Abstract - In this study, biomass-fired power generation in Japan was evaluated from the viewpoints of economics and the effects on the environment. Feedstock cost, plant capacity, and the efficiency of electricity generation were estimated with regard to the collection distance. Accordingly, the cost of electricity generation and the effect on CO₂ mitigation were obtained as functions of the collection distance. From the economic viewpoint, a collection distance of approximately 50 km was considered realistic. However, since forest biomass is expensive, a policy that excludes the feedstock cost and includes tax reduction would be required. On the other hand, from the environmental viewpoint, the effect on CO₂ mitigation was maximum when the collection distance was approximately 50 km; therefore, this was estimated as the optimum collection distance. In conclusion, a biomass-fired power plant is expected to contribute toward mitigating global warming.

Keywords - Biomass-fired power generation, economic and environmental evaluation, CO₂ mitigation, LCA

1. INTRODUCTION

Global warming has become a serious problem because of an increase in greenhouse gases such as CO₂. Utilization of biomass as an energy resource is required for a sustainable society since biomass is carbon-neutral. Considering this, woody biomass-fired power plants present attractive options, and some plants have already been constructed in Japan. However, woody biomass is more expensive than fossil fuels such as coal because it is used not only as power plant feedstock but also for building materials. Therefore, the economics of this process is an important issue, and an economical power generation system is required. Generally, because an increase in plant capacity leads to a decrease in heat loss, the efficiency of power generation increases. Besides, the cost of construction of a power plant unit is lowered, thus reducing the cost of power generation. However, a considerable amount of feedstock has to be supplied to increase the plant capacity. Consequently, the costs of feedstock and its collection would increase. In order to form an economic estimate of the process, the plant capacity and the costs involved in the purchase and collection of feedstock should be considered.

On the other hand, since woody biomass is carbon-neutral, power generation using it is expected to lead to mitigation of CO₂ emission. However, even in this case, CO₂ is emitted during the collection of feedstock and the construction of the plant. Besides, low efficiency of power generation reduces the mitigation of CO₂. Tahara et al. indicated a trade-off between CO₂ mitigation that is related to plant capacity and CO₂ emission during feedstock collection for biomass power generation with sustainable afforestation [1]. In other words, although an increase in afforestation area leads to an increase in feedstock and a subsequent improvement in the efficiency of power generation, CO₂ emission increases during the collection and transport of feedstock. From the viewpoint of reducing environmental load, an optimum design condition in which the collection, transport, and plant capacity are considered should be investigated.

In this study, the economics and environmental effect of a woody biomass-fired power plant were evaluated. Factors such as the amount of feedstock and plant capacity were estimated with regard to the distance from the site of collection to the plant. The effect of these factors on the cost of electricity and CO₂ mitigation was studied. The economic constraints in the construction of biomass-fired power plants were discussed, and the optimum operating condition was evaluated.

2. EVALUATION METHOD

In this study, woody biomass was used as feedstock. Woody biomass can be classified into forest biomass and waste biomass. Forest biomass includes thinning wood and forest residue that can be used as an energy resource, and waste biomass includes sawmill residue and construction waste wood. The distance from the site of woody-biomass collection to the plant and the amount of collection were related to the emission density. The amount of collection enables the estimation of plant capacity and the efficiency of power generation. The cost of construction and the running cost are calculated from the plant capacity. These costs were correlated with the plant capacity. Therefore,
the unit cost of power generation can be estimated from combination of all these factors.

On the other hand, CO₂ was emitted during the collection of feedstock and the construction of the plant. Collection involves the harvest and the transport of feedstock. Thinning is performed not for the feedstock for power generation but for the growth of the remaining trees in a stand. Therefore, CO₂ emission during thinning should not be taken into account in this study. The CO₂ emitted during collection includes only that emitted during the transport. Similarly, for sawmill residue and construction waste wood, only the CO₂ emitted during transport is taken into account. On the other hand, it can be considered that the electricity produced from biomass mitigates CO₂ emission.

