LCCO\textsubscript{2} of coal co-firing with imported torrefied woody biomass in Japan

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Abstract. In response to Japan’s increase on coal dependence, co-firing of woody biomass in a coal power plant has been considered as the most feasible sustainable alternative. We propose torrefaction as an effective method to improve the quality of biomass fuel. To measure how much CO\textsubscript{2} can be avoided by utilizing torrefied fuel, Life Cycle CO\textsubscript{2} (LCCO\textsubscript{2}) of woody biomass co-firing in the Japanese coal power plant was conducted in this study. As a comparative analysis in the LCCO\textsubscript{2}, scenarios constructed included the use of woody biomass in the form of chip, pellet, and torrefied fuel. Due to the unavailability of large quantity domestic feedstocks in Japan, Indonesia was chosen as the origin of the imported woody biomass in the simulated scenarios. The results showed that significant CO\textsubscript{2} reduction could be achieved especially in the co-firing that includes torrefied fuel. In the case where 30\textsuperscript{cal} of torrefied fuel or 5\textsuperscript{cal} of pellets were used for co-firing in a 50 MW capacity coal power plant, 95,000 t of CO\textsubscript{2} could be avoided annually compared to using 100\textsuperscript{cal} of coal.

1 Introduction

Traditional use of bio-energy, such as direct burning for heating and cooking in households, constitutes more than 50\textsuperscript{%} of the world’s consumption of biomass and waste resources in 2015 [1]. This fact imply that resources are available and accessible, but they have not been efficiently utilized into modern energy.

The aim of this study is to conduct a life cycle CO\textsubscript{2} (LCCO\textsubscript{2}) simulation of the use of various types of woody biomass as advanced biofuels in a coal firing plant replacing a certain amount of coal to carry out biomass co-firing. By conducting a LCCO\textsubscript{2} simulation, we expect to identify which type of biomass fuel has the highest potential to reduce CO\textsubscript{2} emissions. There are three types of woody biomass fuel to be compared in this study: (a) chipped, (b) pelletized, and (c) torrefied. In addition to an LCCO\textsubscript{2} simulation, we have conducted an experiment to determine if it is possible to improve the energy efficiency of the torrefaction process by recovering waste heat and using it to dry the raw material. The assumed type of biomass used in this study was woody biomass from Indonesia, and the output was assumed to be co-fired in a coal power plant in Japan. This strategy is proposed.

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in response to the Japanese increasing dependence on coal after the accident at the Tokyo Electric Power Daiichi Fukushima nuclear power plant [2].

Compared to other renewable energy options, biomass co-firing may be considered as the lowest risk, least expensive, and most efficient and can be conducted immediately as the resources become available [3]. Common biomass pre-treatment processes are chipping and pelleting for size-reduction and compacting techniques. The weakness of woodchip and wood pellet fuels is that there is only a small percentage (less than 5%) that can be used in a coal power plant as a co-firing material [3]. However, IHI company has newly-developed a technology that allows wood pellet mixing ratio up to between 50% [4].

Torrefaction is the process of heating biomass in the absence or drastically-reduced presence of oxygen to a temperature of about 250°C to 320°C [5]. Before the heating process, drying is often recommended to achieve a certain level of moisture (typically about 10-15 %) to improve the efficiency. In the process, volatile matters (about 20%) are lost and the character of the original biomass becomes drastically changed. The changes include becoming more brittle, improved grindability, and becoming less absorbent of moisture [6]. In this particular study, heat recovered from the torrefaction process is used for drying. Our laboratory previous study has shown that the torrefaction results allowed 100% replacement of conventional coal [7]. In this study, we conducted a torrefaction experiment to estimate whether the heat recovered from the process would be sufficient for the biomass feedstock drying process and thus make it energy self-sufficient for the whole process.

Fig. 1. Schematic diagram of experimental torrefaction equipment [8].

