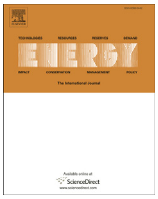
Energy 115 (2016) 303–313

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Life-cycle greenhouse gas emission and energy use of bioethanol produced from corn stover in China: Current perspectives and future prospectives

Lili Zhao [a, b], Xunmin Ou [a, b], Shiyan Chang [a, b, c, *]

[a] Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China
[b] China Automotive Energy Research Center, Tsinghua University, Beijing 100084, China
[c] Laboratory of Low Carbon Energy, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form
20 July 2016
Accepted 15 August 2016

Keywords:
Lignocellulosic biomass
Life cycle analysis
Bioethanol
E10
E100

ABSTRACT

In this study, a life cycle analysis (LCA) of bioethanol production from corn stover is carried out under Chinese context. Three scenarios were developed and assessed based on current and future technology levels of the ethanol conversion process. Well-to-pump (WTP) and well-to-wheels (WTW) results are presented in this paper via functional units of 1 MJ of ethanol produced, 1 MJ of E100 produced and used, and 1 km of distance driven by a light-duty vehicle on E10 fuel, respectively. It was calculated that for 1 MJ of E100, the WTW Greenhouse gas (GHG) emission reduction relative to gasoline reaches 52%–55%, and the savings of fossil fuel and petroleum fuel reach 72%–76% and 74%–85%, respectively. For 1 MJ of ethanol produced, GHG emissions occurred in ethanol conversion process account for 51%–55%, and the contribution of chemical inputs reaches 36%–37% of the total life cycle GHG emissions. Furthermore, the life cycle results were found to be highly sensitive to allocation methods.

1. Introduction

Fuel ethanol, as an important alternative vehicle fuel, has been promoted in many countries to alleviate the concerns over energy security and greenhouse gas emissions (GHG) [1]. The bioethanol is currently dominated by first generation products derived from corn grain and sugarcane syrup in the world. However, due to food versus fuel problem, there has been global resistance to the expansion of first generation ethanol production. As a result, many efforts have been made to develop second generation bioethanol using lignocellulosic biomass, which has been identified as promising feedstock for sustainable biofuel production [2]. Lignocellulosic biomass includes agricultural and forestry residues (e.g., sugar cane bagasse, woodchips, rice rusk), herbaceous plants, etc.[3–5]. This type of feedstock constitutes the world's largest bioethanol renewable resource and possesses advantages over petroleum-based fuels, such as potentially lower life cycle greenhouse gases emissions and reduced consumption of fossil fuels [4,6–10]. The feedstock resources for lignocellulosic bioethanol production in China are available in abundance, among which, crop residues account for 60% with corn stover as the most abundant resources [11,12].

A careful life cycle analysis is critical to evaluate quantitatively the GHG and fossil energy impacts of bioethanol derived from lignocellulosic biomass in Chinese context, as China has claimed to actively promote the bioethanol production from lignocellulosic biomass in long-term period in its *Medium and Long-Term Development Plan for Renewable Energy*, which was enacted in 2007.

Many studies have been done on the life cycle analysis of bioethanol derived from lignocellulosic biomass. Among them, Refs. [7,13,14] assessed well-to-wheels environmental performance of ethanol from lignocellulosic biomass with simplified input data for the ethanol conversion stage. Many other studies [8,15–19] carried out well-to-wheels (WTW) or well-to-pump (WTP) assessment on the bioethanol produced from lignocellulosic biomass mainly or partly based on biochemical processes [20,21] developed by the National Renewable Energy Laboratory (NREL) of the United States (U.S.). Karlsson et al. (2014) [2] made life cycle analysis of ethanol co-production with biogas and electricity in biorefineries using lignocellulosic feedstock. To make a better

---

* Corresponding author. Laboratory of Low Carbon Energy, Tsinghua University, Beijing 100084, China.
E-mail addresses: Julia.beijing@gmail.com (L. Zhao), ouxm@tsinghua.edu.cn (X. Ou), changshiyan@tsinghua.edu.cn (S. Chang).

http://dx.doi.org/10.1016/j.energy.2016.08.046
0360-5442/

understanding of the impacts of enzyme, yeast, process chemicals and nutrients on life cycle performances of lignocellulosic ethanol, some studies [22,23] made careful analysis based on a variety of data resources and found these contribution of the inputs is significant. Borrion et al. (2012) [24] made their reviews on the life cycle analysis of bioethanol production from lignocellulosic biomass, arguing that the conclusion to favor the bioethanol derived from lignocellulosic biomass is quite robust, at least in the categories of fossil energy intensity and GHG emissions. Whereas, there is inconsistency in the contributions of different sources, i.e., some reported that the majority of life cycle fossil fuel consumption and GHG emissions are produced in biomass cultivation stage, yet others concluded that the ethanol conversion process is the biggest contributor. The percentages of GHG and fossil fuel reductions reported in the studies also vary to a large extent due to differences in system boundary, functional unit, data sources, agricultural practice, conversion processes, regional aspects, etc.