3. ECONOMIC STUDY

Feedstock

i) Amount of biomass emission

Thinning wood, forest residue, sawmill residue, and construction waste wood was considered as feedstock for power generation; their properties are listed in table 1.

Although their moisture contents vary under different conditions such as changing atmospheric humidity, the typical values of their moisture content were used in this study. The heating value, which depends on how dry the fuel is, increases with a decrease in the moisture content.

In Japan, many investigations concerning the amount of biomass emission have been performed. The amount of biomass that can be used as an energy resource has been reported in table 2 [2–4]. It was assumed that the biomass was uniformly emitted in Japan and the emission density was estimated from the land area of Japan. The estimated emission density correlates the amount of collected biomass to the collection distance. For example, it is estimated that over a distance of 50 km, 39600 t/y of thinning wood, 41600 t/y of forest residue, 41000 t/y of sawmill residue, and 97200 t/y of construction waste wood are collected.

ii) Transport cost

The forest biomass that was stocked in the lumberyard, the sawmill residue and the construction waste wood have to be transported to the power plant. In this case, the cost of transporting the construction waste wood is borne by the person who emitted it. Therefore, it was assumed that transport of the construction waste wood was without charge. It was assumed that 10 T trucks were used for the transport. The relationship between the transport distance and the transport cost is shown Fig. 1 [3].

Table 2. Emission Amount and Emission Density of Woody Biomass

<table>
<thead>
<tr>
<th></th>
<th>Emission amount t/y²</th>
<th>Emission density t/km²y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinning wood</td>
<td>1870000</td>
<td>5.05</td>
</tr>
<tr>
<td>Forest residue</td>
<td>1960000</td>
<td>5.30</td>
</tr>
<tr>
<td>Sawmill residue</td>
<td>1930000</td>
<td>5.22</td>
</tr>
<tr>
<td>Construction waste wood</td>
<td>4580000</td>
<td>12.40</td>
</tr>
</tbody>
</table>

iii) Transport cost

The forest biomass that was stocked in the lumberyard, the sawmill residue and the construction waste wood have to be transported to the power plant. In this case, the cost of transporting the construction waste wood is borne by the person who emitted it. Therefore, it was assumed that transport of the construction waste wood was without charge. It was assumed that 10 T trucks were used for the transport. The relationship between the transport distance and the transport cost is shown Fig. 1 [3].

Table 3. Log Costs of Thinning Wood and Forest Residue

<table>
<thead>
<tr>
<th></th>
<th>Tree value Yen per ton</th>
<th>Log production cost Yen per ton</th>
<th>Transport cost Yen per ton</th>
<th>Total cost Yen per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinning wood</td>
<td>5900</td>
<td>13500</td>
<td>3100</td>
<td>22500</td>
</tr>
<tr>
<td>Forest residue</td>
<td>-</td>
<td>13500</td>
<td>3100</td>
<td>16600</td>
</tr>
</tbody>
</table>

iv) Feedstock cost

The final feedstock costs of the thinning wood, the forest residue and sawmill residue comprise the log cost and the transport cost. However, it was assumed that of the construction waste wood was independent of distance and that it was ¥1000 per ton.

Power Plant

i) Plant capacity and efficiency of electricity generation

It has been reported that the efficiency of electricity generation is related to plant capacity in that it increases with the increase in plant capacity. In this study, it was
assumed that plants with a capacity of 1000 kW have an efficiency of 10%, those with a capacity of 10000 kW, 20%; and those with a capacity of 100000 kW, 30%; these values were estimated by taking into account previous studies [2, 4].

**ii) Cost of construction**

Although the total cost of construction of a power plant increases with higher plant capacity, the unit cost of construction decreases. Considering a previous study [4], it was assumed that a plant of 1000 kW capacity is constructed at the cost of ¥ 1000,000 per kilowatt; a plant of 10000 kW capacity, at the cost of ¥ 400000 per kilowatt; and a plant of 40000 kW capacity, at the cost of ¥ 200000 per kilowatt. We assumed that the rate of interest for construction was 4% and that the lifetime for the depreciation was 10 years. No subsidy for the construction was taken account of.

