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Life cycle assessment of biochar cofiring with coal

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HIGHLIGHTS

- Biochar cofiring can cause lower damage to ecosystem, climate change, and resources.
- Biochar cofiring can reduce the carbon emission of thermal power plant.
- The electricity generation efficiency of cofiring is critical to reduce its impact.

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ABSTRACT

This study used life cycle assessment software SimaPro 7.2 and impact assessment model IMPACT 2002+ to evaluate the environmental impact and benefits of a biochar cofiring supply chain used for electricity generation. The biochar was assumed to be produced by rice straw torrefaction and the case study was located in Taoyuan County, Taiwan. This supply chain may provide impact reduction benefits in five categories (aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy) but cause higher impacts than coal firing systems in other categories. Damage assessment of cofiring systems indicated that damage to human health was higher while the damage categories of ecosystem quality, climate change, and resources were lower. Carbon reduction could be 4.32 and 4.68 metric tons CO_2 eq/ha/yr at 10% and 20% cofiring ratios, respectively. The improvement of electricity generation efficiency of cofiring systems may be the most important factor for reducing its environmental impact.

1. Introduction

Renewable energy has been attracting more and more interest due to concerns about limited fossil fuel supplies and increasing prices. In addition, CO_2 released by the combustion of fossil fuels is causing global warming and climate change. However, fossil fuels are still the major source of electricity and energy consumption (IEA, 2011). According to the 2008 ranking of the world's countries by fossil-fuel CO_2 emission rates provided by CDIAC, the CO_2 emission rate of Taiwan was about 11.2 metric tons of CO_2 per capita, ranked twenty-fifth in the world and first in eastern Asia (CDIAC, 2011). Therefore, issues such as developing clean, renewable energy and reducing greenhouse gas (GHG) emissions are very important for Taiwan's sustainable development. Some of the incineration plants in Taiwan are soon to be retired. In order to raise the level of consumption of renewable energy, relevant institutions plan to transform the plants into bioenergy centers that deal with biomass, such as municipal solid waste and agricultural residues (Chiueh et al., 2012).

Tilman et al. (2009) pointed out that the best biofuels should be derived from sustainable biomass feedstocks that neither compete with food crops nor directly, or indirectly, cause land clearing and that offer advantages in reducing emissions of GHG. Therefore, crop residues, double and mixed crops, sustainably harvested wood and forestry residues, perennial plants grown on degraded lands abandoned from agricultural use, and municipal and industrial solid wastes offer great potential (Tilman et al., 2009). Crop residues, including straw, stalk, husk, shell, peel and bagasse, generally have low sulfur and nitrogen content, so they are very suitable for use as feedstocks in the bioenergy supply chain.

Rice straw is a valuable biomass, not only because it is an agricultural residue, but also because it is very abundant (Shie et al., 2011). In Taiwan, the annual production of rice from 2006 to 2010 was about 1.5 million metric tons (COA, Executive Yuan, 2011). For every metric ton of grain harvested, about 1.35 metric tons of rice straw remains in the field (Kadam et al., 2000). Therefore, there is about 2 million metric tons of rice straw generated every year, so it is abundant in Taiwan. However, the cost of rice straw collection is high due to its scattered distribution. This could be a critical factor limiting the use and applications of rice straw. Traditionally, most of the rice straw left on farmland was directly

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burned without proper disposal, causing severe air pollution, damaging scenery and wasting a source of renewable energy. After regulatory control in these years, the rice straw was either shredded and dug into the soil (80–95%) or openly burned (5–15%) (EPA, Executive Yuan, 2005). Another critical factor is the high moisture content and low heating value properties of rice straw, meaning that its direct utilization would decrease the efficiency of thermo-chemical conversion (Yaman, 2004; Bridgeman et al., 2008). In addition, lignocellulosic biomass is difficult to grind, especially when used in pulverizing systems in large-scale utility boilers for cofiring with coal (Arias et al., 2008).

Torrefaction is a mild form of pyrolysis, namely a thermo-chemical, pretreatment technology carried out in the absence of oxygen. In a torrefaction process, biomass is heated slowly (less than 50 °C/min) to 200–300 °C, and it is heated for up to 1 h. After the torrefaction process, most of the biomass remains unreacted while a small part is decomposed into volatile products that can or cannot be condensed. The remaining solid product is known as torrefied biomass or biochar. Torrefaction can improve the combustion characteristics, reduce the volume and increase the grindability of biomass (Bergman et al., 2005).

One of the potential uses of the bioenergy centers in Taiwan could be the pretreatment of rice straw by using torrefaction technology to convert it into biochar, which can then be used for electricity generation by cofiring. Therefore, a rice straw supply chain would need to be established. Such a supply chain, from rice harvesting to the conversion of rice straw into usable energy, includes several stages: collection, transport, pretreatment, storage and combustion (Chiueh et al., 2012). Each stage involves inputs and outputs of mass and energy, which may cause direct or indirect impacts on the environment. Thus, the environmental benefit and impact of the overall bioenergy supply chain should be evaluated by using the concept of life cycle assessment (LCA).

