Renewable and Sustainable Energy Reviews 97 (2018) 301–322

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Life cycle assessment of biofuels in China: Status and challenges

Huacai Liu, Yanqin Huang, Hongyou Yuan, Xiuli Yin*, Chuangzhi Wu

Key Laboratory of Renewable Energy, CAS, Guangdong Key Laboratory of New and Renewable Energy Research and Development, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, PR China

ARTICLE INFO

Keywords:
Life cycle assessment
Bioethanol
Biodiesel
China

ABSTRACT

Biofuels using as transportation fuels represents great potential for reduction of fossil energy consumption and mitigation of greenhouse gases (GHG) emissions. China has undertaken ambitious targets and relevant policies to promote the development of biofuel industry. But a general picture showing the environmental sustainability of biofuels in China has been lacking. A comprehensive review of life cycle assessment (LCA) of bioethanol and biodiesel in China is presented in this study. Most of the surveyed studies have not gone beyond energy and GHG emission assessments. A high variability of fossil energy consumption and GHG emissions has been observed, especially for bioethanol. Cellulosic bioethanol has the best performance on reduction of fossil energy consumption. Bioethanol produced from corn, wheat, sweet sorghum and sugar crops are more energy intensive and less competitive for fossil energy saving. Significant disagreement and controversies exist regarding the GHG benefits of bioethanol, especially that of the starch- and sugar-based bioethanol. In contrast, biodiesel using as a substitute of conventional diesel can generally ensure net reductions of fossil energy consumption and GHG emissions. LCA results exhibit strong dependency on methodological choices such as system boundary and allocation method. The study identifies methodological constraints in surveyed studies and concludes with future challenge and recommendations.

1. Introduction

Energy consumption in China has been significantly rising for decades due to rapid economic development. According to data of International Energy Agency, China has become the world's largest energy consumer since 2010. In 2015, the primary energy consumption was 4.3 billion tons of standard coal equivalent (equals to 3.0 billion tons of oil equivalent), 63.7% of which came from coal [1]. Enormous amount of greenhouse gases (GHG) are generated by the extensive utilization of fossil fuels, especially coal. The global warming caused by GHG is believed to be the greatest challenge to human being while China was ranked as the world's largest emitter of GHG [2]. There is, thus, increasing international pressure to take measures to combat global warming. On the other hand, demand for oil imports has also been significantly grown in China. In 2015, China imported 397 million tons of crude oil, which accounted for 72% of China's total petroleum consumption in the year and made China the world's second largest oil importer [1]. China needs to reduce its dependence on imported oil and improve the range of fuels to ensure long-term energy security.

In order to solve the issues of GHG emission and energy security, China has made significant achievements in renewable energy development. Biomass is the only renewable energy source that can be transformed into liquid fuels. Bioethanol and biodiesel are currently the most important liquid fuels which have been used as transportation fuels and considered as a promising solution to the mentioned issues in China and even worldwide. Technical preparation for commercial utilization of liquid biofuels in China was initiated before 2000, mainly with the support of Ministry of Science and Technology. From 2001 to 2005, a series of supporting policies were issued to promote the production of bioethanol and utilization of E10 automobile fuel (fuel blend consisting of 10 vol% ethanol and 90 vol% gasoline). However, the first policy which explicitly promote the development of biodiesel industry was issued by Ministry of Finance in 2006 [3]. The bioethanol industry was primarily established to digest the stale grain reserve stocks. With depletion of stale grain and sharp increase of grain price, an urgent policy announcement required using non-food feedstock for bioethanol production was issued by the National Development and Reform Commission in 2006.

From 2006 to 2012, China has undertaken more ambitious biofuels targets and relevant policies. As stated in The 12th Five-Year Plan for Renewable Energy Development [4], annual use of bioethanol and biodiesel will reach 3.5–4.0 million tons and 1.0 million tons in 2015, respectively. Moreover, in the Medium and Long-Term Development Plan for Renewable Energy [5], annual consumptions of bioethanol and

* Corresponding author.
E-mail addresses: liuhc@ms.giec.ac.cn (H. Liu), xlyin@ms.giec.ac.cn (X. Yin).

https://doi.org/10.1016/j.rser.2018.08.052
Received 15 March 2018; Received in revised form 28 August 2018; Accepted 28 August 2018
1364-0321/

Nomenclature

AP	acidification potential
CD	conventional diesel
CG	conventional gasoline
EP	eutrophication potential
FAETP	freshwater aquatic ecotoxicity potential
GHG	greenhouse gases
HC	hydrocarbon
HTP	human toxicity potential
IPCC	The Intergovernmental Panel on Climate Change
LCA	life cycle assessment
MAETP	marine aquatic ecotoxicity potential
NER	nonrenewable energy requirement
PM	particle matter
POCP	photochemical oxidation potential
SOC	soil organic carbon
TETP	terrestrial ecotoxicity potential
WtW	well-to-wheels
WtT	well-to-tank
VOC	volatile organic compound

biodiesel are planed to reach 10.0 million tons and 2.0 million tons in 2020. Up to 2013, the production capacity of bioethanol and biodiesel would had reached 2.3 and 3.1 million tons, respectively [6]. In 2014, China produced about 2.16 million tons of bioethanol and 1.21 million tons of biodiesel [7] and became the fourth biggest producer of liquid biofuels in the world after the United States, Brazil and Germany [8].

