Environmental Assessment on Paper Sludge to Electricity in Paper Mills in Thailand

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In the paper production industry, typically, waste from the papermaking process, such as woody waste, waste reject, and paper sludge, is used for internal energy recovery. Our research focuses on paper sludge that has high moisture content. Our previous study that showed that hydrothermal treatment can convert paper sludge into solid fuel. In this study, we calculated the CO2 emissions from the paper sludge valorization to generate electricity in actual paper mills in Thailand. As a result, when hydrothermal treatment was applied on paper sludge and the product was cofired with coal, it was better in terms of an environmental perspective and technical feasibility in the case of the small- and medium-size boilers, 50 and 80 t/h.

Key Word
Environmental assessment, Paper sludge, Hydrothermal treatment

1. Introduction
1.1 Paper industry and waste

Asia is the biggest market of the paper industry compared with other areas in the world, which accounts for 45% of production and 45% of consumption 1).

Recently, the demands of paper have been increasing among developing countries, especially in Southeast Asia, along with their economic development. This movement continues because of changing social awareness of hygiene and the movement away from plastic products. Moreover, the Chinese strategy regarding the importing of old paper has influenced the paper industry in Southeast Asia.

However, every industry has to consider their relationships with various stakeholders, such as investors, customers, and local communities, regarding corporate social responsibility (CSR). In particular, for industries that utilize natural resources, such as the palm oil industry, forest industry, and paper industry, the oppression from society gradually becomes stronger; thus, these industries need to be eco-friendlier for the society and environment.

How to treat waste is also one of the major issues regarding CSR in addition to the greenhouse gas emissions (e.g., CO2). In the paper industry, there is considerable waste from papermaking processes, such as woody waste, waste...
reject, and paper sludge. These wastes are known as solid fuels that can be used to generate energy for the internal facilities of paper mills. Paper sludge (PS) is usually sent to landfills at a rate of 63%. Only 21% of PS is incinerated. Landfilling is not sustainable because it requires land and negatively affects the environment. Thermochemical conversion process is promising for paper sludge treatment. Combustion and gasification processes of paper sludge have been studied by several researchers. Bubbling fluidized bed gasification was designed especially for energy recovery from paper sludge. Paper sludge was co-fired with coal and this conversion method has been utilized by paper industries. However, burning wet paper sludge is not a good option because of its high moisture content and low energy density. Therefore, this work focused on paper sludge upgrading and final utilization in an eco-friendlier way to provide an alternative solution.

As mentioned earlier, many approaches have been developed to manage paper sludge, such as gasification and combustion. Alternatively, hydrothermal treatment (HTT) is an approach that does not require a low moisture content raw material. Our previous study showed that HTT can upgrade paper sludge and its lower heating value (LHV) was increased from 2.24 to 13.0 MJ/kg and when the moisture content decreased from 70% to 5%.

1.2 Hydrothermal treatment

HTT is a pretreatment method for biomass. It can convert high moisture biomass into solid fuel via several reactions such as hydrolysis, dehydration, and decarboxylation.

Moreover, HTT improves dewatering and drying characteristics of the treated material. Although the moisture content of the product increases slightly just after HTT, it will be approximately 50% or less upon mechanical dehydration. Then, after the natural drying process, the moisture content will further decrease to 10–20%. The dried material can be used as a solid organic fertilizer or solid fuel. Conventionally, the drying process of materials with a high moisture content, such as over 80%, requires a large amount of energy for heating and drying. When HTT is applied, there is not only a significant reduction in the cost of the drying process but also a reduction of waste, an improvement in mobility, and a reduction in transportation costs are realized.

HTT requires only steam with a high temperature around 200°C and high pressure around 2 MPa; thus, it is a simple technology that can be implemented. Previous studies already showed that the HTT can be used to improve the physical and chemical properties of various materials, such as wood chips, waste papers, paper bags, and dog food. It has already confirmed by our previous study that HTT can be the solution to the paper sludge issue and bring about many benefits as mentioned previously.

In this study, we focused on the environmental aspects (both waste management and CO2 emissions) and evaluated in terms of using hydrothermally treated paper sludge in an actual power generation situation in Thailand.

