Original scientific paper – *Izvorni znanstveni rad*

Discussion on Economic and Energy Balances of Forest Biomass Utilization for Small-Scale Power Generation in Kanuma, Tochigi Prefecture, Japan

Kazuhiro Aruga, Ayami Murakami, Chikara Nakahata, Reiko Yamaguchi, Takuyuki Yoshioka

Abstract – Nacrtak

In this study, the economic and energy balances of forest biomass utilization for small-scale power generation are discussed, considering the spatial distribution of the forest biomass resources using the geographic information system (GIS) in the Kanuma area of Tochigi Prefecture, Japan. First, the optimum scales of two power-generation plants are discussed. For a direct combustion power-generation plant operating at an optimum scale of 5 MW generation capacity, the electricity cost would be 23.7 yen/kWh. For a small-scale gasification power plant operating at an optimal scale of 2.4 MW generation capacity, the electricity cost would be 12.8 yen/kWh. As the average electricity price in Japan is 22.2 yen/kWh, the electricity generated from the small-scale gasification power-generation plant could be economical. The energy balance and CO_2 emissions from the energy utilization of forest biomass resources were analyzed using the life cycle inventory (LCI) method. For both types of power generation, the ratio of energy output to input was calculated to be about 20, indicating that the system examined in this study could be feasible as an energy production system. The CO_2 emission from the direct combustion power generation with a generation capacity of 5 MW was 754.9 tCO_2/year, while the CO_2 emission of the small-scale gasification power plant with a generation capacity of 2.4 MW was 381.9 tCO_2/year. However, the reductions in the amount of CO_2 emission that would result from replacing fossil fuel were 15,707 tCO_2/year and 6,275 tCO_2/year, respectively.

€1 = 114 yen on June 27, 2011.

Keywords: economy balance, energy balance, CO_2 balance, forest biomass resources, small-scale power generation, GIS, LCI

1. Introduction – *Uvod*

Forests play an important role in the carbon balance of the planet by drawing carbon from the atmosphere and producing wood, a renewable resource that stores the removed carbon. Therefore, forests need to be continuously and properly managed and the wood utilized at all levels – from building materials, furniture, board and paper, to chemical products and fuel. Woody biomass can be categorized into forest residues (referred to as forest biomass resources in this study), sawmill residues, and construction waste timber. The recent years have witnessed a steady increase in the introduction of wood-fired boilers and generators and the production of wood pellets in Japan. However, a large amount of woody biomass, particularly forest residues, still remains unused (Forestry Agency 2009).

In order to utilize forest biomass resources for bio-energy, it is crucial to determine the relationship between the annual available amounts and the procurement (harvesting and transporting) costs of forest biomass resources. Ranta (2005) and Yoshioka and Sakai (2005) carried out detailed analyses of the potential supply of forest biomass using a geographic information system (GIS). Nord-Larsen and Talbot (2004) and Aruga et al. (2006a) discussed the long-term feasibility of timber and forest biomass resources by predicting future forest resources using growth models while optimizing the allocation of fuelwood using linear programming or random search. Yagi and Nakata (2006), Aruga et al. (2006b), and Panichelli and Gnansounou (2008) discussed the scales and locations of bio-energy facilities based on the relationship between the annual available amounts and the procurement costs of forest biomass resources.

In addition to the economic balances discussed in these studies, many other studies have discussed energy balances (Faaij et al. 1997, Forsberg 2000). However, these studies have focused on large-scale power plants whose net power outputs ranged from tens to hundreds of megawatts for the energy conversion of biomass. Therefore, Yoshioka et al. (2005) conducted analyses of energy and CO_2 balances for a small-scale energy-conversion system that used forest biomass resources from conventional Japanese forestry as fuel. However, the study did not consider the spatial distribution of the forest biomass resources. Therefore, the present study discusses the economy and energy balances of forest biomass utilization for small-scale power generation considering the spatial distribution of forest biomass resources using GIS in the Kanuma Area of Tochigi Prefecture, Japan.

2. Materials and Methods – *Materijal i metode*

Forest biomass resources can be categorized into logging residues, thinned wood, and broad leaved trees (Yoshioka and Sakai 2005). Forest resources, the slope of the land, and public and forest road layers of GIS were obtained from the Tochigi Prefectural Government in order to estimate the harvesting volumes and costs of timber and forest biomass resources. Future forest resources in each stand were predicted using the system yield table, Local Yield Table Construction System (LYCS, Shiraishi 1985). Then, the

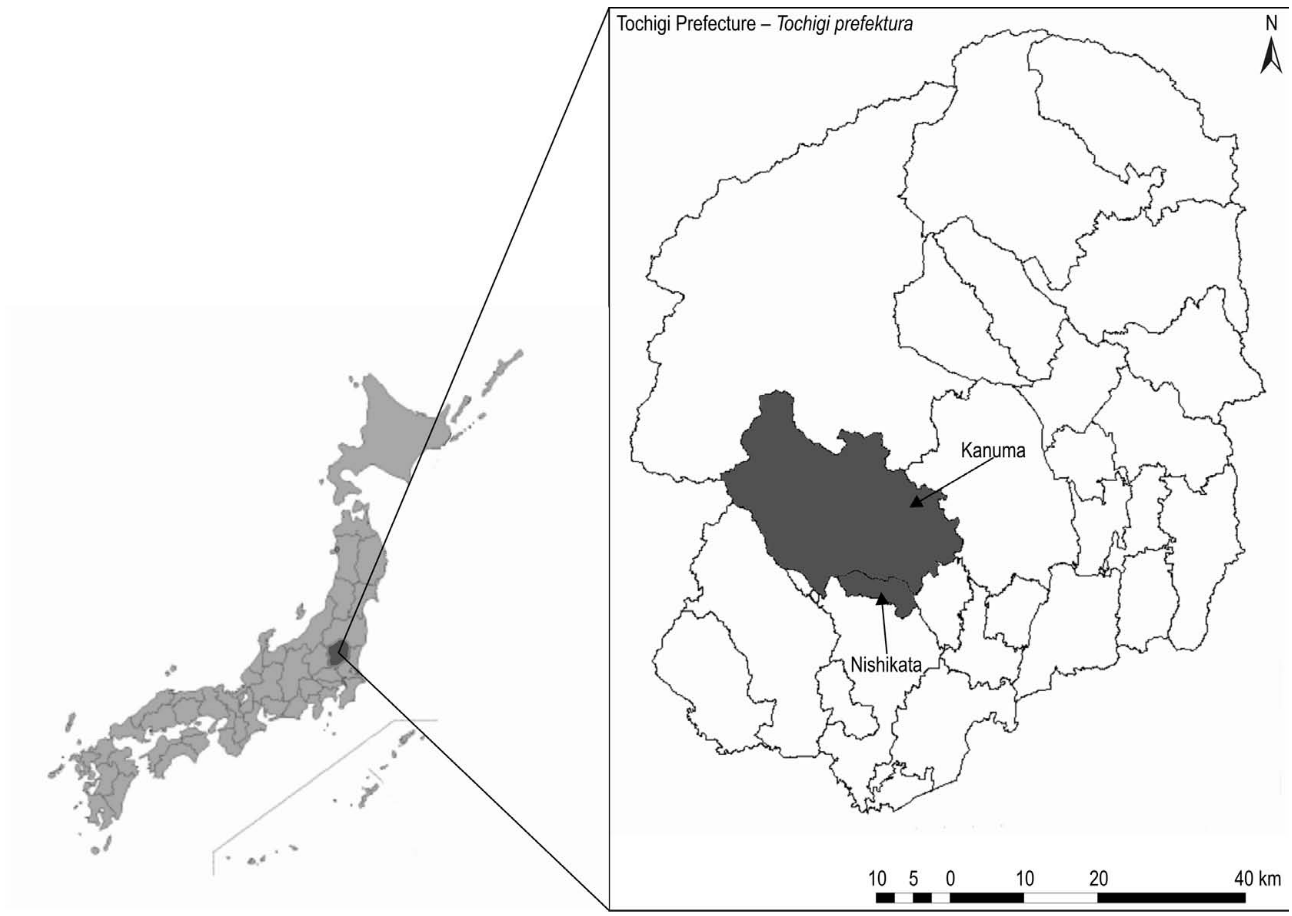


Fig.1 Study site
Slika 1. *Područje istraživanja*

stand harvesting schedules were planned by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing procurement costs. First, the optimum scales of a direct combustion power plant and a small-scale gasification power plant were discussed with the viewpoint of economic balances. Then, the energy balance and the CO_2 emission from the energy utilizations of the forest biomass resources were analyzed using the life cycle inventory (LCI) for the power-generation plants with the optimum generation capacity determined by the analyses of the economical balances.