Japan has a significant amount of forest, especially in the Hokkaido prefecture area. However, the topography and landscape of the Japanese islands are not suitable for the collection and transportation of significant amounts of woody biomass from the forest (Fig. 2 and 3) [9].

Fig. 2. Unutilized woody biomass availability

Fig. 3. Distribution of unutilized woody biomass
2 Methods

2.1 Heat recovery in torrefaction

To recover the low-grade waste heat from torrefaction process, we used Organic Rankine Cycle (ORC) system. It was chosen because it uses organic fluid that has a lower boiling point that enables the generation of electricity from lower temperature heat waste [10]. We tested whether the recovered energy is sufficient for the drying process in torrefaction.

2.2 LCCO\textsubscript{2}

There scenarios constructed (CASES) are the following: CASE 0 is the baseline scenario that used 100% coal, CASE 1 used 3cal% (calorific percentage) of woodchips, CASE 2 used 5cal% wood pellets, CASE 3 used 30cal% wood pellets, and CASE 4 used 30cal% torrefied fuel (Fig. 5). This study only covers the CO\textsubscript{2} because changes in SOx and NOx levels when co-firing coal with biomass is already well researched [3, 11].

2.2.1 Goal and scope

The goal of this LCCO\textsubscript{2} is to identify the least CO\textsubscript{2} emitting fuel among the three constructed scenarios. With the considerations mentioned in the previous sections, the scenarios were constructed based on the following assumptions: (a) the source of the raw material is Indonesia, (b) land transport distance is 20 km, (c) raw material moisture content is 45%, (d) the torrefaction process takes place in Indonesia, (e) marine transportation is used from Indonesia to Japan, (f) co-firing is done in Japan, and (g) coal power plant generation efficiency in Japan is 38.9%. The system boundaries of the LCCO\textsubscript{2} conducted is shown in Figure 4.

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Fig. 4. LCCO\textsubscript{2} system boundary.

Fig. 5. LCCO\textsubscript{2} scenarios.
2.2.2 Inventory

As an LCCO2 study, the inventory covers only the CO2 emissions of each scenario constructed. The steps involved in the LCCO2 boundary are the following: (a) land transportation for raw material, (b) fuel production, (c) marine transport, and (d) coal-fired power plant. The emission inventory for each step are presented in Tables 1 and 2. The other factors required to conduct LCCO2 such as fuel density, calorific value, emission factor, and ship load capacity are presented in Tables 3 to 10.

Table 1. CO2 emission from producing 1 kg of torrefied fuel.

| Process Name               | Unit     | Value  |
|----------------------------|----------|--------|
| Woodchip land transport    | kg-CO2   | 0.00471|
| Woodchip production        | kg-CO2   | 0.01151|
| Torrefied fuel production  | kg-CO2/kg| 0      |
| Total                      | kg-CO2/kg| 0.01622|

Table 2. Property comparison between torrefied fuel and coal.

| Item                  | Unit   | Torrefied fuel | Coal |
|-----------------------|--------|---------------|------|
| Density               | kg/m³  | 200           | 900  |
| Calorific value       | MJ/kg  | 22.3          | 26.6 |
| CO2 emission          | kg-CO2/kg| 0.1054    | 2.409|

Table 3 CO2 emission from each fuel type production.

| Process Name               | Unit     | Woodchip fuel | Pelletized fuel | Torrefied fuel |
|----------------------------|----------|---------------|-----------------|----------------|
| Wood material transportation| kg-CO2/kg| 0.0013        | 0.0019          | 0.0047         |
| Woodchip production        | kg-CO2/kg| 0.0031        | 0.0046          | 0.0115         |
| Pellet Production          | kg-CO2/kg| -             | 0.4852          | -              |
| Torrefied fuel production  | kg-CO2/kg| -             | -               | 0              |
| Total                      | kg-CO2/kg| 0.0044        | 0.4917          | 0.0162         |

Table 4 Calorific value and CO2 emission from the production and use of each type of fuel.

