Bioresource Technology xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Bioresource Technology

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

Life-cycle analysis of bio-based aviation fuels

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HIGHLIGHTS

- Bio-based jet can reduce WTWa GHG emissions up to 89% to petroleum jet.
- H_2 and NG consumptions in HRJ production is the largest GHG contributor for HRJ.
- HRJ's GHG emissions vary by crops mainly due to fertilizer use and N_2O emissions.
- For bio-based jet, co-product handling methods affect WTWa results significantly.
- Allocation boundaries are also an important factor for WTWa GHG emissions of HRJ.

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Greenhouse gas emissions
Life-cycle analysis
Bio-based aviation fuels
Well-to-wake analysis

ABSTRACT

Well-to-wake (WTWa) analysis of bio-based aviation fuels, including hydroprocessed renewable jet (HRJ) from various oil seeds, Fischer–Tropsch jet (FTJ) from corn-stover and co-feeding of coal and corn-stover, and pyrolysis jet from corn stover, is conducted and compared with petroleum jet. WTWa GHG emission reductions relative to petroleum jet can be 41–63% for HRJ, 68–76% for pyrolysis jet and 89% for FTJ from corn stover. The HRJ production stage dominates WTWa GHG emissions from HRJ pathways. The differences in GHG emissions from HRJ production stage among considered feedstocks are much smaller than those from fertilizer use and N_2O emissions related to feedstock collection stage. Sensitivity analyses on FTJ production from coal and corn-stover are also conducted, showing the importance of biomass share in the feedstock, carbon capture and sequestration options, and overall efficiency. For both HRJ and FTJ, co-product handling methods have significant impacts on WTWa results.

1. Introduction

The aviation industry consumed 11.2% of energy supplied to the U.S. transportation sector in 2012 and accounted for 8.3% of greenhouse gas (GHG) emissions by the U.S. transportation sector in 2011 (U.S. EPA, 2011; U.S. EIA, 2013). Moreover, air traffic worldwide is expected to grow steadily in the near future. In response to growing environmental concerns, the aviation industry is exploring economical, societal, and environmental solutions to reduce fuel consumption and GHG emissions for the sustainable growth of air traffic. While fuel consumption can be reduced by the development and use of more efficient aircraft, shorter routing, and optimized flight management and planning, it is also beneficial to displace petroleum jet fuels with bio-based aviation fuels in order to attain significant reductions in GHG emissions that result from using petroleum fuel. Thus, many organizations—including the U.S. Federal Aviation Administration, the U.S. Air Force, the U.S. Navy, and the European Union—have set targets for using a certain amount or share of biofuels. Promising bio-based aviation fuels for reductions in GHG emissions include (1) Fischer–Tropsch jet (FTJ) and pyrolysis jet fuel from cellulosic biomass and (2) hydroprocessed renewable jet (HRJ) fuel, which is also known as hydroprocessed esters and fatty acids (or HEFA) from oil crops, algae, and waste oil. Estimating the benefits of using bio-based aviation fuels to reduce GHG emissions relative to conventional jet fuels requires a life-cycle analysis (LCA) of these fuels from well-to-wake (WTWa). A WTWa analysis accounts for energy and emissions associated with all stages in the development and use of an aviation fuel, including feedstock recovery and transportation, fuel production and transportation, and fuel consumption during aircraft operation.

LCA has been applied to evaluate the environmental impacts of newly introduced fuel pathways for stationary and ground transportation applications, such as biomethane and biodiesel production from various algae cultivation and processing methods (Resurreccion et al., 2012; Patterson et al., 2013). Similarly, WTWa analyses have been applied to examine various aviation fuel

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http://dx.doi.org/10.1016/j.biortech.2013.07.153

Please cite this article in press as: Han, J., et al. Life-cycle analysis of bio-based aviation fuels. Bioresour. Technol. (2013), http://dx.doi.org/10.1016/j.biortech.2013.07.153

pathways. Bailis and Baka discussed jatropha-derived HRJ fuel development in Brazil and estimated GHG emissions of 40 g CO_2e/MJ resulting from the development and use of HRJ fuel, not including land use change (LUC) impacts (Bailis and Baka, 2010). They estimated direct LUC (dLUC) emissions to be in the range of −27 to 101 g CO_2e/MJ, depending on the soil type. In the U.S. context, Shonnard et al. estimated the GHG emissions from camelina-derived HRJ fuel at 22.4 g CO_2e/MJ, not including LUC (2010). The study by Shonnard et al. relied on an engineering dataset supplied by Universal Oil Products (UOP). On the other hand, Skone and Harrison developed a process engineering model for FTJ fuel production from coal and biomass and estimated GHG emissions in the range of 55.2–98.2 g CO_2e/MJ, depending on the biomass share, catalyst type, carbon management strategy (either carbon capture and sequestration [CCS] or application for enhanced oil recovery), and co-product handling methods (Skone and Harrison, 2011). These studies, however, were conducted with different assumptions and approaches and therefore cannot be directly compared on the same basis. Stratton et al. (2010) compared WTWa GHG emissions associated with the use of various aviation fuels, including FTJ fuel produced from natural gas (NG), coal, and biomass, as well as HRJ fuel produced from several oil crops and algae, with the emissions associated with the development and use of petroleum jet fuel. Further investigations on several parametric assumptions, co-product handling, and LUC were presented in Stratton et al. (2011). Elgowainy et al. (2012) expanded the WTWa analysis effort by adding pyrolysis jet fuel derived from corn stover and adopting recent findings on crude oil recovery and refining, cellulosic biomass farming, FT production from coal and cellulosic biomass, and cultivation and oil extraction from algae and camelina. Agusdinata et al. (2011) conducted WTWa analyses of bio-based jet fuel from non-food crops (e.g., camelina, algae, corn stover, switchgrass, and woody biomass) and projected the reductions in GHG emissions in 2050 by incorporating the economic and political factors.

