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Life cycle assessment of lignite pyrolysis: a case study in China

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ABSTRACT

In this study, a life cycle assessment was conducted using the ReCiPe method to estimate the environmental impact of lignite pyrolysis, which is one of the most commonly used technologies for lignite upgrading. Technological advancements significantly affect climate change, human health, and fossil depletion. The influence of lignite pyrolysis on the effect of other categories on the environment was small. Improved efficiency in electricity consumption and energy (i.e., steam and electricity) recovery from oven gas, optimized transportation (i.e., type and distance), and lignite drying technologies, as well as decreased levels of mined lignite and direct air emissions (e.g., heavy metals, benzene, and carbon dioxide) from the lignite pyrolysis stage, are the key factors in reducing the overall environmental impact of lignite pyrolysis.

1. Introduction

Abundant reserves, easy access, and low mining costs are features of lignite (Zheng et al., 2014). This material is commonly used as a main fossil fuel for electricity generation in Europe (Bruninx et al., 2013). Although lignite accounts for almost half of the coal recoverable reserves worldwide, its application is limited because of its low calorific value, rich moisture content, active chemical reactivity, and flammability, among others (Sivrikaya, 2014; Sun et al., 2014). The use of lignite can generate a series of problems, including low thermal efficiency, high operation and maintenance costs (Zheng et al., 2014), and high carbon dioxide (CO_2) and pollutant emissions (Yang et al., 2015). To date, the technological improvement of lignite utilization, such as for pyrolysis (Xu et al., 2013a, 2013b), gasification (Ji et al., 2014; Ahmed and Gupta, 2013), drying (Zheng et al., 2014; Agraniotis et al., 2012), and coke production (Mori et al., 2013), has been extensively studied. However, a few studies have evaluated the environmental impact of the technologies involved in lignite use (e.g., gasification, pyrolysis, electricity, Kaldellis et al., 2009). Thus, the evaluation of the environmental impact of lignite utilization through a systematic approach is highly needed.

As a systematic tool for environmental impact evaluation, life cycle assessment (LCA) is associated with product, process, or activity; this tool has been extensively applied in policymaking, strategy planning, product design, and product improvement, marketing, eco-labeling programs, and consumer education. Several studies on the CO_2 capture and storage of various lignite power plant technologies have been studied (Pehnt and Henkel, 2009; Zapp et al., 2012) from a life cycle perspective. However, none of the previous LCA studies have investigated lignite pyrolysis. Given the urgency of lignite utilization and the increasing environmental pressure, the LCA of lignite pyrolysis, which is a major direction for lignite upgrading, was conducted in this study. This research aimed to introduce a database of lignite pyrolysis to the world, identify the key factors in reducing the overall environmental burden of lignite pyrolysis sites, and encourage the most appropriate decisions for lignite upgrading.

2. Scope definition

2.1. Functional unit and system boundary

A functional unit is the service delivered by the product system. In this study, the processing of 1 t dried lignite for pyrolysis was

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selected as the functional unit. All infrastructure, energy and raw materials consumption, road transport, onsite wastewater and waste gas disposal, solid waste reused or treated to landfill, and direct emissions levels are based on this functional unit. LCA was conducted by using the cradle-to-gate approach. Fig. 1 presents system boundary and mass flow of lignite pyrolysis. The scenario involved underground mining, microwave drying technology (2600 kW, 12 t/h), road transportation, pre-treatment, carbonization, and oven gas purification and energy recovery processes. The processes involved the background inventory data of energy generation, raw materials production and transportation, direct air emissions, onsite wastewater and solid waste treatment, land occupation, buildings, and dedusting with bag filters. Table 1 shows the characterizing factors of the lignite considered in this study.

