



# Life cycle assessment for co-firing semi-carbonized fuel manufactured using woody biomass with coal: a case study in the central area of Wakayama, Japan

Tabata, Tomohiro

Torikai, Hitoshi

Tsurumaki, Mineo

Genchi, Yutaka

Ukegawa, Koji

---

## (Citation)

Renewable and Sustainable Energy Reviews, 15(6):2772-2778

## (Issue Date)

2011-08

## (Resource Type)

journal article

## (Version)

Accepted Manuscript

## (URL)

<https://hdl.handle.net/20.500.14094/90001715>



## **Title:**

Life cycle assessment for co-firing semi-carbonized fuel manufactured using woody biomass with coal: a case study in the central area of Wakayama, Japan

## **Order of Authors**

Tomohiro Tabata, Hitoshi Torikai, Mineo Tsurumaki, Yutaka Genchi, Koji Ukegawa

## **Author names and affiliations**

Name (1): Tomohiro Tabata

Affiliation (1): Kobe University

Address (1): 3-11 Tsurukabuto, Nada-ku, Kobe 657-8501 JAPAN

E-mail (1): tabata@people.kobe-u.ac.jp

Name (2): Hitoshi Torikai

Affiliation (2): Industrial Technology Center of Wakayama prefecture

Address (2): 60 Ogura, Wakayama city, Wakayama 649-6261, Japan

Name (3): Mineo Tsurumaki

Affiliation (3): Wakayama National College of Technology

Address (3): 77 Nojima, Nata-cho, Gobo, Wakayama 644-0023, Japan

Name (4): Yutaka Genchi

Affiliation (4): National Institute of Advanced Industrial Science and Technology (AIST)

Address (4): 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan

Name (5): Koji Ukegawa

Affiliation (5): Industrial Technology Center of Wakayama prefecture

Address (5): 60 Ogura, Wakayama city, Wakayama 649-6261, Japan

## **Keywords**

Woody biomass, Co-firing biomass with coal, Semi-carbonized fuel, Life cycle assessment, Geographic information system

## **Abstract**

Reducing the use of fossil fuel is one of the prime tasks for preventing climate change. The worst fossil fuel in this regard is coal, which is the largest CO<sub>2</sub>-emitting fossil fuel in terms of weight. Although decreasing the use of coal is difficult because of its increasing demand in worldwide, there is still a possibility of effectively reducing greenhouse gas (GHG) emissions by substituting biomass, even for a subset of coal. One way to reduce the use of

40 coal is to implement co-firing of biomass with coal at coal thermal power stations. In this study, the business  
41 impact of GHG reduction from semi-carbonized fuel produced by co-firing woody biomass with coal in thermal  
42 power plants is evaluated from the perspective of life cycles, using the life cycle assessment (LCA) methodology.  
43 The case study area is the central region of Wakayama prefecture, Japan. In this study, a new business is  
44 considered whose operations would co-fire the woody biomass with coal. A life cycle inventory (LCI) analysis and  
45 a life cycle impact assessment are conducted to evaluate the GHG emissions, taking into account processes such as  
46 cutting timber, manufacturing semi-carbonized fuel, and co-firing with coal. LCI data was collected and calculated  
47 on the basis of the feasibility study and literature survey. The spatial distribution of the woody biomass was  
48 ascertained using a geographic information system, and the location of several facilities and a road transportation  
49 network were determined. Results showed that an annual reduction in GHG emissions of approximately 46,700  
50 tonnes in the case study area is possible if the business is executed. The environmental impact taking into account  
51 climate change, acidification and land use was also reduced. As the result, this business is in fact advantageous to  
52 reduce GHG emissions as well as the environmental impact.

53

## 1. Introduction

Diminishing the usage of fossil fuel is one of the prime tasks faced in the prevention of climate change. The worst fossil fuel in this regard is coal, which is the largest CO<sub>2</sub>-emitting fossil fuel in terms of weight. Coal use has nevertheless been increasing worldwide because of its cheap price and the length of its reserve-production ratio. In 2008, 29.2% of the world's consumed primary energy was derived from coal [1], and 35.4% of the emitted CO<sub>2</sub> (approximately 9 billion tonnes of CO<sub>2</sub>) in the entire world is derived from coal [2]. The complete abolition of coal usage in the short term is a difficult task. That said, there is still the possibility of effectively reducing CO<sub>2</sub> emissions by substituting biomass for even a subset of coal. Incidentally, in Japan, 25.4% of the primary energy consumption depends on coal [1]. Although the rate of coal consumption in Japan is lower than its mean value in the rest of the world (29.2%), the Japanese energy self-sufficiency ratio is approximately 4%. Japan therefore needs to reduce its dependence on imported fuel both to combat climate change and achieve energy security [3].

In Japan, coal is mainly utilized for electric generation and steel production. There have been several studies that address how to reduce the use of coal. One remarkable study in particular discusses the co-firing of biomass with coal at a coal thermal power station. In addition, there has been much R&D and many investigations regarding how to put such new schemes into operation [4, 5]. The Japanese government has also focused attention on this area in terms of measures to prevent climate change and encourage sustainable forest management. These days, many Japanese local governments and power companies are committed to such study that is based on measures such as renewable portfolio standard (RPS) law, and an experimental project involving the co-firing of forest residue at several coal-burning power stations [6-8]. Despite the increasing attention it has received, biomass utilization remains an area that is weakly pursued because of its generally high business cost as compared with coal. In particular, woody biomass has weak cost competitiveness because additional processes such as cutting timber, chipping, drying and transportation are required [9]. To solve these problems, the manufacture of semi-carbonized fuel has been studied in terms of making it operational [10, 11].

On the other hand, although DOE [5] says that it is possible to increase the mixing rate of biomass in the coal thermal power plant up to 20% of the coal weight ratio, Suzuki [12] asserts that the mixing rate can only go up to 3% to prevent a decrease in the performance of coal mills. Therefore, almost all of the biomass co-firing businesses in Japan use a standardized 3% of coal weight ratio, which seems to offer little advantage as a climate change measure. It is possible, however, to cut down approximately 270 million tonnes of the CO<sub>2</sub> emissions produced by coal if only 3% of the coal is replaced with biomass, on a weight basis [2]. This anticipated value corresponds to 21% of the greenhouse gas (GHG) emissions (approximately 1.3 billion tonnes of CO<sub>2eq</sub>) in Japan. In order to maximize this potential reduction, what is required is the development of an operationally feasible biomass co-firing technology that has high cost competitiveness.

