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Well-to-wheel life cycle assessment of transportation fuels derived from different North American conventional crudes

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HIGHLIGHTS

- Development of data-intensive bottom-up life cycle assessment model.
- Quantification of well-to-wheel GHG emissions for five North American crudes.
- Allocation of emissions to transportation fuels (gasoline, diesel, and jet fuel).
- California's Kern County heavy oil is the most GHG intensive of the crudes.

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ABSTRACT

A life cycle assessment (LCA) is an extremely useful tool to assess the greenhouse gas (GHG) emissions associated with all the stages of a crude oil's life from well-to-wheel (WTW). All of the WTW life cycle stages of crude oil consume energy and produce significant amounts of GHG emissions. The present study attempts to quantify the WTW life cycle GHG emissions for transportation fuels derived from five North American conventional crudes through the development of an LCA model called FUNNEL-GHG-CCO (**FUN**damental E**n**gineering Princip**l**E**s**-based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in **C**onventional **C**rude **O**ils). This model estimates GHG emissions from all the life cycle stages from recovery of crude to the combustion of transportation fuels in vehicle engines. The contribution of recovery emissions in the total WTW GHG emissions ranges from 3.12% for Mars crude to 24.25% for California's Kern County heavy oil. The transportation of crude oil and refined fuel contributes only 0.44–1.73% of the total WTW life cycle GHG emissions, depending on the transportation methods and total distance transported. The GHG emissions for refining were calculated from the amount of energy use in the refining of crude oil to produce transportation fuels. All the upstream GHG emissions were allocated to gasoline, diesel, and jet fuel. Refining GHG emissions vary from 13.66–18.70 g-CO_2eq/MJ-gasoline, 9.71–15.33 g-CO_2eq/MJ-diesel, and 6.38–9.92 g-CO_2eq/MJ-jet fuel derived from Alaska North Slope and California's Kern County heavy oil, respectively. The total WTW life cycle GHG emissions range from 97.55 g-CO_2eq/MJ-gasoline derived from Mars crude to 127.74 g-CO_2eq/MJ-gasoline derived from California's Kern County heavy oil.

1. Introduction

California's Low Carbon Fuel Standard [1] and the European Union's Fuel Quality Directive [2] require a reduction of carbon intensity in transportation fuels. These regulations have led to increased attention in quantifying the total life cycle greenhouse gas (GHG) emissions for different conventional crudes. In 2012 in the U.S., the petroleum and natural gas systems sector and the petroleum refinery sector were the second and third highest GHG emitting sectors respectively after the power plant sector [3]. During the same year, the share of conventional crude oil in the total oil production was about 70% [4], which made conventional crude oil the major contributor of GHGs in the petroleum and refining sectors compared to unconventional fossil fuel resources. GHGs are emitted in all life cycle stages of crude oil from recovery to the combustion of transportation fuels in engines. Each crude has different properties, extraction methods, and GHG emissions. It is important to perform a complete life cycle assessment of conventional crude oils from a variety of sources to help in policy making towards sustainability and fulfilling environmental regulations.

There have been a few LCAs analyzing conventional crude oils [5–8]. The Jacobs [5] and TIAX [6] studies did a thorough

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assessment of different North American and imported crudes. These studies reported WTW life cycle GHG emissions for gasoline and diesel derived from specific crude oils. Some crudes were analyzed by both the Jacobs [5] and TIAX [6] studies, but there were variations in the total WTW GHG emissions due to different assumptions, system boundaries, methodologies, and data sources. The TIAX [6] study did not consider GHG emissions from the processing of crude oil, associated gas and water, and oil field fugitives. Refining emissions contribute largely to the WTW GHG emissions, and the Jacobs and TIAX studies have different methodologies to calculate them. None of these studies considered GHG emissions from oil well drilling and associated land-use change. The National Energy Technology Laboratory (NETL) studies [7,8] analyzed American and imported crudes and reported life cycle GHG emissions for gasoline, diesel, and jet fuel. GHG emissions reported by NETL are country-specific and not broken down into specific crudes. The baseline model developed by NETL has limited information about the inputs used in its model. This study is aimed at addressing the gaps in the literature.

There are two prominent North American LCA models to quantify WTW GHG emissions for transportation fuels derived from crude oil. These models are: (i) GREET, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model [9] and (ii) GHGenius, the model developed by $(S\&T)^2$ Consultants [10]. These models consider different stages in the life cycle of crude oil and quantify total life cycle GHG emissions. Another North American LCA tool called OPGEE, the Oil Production Greenhouse gas Emissions Estimator [11], calculates GHG emissions from extraction, processing, and transportation of crude. OPGEE does not calculate total life cycle GHG emissions [11]. All these models are built with their own assumptions, methods, data sources, and system boundaries. To calculate the life cycle GHG emissions for an individual crude oil, one must change the input parameters because these models use default values that might not be appropriate for all crudes.