**iii) Running cost**

The running cost of the power plant mainly comprises the maintenance cost, personnel cost, and the cost of ash treatment. It is assumed that the maintenance cost was 3% of the construction cost.

In plants with a capacity of 1000 kW to 10000 kW, the following equation for the relationship between the capacity and the staff number has been reported [3].

\[
\text{Staff number} = 0.000778 \times \text{plant capacity} + 4.222
\]

In this equation, the figures after the decimal fractions should be rounded up. In plants with a capacity greater than 10000 kW, it was assumed that the staff number was 12. The personnel cost for a staff was assumed to be ¥ 8000000 per year.

Woody biomass contains ash that accounts for 1% of biomass weight. The ash was emitted by biomass combustion; the cost of ash treatment was ¥ 10000 per ton.

**Electricity cost**

The electricity cost can be estimated from the data that were assumed in the preceding section. In this study, we considered the cases in which the thinning wood and forest residue, the sawmill residue, the construction residue, and whole biomass were used. The relationship between the collection distance, the plant capacity, and the efficiency of electricity generation is shown in Fig. 2. The relationship between the collection distance and the electricity cost is shown in Fig. 3. In all the cases, the electricity cost rapidly decreases with increasing distance for short distances. However, for long distances, the effect of distance on the electricity cost decreases with an increase in distance. In plants using forest biomass, although an increase in the capacity is observed, the electricity cost increases even for long distances due to the expensive feedstock. When whole biomass was used, the capacity and efficiency of the plant increased and the electricity cost was reduced even for short collection distances. The system that can collect a considerable amount of feedstock from a smaller area is efficient.

On the other hand, we considered the exclusion of the feedstock cost, barring the transport cost. In this case, the electricity cost remarkably decreased; the cost was ¥ 7.6 per kilowatt for a distance of 50 km and ¥ 5.3 per kilowatt for a distance of 80 km. From an economic point of view, we believe that the exclusion of the feedstock cost and the reduction in tax would be effective for the popularization of biomass-fired power generation.
during the formation of forest residue, sawmill residue, and construction waste wood should be similarly excluded. CO\textsubscript{2} emission during the transport of feedstock was taken into account; the mileage of a 10 T truck was estimated to be 3 km/l of diesel oil. Diesel oil emits 2.644 kg of CO\textsubscript{2} per liter.

**CO\textsubscript{2} Emission during the Construction of Power Plants**

For the construction of a coal-fired power plant with a capacity of 1000 MW, Uchiyama and Yamamoto [7] estimated CO\textsubscript{2} emission by utilizing the materials, electricity and other energy sources. Tahara et al. [1, 5] and Hanaoka et al. [6] estimated that for a power plant which had different capacity from the coal-fired power plant by 0.7th power rule. In this study, CO\textsubscript{2} emitted during the construction of a power plant was also estimated by a method used by them. Table 4 shows the amount of material required and the CO\textsubscript{2} emission in the coal-fired power plant with a capacity of 1000 MW. In this study, the lifetime of the plant was assumed to be 30 years. Accordingly, the annual CO\textsubscript{2} emission was estimated.

**CO\textsubscript{2} Mitigation by Electricity Generated from Biomass**

Biomass-fired power generation can be used as an alternative to power generation by the existing methods that involve CO\textsubscript{2} emission; therefore, the amount of CO\textsubscript{2} mitigated by using biomass-fired power plants also includes that emitted by the existing power plants. The CO\textsubscript{2} emission factor for electricity generation is 0.382 kg-CO\textsubscript{2}/kWh.