In this study, an environmental impact including the effect of GHG reduction in a business setting, taking into account the co-firing of woody biomass with coal, is evaluated from the perspective of life cycles. Semi-carbonized fuel manufactured with woody biomass is the focus of this study, and methods to improve the effects of GHG reduction are investigated, using the life cycle assessment (LCA) methodology. The feasibility of this business is also investigated with consideration for the operational cost of reducing GHG emissions. Several studies have been conducted that evaluate the environmental load of the co-firing of woody biomass with coal, using LCA methodology [13-17]. Almost all of these studies, however, employ a virtual model and little actual value is given to life cycle inventory (LCI) data. It is therefore doubtful whether these studies reflect actual regional conditions and operations. This study offers a more realistic evaluation that focuses on a feasibility study in order to evaluate the effectiveness of producing semi-carbonized fuel

from woody biomass.

## 2. Materials and methods

### 2.1. Case study area

The case study area is the central region of Wakayama prefecture, Japan, whose geographical location is indicated in Figure 1. This region consists of six municipalities that occupy a land area of 1,220 km<sup>2</sup>. The population was approximately 68,000 in 2002, which corresponds to approximately 6.3% of the entire population of Wakayama prefecture. A large part of this region is mountainous, with the forest area occupying approximately 77% of the land area. The port of Hidaka is located on the west side of this region, and its function is to dock various vessels whose size ranges as high as large 30,000 tonne-class ships.

Figure 1 Location of case study area

### 2.2. Semi-carbonized fuel

Larry [9] indicated that the problems associated with the co-firing of biomass with coal are the low heating value of the biomass because of its low energy density compared to that of coal, the difficulty of storage, and the difficulty of co-firing due to differences in particle size, corrosion, and the like. These problems cause poor handling in the co-firing process and increase the cost of operation. With semi-carbonized fuel, on the other hand, it is possible to compress the weight of the woody biomass while losing less of its volatilized carbon. This type of fuel resolves such problems as the difficulty of storage and corrosion. In addition, the heating value of semi-carbonized fuel is thought to be equivalent to that of coal, due to its high energy density. It is also expected to be easy to pulverize. Thus, semi-carbonized fuel is the focus of our attention as a technology to reduce operational costs.

To manufacture semi-carbonized fuel, first, chipped woody biomass is semi-carbonized at a low temperature of around 280 ~ 290 degrees centigrade. It is then formed and shaped into briquettes. Semi-carbonized fuel has the following notable features:

- It is possible to increase its heating value to equal that of coal (26.6 MJ/kg).
- Lower treatment cost is expected because of its high bulk specific gravity.
- Less additional load on the coal mill pulverizer is expected, as compared to woody biomass.
- Additional processes such as semi-carbonization and forming and shaping are needed.
- The fuel weight is less than that of woody biomass because little volatilized carbon is lost in the semi-carbonization process.

### 2.3. Evaluation method

In this study, a new business was hypothesized to operate the co-firing of woody biomass with coal in the case study area. LCI analysis and life cycle impact analysis are conducted to evaluate the environmental impact including the GHG emissions, taking into account processes such as cutting timber, the manufacture of semi-carbonized fuel, and co-firing it with coal. The environmental impact and the effect of reduced GHG emissions is also evaluated and compared for the co-firing of coal and woody biomass, and the single-firing of coal. The woody biomass employed in the study is composed of Japanese cedar (*Cryptomeria*) and Japanese cypress (*Chamaecyparis obtusa*). Approximately 28.3% of the forests in Japan are composed of these tree species, which were cultivated throughout Japan in a

tree-planting program of the central government after 1945 [18]. Timber thinning, however, is relatively non-functional these days because of the slumping Japanese forestry industry. In addition, adverse events such as landslides, pollen allergy, and the production of immature trees with a low commodity price are severe problems in Japan. For these reasons, sustainable forest management for these types of timber has been emphasized [19].

Figure 2 indicates the system boundaries. Two evaluation cases were supposed: one involves the single-firing of coal, the other involves the co-firing of coal and woody biomass. In the former case, the coal is extracted out of state and is transported to Japan by marine transport, after which the coal is fired. Timber thinning is taken into account in this case because standardization of the system boundary between the two cases is required for LCA. It is supposed, however, that thinned timber is not utilized, dumped and corroded. Then, although Keppler *et al.* [20] indicate that dumped timber causes the emission of methane into the air from corrosion, the generation mechanism of methane is not known in full detail, which is why methane emission from thinned timber was not considered in this study. In the latter case, first the forest is thinned and then the thinned timber is chipped in a mountainous area. Next, the chips are transported by dump trucks to the fuel manufacturing plant via a transfer station. The collected chips are semi-carbonized in the plant and then formed and shaped into fuel briquettes. After this, the semi-carbonized fuel is transported to the port of Hidaka (Figure 1) by dump trucks and is transported to the coal thermal power station by bulker. At the coal thermal power station, coal and the semi-carbonized fuel are mixed and are pulverized in a coal pulverizer. After this, they are co-fired.

Figure 2 System boundaries

In order to calculate the LCI data, the system boundary was divided into five processes: (1) thinning and chipping, (2) land transport of chips, (3) fuel manufacture, (4) land and marine transport of semi-carbonized fuel, and (5) co-firing.

The environmental load employed in the study was GHG ( $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$ ).  $\text{NO}_x$ ,  $\text{SO}_x$  and residue as ash of semi-carbonized fuel were also employed as the environmental load to take into account the environmental impact excepting GHG. These GHG were evaluated by weighting in the  $\text{CO}_2$  equivalent using the factor of global warming potential for a time horizon of 100 years, namely  $\text{CO}_2$ : 1,  $\text{CH}_4$ : 25, and  $\text{N}_2\text{O}$ : 298 [21].

