. Croatian J. For. Eng. 26(2): 59-70p.

Yoshioka, T., Aruga, K., Nitami, T., Kobayashi, H. and Sakai, H. (2005) Energy and carbon dioxide (CO_2) balance of logging residues as alternative energy resources: System analysis based on the method of a life cycle inventory (LCI) analysis. Journal of Forest Research 10: 125～134.