Through literature review, it was found that the inputs of the ethanol conversion process for life cycle analysis are either based on simplified generic data or taken from a specific or a mix of processes. However, most of the processes were targeted to the future prospective. Few studies have been focused on the current perspectives of the bioethanol production, or on the comparison between the current and the future except a few number of studies [6,9]. In addition, the levels of conversion technology vary in different countries and regions. Most of the studies with detailed input data of ethanol conversion stage were applied to North America and Europe, rather than China. To our knowledge, few LCA studies have been carried out based on Aspen Plus simulation of current Chinese technology level. And limited literature have taken into consideration the differences between status quo and future development of bioethanol conversion technology. It is also found that the studies focused on life cycle analysis of lignocellulosic bioethanol in Chinese context underestimated the environmental and energy burdens to a considerable extent, as most of them excluded the contributions of process chemicals and nutrients, and they allocated no burdens to crop residues occurred during agricultural cultivation [14]. Tian et al. (2011) [25] consider the aforementioned inputs, but the study did not make any simulation of the ethanol conversion process and the inputs for the process were based on future prospective of the conversion technology, with no consideration of the technology status quo in Chinese context.

This study is focused on bioethanol derived from corn stover in Chinese context with careful consideration of the inputs in ethanol conversion process (including direct process chemicals and the chemicals and nutrients used for breeding enzyme and fermentation microorganism) and in feedstock production (farming energy, pesticides, fertilizers, emissions due to stover collection). With regard to inputs for ethanol conversion stage, the studies investigated life cycle environmental and energy impacts based on current and future technology levels, to understand performance to date and evaluate the transition from present to future performance [6]. Three scenarios were developed and evaluated based on different technology levels of the ethanol conversion process, i.e., current technology (CT) scenario for status quo of Chinese bioethanol industrial practice, medium technology (MT) scenario for near- and mid-term prospective, and high technology (HT) scenario for long-term prospective of ethanol production. Gasoline is assumed to be the reference fuel compared to bioethanol in terms of GHG emissions and energy use. Corn stover is selected to be the feedstock for its abundance in resources, which is the major crop residue in China, accounting for 32% of the total crop residues [15].

The results are expected to inform LCA practitioners, policy makers, researchers and industry stakeholders on the current and potential GHG and energy impacts of lignocellulosic bioethanol in Chinese context.

2. Methodology, key assumptions, and input data

The *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model* (GREET Model) [26] developed by the Argonne National Laboratory (ANL) is used in the study to conduct the life cycle analysis of the bioethanol derived from corn stover. The model has been open to users since 1996 and has undergone continuous update and expansion. It considers energy and emission impacts of transportation fuels in a life cycle perspective. However, the data in the model are based on US context. Some work [13,14] has been done by some Chinese LCA practitioners to develop a localized databank for the GREET model, as life cycle analysis depends heavily on the local energy mix, technology, transportation modes, etc. In this study, the local data were updated and the pathway for Chinese lignocellulosic bioethanol was created.

2.1. Goal and scope

2.1.1. System boundary

The production and use of bioethanol derived from corn stover is integrated in and supported by the energy database developed by the GREET model. The system boundary covers the whole process from feedstock cultivation to ethanol combustion (WTW), which includes: 1) Feedstock growth at farming level, where agrochemical inputs, energy inputs and emissions due to corn stover removal were included; 2) bioethanol conversion processes, which were modeled by Aspen Plus software; 3) fuel combustion in the light-duty vehicle as E100 or E10; 4) other auxiliary processes like transportation and preprocessing of the feedstock, denaturing and transportation of the ethanol, blending of ethanol with gasoline, and transportation and distribution of the fuel. The system boundary of E10 fuel is shown in Fig. 1. For E100 fuel, the system boundary is similar with that of E10 except that the processes of ethanol denaturing and blending are removed. As the upstream part of WTW, the stage of WTP covers feedstock cultivation through transportation of ethanol to the bulk terminal.

The system includes the indirect life cycle flows associated with raw materials, chemicals, nutrients, and fuels used in each life-cycle stage. The construction of equipment, buildings and other basic elements of infrastructure are excluded [28].

For the reference cases, the production of gasoline includes processes of crude oil extraction, gasoline refining, transportation & distribution, and fuel combustion in a light-duty vehicle.

2.1.2. Metrics

The environmental metrics studied in this study includes GHG emissions, fossil energy use and petroleum energy consumption. GHG emissions are CO_2-equivalent (CO_2eq.) emissions as the sum of CO_2, CH_4 and N_2O, with 100 year global warming potentials of 1, 25 and 298, respectively, which were determined based on the recommendation of the Intergovernmental Panel on Climate Change (IPCC) (2006) [27].

2.1.3. Functional unit

Three types of functional units are used in this study: 1) 1 MJ of bioethanol produced in WTP stage; 2) 1 MJ of bioethanol produced and used as E100 in WTW stage; and 3) 1 km distance travelled by a light-duty passenger vehicle in WTW stage.

2.2. Assumptions

The energy database that supports the production and use of bioethanol in the GREET model is assumed to be the same for three