## 2.4. Case study

The case study that this study is used was taken into account the transportation distance of the chips and semi-carbonized fuel and the location of the plant. The reasons to address the location of the fuel manufacturing plant are: (1) the transport distance varies by plant location, (2) the number of plants and the manufacturing scale of the plants varies by transport distance, and (3) the LCI data changes according to the manufacturing scale of the plant. Chips are usually of low bulk specific gravity, and their long distance transport has both economic and environmental disadvantages. For this reason, deciding the location of a plant and its scale of manufacturing are important factors.

Basing on above reasons, Figure 3 presents a brief description of the three evaluation case. Chips are transported from mountainous areas to the fuel manufacturing plant via a transfer station by 2-tonne and 12-tonne dump trucks in all cases. There are six transfer stations in the mountainous area, and one fuel manufacturing plant is placed in the mountainous area. In the next chapter, how the number of transfer stations and plants and the manufacturing scale of the plants were determined are discussed.

Figure 3 Evaluation case

The feasibility study was conducted for a mountain forest of the case study area from November 2009 to March 2010. In this feasibility study, experimental factors such as timber thinning, chipping, land transport by dump trucks, and semi-carbonization were considered. Also, the fuel manufacturing plant was designed based on the burning characteristics of semi-carbonized fuel. In addition, the consumption of utilities such as light oil, gasoline, electricity, and water were estimated in each experiment. Literature data and catalogue data were also considered as being outside the scope of the feasibility study in such areas as marine transport. Table 1 presents the results of the feasibility study and a related survey.

Table 1 Results of feasibility study

## 2.4. LCI data

LCI data was collected for each process from the feasibility study and the literature survey. The functional unit employed was the GHG emission from the operations for each process for 1 MJ of fuel. Light oil consumed in land transport was calculated using minimum road transportation distances obtained from Google Maps API and MappleX Ver.9 (Shobunsha Publications, Inc.). Bunker A consumption in marine transport was calculated using the transportation distances between the port of Hidaka and the coal thermal power plant. Currently, 28 coal thermal power plants are operated by electric companies in Japan. Location of the power plant where semi-carbonized fuel is utilized did not specify, and the mean marine transport distance (1,330 km) from the port of Hidaka to each power plant was considered. The reduction in GHG emissions due to the coal substituted at the coal thermal power plant was also considered.

After this, the unit GHG emissions using JEMAI-LCA Pro, which is an LCA software program for Japan, was calculated and summed them up as the GHG emissions. The GHG emissions were then calculated by multiplying the annual generation of thinned timber or chips or semi-carbonized fuel and the unit GHG emissions for each process. The GHG emissions not only in terms of transportation, fuel manufacture, and energy recovery, but also in terms of the construction of buildings such as transfer stations and fuel manufacturing plants, dump trucks, and the manufacture of utilities were considered. In a similar manner, NO<sub>x</sub> and SO<sub>x</sub> emissions were calculated. Amount of residue was supposed to correspond with 10% of semi-carbonized fuel basing on actual performance of the coal thermal power station.

## 2.5. Environmental impact assessment

For comprehensive evaluation of several environmental loads, the Distance to Target (DtT) method was applied. DtT is one of the methods for environmental impact assessment in LCA. DtT usually assigns a weighting coefficient to each environmental impact, and calculates an indicator value by integrating them [22]. The indicator value is calculated as follows.

$$I = \sum_i \left( \sum_s (Inv_{i,s} \times CF_{i,s}) \times \frac{1}{NV_i} \times \frac{NV_i}{T_i} \right) \quad (1)$$

where,

$I$ : indicator value,  $Inv_{i,s}$ : amount of environmental load  $s$ ,  $CF_{i,s}$ : characteristic coefficient of environmental impact  $i$ ,  $NV_i$ : actual value of environmental impact  $i$  in Japan, and  $T_i$ : target value of environmental impact  $i$  in Japan or target set by an international organization.

The distance between the current and target values for an effect is calculated, and the greater the distance, the more serious the effect [22].

The following environmental impacts were taken into account: climate change due to GHG emissions, land use due to shortage of sanitary landfill, and acidification due to  $\text{SO}_x$  and  $\text{NO}_x$  emissions. These environmental impacts were chosen for the following reasons: climate change is a high priority issue in enhancing renewable energy; shortage of sanitary landfills is a local issue in countries such as Japan with a small land area, and this is of high priority in Japan; and it is important to check local pollution, such as acidification, caused by the renewable energy business. The following target values for 2030 relative to 2005 levels were set: reduction of GHG emissions by 63% to preventing global warming and climate change [23]; reduction of the final disposal volume by 80% to prolong the operational lives of sanitary landfills, because of the shortage of sanitary landfill, with reference to MSW management measures taken by several local municipalities in Japan; reduction of  $\text{SO}_x$  emissions by 21% and  $\text{NO}_x$  emissions by 17% to prevent acidification [24]. Characteristic coefficients of acidification gases were also evaluated by weighting  $\text{SO}_2$  equivalents using a factor of deposition-oriented acidification potential –  $\text{SO}_x$ : 1,  $\text{NO}_x$ : 0.72 [25].

## 2.6. Ascertaining geographic information

In order to determine the location of transfer stations and fuel manufacture plants, an investigation of the spatial distribution of the woody biomass, its vegetation, and the annual production of thinned timber was required. Therefore, a spatial distribution map of the woody biomass was created using a geographic information system (GIS). Vector data and mesh data regarding forest area, angularity, vegetation, road networks, national parks, and other pertinent factors were used for the map. In this study, areas where the maximum angularity exceeds 30 degrees were excluded because of the high operational costs they would incur. National parks were also excluded because of the difficulties involved in conducting thinning as a business in them.

## 3. Results and discussions

### 3.1. Spatial distribution of thinned timber

Figure 4 indicates the spatial distribution of Japanese cedar and Japanese cypress of the case study area. Each mesh (mesh area:  $1 \text{ km}^2$ ) indicates the location of forest area. The shading of each mesh represents the size of the forest area. The total area of the woody biomass in the case study area was estimated using the spatial distribution map. The result was a total area of woody biomass that was approximately 88,900 ha, and a total area without an excluded zone that was approximately 65,600 ha.

