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Evaluation of uncertainty in the well-to-tank and combustion greenhouse gas emissions of various transportation fuels

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HIGHLIGHTS

- A Monte Carlo simulation is used to quantify uncertainty in the WTT + C emissions.
- Gasoline WTT + C emissions ranged from 95.3 to 138.5 gCO_2 eq/MJ.
- Saudi Arabia crude had the lowest emissions at 95.3–99.9 gCO_2 eq/MJ.
- Venezuela crude had the highest emissions at 113.6–138.5 gCO_2 eq/MJ.
- The largest source of uncertainty is the venting, fugitive, and flaring gas volumes.

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ABSTRACT

Growing concern over climate change has created pressure on the oil and gas industry to reduce their greenhouse gas emissions (GHG). There have been multiple well-to-tank + combustion (WTT + C) studies that have examined various crude oils in an attempt to determine their GHG emission intensities. The majority of these studies published deterministic point estimates with a limited sensitivity analysis. Due to the variation in results between studies and the lack of uncertainty analysis the usefulness of these studies to policy makers and industry representatives is limited. The goal of this study is to expand on the previous literature by identifying a range of WTT + C emissions for crude oils from Saudi Arabia, Venezuela, and Iran. First, the previously published **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 (FUNNEL-GHG-CCO) was used to perform a WTT + C analysis of the crudes GHG emissions. Then a Monte Carlo simulation was carried out using existing literature to define input distributions for the key inputs. The resulting gasoline WTT + C GHG emission ranges are 113.6–138.5 (Venezuela High Steam), 101.6–109.9 (Venezuela Low Steam), 101.1–109.2 (Sirri, Iran), and 95.3–99.9 gCO_2eq/MJ (Saudi Arabia). This result indicates that even when uncertainty is taken into account the Venezuelan high steam crude clearly has higher emissions than the Saudi Arabia crude. The results of this study will give policy makers and industry representatives a better understanding of how the WTT + C GHG emissions vary between various crude oils.

1. Introduction

Growing awareness of climate change and global pushes for carbon taxes have led to increased interest in reducing global greenhouse gas (GHG) emissions [1]. Because transportation emissions are responsible for 23% of the global CO_2 emissions, governments have set strategic carbon emission reduction targets. For example, the European Union and California Air Resource Board

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Abbreviations: °API, American Petroleum Institute gravity; ANS, Alaska North Slope; CSS, cyclic steam simulation; EF, emission factor (gCO_2/MJ); F-1, original FUNNEL-GHG-CCO model; F-2, modified FUNNEL-GHG-CCO model published by Di Lullo et al.; F-3, modified FUNNEL-GHG-CCO model created for this study; FUNNEL-GHG-CCO, **FUN**damental **EN**gineering Principl**E**s-based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in **C**onventional **C**rude **O**ils; GHG, greenhouse gas; GOR, gas to oil ratio (m^3/m^3); GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation; GWP, global warming potential; HS, high steam; KYO, know you oil; LCA, life cycle assessment; LHV, lower heating value (MJ/kg); LS, low steam; MD, marine diesel; NG, natural gas; OPGEE, oil production greenhouse gas emissions estimator; OTSG, once through steam generator; P#, #th percentile; P5, 5th percentile; P95, 95th percentile; PG, produced gas; PRELIM, petroleum refinery life cycle inventory model; SF, steam flood; SOR, steam to oil ratio (cold water equivalent m^3/m^3); SP, surface processing; TTW, tank-to-wheel (combustion); ULCC, ultra-large crude carrier; VFF, venting, flaring and fugitive; VLCC, very large crude carrier; WAG, water-alternatin-gas; WF, water Flood; WOR, water-to-oil ratio (m^3/m^3); WTR, well-to-refinery gate; WTT, well-to-tank; WTT+C, well-to-tank + combustion.

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have implemented polices to reduce the carbon intensity of transportation fuels by 6% and 10%, respectively, before 2020 [2,3]. One solution to meet these targets is to consume transportation fuels (gasoline, diesel and jet) with lower upstream emissions.

The upstream emissions from transportation fuels are generated during crude oil extraction, surface processing, transportation, refining, and distribution. Life cycle assessments (LCAs) have been used to quantify emission intensity (emissions produced per unit of product produced) by examining the energy used and emissions generated along the life cycle stages from extraction of natural resources to the end of the product life [4]. The upstream emissions from different crudes will vary depending on the crude properties and the methods used to extract and process the crudes into finished transportation fuels.

A well-to-tank + combustion (WTT + C) analysis is a specific type of LCA which focuses on the transportation fuel only and ignores the emissions associated with vehicle production, maintenance and disposal. As the emissions released from one megajoule of fuel will not vary from vehicle to vehicle a WTT + C analysis of multiple crudes can be used to compare the crude GHG emission intensities. A full LCA including the vehicle would be more appropriate for comparing internal combustion engine emission intensities to hydrogen fuel cell and battery electric vehicles using a regional average gasoline emission intensity. This study is focused on comparing specific transportation fuel production pathways not regional averages.

