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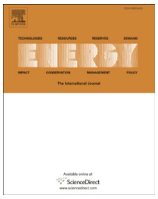

Uncertainty in well-to-tank with combustion greenhouse gas emissions of transportation fuels derived from North American crudes

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ABSTRACT

Many studies have calculated deterministic point estimates of well-to-combustion (WTC) emissions of transportation fuels from crude oil in an attempt to determine which crude oils have lower or higher emissions. However, there is considerable variation in the published results, resulting in uncertainty. The purpose of this study is to identify GHG emissions ranges for five conventional and two unconventional crudes by performing an uncertainty analysis using an improved version of the **FUN**damental E**N**gineering Princip**lE**s-based Mode**L** for Estimation of **G**reen**H**ouse **G**ases (FUNNEL-GHG). Distributions for key inputs in the Monte Carlo simulation were determined based on values obtained from the literature. Eleven scenarios were developed, nine historical and two current, the former using life-long average production data from the oil fields studied and the latter using recent production data to illustrate how WTC emissions change as the fields age. The mean WTC emissions ranges for the eleven scenarios are 97.5–140 gCO_2eq/MJ. The uncertainty in the WTC emissions ranges from ±3% to ±11%. The largest source of uncertainty in the WTC emissions is from the venting, fugitive, and flaring volumes, fluid injection rates, and refinery yields.

1. Introduction

As climate change becomes a growing concern around the world, there is increased focus on the environmental impact of transportation fuel production. In 2014, the United States' greenhouse gas emissions (GHG) emissions for the petroleum and natural gas sector were 236 million tonnes CO_2eq with an additional 175 million tonnes CO_2eq from refineries [1,2]. Growing concern over climate change has led to environmental policies such as the California Low Carbon Fuel Standard, which requires a 10% reduction in California's transportation fuels' 2007 carbon intensity by 2020 [3], and the European Union Fuel Quality Directive, which requires a 6% reduction in transportation fuels' 2010 carbon intensity by 2020. One way to meet these reductions is to reduce the emissions generated during crude production and refining.

The well-to-combustion (WTC) emissions from different crudes vary widely depending on the production method used, the crude's properties, refining methods, regional regulations, and industry practices [4]. Additionally, as a crude reservoir ages, its pressure drops, and production decreases [5,6]. Enhanced oil recovery methods, such as water flooding, gas injection, artificial pump lift, gas lift and steam flooding, are implemented to improve production rates [6,7]. However, these methods increase the amount of energy required and emissions generated.

Well-to-wheel assessments, which are performed to compare gasoline vehicles to alternative drivetrain vehicles such as battery electric and hydrogen fuel cell, present their results in terms of gCO_2eq/km. However, well-to-wheel assessments that aim to

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Abbreviations: API, American Petroleum Institute gravity; API, American Petroleum Institute; FUNNEL-GHG-CCO, FUNdamental ENgineering PrinciplEs-based ModeL for Estimation of GreenHouse Gases in Conventional Crude Oils; FUNNEL-GHG-OS, FUNdamental ENgineering PrinciplEs-based ModeL for Estimation of GreenHouse Gases in Oil Sands; 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; LHV, Lower heating value (MJ/kg); OPGEE, Oil Production Greenhouse gas Emissions Estimator; P5, 5th percentile; P95, 95th percentile; PRELIM, Petroleum Refinery Life Cycle Inventory Model; SAGD, Steam assisted gravity drainage; SCO, Synthetic crude oil; SOR, Steam-to-oil ratio (cold water equivalent m^3/m^3); VFF, Venting, flaring and fugitive; WOR, Water-to-oil ratio (m^3/m^3); WTR, Well-to-refinery gate; WTT, Well-to-tank; WTC, Well-to-wheel + combustion.

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compare the emissions from different crudes present their emissions in gCO_2eq/MJ. Here "MJ" refers to the lower heating value of the fuel that is released in the combustion chamber. The conversion from the fuel's lower heating value to km will depend on the efficiencies of the various components between the combustion chamber and the wheel, and the driving cycle, which will be the same for all crudes. Therefore, ignoring the vehicle's overall fuel efficiency removes unnecessary uncertainty. Technically excluding the vehicle efficiency would make these studies a well-to-combustion assessment.