Figure 4 Spatial distribution of thinned timber

Next, the annual generation of thinned timber in the case study area was estimated based on Figure 4. The estimated data for the annual generation of thinned timber is  $35 \text{ m}^3$  per one hectare, and the specific gravity of the woody biomass is 0.91 tonne per one cubic meter, from Table 1. Thus, the annual generation of thinned timber in the case study was approximately 2,089,000 tonnes in wet weight. This total, however, represents the potential for woody biomass generation, and sustainable management would be difficult if all of the timber available for thinning were thinned in one year. Therefore, the forest area available for thinning is supposed to subdivide into twenty sections, with thinning conducted at a rate of one section per year. Based on this assumption, the annual generation of thinned timber in each



200 section was approximately 104,460 tonnes.

201 Next, the location of transfer stations and plants was investigated according to the spatial distribution of the woody  
202 biomass. It was supposed that six transfer stations would be located at intersections such that everywhere in the entire  
203 forest area was within 10 km of a station. Figure 5 indicates the locations of the transfer stations. Chipped timber in each  
204 forest area within a transportation zone is transported to the transfer station in that zone. If a forest area is overlapped by  
205 several zones, the transportation zone that is the minimum transport distance from the forest area is given priority.

206

207 Figure 5 Location of transfer stations and fuel manufacturing plants

208

209 The material flow of the woody biomass was estimated as shown in Table 2, taking into account the annual  
210 generation of woody biomass. The annual manufacture of semi-carbonized fuel is approximately 25,830 tonnes. If the  
211 daily consumption of coal were 8,000 tonnes at a 1 GW-class coal thermal power station, an approximately 0.9%  
212 reduction of coal would become possible.

213

214 Table 2 Material flow of woody biomass

215

216 According to the above results for material flow, it was supposed that one fuel manufacturing plant with a capacity  
217 of 400 tonnes per day would be built. The location of each plant is indicated in Figure5. This location was determined by  
218 taking into account the location of the transfer stations or forest areas.

219

### 220 3.2. Results for environmental impact

221 Table 3 indicates the annual GHG, NO<sub>x</sub> and SO<sub>x</sub> emissions and residue. The net GHG emission is minus because of  
222 the large reduction in GHG due to the co-firing process. In the results, it is possible to reduce the GHG emission by  
223 approximately 46,700 tonnes annually. As a point of reference, the annual GHG emission in Wakayama prefecture was  
224 16,372,000 tonnes in FY2003 [26]. This result implies that the effect of substitution is equivalent to approximately 0.3%  
225 of the GHG emission in this prefecture.

226

227 Table 3 Results of annual environmental load emissions

228

229 The process that produces the largest GHG emission is that of fuel manufacturing, which accounts for  
230 approximately 70% of the GHG emissions, excluding those from co-firing. The second largest GHG-emitting process is  
231 that of thinning and chipping, which accounts for approximately 15% of the GHG emissions, excluding those from  
232 co-firing. Focusing our attention upon the transport process, this process is the least GHG emission in all processes. This  
233 result suggests that the fuel manufacturing operations should take place in a mountainous region to increase the transport  
234 efficiency. Nevertheless, the GHG emissions in the transport process are less than in the other processes, and an increase  
235 in transport efficiency offers advantages from an economic viewpoint.

236 The net NO<sub>x</sub> and SO<sub>x</sub> emissions are plus because the emissions in the fuel manufacturing process are higher than  
237 the reduction in the co-firing process.

238 Fig. 6 shows result of the life cycle impact assessment, taking into account the transition of target values. In the  
239 results, the net indicator value is minus because of large reduction in climate change. On the contrary, acidification and

land use are a little bit contribution. This result implies that the co-firing of the semi-carbonized fuel has better effect from the viewpoint of the environmental impact.

Figure 6 Result of life cycle impact assessment

### 3.3. Sensitivity analysis

The results above imply that the fuel manufacturing process is the main source of GHG emissions. As mentioned above, semi-carbonization is a developing technology. Therefore, the energy usage in semi-carbonization could increase beyond the results in this study, depending on the application conditions. For this reason, a sensitivity analysis was conducted to confirm to what degree GHG emissions would vary due to additional energy use in the fuel manufacturing process.

First, what proportion of the heating value of the semi-carbonized fuel is consumed in its manufacture was calculated. The lower heating value of the fuel was taken to be equivalent to that of coal (26,600 MJ/tonnes). The energy usage for the manufacture of one tonne of the fuel is 5,000 MJ. This implies that approximately 18% of the heating value of the fuel is consumed in its manufacture. Next, how much the GHG emission would vary if the energy used in manufacturing the fuel were varied was investigated. Figure 7 indicates the result, which is that the net GHG emission retains a minus value if the energy usage for manufacturing one tonne of fuel exceeds 36,000 MJ. As the result, the effect of GHG emission reduction is maintained despite the excess energy usage, such as the heating value of the semi-carbonized fuel, as long as approximately 35% of additional energy is required.

Figure 7 GHG reduction effect, taking into account energy usage for the manufacture of semi-carbonized fuel

## 4. Conclusions

In this study, the environmental impact including the GHG reduction effect of a business that takes into account the co-firing woody biomass with coal was evaluated from the perspective of life cycles. Then, the life cycle of GHG emissions from the timber thinning process to that of co-firing was evaluated. The result shows that it is possible to reduce the annual GHG emissions in the case study area by approximately 46,700 tonnes. The result also shows that it has better effect from the viewpoint of environmental impact. The proposed business is in fact advantageous as a net reducer of GHG emissions.

Future areas of investigation include an evaluation of how to implement a woody biomass manufacturing and co-firing system in a wider region. Because the mixing rate of semi-carbonized fuel with coal could exceed 3% in terms of the upward limit of its particle size [10], it is important to investigate how much semi-carbonized fuel it is possible to mix with coal, and how much GHG reduction can then be expected. An evaluation would also need to be conducted for conditions such as tree cultivation, land conditions, road distance, and other factors that are variable. The development of LCI data would be required in order to deal with these varying evaluation conditions.