2.1 Study site and Data – *Područje istraživanja i podaci*

The study site was the Kanuma area, consisting of Kanuma city and Nishikata town (Fig. 1).

This area encompasses 52,000 hectares, of which about 65% is forested (Fig. 2). Most of forests are man-made forests (79%) planted with conifers; Japanese cedar (Sugi) and Japanese cypress (Hinoki) account for 54% and 23% of the trees, respectively. Most of the conifers are about 45 – 50 years old. The Kanuma area was one of the famous forestry areas in Tochigi Prefecture. However, the forestry industry

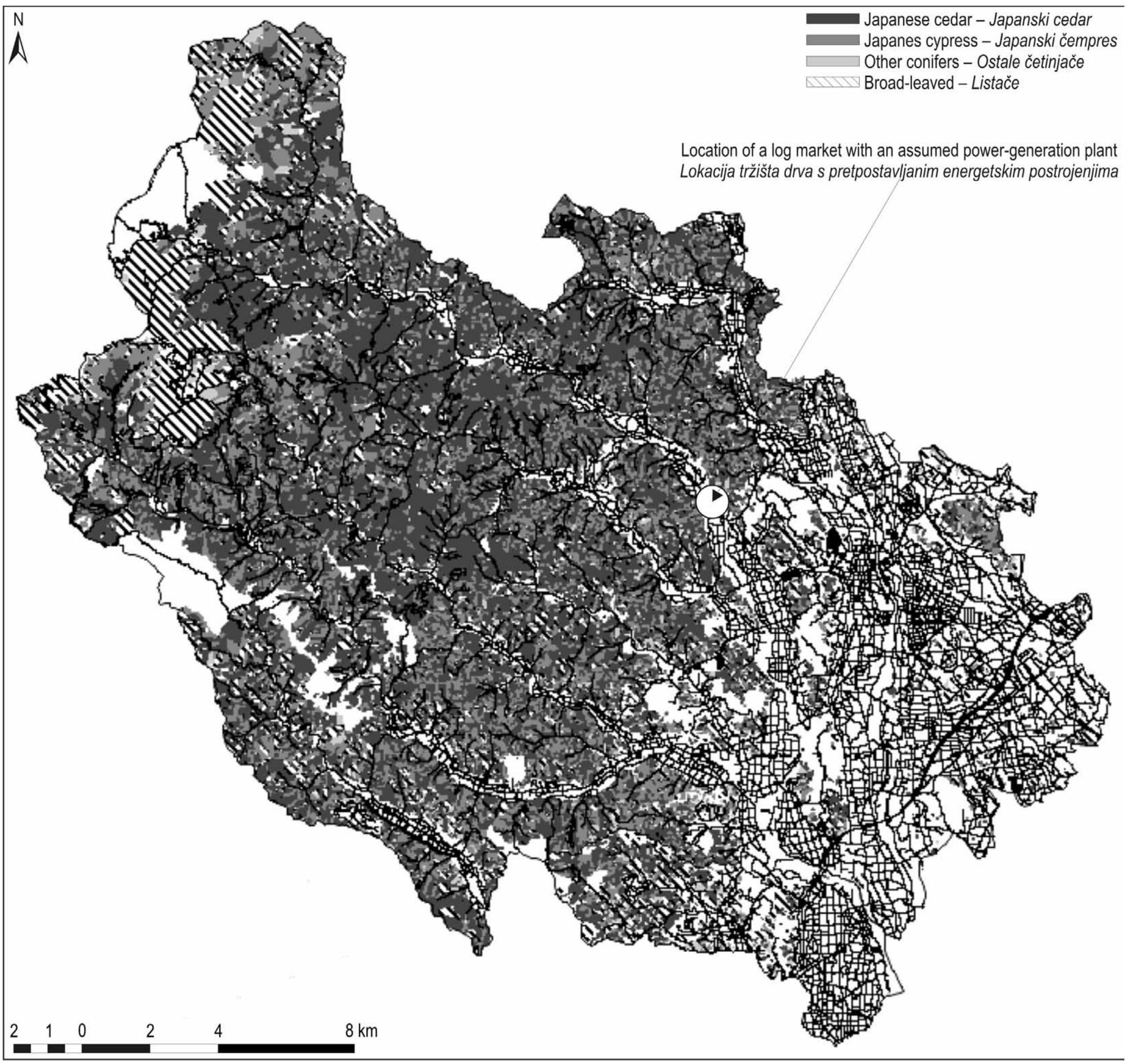


Fig.2 Tree species in the study area
Slika 2. *Vrste drveća na području istraživanja*

Table 1 Operation patterns in sub-compartments to be felled
Tablica 1. *Primjeri postupaka u pododjelima za sječu*

Forest – *Šuma*	Age, year *Dob, godina*	Operation pattern – *Primjer postupaka*
Man-made and coniferous *Umjetno podignute i četinjače*	31–60	[Forest biomass resources: Thinned trees] Thinning is carried out with a 20 – 50% thinning rate based on stand situations, and whole trees are used as energy sources[1] *[Resursi šumske biomase: stabla iz proreda]* *Prorede se izvode intenzitetom od 20 do 50 % na osnovi stanja sastojine i cijela se stabla koriste kao izvor energije[1]*
	Over 61 *Iznad 61*	[Forest biomass resources: Logging residues] Clearcutting is carried out on a 60-year cycle. Trees are limbed and bucked, logs are harvested, and tops and branches are used as energy sources *[Resursi šumske biomase: ostaci pridobivanja drva]* *Čiste se sječe provode u 60-godišnjim ciklusima. Stabla se krešu i izrađuju, trupci se odvajaju, a vrhovi i grane se koriste kao izvori energije*
Naturally regenerated and broad-leaved *Prirodno pomlađene i listače*	Over 31 *Iznad 31*	[Forest biomass resources: Broad-leaved forests] Clearcutting is carried out on a 30-year cycle, and whole trees are used as energy sources *[Resursi šumske biomase: sastojine listača]* *Čiste se sječe provode u 30-godišnjim ciklusima i cijela se stabla koriste kao izvor energije*

[1]In this study, we assume that all the cut material from thinning operations can be used as an energy source, considering the actual Japanese market value
[1]U ovom je radu pretpostavljeno da se sav materijal iz proreda može koristiti kao izvor energije, uzimajući u obzir stvarne vrijednosti na japanskom tržištu

has been in decline for a long time. Therefore, bio-energy is attracting a great deal of attention since energy utilization of forest biomass resources is expected to contribute to the revitalization of the forestry industry as well as the maintenance of the appropriate ecological, economic, and social functions of man-made forests. The site-index ranks the order of the production capacity of the stands into three classes: the smaller the number, the larger is the production capacity. Site-index 1 is 53%, site-index 2 is 43%, and site-index 3 is 4%. As for the operation-site inclination, most of the forests are in relatively steep terrain, sloping 30 degrees or more. The density of the road network in the Kanuma area is 18 m/ha.

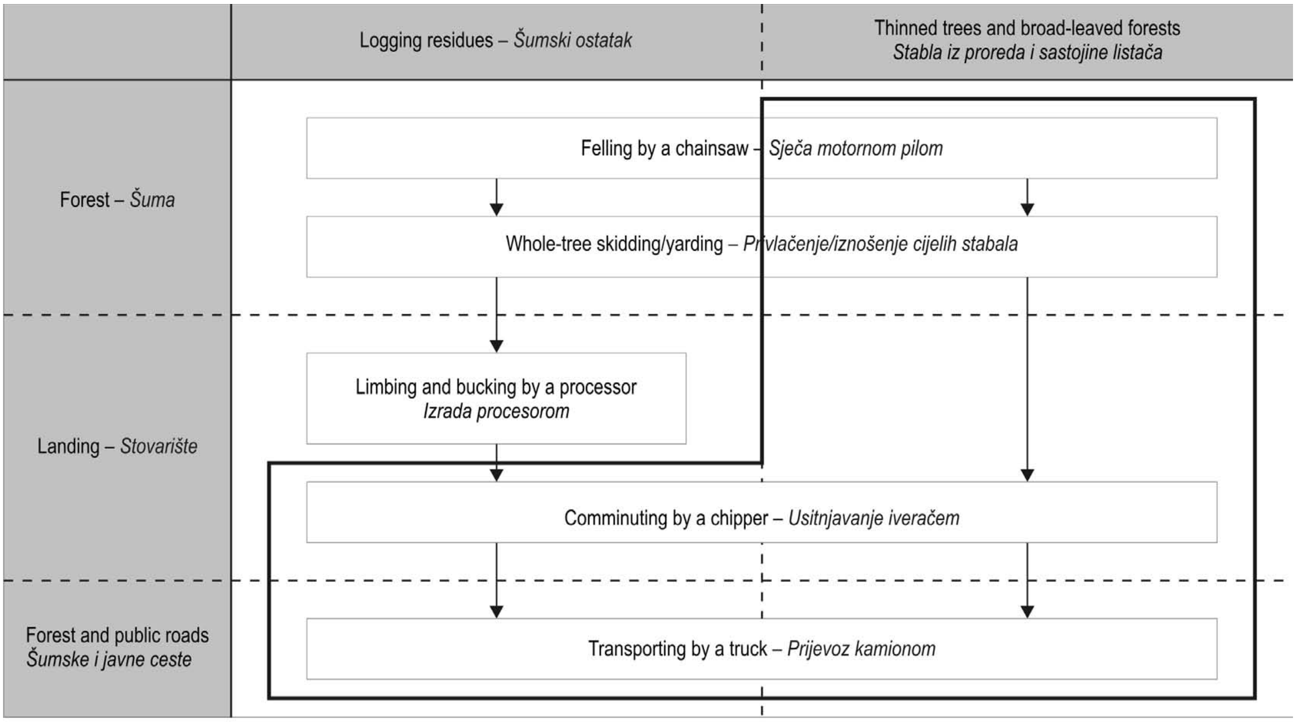
Forest registration data (stand age, tree species, and site indexes) and GIS data (information on roads and sub-compartment layers) from the Tochigi Prefectural Government were used in this study, as well as 50-m-grid digital elevation models (DEM) from the Geographical Survey Institute. The data were converted into 50-m-grid raster data for consistency with the DEM data. Using these materials and the GIS, the annual available amounts of timber and forest biomass resources were estimated based on sub-compartments. The DEM was used to estimate the slope of each sub-compartment and to judge the skidding/yarding direction (uphill or downhill) for cost estimations. The analysis was conducted on the basis of sub-compartments, which are common operational units in Japan.