Sebastian et al. (2011) used LCA to evaluate the GHG emissions of cofiring and biomass-fired power plants, pointing out that when biomass-dedicated steam cycles had net electric efficiencies higher than 29%, approximately the same results could be attained by using either method. Lu and Zhang (2010) combined conventional process-based LCA with economic input–output LCA to evaluate the environmental and economic impacts of applying energy conversion technologies to crop residues. They found that both crop residues cofiring with coal and crop residue gasification offered greater economic scope and technical feasibility for power generation, while the return of crop residues to the fields, silo/amination and anaerobic digestion (on a household scale) offered the greatest ecological benefits (Lu and Zhang, 2010). Cherubini and Ulgiati (2010) used an LCA approach to evaluate biorefinery systems. They indicated that the use of crop residues in a biorefinery could reduce GHG emissions by about 50% and save more than 80% of non-renewable energy, but it has higher eutrophication potential than in fossil fuel systems. The eutrophication would be mostly given by nitrogen fertilization, which could cause leaching of nitrates to groundwater. Besides, the effect of land-use change can have a strong influence on the final balance of GHG emissions (Cherubini and Ulgiati, 2010).

This study used an LCA methodology to evaluate the environmental benefits and impacts of biochar produced by rice straw torrefaction and its supply chain for cofiring electricity generation.

2. Methods

This study used the IMPACT 2002+ model to acquire midpoint and damage assessment results in order to evaluate the environmental benefits and impacts of biochar production from rice straw torrefaction and its application to cofiring power generation. Owing to the lack of relevant input and output data for a full-scale rice straw torrefaction plant, reference materials were used to simulate the processes of a rice straw torrefaction plant and to model the processing outputs and pollutant emissions.

2.1. LCA method

2.1.1. Goal and scope definition

2.1.1.1. System boundary. The cradle-to-grave system boundary of a rice straw supply chain for biomass electricity generation is shown in Fig. 1. The supply chain consisted of several steps including: on-site collection, transport, torrefaction, pelletization (biochar production), storage, cofiring and land use change (caused by the removal of rice straw). Cherubini and Ulgiati (2010) pointed out that the removal of crop residues from farmland (as opposed to crop residues being returned to the soil) would decrease the level of soil organic carbon (SOC) and the SOC loss might enter the atmosphere, increasing the greenhouse effect. Since rice straw could act as an organic fertilizer, its removal might also decrease levels of soil nutrients and thus crop yields (Cherubini et al., 2009). Therefore, this study investigated the effects of land-use change caused by the removal of crop residues, including the change in GHG emission and rice straw production. The addition of chemicals to replenish soil fertility was assumed, so emissions caused by the manufacture, transport and use of these fertilizers were incorporated into the system boundary. The life cycle steps of coal (for cofiring) were also taken into account within the boundary.

To evaluate the impact reduction benefit of biomass electricity, the supply chain of coal-fired power in Taiwan was chosen as a reference system, as shown in Fig. 1. Coal mining, sea transport, storage in harbors, truck transport and combustion in power plants are included inside the system boundary.

2.1.1.2. Functional unit. To compare the potential environmental impacts of coal-fired and biochar cofiring electricity generation systems, the kilowatt hour (kWh) was chosen as the functional unit.

2.1.1.3. Case study location and assumptions. Taoyuan County was used for this case study as it has the largest rice cultivation area in northern Taiwan (31%), thereby generating the most rice straw. The incineration plant in Taoyuan County was assumed to be a bioenergy center, where rice straw is converted into biochar by torrefaction and pelletization. The biochar was assumed to be transported to the Linkou Power Plant and then co-fired with coal to generate electricity.

This study assumed that all the sub-bituminous coal used for electricity generation is obtained by import. Its lower heating value is about 25.17 MJ/kg (Grabner et al., 2010). The primary import sources include Indonesia (38.86%), Australia (35.84%), China (20.92%), Russia (2.19%), and Canada (2.01%) (BOE, MOEA, 2006). Transport of coal over long distances by sea consumes a large quantity of non-renewable energy and it is necessary to calculate the materials and energy inputs and outputs of the imported coal supply chain. Taichung Harbor was assumed to be the import harbor. Sea transport distances were calculated by using common international shipping routes between Taichung Harbor and the major harbors of the coal exporting countries. On arrival at Taichung Harbor, the coal is temporarily stored and then transported to Linkou Power Plant by trucks. This transport distance was assumed to be about 150 km.

This study assumed that rice straw biochar and coal have nearly the same grindability and thus power plants need not renew grinder equipment. However, the cofiring of biochar with coal might influence the stability of combustion flames, lowering the efficiency of electricity generation. Sebastian et al. (2011) indicated