## Acknowledgement

This research was partially supported by the Ministry of Economy, Trade and Industry in its 'Model Project for the Discovery of Technology and Demonstration of a Social System towards a Low Carbon Society (FY2009)', and the Ministry of the Environment in its 'Environmental Research & Technology Development Fund (E-0806)'.

280

## 281 **References**

- 282 [1] BP, BP statistical review of world energy 2009, 2009, [http://www.bp.com/productlanding.do?](http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622)  
283 [categoryId=6929&contentId=7044622](http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622)
- 284 [2] Oak Ridge National Laboratory, Global CO<sub>2</sub> emissions from fossil-fuel burning, cement manufacture, and gas  
285 flaring: 1751-2006, 2009, [http://cdiac.ornl.gov/trends/emis/meth\\_reg.html](http://cdiac.ornl.gov/trends/emis/meth_reg.html)
- 286 [3] NRE (Agency for Natural Resources and Energy), Energy in Japan 2010, 2010, [http://www.enecho.meti.go.jp/](http://www.enecho.meti.go.jp/index_pamph.htm)  
287 [index\\_pamph.htm](http://www.enecho.meti.go.jp/index_pamph.htm) [in Japanese]
- 288 [4] IEA Bioenergy, Biomass combustion and co-firing: An overview, 2001, [http://www.ieabcc.nl/](http://www.ieabcc.nl/publications/t32.pdf)  
289 [publications/t32.pdf](http://www.ieabcc.nl/publications/t32.pdf)
- 290 [5] DOE (Department of Energy), Federal technology alert: Biomass cofiring in coal-fired boilers, 2004,  
291 [http://www1.eere.energy.gov/femp/pdfs/fta\\_biomass\\_cofiring.pdf](http://www1.eere.energy.gov/femp/pdfs/fta_biomass_cofiring.pdf)
- 292 [6] Nakamura T., Takahashi Y., Research and development of woody biomass co-firing in coal-fired plant, Eco Ind.,  
293 8-4, 13-18, 2003 [in Japanese]
- 294 [7] Yoshioka T, Hirata S., Matsumura Y., Sakanishi K., Woody biomass resources and conversion in Japan: The current  
295 situation and projections to 2010 and 2050, Biomass Bioenergy, 29, 336-346, 2005.
- 296 [8] Asia Biomass Office, Six coal-burning power stations adopted biomass co-firing using forest residue, 2010,  
297 [http://www.asiabiomass.jp/english/topics/1002\\_01.html](http://www.asiabiomass.jp/english/topics/1002_01.html)
- 298 [9] Larry B., Biomass-coal co-combustion: opportunity for affordable renewable energy, Fuel, 84, 1295-1302, 2005
- 299 [10] Sawai T., Kajimoto T., Akasaka M., Kaji M., Ida T., Fuchihata M., Honjyo T., Sano H., Properties of compressive  
300 strength and heating value of compressed semi-carbonized Sugi thinning, J. High Temp. Soc., 33, 31-37, 2007. [in  
301 Japanese]
- 302 [11] Ishimura K., Ida T., Fuchihata M., Honjyo T., Sano H., Improvement of thermal energy characteristics of wood  
303 biomass pelletized using a half carbonized technology, J. High Temp. Soc., 33, 38-42, 2007 [in Japanese]
- 304 [12] Suzuki A., Brief overview of woody biomass co-firing in Saijyo coal-fired power plant, Electrical Review, 90-12,  
305 74-77, 2005 [in Japanese]
- 306 [13] Hartmann D., Kaltschmitt M., Electricity generation from solid biomass via co-combustion with coal energy and  
307 emission balances from a German case study, Biomass Bioenergy, 16, 397-406, 1999
- 308 [14] Mann M.K., Spath P.L., A life cycle assessment of biomass cofiring in a coal-fired power plant, Clean Products  
309 Process, 3, 81-91, 2001
- 310 [15] Enrico B., Emil-Corneliu P., Patrick R., Jacques B., Life cycle assessment of fossil CO<sub>2</sub> emissions reduction  
311 scenarios in coal-biomass based electricity production, Energy Conversion Manag., 45, 3053-3074, 2004
- 312 [16] Nishiyama A., Feasibility study for woody biomass co-combustion in coal fired power plant, The Thermal Nucl.  
313 Power, 53, 219-228, 2007 [in Japanese]
- 314 [17] De S., Assadi M., Impact of cofiring biomass with coal in power plants- A techno-economic assessment, Biomass  
315 Bioenergy, 33, 283-293, 2009
- 316 [18] Forest Agency, Current situation of forest resources, 2007, <http://www.rinya.maff.go.jp/toukei/genkyou/index.htm>  
317 [\[in Japanese\]](http://www.rinya.maff.go.jp/toukei/genkyou/index.htm)
- 318 [19] Fujimori T., Why do we need thinning?, Forest Sci., 44, 4-8, 2005 [in Japanese]
- 319 [20] Keppler F., Hamilton T.G. J., Braß M., Röckmann T., Methane emissions from terrestrial plants under aerobic

320 conditions, *Nature*, 439, 187-191, 2006

321 [21] IPCC (Intergovernmental Panel on Climate Change), *Climate Change 2007-The Physical Science Basis-*, pp.33,  
 322 2007

323 [22] PRé Consultants: *The Eco-indicator 95 final report*, 1997, 19–20, <http://www.pre.nl/download/EI95FinalReport.pdf>

324 [23] IPCC, *Climate change 2007–Mitigation of climate change*, pp.9, 2007

325 [24] OECD, *NO<sub>x</sub>/SO<sub>x</sub> emissions and carbon abatement*, 1994, pp.20, <http://www.oecd.org/dataoecd/32/27/1862694.pdf>

326 [25] NEDO (New Energy and Industrial Technology Development Organization), *Research Report of LCA Project*, pp.  
 327 860, 2004