2.2 Procurement costs – *Troškovi pridobivanja*

The harvesting and transporting systems for forest biomass resources were classified into two types (Fig. 3) depending on the resources used (logging residues or the whole tree). Table 1 lists the operation patterns of the sub-compartments to be felled. Logging residues are considered to be a by-product in conventional forestry. Therefore, the system boundary of logging residues begins with comminuting the logging residues at the landing of the logging site by a mobile chipper (Fig. 3).

In this study, it is assumed that tractors (cable skidders), swing yarders (backhoe with winch drums), tower yarders (mobile yarders), and yarders are used for the skidding/yarding process. Tractors can be used on slopes below 11 degrees for uphill travel and 19 degrees for downhill travel. Swing yarders and tower yarders can be used within 100 m and 300 m yarding distances, respectively. In this study, one type of machine from the four types mentioned here is assumed to be selected for each stand so that skidding/yarding costs are minimized within the topographic condition of each stand.

Table 2 shows the equations for estimating the efficiency, and Table 3 shows the equations for estimating the procurement costs of timber and forest biomass resources. In both sets of equations, the variables are the slope θ[degree], average stem volume V_n[m^3/stem], harvesting volumes per ha V[m^3/ha], number of trees harvested per ha N_F[stem/ha], skid-



Only processes inside the bold line are considered when analyzing the economic and energy balances on forest biomass utilization for bio-energy
Pri analizi ekonomske i energetske bilance u korištenju šumske biomase za bioenergiju uzimaju se samo postupci unutar podebljano označenih linija

Fig.3 Classification of systems according to wood material harvested
Slika 3. *Klasifikacija sustava prema pridobivanomu drvnomu materijalu*

Table 2 Machine specification
Tablica 2. *Značajke strojeva*

Machine – *Stroj*	Remarks *Napomena*	Mass, kg *Masa*, kg	Lifetime, hour *Životni vijek*, sat	Efficiency, m^3/hour *Efikasnost*, m^3/sat	Fuel consumption, l/hour *Potrošnja goriva*, l/sat
Chainsaw *Motorna pila*	Conifer *Četinjače*	6	2,700	$\frac{21{,}600 V_n \sqrt{N_F}}{219 V_n \sqrt{N_F} + 3{,}000}$	2.8
	Broadleaf *Listače*	6	2,700	2.0	2.8
Tractor *Traktor*	Whole tree *Cijelo stablo*	6,000	6,480	$5{,}440/L_Y$	4.3
Swing yarder *Okretna žičara*	Whole tree *Cijelo stablo*	3,200	4,200	$1{,}080/(2L_Y+80)$	13.0
Tower yarder *Stupna žičara*	Whole tree *Cijelo stablo*	7,425	5,400	$4{,}860/(2L_Y+243)$	3.0
Yarder *Žičara*	Whole tree *Cijelo stablo*	3,000	6,300	$12L_Y^{-0.21}$	2.8
Processor *Procesor*	Whole tree *Cijelo stablo*	6,770	6,480	$151V_n$	2.0
Chipper *Iverač*	Solid *Kruto*	7,802	5,000	13	28.0
Truck *Kamion*	Log *Trupac*	7,960	5,500	$247{,}422/L_T$	8.2
	Chip *Iver*	7,960	5,500	$199{,}500/L_T$	8.2

Table 3 Procurement cost, yen/m^3
Tablica 3. *Troškovi pridobivanja, jen/m^3*

Machine *Stroj*	Remarks *Napomena*	Cost – *Trošak*
Chainsaw *Motorna pila*	Conifer *Četinjače*	$179 + 2{,}453/V_n\sqrt{N_F}$
	Broadleaf *Listače*	1,472
Tractor *Traktor*	Whole tree *Cijelo stablo*	$0.97L_Y + 27{,}510e^{0.12\theta}/V + 1{,}771$
Swing yarder *Okretna žičara*	Whole tree *Cijelo stablo*	$22L_Y + 3{,}913{,}500/L_YV + 919$
Tower yarder *Stupna žičara*	Whole tree *Cijelo stablo*	$5.4L_Y + 5{,}870{,}250/L_YV + 747$
Yarder *Žičara*	Whole tree *Cijelo stablo*	$991L_Y^{0.21} + 5{,}071{,}896/L_YV + 161{,}236/V + 196$
Processor *Procesor*	Whole tree *Cijelo stablo*	$532/V_n$
Chipper *Iverač*	Solid *Kruto*	1,093
Truck *Kamion*	Log *Trupac*	$0.027L_T + 778$
	Chip *Iver*	$0.033L_T + 778$

ding/yarding distance L_Y [m], and transporting distance L_T [m]. In addition to the direct costs of labor, machinery, and fuel, the indirect costs of labor (55% of the direct cost of labor), machine moving costs (50,000 yen/each), and overhead costs (20% of the total direct costs) are also considered.

Finally, the following items on topography are processed by the GIS software. The average angle of inclination of each sub-compartment is calculated. To determine the skidding/yarding distance of each sub-compartment, the distance between the center of gravity of the sub-compartment and the nearest road from the sub-compartment is calculated. A landing is to be arranged at a point on the nearest road from the sub-compartment. The skidding/yarding direction (uphill or downhill) is judged by comparing the altitude between the center of gravity and the landing. The transporting distance from the landing to the energy-conversion plant is calculated by the shortest path algorithm using the Dijkstra method (Dijkstra 1959). The energy-conversion plant is assumed to be located on the log market. By applying the topographical data for each sub-compartment to the equations listed in Table 3, the procurement costs of timber and forest biomass resources can be calculated.

2.3 Available amounts of timber and forest biomass resources – *Raspoložive količine drva i šumske biomase*

The available amounts of timber and forest biomass resources can be estimated from the stem volume recorded in the forest register and the coefficients listed in Table 4. Consequently, by applying Tables 1 and 4 to the forest register, the available amounts of timber and forest biomass resources for the first year can be estimated. To estimate the future available amounts of timber and forest biomass resources, the system yield table, LYCS (Shiraishi 1985)

Table 4 Methods for calculating the amount of forest biomass resources
Tablica 4. *Metode za izračun količine resursa za šumsku biomasu*

Biomass resources *Resursi biomase*	Equation (s.v.: Stem volume) *Jednadžba (s.v.: obujam debla)*	Notes *Zabilješke*
Logging residues[1] *Šumski ostatak*[1]	Amount (tDM) – *Količina (tST)* = s.v. × 15/92 × 0.40	15/92: Ratio of top and branches' volume to stem volume 0.40: Density of a coniferous tree *15/92: Odnos obujma ovršaka i grana prema obujmu debla* *0,40: Gustoća četinjača*
Thinned trees *Stabla iz proreda*	Amount (tDM) – *Količina (tST)* = s.v. × t.r. × 100/92 × 0.40	t.r.: Thinning rate, 20 – 50/100 100/92: Ratio of the whole tree's volume to stem volume 0.40: Density of a coniferous tree *t.r.: Intenzitet prorede, 20 – 50/100* *100/92: Odnos obujma cijeloga stabla prema obujmu debla* *0,40: Gustoća četinjača*
Broad-leaved forests *Sastojine listača*	Amount (tDM) – *Količina (tST)* = 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 *100/80: Odnos obujma cijeloga stabla prema obujmu debla* *0,56: Gustoća listača*

[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)
[1]Metoda za izračun obujma trupaca u čistim sječama je sljedeća: obujam trupaca (m^3) = s.v. × 85/92 (85/92: odnos obujma trupaca prema obujmu debla)

is applied to the forest register. The time interval is five years. In order to allow the steady operation of the energy-conversion plant, the forest biomass resources should be provided to the plant on a continuous basis. In this study, stand harvesting schedules were planned for sixty years by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing procurement costs (Aruga et al. 2006a).