Current literature examines WTT + C emissions of transportation fuels, which includes the upstream to combustion emissions, through models. These models can be divided into two types. Type 1 models, such as Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) [5], GHGenius [6], and Orsi et al. [7] use a top-down approach in which high level aggregated facility- and country -level data are used to calculate industry average emissions. However, the use of aggregated data makes it difficult to determine emission intensity for specific crudes. Type 2 models, such as Jacobs [8,9], TIAX [10], Oil Production Greenhouse gas Emissions Estimator (OPGEE) [11], Petroleum Refinery Life Cycle Inventory Model (PRELIM) [12], and **FUN**damental **EN**gineering Princip**lE**s-based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in **C**onventional **C**rude **O**ils (FUNNEL-GHG-CCO) [13–16], use a bottom-up approach wherein energy consumed and emissions generated are calculated using engineering first principles for each stage. Due to the lack of information and process complexity, the bottom-up models only examine processes that consume or produce large amounts of energy or pollution, and so they do not capture all the emissions produced and may lead to modeling results with limited accuracy. However, a bottom-up model can calculate the emissions for specific crudes and provide detailed results for each sub-process.

Various bottom-up models have determined the WTT + C emissions for over 35 crudes; however, the results are difficult to compare due to differences in the boundaries and assumptions used. Additionally, the TIAX and Jacobs models lack transparency and reproducibility as they were conducted by consulting companies and used confidential data [8–10]. Gordon et al.'s report "Know Your Oil" (KYO) used the PRELIM and OPGEE models to develop WTT + C estimates for thirty crude oils using consistent boundaries [17]. However, all these models provide deterministic point estimates for the WTT + C emissions. Without an uncertainty analysis, it is not possible to accurately compare crudes based on their WTT + C emissions. If model uncertainty is high compared to the difference in the emissions between two crudes, it would not be accurate to claim that one crude has lower emissions than the other. Di Lullo et al. examined the uncertainties in five North American crudes using a updated version of the FUNNEL-GHG-CCO model and found that the uncertainties in the WTT + C emissions ranged from ±2.6 to ±10.4% [16]. Although the uncertainty ranges could be large it was still possible to differentiate between the highest and lowest emitting crudes [16]. This work also looks to examine specific crude production pathways rather than regional averages. While regional averages are beneficial for high level policy decisions and examination of specific pathways allows a more detailed comparison of various technologies. Future work will compare these results to oil sand pathways as well as alternative technology pathways.

There are three main gaps in the previously published work. First, the Jacobs [8,9] and TIAX [10]models lack transparency, and reproducibility. Second, the published literature only examines uncertainty in 5 out of the 35 crudes studied. Both gaps are important to policy makers and industry representatives because quantifying the uncertainty in WTT + C emissions will provide a more accurate representation of the industry.

The general objective of this study is to determine the WTT + C emission uncertainties for Saudi Arabia, Iran, and Venezuela oils. The specific objectives are to:

1. Conduct a transparent and reproducible WTT + C analysis of crude oils from Saudi Arabia, Iran, and Venezuela previously examined by Jacobs and TIAX with the FUNNEL-GHG-CCO model.
2. Determine the WTT + C emission uncertainty by performing a Monte Carlo simulation using a range of values from multiple data sources.

The remaining 27 crudes are not examined as it is difficult to find sufficient data due to the depth of the analysis. To limit the scope to a reasonable size and align with previous literature only U.S. refineries are examined. The Saudi Arabia and Venezuela crudes were chosen as they represent 17% and 11% the crude imported to the USA from 2011 to 2015 [18], a significant portion of the USA's imports. While the USA does not currently import any Iranian oil, this oil was included due to the potential for imports as a result of the lifting of the Iranian trade embargo in 2016 [18,19].

The uncertainty ranges determined from this study will provide a fair representation of the industry and a GHG emission comparison among the three crude oils. The results will help policy makers understand the limitations of WTT + C models and will help identify data gaps from industry in order to improve the accuracy of the WTT + C GHG emission estimates.

2. Methodology

This study was conducted in two stages. In the first stage we performed a WTT + C analysis for crude oils from Saudi Arabia, Iran, and Venezuela. Data were collected and fed into a modified version of the FUNNEL-GHG-CCO model to complete the WTT + C analysis. The scope of this WTT + C model comprises of site preparation, extraction, surface processing, crude transportation, refining, distribution, and combustion stages. The study's second stage was an uncertainty analysis on the WTT + C emissions. First, a sensitivity analysis was used to identify sensitive inputs that would have a significant effect on the results. Uncertainty distributions were then determined for the sensitive inputs and were used in a Monte Carlo simulation to determine the uncertainty. The Monte Carlo simulations are run using ModelRisk which is a Microsoft Excel add-in [20].

2.1. Base case model

The original FUNNEL-GHG-CCO model was created by Rahman et al. in 2014 and uses engineering first principles to perform a