328 [26] Wakayama prefecture: *The climate change action plan*, 2006, [http://www.pref.wakayama.lg.jp/](http://www.pref.wakayama.lg.jp/prefg/032000/chiiki/kei.pdf)  
 329 [prefg/032000/chiiki/kei.pdf](http://www.pref.wakayama.lg.jp/prefg/032000/chiiki/kei.pdf) [in Japanese]

Figure 1 Location of case study area

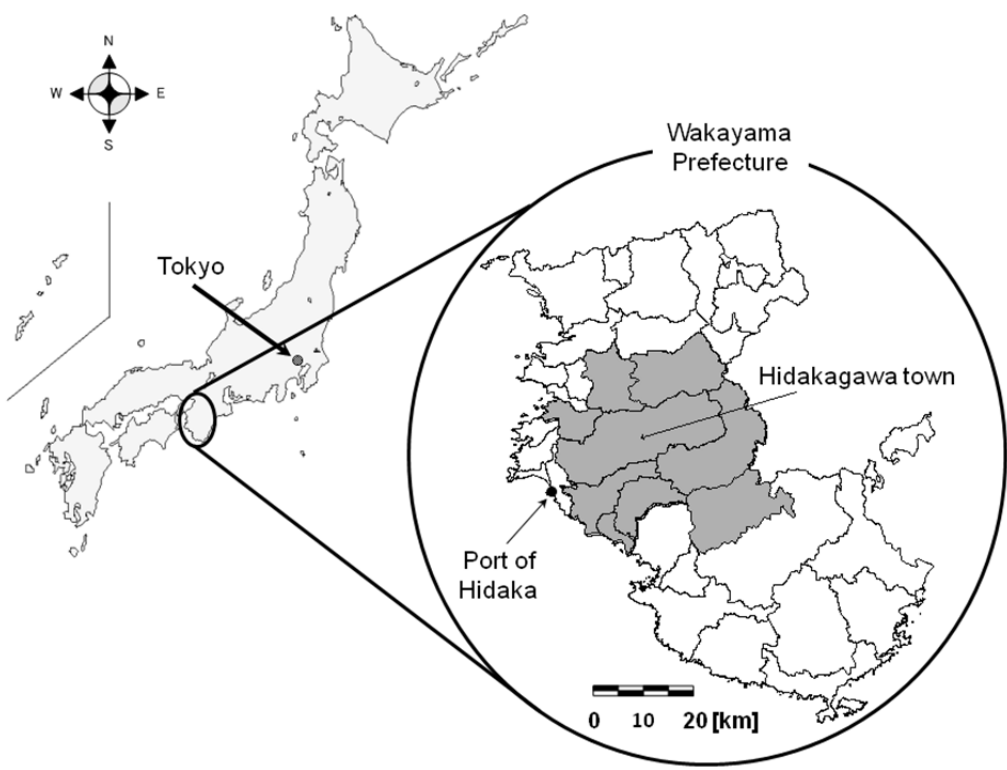
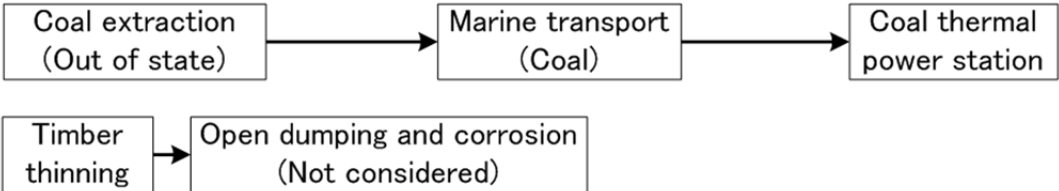
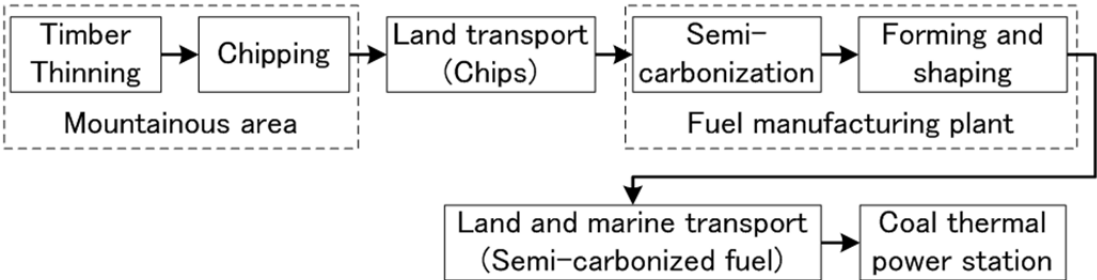