2.4 Energy-conversion plants – *Energetska postrojenja*

Two types of energy-conversion are considered in this study. One is direct combustion and the other is small-scale gasification. Small-scale gasification is a technology currently under development. Table 5 shows the basic specifications for the power-generation plants. The net power output and steam flow change in relation to the plant scale.

Yagi and Nakata (2007) reported that the energy-conversion efficiency E [%] of direct combustion and small-scale gasification could be expressed by the following equations as a function of the generation capacity G [kW]:

Direct combustion power-generation:

$$E = 5.35 \times \mathrm{LN}(G) - 24.59 \tag{1}$$

Small-scale gasification power-generation:

$$E = 3.14 \times \mathrm{LN}(G) + 5.10 \tag{2}$$

The generation capacity of small-scale gasification was assumed to be within 3,000 kW. Fig. 4 shows the relationship between the generation capacity and the demand for fuels. The costs of the power-generation plant construction C [yen] are assumed to be proportional to the power of 0.7 of the net power output of the plant, $C \propto G^{0.7}$ because the quantity of materials required for a power-generation plant is reported to be proportional to the power of 0.7 of the net power output of the plant (Tahara et al. 1998). Half of the initial costs are assumed to be subsidized. Some of the generated power and steam is assumed to be utilized in the plant, and the surplus power and steam are assumed to be sold.

2.5 Energy balance – *Energetska bilanca*

The energy input into the system consists of the equipment and operation energies over the entire lifetime of the plant (Yoshioka et al. 2005). Equipment energy is defined as the energy used for manufacturing the equipment that constitutes the system, that is, the forestry machinery and the power-generation plant in this study, and is composed of the »material«, »production«, »transport« and »construction« energies. On the other hand, operation energy

Table 5 Power-generation plant specifications
Tablica 5. *Značajke energetskoga postrojenja*

Item – *Značajka*	Direct combustion *Izravno izgaranje*	Small-scale gasification *Malo plinoficiranje*
Fuel consumption, tDM/day – *Potrošnja goriva*, tST/dan	202	6.8
Operating rate, % – *Stupanj korištenja*, %	72	87
Net power output, kW – *Proizvodnja energije, neto*, kW	2,663	208
Steam flow, t/h – *Protok pare*, t/h	24	6
Initial cost, million yen – *Početni troškovi*, milijun jena	1,464	68
Subsidy ratio, % – *Iznos potpora*, %	50	50
Repair and maintenance coefficient, % – *Koeficijent popravaka i održavanja*, %	5	5
Operators, n – *Rukovatelji*, n	7	1
Labor cost, yen/year/person – *Trošak radne snage*, jen/godina/osoba	7,000,000	7,000,000
Land tenancy cost, yen/year – *Trošak zakupa zemljišta*, jen/godina	8,400,000	0
Overhead rate to initial cost, % – *Opći troškovi prema početnomu trošku*, %	5	5
Surplus power ratio, % – *Stupanj viška energije*, %	79	75
Surplus steam ratio, % – *Stupanj viška pare*, %	83	100
Power selling price, yen/kWh – *Prodajna cijena energije*, jen/kWh	8	8
Steam selling price, yen/kg – *Prodajna cijena pare*, jen/kg	0.5	0.5
Life time, years – *Životni vijek*, godine	30	30

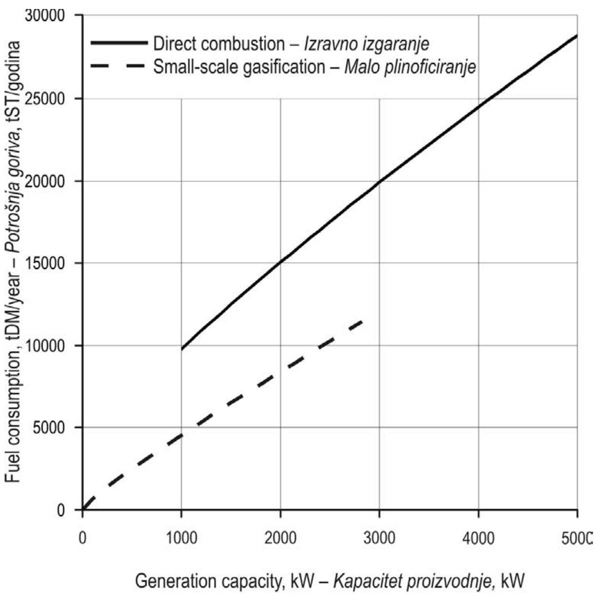


Fig.4 Generation capacity and fuel consumption
Slika 4. *Proizvodni kapacitet i potrošnja goriva*

is defined as the energy necessary for operating the system and is composed of the fuel consumption of the forestry machinery and the »repair and maintenance« energy of the power-generation plant.

The material energies are calculated using the weight of each kind of material used and the energy density of each material. Based on 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 lifetime of each machine, the productivity of each machine, and the annual amount of forest biomass resources required for the plant (Yoshioka et al. 2005). The required materials for a forest biomass power-generation plant are calculated with reference to a 1,000 MW coal-fired power-generation plant (Uchiyama and Yamamoto 1991). The energy density of steel is 4,709 MJ/t (500 kWh) electricity and 20,930 MJ/t coal. The energy density of aluminum is 164,826 MJ/t (17,500 kWh) electricity and 46,047 MJ/t oil. The energy density of concrete is 184 MJ/t (20 kWh) electricity, 435 MJ/t oil, and 255 MJ/t coal. According to Uchiyama and Yamamoto (1991), the sum of the production, transport, and construction energies is assumed to be equivalent to 20% of the total material energy.

The quantity of required fuel is calculated from the fuel consumption of each machine, the productivity of each machine, and the annual amount of forest biomass resources required for the plant. Gasoline (petrol) is used as fuel for chainsaws, and diesel fuel is used for all other machines. The energy densities of gasoline and diesel fuel 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 lifetime of the plant provided that the repair and maintenance of the plant is 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 bio-energy supply chain. First, the energy balance factor (EBF) is the ratio of energy output to input, which is used to examine 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 its entire lifetime. The forest biomass power generation is compared to fossil and renewable resources from the perspectives of EBF and EPT. The basic theoretical equations for the two environmental load profiles defined in this study (EBF and EPT) are based on the rule of Uchiyama and Yamamoto (1991).

Furthermore, the CO_2 emissions from all the processes of the system are examined. These emissions are calculated from the energy input into each process and the CO_2 emission per unit energy of each energy resource. The CO_2 emissions from the electricity, coal, gasoline, and diesel fuel 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).

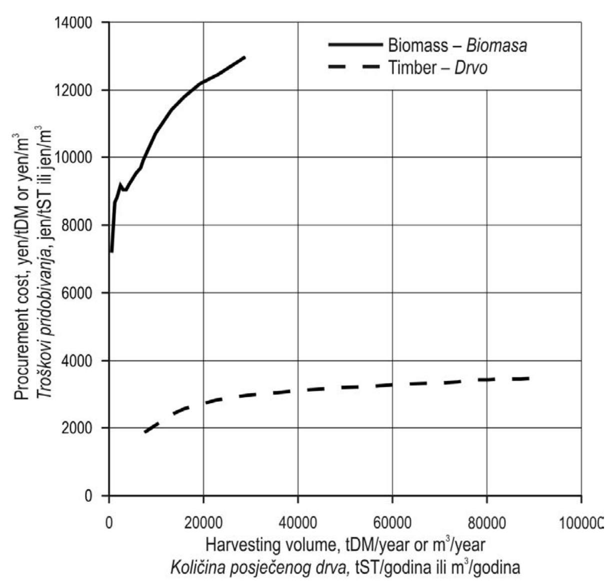


Fig.5 Harvesting volumes and procurement costs
Slika 5. *Količina i troškovi pridobivanja goriva*

3. Results and discussion – *Rezultati i rasprava*

3.1 Economic balance – *Ekonomska bilanca*

The maximum available amount of forest biomass resources is 28,872 tDM/year, which is enough to meet the fuel requirement of a 5 MW direct combustion power plant (Fig. 4 and 5).

