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Life cycle water footprint of hydrogenation-derived renewable diesel production from lignocellulosic biomass

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A B S T R A C T

The conversion of lignocellulosic biomass to biofuel requires water. This study is focused on the production of hydrogenation-derived renewable diesel (HDRD) from lignocellulosic biomass. Although there has been considerable focus on the assessment of greenhouse gas (GHG) emissions, there is limited work on the assessment of the life cycle water footprint of HDRD production. This paper presents a life cycle water consumption study on lignocellulosic biomass to HDRD via pyrolysis and hydrothermal liquefaction (HTL) processes. The results of this study show that whole tree (i.e., tree chips) biomass has water requirements of 497.79 L/MJ HDRD and 376.16 L/MJ HDRD for production through fast pyrolysis and the HTL process, respectively. Forest residues (i.e., chips from branches and tops generated during logging operations) have water requirements of 338.58 L/MJ HDRD and 255.85 L/MJ HDRD for production through fast pyrolysis and the HTL process, respectively. Agricultural residues (i.e., straw from wheat, oats, and barley), which are more water efficient, have water requirements of 83.7 L/MJ HDRD and 59.1 L/MJ HDRD through fast pyrolysis and the HTL process, respectively. Differences in water use between feedstocks and conversion processes indicate that the choices of biomass feedstock and conversion pathway water efficiency are crucial factors affecting water use efficiency of HDRD production.

1. Introduction

Water is critical for humans. Water is consumed primarily through farming, industrial, and domestic uses (Rosegrant et al., 2002). Canada's semi-arid prairies have limited water availability, a consideration for crop growth, and depend on irrigation to compensate for the lack of water from precipitation (Pereira et al., 2002; Krobel et al., 2014). Water sustains growth in dry boreal forest areas and could change the landscape from forest to grassland if availability drops low enough (Hogg, 1994). The speed of plant growth and water demand varies with plant species. These differences can affect the amount of dry mass produced per unit of water used and water use efficiency for biomass production (Kirkpatrick et al., 2006; Hsiao and Acevedo, 1974). In addition to water consumption during plant growth, water is consumed in chemical processes that convert biomass to usable energy sources (Dominguez-Faus et al., 2009). Therefore investigating water requirements for different lignocellulosic biomass and various chemical processes to convert biomass to energy sources is crucial in a water footprint study of biomass as an energy source.

The production of biofuels not only depends on biomass but also the type of biofuels produced. There are different types of biofuels available through current technology that can replace fossil-based diesel. Among these biofuels are biodiesel and hydrogenation-derived renewable diesel (HDRD). The difference in biodiesel and HDRD is in their chemical composition and structure (Natural Resources Canada, 2012). Biodiesel contains straight-chain fatty acid alkyl esters produced from the transesterification process and HDRD contains alkanes, aromatic compounds, and alkyl side chains produced from hydroprocessing (Knothe, 2010). The differences in chemical composition and structure between biodiesel and HDRD result in different physical properties, for example in cetane number and cloud point (Natural Resources Canada, 2012; Knothe, 2010). A higher cetane number and ability to alter the isomerization process for better cold flow properties make HDRD a better biofuel for use in colder climates than biodiesel (Natural Resources Canada, 2012). The focus of this study is on HDRD because HDRD's

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physical properties are suitable for both cold and warm climates, and so this study's results will apply to both cold and warm climatic regions. To date, there has been limited research done on the assessment of water footprints for the conversion of biomass feedstocks to HDRD.