Figure 2 System boundaries



(a) Single-firing of coal



(b) Co-firing of coal and woody biomass

Figure 3 Evaluation case

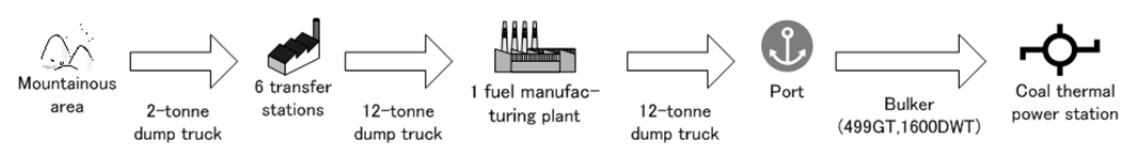


Figure 4 Spatial distribution of thinned timber

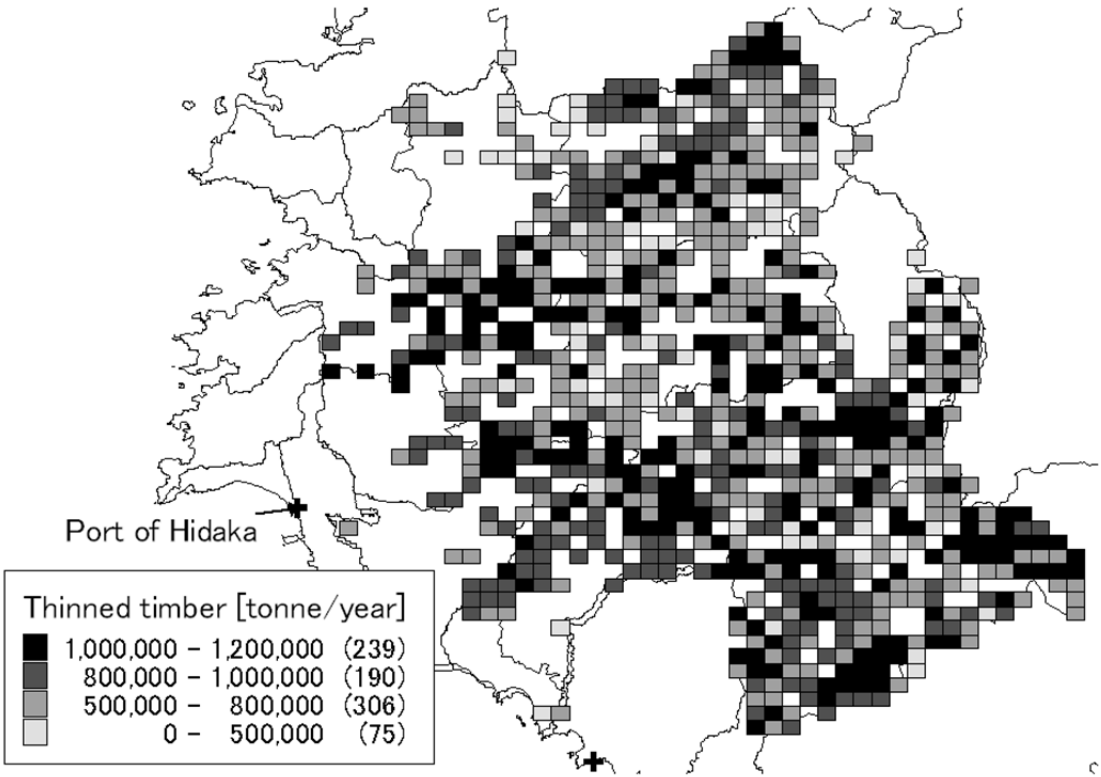




Figure 5 Location of transfer stations and fuel manufacturing plants

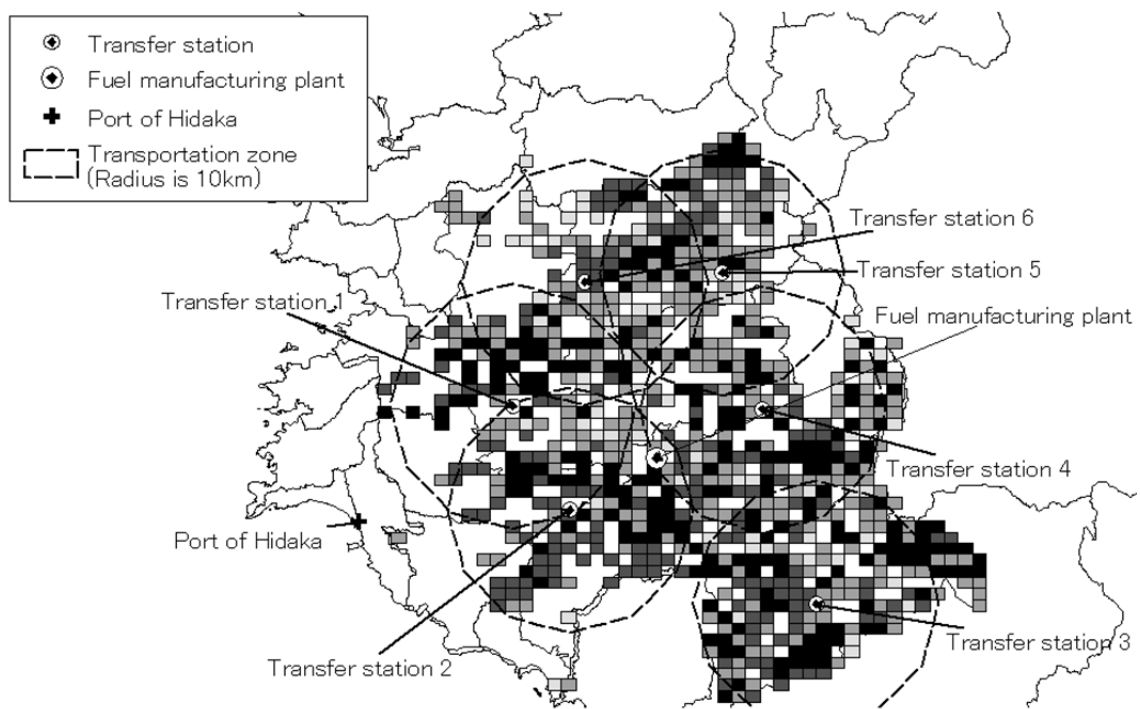


Figure 6 Result of life cycle impact assessment

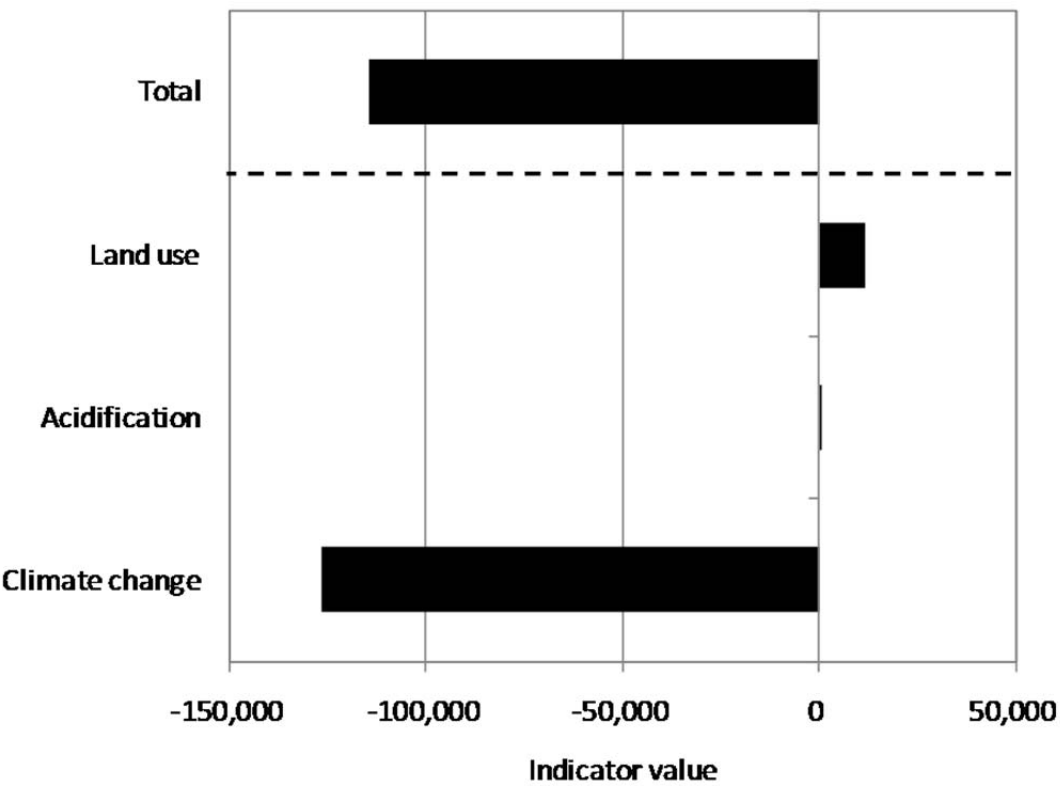
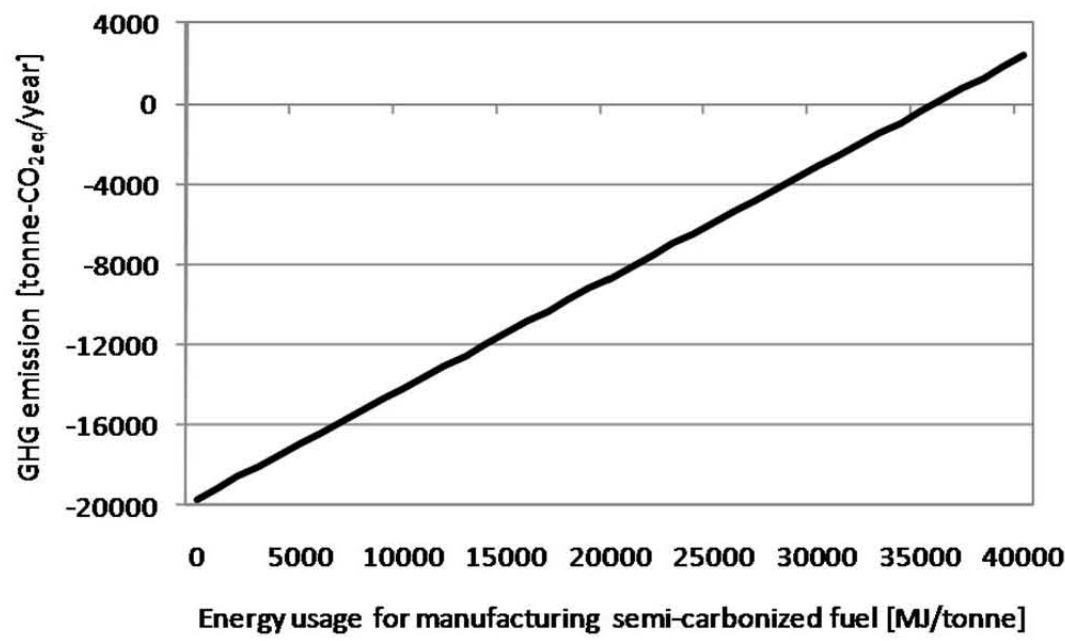


Figure 7 GHG reduction effect, taking into account energy usage for the manufacture of semi-carbonized fuel



## Tables

Table 1 Results of feasibility study

		Unit	Remarks
Annual generation of thinned timber	35	m <sup>3</sup> /ha	Estimated data
Specific gravity of the woody biomass	0.91	tonne/m <sup>3</sup>	Experimental data
Water content of the woody biomass	57.7	%	Experimental data, wet weight
Material loss	1.37	%	Evaporated water in chipping, experimental data
	43	%	Gas in semi-carbonizing (Volatized carbon, etc.), experimental data, dry weight
Residual carbon in semi-carbonized fuel	74	%	Experimental data, compared to original woody biomass
Bulk specific density	0.34	-	Chips, experimental data
	0.60	-	Semi-carbonized fuel, estimated data