According to the harvesting volumes of the forest biomass resources, the logging residues can be harvested based on the stand harvesting schedule. If the forest biomass resources are insufficient, broad-leaved forests and thinned trees can be harvested to meet the required volumes (Fig. 6).

A comparison of the procurement costs of the forest biomass resources revealed that logging residues were the cheapest at 9,271 yen/tDM; this was fol-

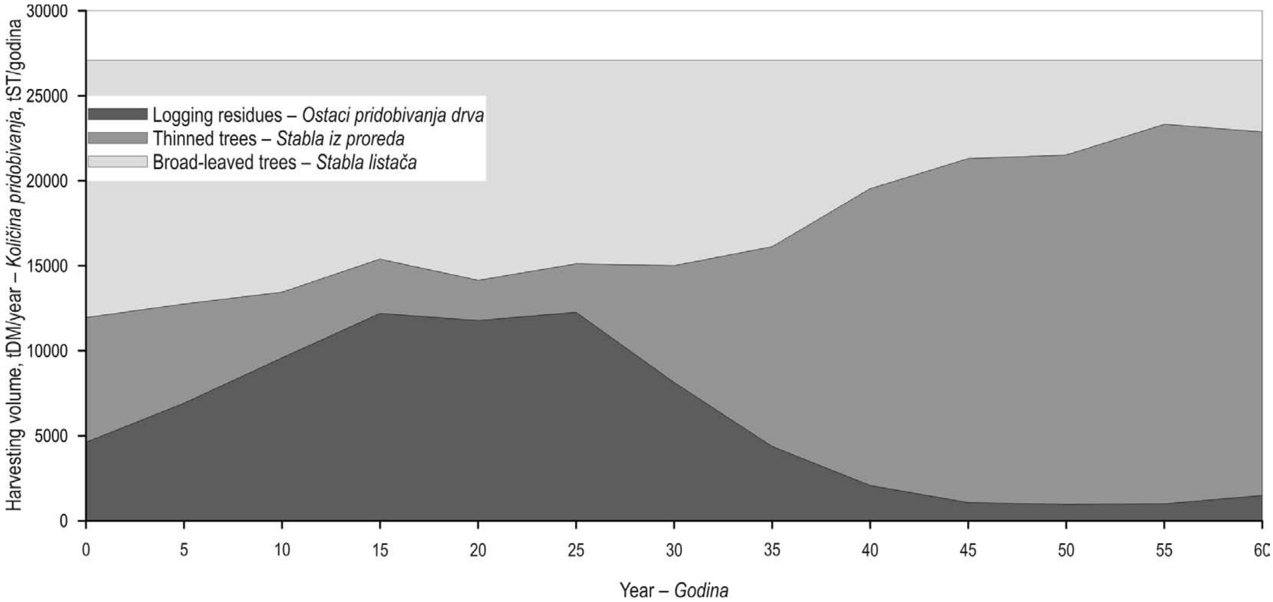


Fig.6 Harvesting volumes
Slika 6. *Količina priodobivanja drva*

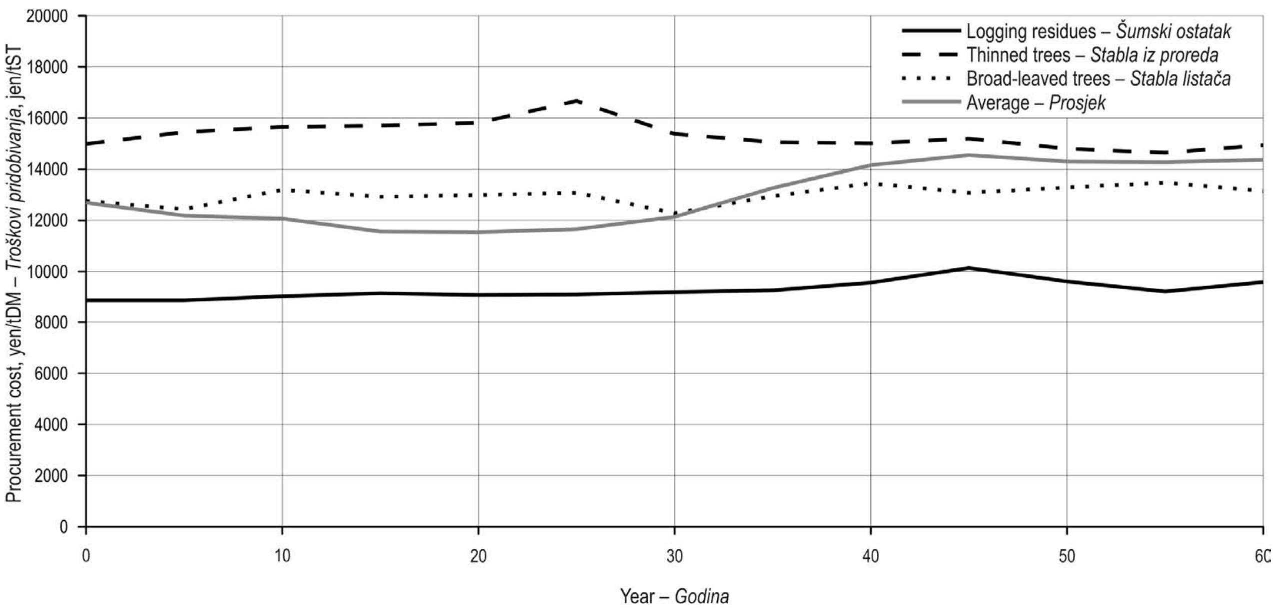


Fig.7 Procurement costs
Slika 7. *Troškovi pridobivanja*

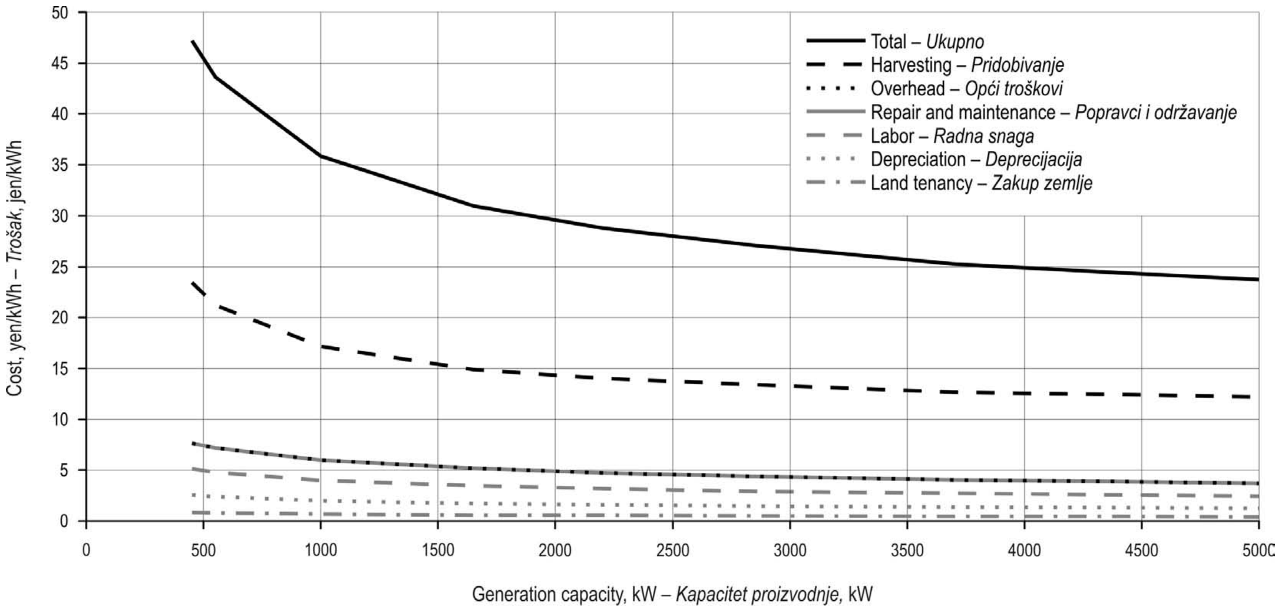


Fig. 8 Generation capacity and cost of a direct combustion power plant
Slika 8. *Proizvodni kapacitet i troškovi energetskoga postrojenja s izravnim izgaranjem*

