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Quantifying uncertainties in greenhouse gas accounting of biomass power generation in China: System boundary and parameters

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ABSTRACT

Systematically quantifying the greenhouse gas (GHG) emissions of biomass power generation is a prerequisite for robust decision-makings associated with the technology's scale deployment. This study compared the planting-to-wire GHG emissions of a typical corn-stover-based power generation system in China, estimated using one process-based and two hybrid life-cycle assessment (LCA) models. Results showed that emissions calculated by process-based LCA were 11% lower than that of hybrid models because of the truncations on services and accessory equipment. The two tiered hybrid approaches yielded total-supply-chain GHG footprints of material and equipment with a negligible difference (0.7%). The parameter settings varied by time and regions/countries resulted in temporal and spatial uncertainties of process-based LCA at 4%–10% and 0.1%–16% respectively. We proposed adopting hybrid LCA models for footprint calculation because of their strength in comprehensive accounting coverage, less dependence on data acquisition, and reduced temporal and spatial uncertainties. As the GHG footprint of biomass energy utilization is region-specific and determined by multiple factors, such as supply-chain configurations and landscape of power generation technology, results of this study help to understand the uncertainties and trade-offs associated with different LCA model deployments in China, and thus, contribute to advancing the country's biomass power sector moving forward.

1. Introduction

China has become the world's largest CO_2 emitter since 2007, mainly because of its coal-dominant energy supply [1]. To optimize the energy mix and mitigate the greenhouse gas (GHG) emissions, the country has been resorting to renewable and cleaner energy alternatives over the past few decades. As a critical component of China's climate change adaption strategy, the scale of biomass power generation has increased considerably in terms of the capital investment and the installed capacity (see Fig. S1 in Supporting Information, hereinafter referred to as SI), which were accelerated by the *Renewable Energy Law* and a series of supportive industrial policies, such as price subsidies and the mandatory grid connection of renewable electricity. The straw direct-fired power generation rapidly developed and accounted for the largest share in China's total biomass power installed capacity by 2010, approximately 62% or 2.65 GW [2,3].

However, the GHG emissions of biomass power generation systems must be reliably and systematically quantified to enable robust decisions and policies relevant to the technology deployment. Such quantification must be conducted under a complete system boundary and consider the regional and temporal variations. For example, biomass energy could be carbon neutral if only the growth (primarily, the photosynthesis) and combustion processes are considered, but a considerably broader “planting-to-wire” (PTW) system outlines the GHG footprints of crop production, transportation, and power-plant construction and operation [4,5]. Furthermore, more GHGs, including CH_4 and N_2O, are emitted during straw combustion and fertilizer use, and they cannot be

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absorbed by photosynthesis. Therefore, the GHG mitigation benefit of biomass power generation is questioned [6–8].

Life-cycle assessment (LCA) provides a holistic approach to the footprint quantification of entire PTW systems. Process-based life-cycle assessment (PLCA) has been widely used to evaluate the GHG emissions of biomass power generation from biomass residue collection, power-plant construction and plant operation stages [9–15]. However, a subjective system boundary definition inherently exists in the PLCA method [16–18], introducing truncation uncertainties to model results due to the subjectively censored processes, such as equipment manufacturing and services [19,20]. The truncation uncertainties associated with environmental impacts are estimated at 20%–60% [21], while for the services and capital-intensive sectors, the uncertainties will be significantly larger [22,23]. Thus, boundary definition may severely influence the model results, particularly those of comparative studies, leading to erroneous research conclusions [24,25].

Hybrid life-cycle assessment (HLCA) presents more complete inventories than PLCA estimates by using an environmental input-output-LCA (IO-LCA) model, and it has been used to systematically estimate the footprint of biomass power generation and other biomass energy conversion systems [1,26–28]. The IO-LCA model is rarely used alone to estimate the environmental footprints of energy products because the approach is incapable of calculating the environmental impact of product use, i.e., emissions from fuel combustion [21,24,29,30]. The IO-LCA model yields a complete and unified system boundary for footprint calculation, because it is established on the basis of the national input-output table that includes complex interdependencies of industries within an economy [31], and truncation is thus avoided. However, the model is subject to the uncertainties derived from industrial sector aggregation and outdated sectoral correlation statistics for the latest practices [32].