Despite the regulations promoting biofuels and the rapid development of biofuel industry, questions about sustainability of biofuels have been emerging even all over the world [9–12]. Life cycle assessment (LCA) is a method to evaluate the potential environmental impacts and address the sustainability aspects of a product throughout its life cycle [13]. In China, the LCA research and application on biofuels was initiated around 2000 [14,15]. Now, dozens of LCA studies of bioethanol and biodiesel system are already available. These studies may vary significantly in scope, level of detail and final results. However, review papers on LCA of biofuels in China can hardly be found. Yan and Crookes [16] compared energy balance and greenhouse gas emissions for various road transportation fuels in China, including bioethanol, biodiesel and conventional fossil fuels. It is concluded that in terms of life cycle fossil fuel use and GHG emissions, biodiesel derived from rapeseed and soybean are the best choice, followed by bioethanol derived from cassava and sugarcane. Cereal-based ethanol offer moderate fossil fuel use benefits and no GHG emissions benefits at all [16]. In a later review study of Yan and his colleagues [17], direct land use change is considered and significant increase of GHG emissions is found. But the assumption that energy crops are responsible for carbon debt induced by converting forest and grassland into cropland may be questionable, since competition with grains for land and competition with people for grains are not allowed in China. A rather limited number of studies was covered as these two review was accomplished as early as 2009. Many articles have been published afterwards. Moreover, important feedstocks such as lignocellulose and microalgae are not included and there is even no comparison of the performance between first and second generation biofuels. Our review attempts to cover a more comprehensive number of LCA studies of bioethanol and biodiesel system in China.

On the other hand, quite a few reviews of bioenergy LCA studies outside China have been published and a high variability of results is reported [18–20]. Several issues have been found to be responsible, i.e., data quality for key input parameters and LCA methodological choices. Important aspects of the LCA methodology of biofuel system include the definition of system boundary, functional unit, allocation method, treatment of carbon sequestration, selection of impact categories, reference system and indirect effect like land-use change. It is difficult to distinguish the influences of above-mentioned issues from each other, which makes comparison and interpretation of the LCA results complicated. Nevertheless, to the best of our knowledge, no systematic reviews specifically focused on variability of China's biofuel LCA results and corresponding reasons (e.g. impacts of methodological choices) have been performed. Without a deep understanding of the variability and its sources, the biofuel LCA results could be confusing and lead to inappropriate decisions.

Considering the above-mentioned situation, this review has two main objectives. Firstly, to perform an up-to-date quantitative overview of LCA studies and provide comprehensive and objective information about environmental impacts of bioethanol and biodiesel in China. Secondly, to analyze the effect of methodological choices on LCA results and identify key issues to be resolved for a good LCA practice. The uncertainties and methodological constraints in surveyed studies are investigated to identify existing shortcoming and future challenges. The outcome is supposed to help researchers develop a LCA framework for biofuel system that is less prone to biased results, and provide biofuel practitioners, energy policy decision maker and certification authority with a better understanding of the biofuel system.

2. Methodology

Journal articles are searched from ISI Web of Science and the Chinese language database CNKI, with the search terms: life cycle and (bioethanol OR ethanol OR biodiesel). The reference lists of included studies for other relevant research are also taken into consideration. Relevance and eligibility are assessed independently for all of the included studies. Finally, a total of 45 LCA studies are surveyed in this review, including 44 peer-reviewed journal articles and 1 book. The number of studies for bioethanol and biodiesel are 30 and 17, respectively. Two comprehensive studies have assessed bioethanol and biodiesel at the same time [21,22]. These studies cover 13 types of bioethanol feedstock and 11 types of biodiesel feedstock, which are supposed to be comprehensive enough to draw some general conclusions in accordance with the aim of this study. Basic information and key LCA elements of the surveyed studies can be found in Appendix A and B.

The review is initiated by presenting a quantitative analysis of LCA results for bioethanol and biodiesel from various studies. Considering data availability, comparison of LCA studies are made mainly based on nonrenewable energy requirement (NER) and GHG emissions. The difference and comparability of LCA results, namely NER and GHG emissions, derived from well-to-wheels (WtW) and well-to-tank (WtT) approach are analyzed. The contribution of biofuel subsystems and key process is also identified. Then possible reasons for different outcomes for the same feedstock are discussed, including assumptions, methodological choices and key data inputs. The specific life cycle inventory data in China like energy consumption and GHG emissions associated with N fertilizer are investigated in detail. Besides, research challenges and recommendations for future studies are provided.

For the comparison of various studies, the results in terms of NER and GHG emissions are normalized to MJ primary fossil fuel consumption per MJ final fuel product (MJ/MJ) and grams of carbon dioxide equivalent per MJ final fuel product (g CO_2-eq/MJ), respectively. The lower heating value of bioethanol and biodiesel is set to be 27.00 MJ/kg (21.18 MJ/L) and 38.00 MJ/kg (33.42 MJ/L) [16], whenever these data are not specified in original studies. Besides, the global warming potential factors of CO_2, CH_4 and N_2O are set to be 1, 25, and 298 kg CO_2-eq/kg, respectively [23]. Most of the data are found in