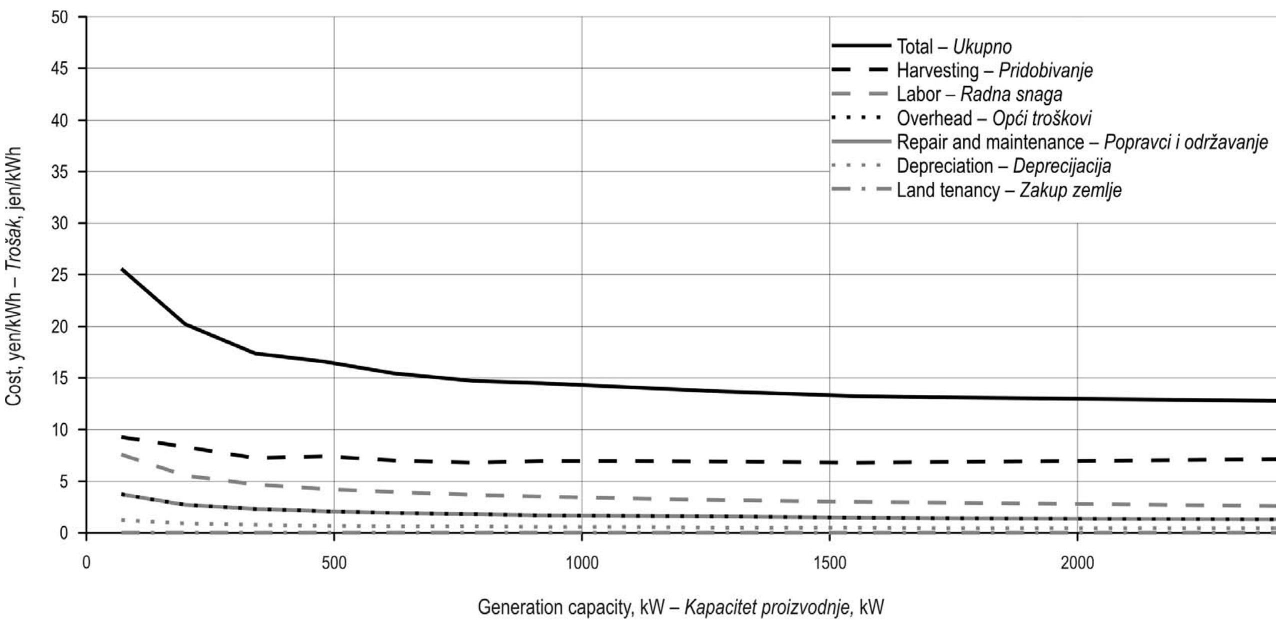


Fig. 9 Generation capacity and cost of a small-scale gasification power plant
Slika 9. *Proizvodni kapacitet i troškovi maloga energetskoga postrojenja s plinoficiranjem*

lowed by broad-leaved forests at 12,995 yen/tDM; thinned trees were the most costly, 15,325 yen/tDM (Fig. 7). As the target volume of the forest biomass resources decreases, the procurement costs of the forest biomass resources also decreases due to the reduction in the harvesting volumes of thinned trees and broad-leaved trees that have high procurement costs (Fig. 5).

Next, the optimum scale of the power-generation plant was discussed using data from Fig. 4 and 5, applied to a direct combustion power plant and a small-scale gasification power plant. With regard to direct combustion power generation, the optimum scale of the power-generation plant was a generation capacity of 5 MW and an energy-conversion efficiency of 21% (Fig. 8).

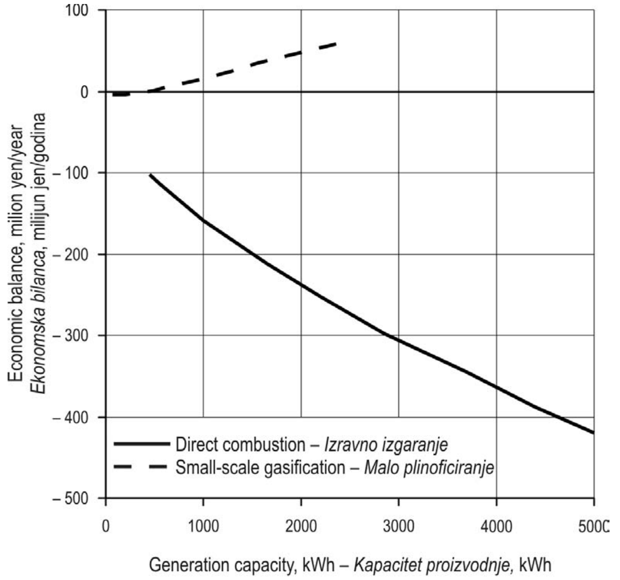


Fig. 10 Generation capacity and economic balance
Slika 10. *Proizvodni kapacitet i ekonomska bilanca*

The component of the cost of electricity referred to fuel procurement was 12.2 yen/kWh for a 5 MW generation capacity. Furthermore, other costs were reduced with an increase in generation capacity. Therefore, the total cost of electricity was the smallest for a 5 MW generation capacity: 23.7 yen/kWh. On the other hand, the minimum fuel cost of a small-scale gasification power plant was 6.8 yen/kWh for 1.5 MW generation capacity, which was within the estimations in this study; however, a lower cost can be obtained if the generation capacity of the plant is increased. Moreover, other costs can be reduced with an increase in generation capacity. For 2.4 MW generation capacity, the minimum total cost was 12.8 /kWh (Fig. 9).

Since this estimated cost was lower than the average electricity price in Japan, 22.2 yen/kWh, the electricity generated from the small-scale gasification power-generation plant can be used in houses; hence, it is important to develop small-scale gasification technology. On the other hand, this estimated cost was higher than the average price of electricity sold to grids in Japan, 8 yen/kWh; therefore, selling the electricity to grids was not a viable option even for small-scale gasification. If the steam could be sold to houses at a price of 0.5 yen/kg, the economic balance of small-scale gasification would be positive, while the economic balance of direct combustion would remain negative (Fig. 10). In this case, half of the initial costs that are assumed to be borrowed for constructing the 2.4 MW small-scale gasification power-generation plant would be paid back over 3.2 years.

3.2 Energy balance – *Energetska bilanca*

Energy input increases with an increase in generation capacity. For direct combustion of 5 MW generation capacity, the harvesting equipment and operation energy inputs are 442 GJ/year and 7,159 GJ/year, respectively, while plant equipment and operation

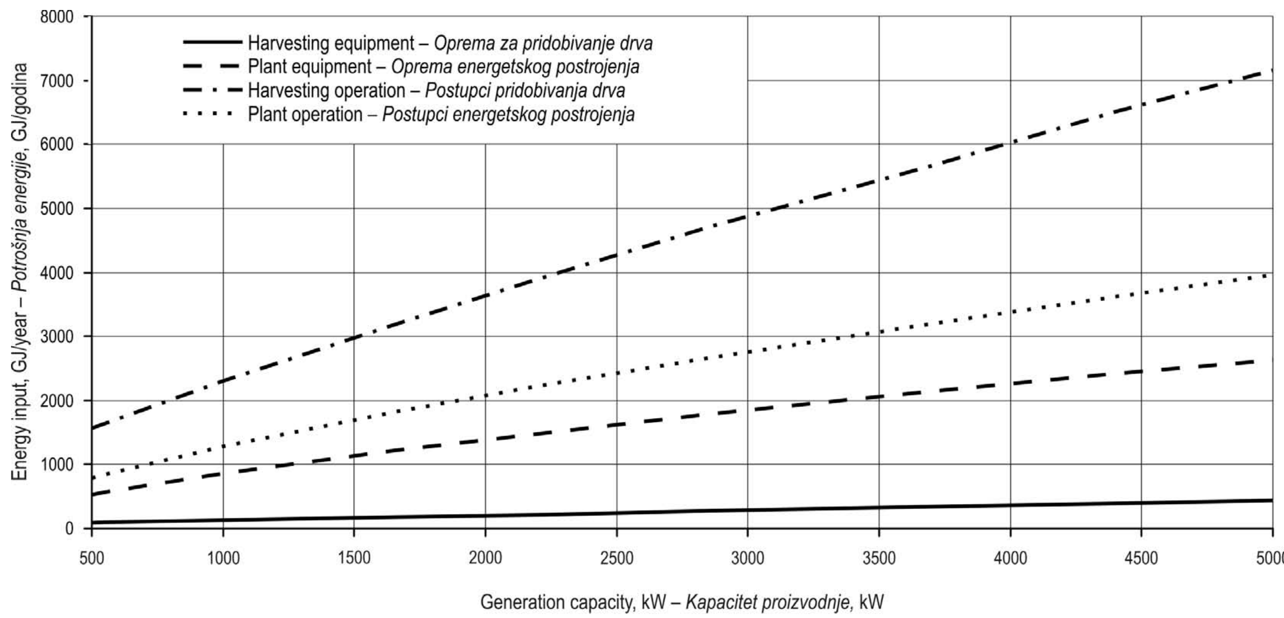


Fig. 11 Generation capacity and energy input of a direct combustion power plant
Slika 11. *Proizvodni kapacitet i potrošnja energije energetskoga postrojenja s izravnim izgaranjem*