The production of energy and fuels from biomass sources requires water both during the growth of the biomass and during its conversion to fuels. Because water is an important resource, water requirements are one of the factors to consider for the long-term sustainable production of HDRD. The growing emphasis on renewable fuels emphasizes the need for a better understanding of the water requirements of hydrogenation-derived renewable diesel from renewable sources. To date there have been several studies on the water footprint of biofuel production in general (Yang et al., 2011; Dominguez-Faus et al., 2009; King and Webber, 2009). Singh et al. (2015) assessed the impact of producing biofuel in Alberta and concluded that southern Alberta does not have enough water to meet the high irrigation water requirements due to its dry climate. Singh et al.'s (2015) study highlighted that 860–1530 billion liters of water are required to produce 4 billion liters of biofuel to partially meet the projected demand of biofuel in Canada in the year 2025. Yang et al. (2011) examined the life cycle water footprint of biodiesel production from microalgae and found that 3726 kg of water are required to produce 1 kg of biodiesel if water is not recycled during biodiesel production. Dominguez-Faus et al. (2009) looked into the water requirement for energy crops to produce ethanol and compared the water footprint with that of existing power sources. Their results showed that when corn is irrigated for ethanol production, 2.2–8.6 million liters of water are used, while biodiesel from soybean crops requires 13.9–27.8 million liters for one MWh of energy produced. The study also revealed that the water requirement fluctuates depending on the type of biofuel produced and the geographical location at which the biomass is grown; a higher precipitation area will reduce the water required from irrigation (Dominguez-Faus et al., 2009). Singh and Kumar (2011) developed water requirement factors for twelve biomass conversion pathways to ethanol and electricity. The water requirement factors of ethanol production pathways of corn and wheat biomass range from 38.7 to 55.5 L H_2O/MJ of ethanol while the water requirement factors of electricity production from corn stover and wheat straw range from 72.0 to 129.4 L H_2O/kWh of electricity (Singh and Kumar, 2011). Differences in conversion pathways and water required for biomass production due to geographical location resulted in a water requirement disparity between the values for the production of a unit of electricity calculated by Singh and Kumar and those of Dominguez-Faus et al. King and Webber (2009) concluded that biofuels derived from soy and corn require more water than fuels derived from fossil fuels, and soy requires less water than corn. King and Webber (2009) also showed that irrigation plays a large part in water requirement; biomass feedstock that requires irrigation uses 47–141 L H_2O/km (distance travelled by light duty vehicle using the biofuel produced), a water consumption of 3 orders of magnitude higher than similar feedstock that does not require irrigation (0.12–0.94 L H_2O/km). Singh et al. (2011) studied the water requirement to produce biofuel from six different biomass feedstocks. In their study, corn and wheat require 178 L H_2O/MJ of ethanol and 325 L H_2O/MJ of ethanol, respectively. With little research done on the water requirements of HDRD production, especially in colder climatic regions such as Canada, this study intends to fill the gap in knowledge on the life cycle water requirements for converting the lignocellulosic biomass readily available in western Canada to HDRD.

The overall objective of this study is to assess the life cycle water footprint of HDRD production from biomass feedstocks. The specific objectives include:

- The development of a framework to assess the water footprint for all stages of HDRD production from lignocellulosic biomass for two conversion pathways. These two pathways are:
  - Pathway 1: Conversion of lignocellulosic biomass to bio-oil through fast pyrolysis and further conversion of bio-oil to HDRD.
  - Pathway 2: Conversion of lignocellulosic biomass to bio-crude through hydrothermal liquefaction (HTL) and further conversion of bio-crude to HDRD.
- The study of the effects of the input parameters on the life cycle water footprint of HDRD production from lignocellulosic biomass through sensitivity and uncertainty analyses.

The life cycle water footprint assessment methodology is explained in Section 2. Section 3 presents the water requirement inventory for each operation in the product life cycle and Section 4 develops several scenarios to examine the sensitivity of the selected model factors. Section 5 concludes the paper with the key findings and addresses future research on this topic.

2. Methodology

Water requirement considerations for the production of HDRD from lignocellulosic biomass encompass the life cycle of lignocellulosic biomass from well to wheel. ISO 14040 suggests a life cycle assessment framework with the following steps: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation (International Organization for Standardization, 2006). The goal and scope section defines the system boundary adopted for the study and discusses how the results can benefit the intended industry and government. The life cycle inventory is a compilation of the inputs required for computation and analysis and states the assumptions for input values. The computation and analysis allow the environmental impact to be assessed and interpreted for meaningful knowledge to be obtained from the study. This study uses an energy functional unit of 1 MJ of HDRD as the basis of analysis; accordingly, the inputs are converted to L H_2O/MJ HDRD to compile water use results. The functional unit used will measure the amount of water required to produce 1 MJ of HDRD on a well-to-wheel basis. Scenarios were developed to examine how some important factors can affect the overall results. An uncertainty analysis using a Monte Carlo simulation is also included to find out how the distribution of the results is affected by the uncertainty of inputs.

The process of lignocellulosic biomass production and conversion to HDRD by fast pyrolysis or HTL and the subsequent hydroprocessing has several unit operations. The unit operations for the conversion pathway via fast pyrolysis include: (1) production and harvesting of whole tree, forest residues, and agricultural residues, (2) transportation of whole tree and forest residues in the form of chips and agricultural residues in the form of bales to a fast pyrolysis plant, including road construction, (3) bio-oil production via fast pyrolysis, (4) transportation of bio-oil to a hydroprocessing plant, (5) bio-oil conversion to HDRD, and (6) transportation of HDRD to a refinery for blending with fossil fuel-derived diesel and to the consumer. The conversion pathway is illustrated in the system boundary diagram in Fig. 1 with inputs and outputs indicated. For the conversion of lignocellulosic biomass to HDRD via HTL, the unit operations include: (1) production and harvesting of whole trees, forest residues, and agricultural residues, (2) transportation