Garg et al. [12] conducted an LCA for domestic and imported crudes in India and reported GHG emissions for diesel, petrol, kerosene, and LPG (Liquefied Petroleum Gas). The boundary of the LCA extends from the well to the point of storage of refined products. The authors found that 60–66% of the GHG emissions of the total LCA (without combustion) come from the exploration and production of crude oil. Yan et al. [13] reviewed different LCA studies and reported WTW GHG emissions for transportation fuels in China. This study considered the LCA boundary from crude recovery to fuel consumption in vehicle engines. The authors reported the same life cycle GHG emissions (89 g-CO_2eq/MJ) for conventional gasoline and conventional diesel. Furuholt [14] performed an LCA of gasoline and diesel. He found that diesel had lower GHGs than gasoline because less energy is consumed in the production of diesel in the refinery.

There are some academic LCA studies that evaluate GHG emissions from oil sands products that are different from conventional crudes by their properties. Tarnoczi [15] developed an LCA model to calculate energy use and resulting GHG emissions from the transportation of Canadian oil sands products to different markets. The author worked on sixteen projects for pipeline, rail, and the combination of pipeline and rail transportation. Pipeline length and diameter and grid intensity are the reasons for variation in GHG emissions for pipeline. The combustion of diesel is the main reason for variation in GHG emissions from rail transportation, as mentioned by the author. Thirteen LCA studies were reviewed by Charpentier et al. [16] to compare GHG intensities of oil sands-derived fuels and conventional crude oil-derived fuels. The authors found lower GHG emissions for conventional crude oil-derived fuels. The production of conventional crude requires less energy than synthetic crude oil (SCO), which is upgraded from bitumen. Bergerson et al. [17] quantified life cycle GHG emissions from the extraction of bitumen using the GHOST (GreenHouse gas emissions of current Oil Sands Technologies) model developed by Charpentier et al. [18]. The authors found overlaps between the well-to-wheel GHG emissions for conventional crude oil and oil sands products. Abella et al. [19] developed a model, PRELIM, to calculate energy consumption and resulting GHG emissions from the refining of crude slates. The authors investigated the effect of refinery configuration and crude quality on GHG emissions but did not conduct the whole LCA of different crudes. PRELIM does not calculate total GHG emissions from well-to-wheel. Brandt [20] reviewed different oil sands LCA studies and found inconsistencies in the results. He looked into all the unit operations required to transform oil sands products to finished products. Differences in methodologies, data quality, and LCA boundaries were found to be the reasons for variations in the results obtained by different LCA studies. Recent studies by Nimana et al. [21,22] quantified GHG emissions in the recovery, and upgrading and refining of Canada's oil sands products but did not consider conventional crudes. In another article [23], the authors developed a model to estimate life cycle WTW GHG emissions from oil sands products but the model does not quantify GHG emissions from conventional crudes. Earlier studies [16–28] mainly worked on different oil sands products such as synthetic crude oil (SCO), dilbit, and bitumen, which differ from conventional crude oils in their properties and extraction methods. For the sake of comparison of GHG emissions for conventional crude oil and oil sands products (SCO, bitumen), it is necessary to conduct a comprehensive and independent LCA study on conventional crude oils.

There are a limited number of studies [5–8] that conduct LCAs of conventional crude oils from various sources around the globe. Most of the models developed earlier looks at a particular unit operation of the whole life cycle and hence there is a need to look at the whole chain. Some of the studies done earlier integrated different models to get the whole life cycle emissions but there is very limited work on a single dedicated model for a particular crude is missing. This paper develops a data-intensive bottom-up engineering LCA model called FUNNEL-GHG-CCO (**FUN**damental E**n**gineering Principl**E**s- based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in **C**onventional **C**rude **O**ils) based on fundamental scientific principlest o quantify the GHG emissions of the life cycle stages of different conventional crudes, in order to fill in the gaps in current literature. Five conventional crudes – Alaska North Slope, California's Kern County heavy oil and Mars crude (U.S.), Maya crude of Mexico, and Bow River heavy oil of Canada – were studied to calculate GHG emissions from the life cycle stages: crude recovery, transportation of crude to the refinery, the refining of crude, the transportation and distribution of finished fuels to the refueling stations, and the combustion of transportation fuels in vehicle engines. Previously, Rahman et al. [29] quantified the GHG emissions from the recovery of the same crudes considered in this study. The authors included GHG emissions from oil well drilling and associated land-use change, extraction, processing of crude, and venting, flaring, and fugitives in the total recovery emissions. The percentage contribution of recovery emissions is small in the total WTW life cycle GHG emissions. To capture the entire picture, which will help in decision making towards sustainability, it is important to calculate the total life cycle GHG emissions for transportation fuels derived from different conventional crudes.

2. Method

2.1. Goal and scope

The purpose of this study was to quantify the total WTW life cycle GHG emissions for transportation fuels converted