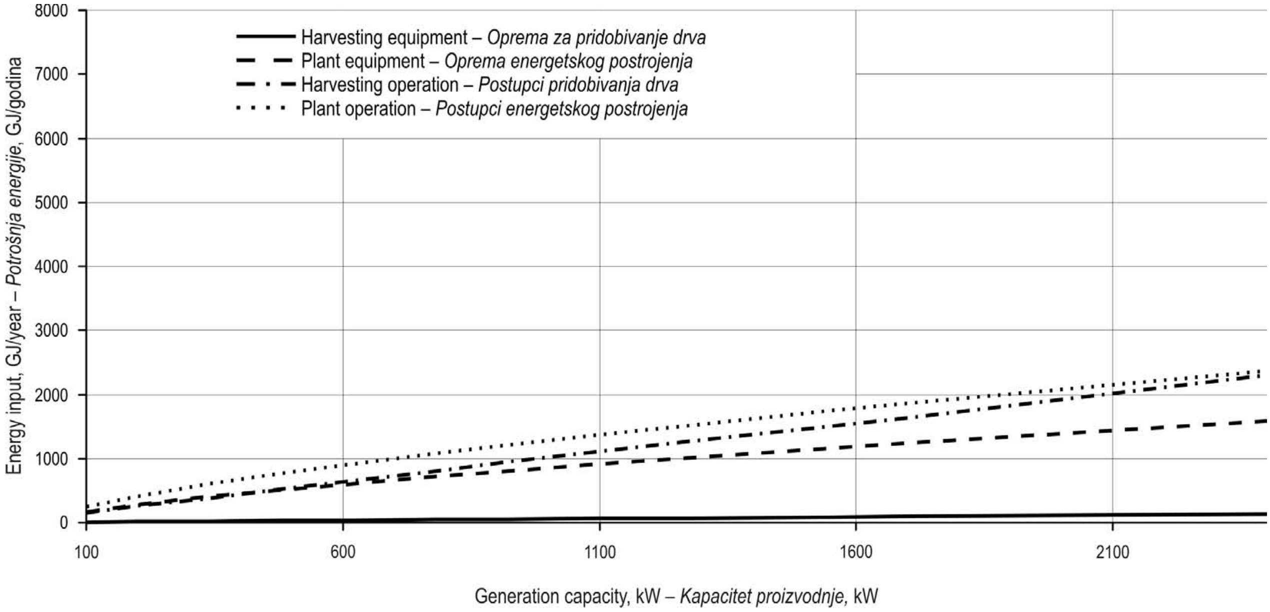


Fig. 12 Generation capacity and energy input of a small-scale gasification power plant
Slika 12. *Proizvodni kapacitet i potrošnja energije maloga energetskoga postrojenja s plinoficiranjem*

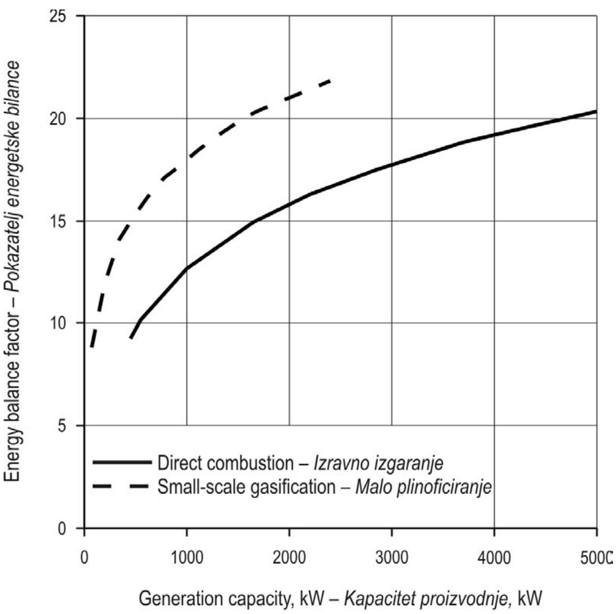


Fig. 13 Generation capacity and energy balance factor
Slika 13. *Proizvodni kapacitet i pokazatelj energetske bilance*

energy inputs are 2,636 GJ/year and 3,954 GJ/year, respectively (Fig. 11).

On the other hand, for the small-scale gasification of 2.4 MW generation capacity, the harvesting equipment and operation energy inputs are 127 GJ/year and 2,301 GJ/year, respectively, while plant equipment and operation energy inputs are 1,577 GJ/year and 2,365 GJ/year, respectively (Fig. 12).

The energy balance factors of direct combustion with 5 MW generation capacity and small-scale gasification with 2.4 MW generation capacity are 20.3 and 21.8, respectively (Fig. 13).

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 times of plants using direct combustion with 5 MW generation capacity and small-scale gasification with 2.4 MW generation capacity are 0.33 and 0.38 years, respectively (Fig. 14). The energy payback times of wind power generation and solar power generation are 1.99 and 10.00 years, respectively (Uchiyama and Yamamoto 1991). Therefore, forest biomass power-generation is relatively superior to other renewable energy resources from the perspective of energy payback time while being similar to fossil energy resources from the perspective of the energy balance factor.

Regarding the energy input, the CO_2 emission increases as the generation capacity increases (Fig. 15). For direct combustion of 5 MW generation capacity, the harvesting equipment and operation CO_2 emission are 36.1 tCO_2/year and 202.5 tCO_2/year, respectively, while the plant equipment and operation CO_2 emission are 206.5 tCO_2/year and 309.8 tCO_2/year, respectively. On the other hand, for small-scale gasification of 2.4 MW generation capacity, the harvesting equipment and operation CO_2 emission are 10.4 tCO_2/year and 62.7 tCO_2/year, respectively, while

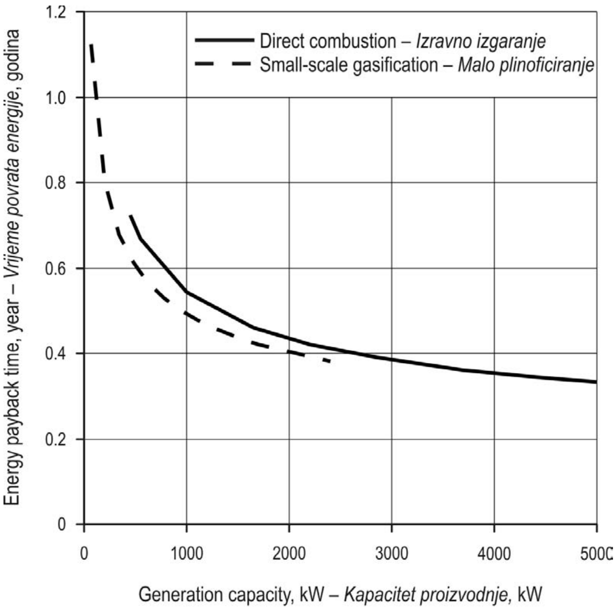


Fig. 14 Generation capacity and energy payback time
Slika 14. *Proizvodni kapacitet i vrijeme povrata energije*

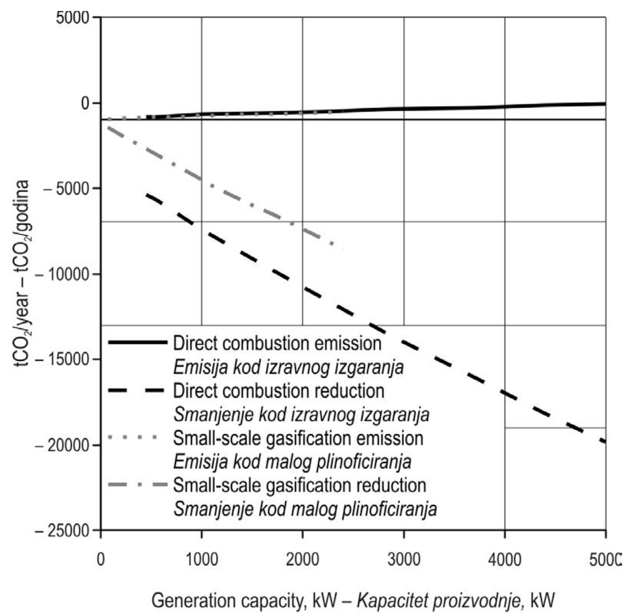


Fig. 15 Generation capacity and CO_2 emission
Slika 15. *Proizvodni kapacitet i emisija CO_2*

plant equipment and operation CO_2 emission are 123.5 tCO_2/year and 185.3 tCO_2/year, respectively.