**Effect of Biomass-fired Power Generation on CO\textsubscript{2} Mitigation**

Figure 4 shows the relationship between the collection distance and the extent of CO\textsubscript{2} mitigation. The relationship between the plant capacity and the extent of CO\textsubscript{2} mitigation is shown in Fig. 5. In case of a very short collection distance, the effect on CO\textsubscript{2} mitigation was less due to the small amount of feedstock and lower efficiency of electricity generation. On the other hand, an increase in the amount of feedstock improves the efficiency. However, in cases of long collection distances, CO\textsubscript{2} emission increases due to transport. Accordingly, the effect on CO\textsubscript{2} mitigation is reduced. From the viewpoint of CO\textsubscript{2} mitigation, we estimated an optimum collection distance and a plant capacity of approximately 50 km and 10 MW, respectively.

On the other hand, with regard to the effect of the type of feedstock on CO\textsubscript{2} mitigation, it was believed that feedstock that can be collected over a shorter distance and large amounts has a greater effect. A maximum amount of feedstock should be collected within a distance of approximately 50 km from the plant, and whole biomass should be used.

**Table 4. Amount of CO\textsubscript{2} Emission for Coal-fired Power Plant with a Capacity of 1000 MW**

<table>
<thead>
<tr>
<th>Materials and energy</th>
<th>Amount of materials and energy [t or MWh]</th>
<th>CO\textsubscript{2} emission factor [kg-CO\textsubscript{2}/kg or kg-CO\textsubscript{2}/kWh]</th>
<th>CO\textsubscript{2} emission [t-CO\textsubscript{2}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>62200</td>
<td>1.180</td>
<td>73367</td>
</tr>
<tr>
<td>Aluminum</td>
<td>624</td>
<td>2.040</td>
<td>1270</td>
</tr>
<tr>
<td>Concrete</td>
<td>178220</td>
<td>0.099</td>
<td>17122</td>
</tr>
<tr>
<td>Coal</td>
<td>14319</td>
<td>2.860</td>
<td>34175</td>
</tr>
<tr>
<td>Oil</td>
<td>769</td>
<td>3.220</td>
<td>2279</td>
</tr>
<tr>
<td>Electricity</td>
<td>12700</td>
<td>0.382</td>
<td>4852</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>133665</td>
</tr>
</tbody>
</table>

**Fig. 4. Relationship between collection distance and extent of CO\textsubscript{2} mitigation.**

**Fig. 5. Relationship between plant capacity and extent of CO\textsubscript{2} mitigation.**

It was confirmed that the effect of power generation on CO\textsubscript{2} mitigation increased when whole biomass such as forest biomass and waste biomass were used. However, forest biomass is expensive and raises the electricity cost. This would be disadvantageous for the economy. Therefore, a policy involving a reduction in tax and/or the exclusion of the forest biomass cost in the computation of tax would be required if the forest biomass is to be used in order to optimize the effect on CO\textsubscript{2} mitigation. For example, environmental tax such as carbon tax has already been introduced in some countries. Generally, renewable energy resources are tax-free although fossil fuels are taxed. It should be possible to use the tax revenue to reduce the cost of expensive renewable energy resources such as forest biomass.

In addition, purchase of the electricity generated from renewable energy resources must be ensured. For example,
in Germany, Erneuerbare Energien Gesetz (EEG) was enforced, and the electricity generated from renewable energy resources was traded at a premium. Further, in Japan, renewables portfolio standard (RPS) was enforced, and it was made obligatory for renewable energy to be used in excess of a specified amount.

Finally, these policies would help popularize biomass-fired power generation. Biomass-fired power plants are expected to contribute toward mitigating global warming.

5. CONCLUSIONS

Biomass-fired power generation in Japan was evaluated from the viewpoints of economics and the effect on the environment. In order to improve the efficiency of power generation and to reduce the electricity cost, not only waste biomass but also forest biomass should be utilized. However, since forest biomass is expensive, a policy that excludes the cost of feedstock and includes tax reduction would be required. Because the increase in transport distance increases the CO₂ emission, an optimum collection distance of approximately 50 km was estimated to be adequate. Finally, biomass-fired power plants are expected to contribute toward mitigating global warming.

REFERENCES