2.2. Data sources

The life cycle inventory data on the operation processes (i.e., raw materials and energy consumption, direct emissions, waste disposal) undertaken in the environmental report of lignite pyrolysis in Xinjiang, China, were used in the present study. The installed capacity of the site reported produced approximately 9.0×10^5 t/y of semicoke. The heavy metals emitted to air were obtained on the basis of experiment data and theoretical calculation. The heavy metals in lignite (Table 1) were monitored by a tube-above wavelength dispersive X-ray fluorescence spectrometer (ZSX Primus II, Rigaku, Japan) and calculated as described in the literature (Di et al., 2007). The air pollutions of polycyclic aromatic hydrocarbons (PAHs) are taken from Zhang and Tao study (2009) because of the lack of related information shown in the lignite pyrolysis site. Energy consumption and waste generation data for lignite drying with microwave technology were monitored from a lignite-based power site in Neimenggu Province, China. Data on road transport (Chen et al., 2015), coal-based electricity generation (Cui et al., 2012), coal mining (Hong et al., 2015), ammonia production (Hong and Li, 2013) in China were used in this study. Notably, the release of methane during coal mining is the most important source of fugitive methane emissions. The national average usage rate of steam gas drainage of 31.5% and steam gas production rate of 9.76 m^3/t coal were considered (Zhu, 2011; Li and Hu, 2008) in this study because of the lack of detailed information on the coal mining site. In addition, data on the infrastructure and the rest of the chemical production were taken from Europe (Ecoinvent centre, 2010) to compensate for the lack of data in China. Table 2 presents the main inventory data.

2.3. Life-cycle impact assessment methodology

Life-cycle impact assessment (LCIA) is assessed by using ReCiPe method (Schryver et al., 2009; Goedkoop et al., 2009), which is the latest and commonly used LCIA approach world widely. This method uses impact mechanisms that have a global scope and considers a broad set of midpoint impact categories (i.e., climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion). In addition, normalization is applied in this study to compare midpoint impacts and to analyze the respective share of each midpoint impact to the overall impact. The normalized factor of midpoint impact is determined by the ratio of the impact per unit of emission divided by the per capita world impact for the year 2000 (Sleeswijk et al., 2008). The detailed methodology and complete characterization factors for the ReCiPe are available on the website of the Institute of Environmental Science of Leiden University of the Netherlands (http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/recipe.html).

3. Results

3.1. LCIA results

Table 3 shows the LCIA midpoint results and the contribution of the most significant processes. The electricity generation and electricity recovery from waste processes had the greatest contribution to the climate change, terrestrial acidification, human toxicity, terrestrial and marine ecotoxicity, natural and urban land transformation, photochemical oxidant formation, particulate matter formation, and water depletion categories, whereas the coal mining process had an important contribution in most categories except for ozone depletion, terrestrial ecotoxicity, marine ecotoxicity, land transformation, and metal depletion. The transport process dominated most categories except for fossil depletion and climate change. Similarly, direct air emissions had dominant contributions to climate change, terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and terrestrial ecotoxicity. The ammonia process served an important function in ozone depletion, human toxicity, terrestrial and marine ecotoxicity, natural land transformation, and water depletion, whereas wastewater treatment had a dominant contribution to freshwater and marine eutrophication. Infrastructure had a dominant contribution to freshwater ecotoxicity, ionizing radiation, agricultural land occupation, water depletion, and metal depletion impacts.

3.2. Normalized LCIA results

Fig. 2 shows the normalized ReCiPe midpoint results. The effect on climate change, human toxicity, and fossil depletion was significant. By contrast, the effect on photochemical oxidant formation and particulate matter formation were small, and its effect on the rest of the categories was negligible. The processes that contribute the most to the climate change and fossil depletion categories were coal mining, electricity consumption, and electricity recovery from coal oven gas. The road transport, electricity consumption, electricity recovery, and direct air emissions from pyrolysis site were the most significant contributors in the human toxicity category. Conversely, although ammonia, wastewater disposal, and infrastructure had great contribution to the categories except for aforementioned three key categories as shown in Table 3, the overall environmental effect generated from these processes was extremely small. Thus, although the European data on chemicals and infrastructure were used in the present study, its contribution to the overall environmental effect was small. The contributions of the most significant substance to the aforementioned key midpoints are presented in Fig. 3. The substances contributing the most to climate change were carbon dioxide and methane emissions in the air. Benzene, mercury, lead, and arsenic showed major contributions to human toxicity, whereas the use of lignite resulted in the highest contributions for fossil depletion. These results indicate that the optimum energy consumption (i.e., electricity and lignite), electricity recovery, and transport efficiency, are crucial to reduce the overall environmental impact.