However, using surplus electricity and steam reduces CO_2 emissions from fossil energy resources (Aruga et al. 2007). The CO_2 reduction from direct combustion with 5 MW generation capacity and small-scale gasification with 2.4 MW generation capacity are 15,707 tCO_2/year and 6,275 tCO_2/year, respectively. These reductions are much larger than the CO_2 emissions from forest biomass power generation; thus, they can contribute to achieving the goals of the Kyoto Protocol in the first period of commitment, starting in 2008, when Japan's goal was to reduce its greenhouse gas emissions by 6% of the amount recorded in 1990. Yoshioka et al. (2005) assumed that Japan has the potential of forest biomass resources to supply 100 direct combustion power-generation plants with 3 MW generation capacity. The CO_2 emission and reduction from a direct combustion plant with 3 MW generation capacity are 507 tCO_2/year and 10,471 tCO_2/year, respectively. Therefore, 100 power-generation plants can reduce CO_2 emissions by 996,400 tCO_2/year. This figure is 1.3% of the 74,000,000 tCO_2/year that is the amount of greenhouse gas emission that Japan must reduce.

4. Conclusions – *Zaključci*

In this study, the economic and energy balances of forest biomass utilization for small-scale power generation were discussed considering the spatial distribution of forest biomass resources using GIS in the Kanuma Area of Tochigi Prefecture, Japan. First, the optimum scales of a direct combustion power plant and a small-scale gasification power plant (technology currently under development) were discussed. It is important to develop this small-scale gasification technology because its electricity cost, 11.5 yen/kWh, with the optimum scale of a small-scale gasification power plant, was lower than the average electricity price in Japan, 22.2 yen/kWh. Next, the energy balance and CO_2 emissions from the energy utilization of forest biomass resources were analyzed using LCI. The results show that the system examined in this study is feasible as an energy production system.

Although the spatial distribution of forest biomass resources was considered in this study, only one power-generation plant was discussed. The introduction of wood-fired boilers and generators and the production of wood pellets have been increasing steadily in recent years in Japan. Multiple forest biomass utilization facilities can be located in a single area. Therefore, multiple facilities should be considered, and the scales and locations of these facilities should be optimized in a future study.

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Sažetak

Rasprava o ekonomskoj i energetskoj bilanci korištenja šumske biomase za malu proizvodnju energije u Kanumi, prefekturi Tochigi, u Japanu

Šume imaju značajnu ulogu u održavanju ravnoteže ugljika na Zemlji povlačenjem ugljika iz atmosfere i proizvodnjom drva, obnovljivoga resursa koji pohranjuje odstranjeni ugljik. Zbog toga šumama treba kontinuirano i pravilno gospodariti, a drvo treba biti korišteno na svim razinama – od građevnoga materijala, namještaja, ploča i papira do kemijskih proizvoda i goriva. Drvna se biomasa pritom može kategorizirati na šumske ostatke (u ovom se istraživanju spominju kao resursi šumske biomase), ostatke pilana i građevno otpadno drvo. Posljednjih je godina u Japanu zabilježen siguran porast u uvođenju kotlovnica i generatora u kojima se koristi drvo te u proizvodnji drvnih peleta. Ipak, velik dio drvne biomase, osobito šumskih ostataka, i dalje ostaje neiskorišten. Radi korištenja izvora šumske biomase za proizvodnju bioenergije ključno je odrediti odnos između godišnje raspoloživih količina i troškova pridobivanja (prikupljanja i transporta) šumske biomase. Mnogobrojna su istraživanja uz ekonomska pitanja koja se raspravljaju u ovom radu analizirala i energetska pitanja korištenja biomase. Međutim, većina je tih istraživanja usmjerena na velika energetska postrojenja čija se neto proizvodnja energije kreće u rasponu od nekoliko desetaka do više stotina megavata energije. Neki su autori analizirali sustave maloga opsega koji kao gorivo za pretvaranje energije upotrebljavaju šumsku biomasu iz konvencionalnoga japanskoga šumarstva, ali pritom nisu uzimali u obzir prostorni raspored raspoloživih resursa šumske biomase.

U ovom se radu razmatraju ekonomske i energetske bilance korištenja šumske biomase u proizvodnji energije maloga opsega, uzimajući u obzir prostornu razdiobu resursa šumske biomase i primjenu geografskoga informacijskoga sustava (GIS) na području Kanuma, u prefekturi Tochigi, u Japanu. Područje Kanuma, koje se kao istraživački poligon sastoji od gradova Kanuma i Nishikata, obuhvaća 52 000 hektara, od čega je oko 65 % pošumljeno. Većina je šumskih sastojina umjetno podignuta (79 %), prevladavaju četinjače i glavnina je sastojina stara oko 45 – 50 godina. U radu su korišteni inventurni podaci (šumski resursi, dob sastojina, vrste drveća, indeksi staništa) i podaci GIS-a (informacije o javnim i šumskim cestama, nagib terena i dr.) koji su dobiveni od Uprave prefekture Tochigi. Na osnovi toga materijala i podataka, uz pomoć GIS-a, u radu su procijenjene godišnje dostupne količine drva i šumske biomase te troškovi njihova pridobivanja na razini pododjela koji su uobičajena operativna jedinica u japanskom šumarstvu.

Istraživanjem su obuhvaćene dvije vrste elektrana, odnosno dva tipa pretvaranja i proizvodnje energije. Jedno je energetsko postrojenje s izravnim izgaranjem, a drugo je malo energetsko postrojenje s plinoficiranjem. Postrojenje s plinoficiranjem predstavlja tehnologiju koja je trenutačno u razvoju. U radu su prvo na osnovi ekonomske bilance određeni optimalni kapaciteti promatranih postrojenja za proizvodnju energije, a zatim su analizirane energetska bilanca i emisija CO_2 u proizvodnji energije korištenjem resursa šumske biomase. Pritom je upotrijebljena metoda inventure životnoga ciklusa (LCI). Dodatno su uspoređene proizvodnja energije iz šumske biomase s energijom iz fosilnih goriva i drugih obnovljivih izvora.

Rezultati istraživanja pokazuju da bi u slučaju energetskoga postrojenja s izravnim izgaranjem, kojemu je optimalni proizvodni kapacitet 5 MW, cijena struje iznosila 23,7 jena/kWh (1€ = 114 jena, 27. lipnja 2011). Za malo energetsko postrojenje s plinoficiranjem i optimalnim kapacitetom proizvodnje od 2,4 MW cijena bi struje iznosila 12,8 jena/kWh. S obzirom na to da je prosječna cijena struje u Japanu 22,2 jena/kWh, proizvodnja struje u malom energetskom postrojenju s plinoficiranjem mogla bi biti ekonomična. Što se tiče energetske bilanca i emisije CO_2, za oba dva tipa proizvodnje energije utvrđeno je da odnos između outputa i inputa energije iznosi oko 20, što pokazuje da elektrane analizirane u radu mogu biti ostvarivi sustavi za proizvodnju energije. Emisija CO_2 kod energetskoga postrojenja s izravnim izgaranjem proizvodnoga kapaciteta 5 MW iznosila je 754,9 tCO_2/godina, dok je kod maloga postrojenja s plinoficiranjem i proizvodnim kapacitetom 2,4 MW iznosila 381,9 tCO_2/godina. Ipak, smanjenje količine emisije CO_2 koje bi se postiglo zamjenjivanjem fosilnih goriva iznosi 15 707 tCO_2/godina, odnosno 6275 tCO_2/godina. Također je utvrđeno da je u usporedbi s fosilnim gorivima i drugim obnovljivim izvorima energije proizvodnja energije iz šumske biomase relativno superiorna s obzirom na vrijeme povrata energije *(indeks koji računa broj godina potrebnih za dobivanje energije ukupno unesene u sustav) i slična po faktoru energetske bilance (odnos između izlaza i ulaza energije). Rezultati rada pokazuju da su prikazani sustavi izvedivi i da mogu biti vrijedna rješenja u proizvodnji energije.*

Ključne riječi: ekonomska bilanca, energetska bilanca, bilanca CO_2, resursi šumske biomase, mala proizvodnja energije, GIS, LCI

Authors' address – *Adresa autorâ*:

Assoc. Prof. Kazuhiro Aruga, PhD.
e-mail: aruga@cc.utsunomiya-u.ac.jp
Ayami Murakami, MSc.
e-mail: ayamy_mumu@yahoo.co.jp
Chikara Nakahata, BSc.
e-mail: c.nakahata0927@gmail.com
Reiko Yamaguchi, BSc.
e-mail: r.yamaguchi0210@gmail.com
Utsunomiya University
Faculty of Agriculture
Department of Forest Science
350 Mine
Utsunomiya 321-8505
JAPAN

Asst. Prof. Takuyuki Yoshioka, PhD.
e-mail: yoshioka.takuyuki@nihon-u.ac.jp
Nihon University
College of Bioresource Sciences
Department of Forest Science and Resources
1866 Kameino
Fujisawa 252-0880
JAPAN

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