Working days	200	days/year	Tree thinning and chipping process and land transport (chips) one
	300	days/year	Fuel manufacturing process and land and marine transport (fuel)
	365	days/year	Co-firing process
Fuel consumption	10.5	km/L	2-tonne dump truck, experimental data, light oil
	5.4	km/L	12-tonne dump truck, catalog data, light oil
	0.10	km/L	499GT type various vessels, DWT: 1 600, hold capacity: 2 490 m <sup>3</sup> , Bunker A

Table 2 Material flow of woody biomass

		Unit	Remarks
Generation of thinned timber	104,460	tonne/year	
Production of chips	103,040	tonne/year	
Water loss in chipping	1,420	tonne/year	By evaporation
Manufacture of semi-carbonized fuel	25,830	tonne/year	
Water loss in semi-carbonization	58,040	tonne/year	
Gas loss in semi-carbonization	19,170	tonne/year	
Lower heating value	26,600	MJ/tonne	Equivalent to coal
Amount of reduction of coal	25,830	tonne/year	

Table 3 Results of annual environmental load emissions

	GHG	NO <sub>x</sub>	SO <sub>x</sub>	Residue
	[tonne-CO <sub>2</sub> eq]	[tonne-NO <sub>x</sub> ]	[tonne-SO <sub>x</sub> ]	[tonne-residue]
Thinning and chipping process	3,363	1.86	1.22	
Land transport (chip) process	96	0.12	0.14	
Fuel manufacture process	9,126	4.44	6.89	
Land and marine transport (fuel) process	1,340	0.66	0.93	
Co-firing process	-60,691	-1.26	-0.50	
Total	-46,767	6	9	2,324