2. Methodology

We evaluated the environmental aspect by using the CO2 emission factor. An emission factor is defined as the average emission rate of a given GHG for a given source relative to units of activity by the United Nations Framework Convention on Climate Change (UNFCCC). It indicates how much CO2 exhaust occurs from the production process from making a certain amount, which called the functional unit, such as 1 kW, 1 t, or 1 L. For example, the CO2 emission factor is used for life-cycle assessment, which is an analysis technique used to assess environmental impacts associated with all the stages of a product's life from raw material extraction to materials processing, manufacture, distribution, and use.

The papermaking process is shown as Fig. 1 (a). However, in terms of applying waste to energy, there is no need to calculate the CO2 emission from all the processes, and we calculated only the red part in Fig. 1 (a). The functional unit of this assessment is 1 t of paper production.

Details about the red part are shown as Fig. 1 (b). Especially in terms of the red part, we calculated the amount of CO2 emission from the boiler, transportation, buying energy from outside, and landfill for different cofiring ratios and hydrothermal treatments. In terms of CO2 emission from the boiler, we calculated it based on the carbon contents of each fuel using the following formula. Regarding the calculation parameters for the energy facilities, we assumed the energy efficiencies of the boiler and the turbine were 88% and 60%, respectively. Parameters that were used in the calculation are shown in Table 1. Raw paper sludge (Raw-PS) is the waste and it has the moisture content of 70% after the screw dewatering process. The HTT-PS is the candidate material while the substitute coal is default fuel that currently uses in the solid fuel boiler in the paper mill.

\[ CEF_{wi} = CC_i \times (44/12) \times (1 - MS_i) \]  
\[ CEF_{wi} : \text{CO2 emission factor (kg-CO2/kg)} \]  
\[ CC_i : \text{Carbon content of fuel i (%)} \]  
\[ MS_i : \text{Moisture content of fuel i (%)} \]  
\[ CEF_{wi} = CEF_{wi} \times CV \]  
\[ CEF_{wi} : \text{CO2 emission factor (kg-CO2/MJ)} \]

\[ CEFei = CC_e \times (44/12) \times (1 - MS) \]  
\[ CEFei : \text{CO2 emission factor (kg-CO2/kg)} \]  
\[ CC_e : \text{Carbon content of fuel i (%)} \]  
\[ MS : \text{Moisture content of fuel i (%)} \]  
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Regarding the CO₂ emission from transportation, we calculated two parts: the transportation of coal from Indonesia and the transportation of unutilized PS to the landfill. The calculation parameters for coal imports, we assumed the distance from Indonesia to Lam Cha Bang (Chonburi Province, Thailand), which is a major port near Bangkok, as 2300 km. Additionally, we assumed that the landfill is located 50 km from the paper mill. In this study, we calculated the CO₂ emission for the possible following five cases.

Case 1: No internal energy generation of the facilities and buying energy from elsewhere
Case 2: Raw PS at 10% and coal at 90% cofiring with buying elsewhere for the shortage part
Case 3: Raw PS at 20% and coal at 80% cofiring and buying elsewhere for the shortage part
Case 4: All raw PS and coal cofiring and buying elsewhere for the shortage part
Case 5: All hydrothermally treated PS (HTT-PS) and coal cofiring and buying elsewhere for the shortage part

We set the boiler sizes to 50, 80, and 100 t/h in every case by considering the difference of weights between the raw PS and HTT-PS because HTT-PS is 88% lighter than raw PS. Other parameters for the calculations are shown in Table 2. The amount of electricity generation from internal energy generation is calculated by following formula.

\[ \text{IEG} = \left( \sum \text{CV}_i \times \text{FA}_i \right) \times \text{EEB} \times \text{EET} \]  

where CV: Calorific value of fuel i (MJ/kg in Lower Heating Value)

FA: amount of fuel i (kg/h)

EEB: Energy efficiency of the boiler (%)

EET: Energy efficiency of the turbine (%)

Each CO₂ emission factors are shown in Table 3. The CO₂ emission factor as a solid fuel, the CO₂ emission factor for HTT-PS was 41% less than that of Raw PS. However, the CO₂ emission factor of solid fuels could not be compared with the CO₂ emission factor of external energy because it did not consider the energy efficiency of the turbine and boiler.