In addition to the system boundary uncertainty (truncation and aggregation), spatial and temporal variations should be considered for the systematic footprint quantification of biomass power generation. Biomass energy is region-specific because of the diversities in the climatic and soil conditions, farming methods, biomass collection modes, and power generation technologies in different regions/countries. Moreover, technologies continuously evolve, reducing the emissions of materials and equipment manufacturing and energy combustion. For example, the energy consumption per metric ton of steel output annually fell by 3% in China because of technological advances [33]. Therefore, uncertainties arise when the temporal- and spatial-specific parameters used for the evaluation are inconsistent with the considered system [34–36]. Both PLCA and IO-LCA are vulnerable to spatial and temporal uncertainties, which were often ignored in the LCA studies [37–39]. Note that the two uncertainties are likely to be more significant in LCA studies (particularly PLCA studies) in China because of the relative lack of databases specific to China's practices (such as the Eco-invent database for Europe).

Obviously, the aforementioned variation in the system boundary and spatial/temporal situation affects the quality of PTW GHG quantification. Both the PLCA and the IO-LCA models have advantages and drawbacks. Even HLCA, the so-called state-of-the-art method, has its own uncertainties, such as the boundary definition between the process and the IO analysis [24,40]. As the system boundary of the process and the IO analysis in the HLCA model varies, the uncertainty of the model results in changes to a different extent. Thus, such uncertainty must be assessed before the model's adoption for the GHG emission estimation of biomass power generation. A further introduction of the PLCA and the IO-LCA models and their uncertainties is presented in SI.

In this study, we developed an uncertainty analysis framework to quantify the truncation, aggregation, spatial, and temporal uncertainties of different LCA modeling approaches in the GHG emission calculation of a biomass power generation system in China on the basis of a typical corn-stover-based power generation system (CSPGS). Uncertainties were quantified by comparing the PTW GHG emissions calculated by using LCA models with different system boundary and parameter selection scenarios. The purpose of this study was to quantitatively understand the uncertainties associated with different LCA model types, to identify the key factors for accuracy improvement and to find a reasonable (accurate, specific and time-saving) model for the environmental assessment of biomass power generation. Note that the analytical framework developed in this study could also be used to analyze the uncertainties of LCA studies on a broader category of energy technologies.

2. Materials and methods

2.1. System description

The CSPGS considered in this study was a direct-fired power generation system fueled by corn stover. The power plant was constructed in 2007 with the installed capacity of 30 MW. The designed life span was 15 years, and power generation efficiency was 19% (see Fig. S2, the energy balance of the entire process). The annual consumption of the stover was approximately 203000 metric tons, and the electricity output was 180 GWh, including 162 GWh of on-grid electricity and 18 GWh of self-consumption of the system. To enable complete GHG emissions accounting for the CSPGS, the system scope in this study was defined to include the agricultural process, corn stover transportation, and pretreatment and stover combustion for electricity generation (see Fig. 1). As the ash from burning biomass was provided free of charge to local farmers and orchardmen, its disposal was not considered. Corn stover in this study is regarded as a byproduct of maize cultivation, an energy-intensive farming activity using fertilizers, pesticides, electricity, and fossil fuels. The corn stover was transported to the power plant and then pulverized and burned for power generation. The GHG emissions of the CSPGS were categorized into two parts: 1) onsite emissions, including N_2O emission from the nitrification and denitrification processes in the soil, CO_2 emission from the soil tilling and erosion processes, CH_4 and N_2O emitted by biomass burning, and GHG emitted by fossil energy combustion; and 2) supply-chain emissions derived from material (building materials, fertilizers, pesticides, and water) production, power-plant equipment manufacturing, services provision (including transport, installation, and repair services), and fossil energy production and supply. Further details of the system boundary and the material and energy flows of the system are presented in SI.

2.2. System boundary and parameter selections

2.2.1. System boundary of PLCA

The PLCA model considered both onsite and supply-chain emissions. As mentioned earlier, onsite emissions consist of direct emissions from agricultural processes and energy combustion. Direct emissions from agricultural processes include N_2O emissions from the nitrification and denitrification processes in soil caused by the use of nitrogen fertilizers and CO_2 emissions induced by the soil carbon loss. These emissions were estimated on the basis of the results of previous studies; the calculation details are presented in SI [41–43]. Energy combustion emissions include the emissions of diesel consumption in corn production and the stover transportation processes and the emissions of stover burning. The