| Item                  | Unit   | Coal     | Woodchip | Wood pellets | Torrefied fuel |
|-----------------------|--------|----------|----------|--------------|----------------|
| Calorific value       | MJ/kg  | 22.6     | 9.4      | 15.9         | 22.3           |
| CO2 emission          | Production kg-CO2/kg | - | 0.0044 | 0.4917 | 0.0162 |
|                       | Use kg-CO2/kg | 2.409 | Carbon Neutral |  | Carbon Neutral |

Table 5 Density for each type of fuel.

| Fuel type | Unit     | Value |
|-----------|----------|-------|
| Coal      | t/m³     | 1.2   |
| Woodchip  | t/m³     | 0.287 |
| Wood pellets | t/m³   | 0.697 |
| Torrefied fuel | t/m³ | 0.2   |

Table 7. Ship capacity.

| Fuel type | Unit | Value |
|-----------|------|-------|
| Volume    | m³   | 45,000|
| Load weight | t   | 45,000|

Table 8. Ship load weight capacity per 45,000m³.

| Fuel type | Unit | Value |
|-----------|------|-------|
| Coal      | t    | 54,000|
| Woodchip  | t    | 12,915|
| Wood pellets | t   | 31,365|

Table 9. Fuel volume per 45,000 t.
3 Results and discussions

3.1 Heat recovery in torrefaction

The results from using the ORC system for heat recovery for the torrefaction pyrolysis gas showed that the energy generated was sufficient to run the torrefaction process. As comparative ratios, the heat necessary for drying the raw material is only 17.8 units, the 21.8 units of heat generated was more than sufficient for the drying process (Fig. 6). The actual value of energy and material balance from our commercial plant scale experiment (2 lines of 500 t/day capacity) of 3 MWh/h is shown in Figure 7. The energy density of the output fuel is improved after the drying process by 1.67 times, and by 2.33 times after the torrefaction process. This implies that there will be less amount of fuel required to generate the same amount of energy.

![Fig.6. Material and energy balance in the energy-self-sufficient torrefaction process explained in ratio comparison.](image-url)
3.2 LCCO₂

It is evident from the results (Fig. 8) that the two scenarios with the lowest CO₂ emissions are CASES 3 and 4, with 17.8 t CO₂/y and 28.5 t CO₂/y emission reduction potentials respectively. However, in CASE 3, where the mix is 30cal% wood pellets, there is a significant amount of CO₂ emissions from biomass (about 8,392 t CO₂/y) and higher emissions from transportation. CASE 4 with 30cal% torrefied fuel is then clearly the scenario with the lowest environmental load in terms of CO₂ emissions. For comparison, an additional scenario (CASE X) where a mix with 50cal% wood pellets (assuming the technology development by IHI would reach that level in the future) was simulated. The result was almost similar with the 30cal% torrefied fuel scenario (CASE 4) with a 29.7 t CO₂/y reduction potential.
Fig. 8. CO\textsubscript{2} emission amount of each scenario.

Furthermore, because it is understood that mixing 50% of IHI special wood pellets and using 100% of our experimented torrefied fuel can be utilized for firing in a coal power plant, we ran a simulation to show what amount of raw material is required for various mixture percentage, how much CO\textsubscript{2} is emitted and from which part of activity within the scenario boundary are those CO\textsubscript{2} emitted. Figure 9 and 10 presents the simulation results. Depending of what the favorable and feasible situation is (for example, raw material availability, existence of Fit-In-Tariffs, transport and time considerations), one could identify what amount of biomass fuel mix ratio is optimal.

Fig. 9. CO\textsubscript{2} from co-firing wood pellets. 

Fig. 10. CO\textsubscript{2} from co-firing torrefied fuel.

4 Conclusions

This study conducted an LCCO\textsubscript{2} evaluation to measure how much CO\textsubscript{2} emissions can be avoided by using varying amounts of biomass fuel in a coal power plant for co-firing. We found that the use of 30% torrefied fuel could reduce the amount of CO\textsubscript{2} emissions by about 28.5% or around 95,000 t annually.

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