These previous studies of HRJ fuel pathways used the same assumptions for the production of HRJ fuel without careful examination of the variation in oil characteristics from various feedstock sources. For example, the H_2 requirement for the hydroprocessing of seed oils depends on the specific oil characteristics (e.g., fatty acid profile), catalyst, and process pressure and temperature, all of which impact the results of WTWa analysis of HRJ fuel development and use significantly. On the other hand, the key parameters for the production of FTJ fuel vary widely in several studies, depending on design scheme, which warrants further investigation of those parameters and their impact on WTWa GHG emissions. Moreover, the influence of co-product handling methods and an allocation boundary needs to be carefully evaluated and discussed.

This study aims to systematically address some of these issues by carefully examining the key parameters and using a consistent methodology and system boundary for various jet fuel pathways, including petroleum jet, HRJ, FTJ, and pyrolysis-based jet fuels. In this study, H_2 consumption during the hydroprocessing of seed oils is estimated on the basis of the fatty acid profile of the oil derived from various feedstock sources. Also, a sensitivity analysis of the key parameters of FTJ fuel production is conducted to identify the most important factors impacting GHG emissions. The impacts of co-product handling methods and allocation boundary on WTWa analysis are also evaluated and discussed.

2. Methods

The Greenhouse gasses, Regulated Emissions, and Energy use in Transportation (GREET™) model[4] is employed in this study to examine the WTWa GHG emissions of various biofuels for aviation use and compares them with the GHG emissions of conventional petroleum jet fuel. Developed by Argonne National Laboratory with the support of several programs in DOE's Office of Energy Efficiency and Renewable Energy (EERE), GREET is structured to systematically examine the life-cycle energy use and emissions associated with a wide range of fuel production pathways from various feedstock sources and aircraft technologies. The aviation fuel pathways investigated in this study include conventional jet fuel from crude oil; HRJ fuel from soybean, palm, rapeseed, jatropha and camelina; FTJ fuel from cellulosic biomass and coal; and pyrolysis jet fuel from cellulosic biomass. Corn stover is selected as a cellulosic biomass feedstock in this study. Fig. 1 presents the system boundary and major stages in these pathways. A WTWa pathway consists of a well-to-pump (WTP) stage—covering (1) feedstock recovery and transportation and (2) fuel production and transportation—followed by a pump-to-wake (PTWa) stage—representing the fuel combustion during aircraft operation. Key parameters for feedstock and fuel production in the pathways are illustrated in Fig. 1, and the co-product handling methods are discussed in this section.

The choice of functional units affects the LCA results significantly. Since this study focuses on fuel production stages, an energy functional unit (e.g., MJ of fuel produced) is selected such that the differences in aircraft operation and efficiency do not influence the WTWa results. The energy use and emissions due to fuel combustion in aircraft operation are examined in detail by Elgowainy et al. (2012) for various passenger and cargo aircraft classes and types by using a service functional unit, such as kilometers traveled carrying a specific payload. This service functional unit contrasts with the service functional unit for ground transportation fuels, which is typically kilometers traveled by a vehicle (Resurreccion et al., 2012; Patterson et al., 2013). Another functional unit commonly used to assess biomass resources for different production volumes of biofuels is the "unit of biomass input," which can show the potential of conventional fuel displacement and GHG savings by limited resources (Han et al. 2013).

2.1. Petroleum jet fuel pathways

GREET evaluates two sources of crude oil: conventional crude oil and synthetic crude from Canadian oil sands. The GHG intensities of these crude types are quite different as a result of the differences in recovery techniques and the amount of methane vented and flared in recovery. The efficiency of conventional crude recovery is estimated at 98%, while the majority of GHG emissions in this stage results from flaring and venting of associated gas. The amount of flared associated gas is estimated at an average rate of 21.2 standard m^3/m^3 of crude on the basis of data on flaring emissions collected by the Global Gas Flaring Reduction Partnership (GGFR) and the amount of U.S. crude oil imported/produced by the country of origin (Burnham et al., 2011). The amount of vented associated gas is estimated at 4.2 standard m^3/m^3 of crude by assuming an average venting-to-flaring ratio of 0.2. With the associated gas composition (82.3% CH_4) and average CH_4 destruction efficiency of 98%, the CH_4 and CO_2 emissions from associated gas flaring and venting are estimated at 0.076 g CH_4 and 1.36 g CO_2e/MJ crude, respectively.

For Canadian oil sands recovery, both surface mining and *in situ* production are considered. The share of surface mining is estimated to be 50% in 2010 (Elgowainy et al., 2012). Oil sand recovery consists of the extraction and treatment (upgrading) of bitumen in oil sand fields. The extraction efficiencies of surface mining and *in situ* production are estimated to be 94.8% and 84.3%, respectively (Elgowainy et al., 2012). Also, the upgrading efficiencies of bitumen from surface mining and *in situ* production are estimated to be 91% and 95.6%, respectively (Elgowainy et al., 2012). A large amount of

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[4] http://www.greet.es.anl.gov/main.

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