\[ \text{CO₂ emission factor} = \frac{0.17 \text{ kg-CO₂/MJ}}{} \]

\[ \text{CO₂ emission factor for HTT-PS} = 0.10 \text{ kg-CO₂/MJ} \]

\[ \text{CO₂ emission factor for Substitute Coal} = 0.15 \text{ kg-CO₂/MJ} \]

\[ \text{CO₂ emission factor for Thailand grid} = 0.13 \text{ kg-CO₂/MJ} \]

\[ \text{CO₂ emission factor for Thailand Steam} = 0.058 \text{ kg-CO₂/MJ} \]

\[ \text{CO₂ emission factor for Land fill of PS} = 2.7 \text{ kg-CO₂/kg} \]

\[ \text{CO₂ emission factor for Transportation via sea} = 0.038 \text{ kg-CO₂/t*km} \]

\[ \text{CO₂ emission factor for Transportation via road} = 0.23 \text{ kg-CO₂/t*km} \]

### Results

In Cases 4 and 5, the cofiring ratio depended on the boiler size; thus, they are shown as Table 4. The result of the calculation by using these CO₂ emission factors is shown in Fig. 2. The result depends on the energy ratio because the CO₂ emission from energy facilities (direct one only, excluding the construction and decommission stages) and the grid accounts for the largest percentage, although buying elsewhere for the shortage part

Case 4: All raw PS and coal cofiring and buying from elsewhere for the shortage part

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we calculated CO2 emission from the boiler, transportation, buying energy from elsewhere, and landfill. No scale effects are counted in the calculation because of simplification. CO2 emission increased along with the coal supplied to the boiler. The order of the amount of CO2 emission depends on the boiler size. However, Case 4 was the lowest CO2 emission for every boiler size. The result depends on the energy generation shown in Table 5.

### 4. Discussion

When other cases were compared with Case 1 (as a baseline), which did not use internal energy facilities, it could not be confirmed that having energy facilities is better from an environmental perspective. The CO2 emission for Case 1 can be lower than those for both Case 2 and Case 3 with each boiler size because the Thai grid electricity is mainly sourced from natural gas at a rate of approximately 70%. However, from the view point of economic feasibility, it should be noted that electricity from the grid will cost more than the internal power generation.

CO2 emission for all the cases except for Case 5 with the 100 t/h boiler was lower than that of case 1. CO2 emission for Case 5 with the 100 t/h boiler was more than that of Case 1 because the coal ratio of cofiring was high such as 97% and the usage of coal is also more than other boiler size. Our results showed that the lowest CO2 emission corresponded to Case 4 with a 50 t/h boiler. However, the cofiring ratio of raw PS was 47%, as shown in Table 4, and it was not technically feasible because it is difficult to achieve such a high percentage raw PS cofiring with coal. This is because raw PS has very high moisture content and low heating value. The boiler will not be able to operate with efficiency. Moreover for larger boiler capacity scenarios, the raw PS will face difficulty in practical situation, even though the mixing proportion is lowered. Therefore, CO2 emission via case 5 with 50 and 80 t/h are the most feasible in terms of CO2 emission reduction as they are lower than the Case 1.

### 5. Conclusion

Our study showed the environmental impact by calculating CO2 emissions from a paper sludge system to generate electricity in actual paper mills in Thailand for different cofiring ratios and applications of HTT. We calculated 5 cases as follows: Case 1 (no internal energy generation of the facilities and buying energy from elsewhere), Case 2 (raw PS at 10% and coal at 90% cofiring with buying elsewhere for the shortage part), Case 3 (raw PS at 20% and coal at 80% cofiring and buying elsewhere for the shortage part), Case 4 (all raw PS and coal cofiring and buying elsewhere for the shortage part), Case 5 (All HTT-PS and coal cofiring and buying elsewhere for the shortage part). We set the boiler sizes as 50, 80, and 100 t/h in every case by considering the difference in weights between the raw PS and HTT-PS. To conclude, the best case in terms of the environmental perspective and technical feasibility is Case 5 with small- to medium-scale boiler capacity, which used HTT-PS and cofiring with coal and buying elsewhere for the shortage part, produced the lowest CO2 emission.

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