Current transportation fuel WTC assessments consist of either a high-level top-down analysis to determine industry average emissions or a bottom-up analysis to determine pathway-specific emissions. Top-down models such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) and GHGenius use aggregated data, which makes it difficult to compare crudes and identify areas for improvement [8,9]. Bottom-up models such as the Jacobs, TIAX, Oil Production Greenhouse gas Emissions Estimator (OPGEE), Petroleum Refinery Life Cycle Inventory Model (PRELIM), **FUN**damental **EN**gineering Principl**E**s-based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in the **O**il **S**ands (FUNNEL-GHG-OS), and **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 (FUNNEL-GHG-CCO) use engineering first principles to calculate the amount of energy required and emissions produced at each stage [10–16]. Bottom-up models have uncertainties as they focus only on the large pieces of equipment and do not capture every source of emissions; however, the models provide details on the emissions from specific sub-processes.

The previous transportation fuel WTC assessments produce deterministic point estimates (versus Monte Carlo, which uses distributions to determine inputs), which vary significantly among models. The variations are due to inconsistent boundaries, assumptions among the models, and differences in the model inputs. The Carnegie Endowment for International Peace published a report titled "Know Your Oil" on the WTC emissions from thirty different crudes with consistent system boundaries using the OPGEE and PRELIM models [4]; however, the report does not include an uncertainty analysis, without which the confidence of the models is not determined. In order to compare crudes and determine which crudes have high and low emissions, a quantified uncertainty range is required. If the uncertainty in the emissions were larger than the difference in emissions between two crudes, it would not be possible to confidently state which crude has lower emissions.

Quantifying the effect each input uncertainty has on the total uncertainty will provide insight into how the model's accuracy can be improved. Furthermore, the assumptions made in WTC assessments are frequently questioned. Interested parties will ask how the results will change if certain parameters are varied and use the lack of information as justification to invalidate the work. By using ranges for the inputs we can show that with reasonable certainty, the emissions will be within the specified range. Input ranges also help reduce the effect of author bias (intentional or more often unintentional) as the ranges are generated from multiple data sources.

Uncertainty has been examined in top-down models such as GREET [17,18] and by Venkatesh et al. [17–19]; however, as mentioned earlier, the top-down models do not allow the examination of specific crude pathways. And although researchers like Spatari and MacLean performed a bottom-up uncertainty analysis, they focused on lignocellulose-based ethanol fuels and not conventional gasoline, diesel, and jet fuel [20].

Work by Vafi and Brandt [21] and Brandt et al. [22] assessed uncertainty in the regional well-to-refinery gate (WTR) emissions using smart defaults when crude-specific data are unknown. The goal of our work is to use crude-specific data as much as possible and focus on specific fields rather than regions. This will allow us to identify the high and low emission-intensive areas for comparison. The narrower scope will not only allow the examination of specific crude pathways but different technology pathways as well. Additionally, this work adds on the refinery-to-wheel stages to complete the WTC scope. Adding the refinery is important as the refinery yields will magnify the pre-refinery emissions and have a significant effect on the final WTC emissions.

In conclusion, a model that can accurately calculate the WTC emissions of various crudes with uncertainty is needed to fill the current gap in the literature. This work focuses on the uncertainty and variability along a specific crude production pathway. Uncertainty from using alternative technologies, such as different refinery configurations, is outside the scope of the current work.

The main goal of this study is to quantify the uncertainty of the WTC emission estimates; this will be accomplished through the following three stages. The first is to perform an uncertainty analysis and determine the GHG emissions ranges of the five selected conventional crude oils and two unconventional crudes. The second is to identify what additional data are required to improve the accuracy of the emission estimates of each crude oil. The third is to examine how emissions change as the condition of the crude field declines near the end of its useful life. The results of this study will enhance the understanding of the accuracy of the WTC emission estimates that are used in developing GHG reduction policies. The results showing how emissions increase as a field ages will also be useful to policy makers and industry leaders when assessing whether to keep producing from an aging field.

2. Methodology

This study uses the FUNNEL-GHG-CCO&OS modules, published in 2014 [12–16,23], as the basis for our uncertainty assessment. The goal of this study is to integrate the two previous models into a single universal model and enhance the model by adding an uncertainty analysis. The Excel-based models are flexible and transparent, making them ideal for this study. First, we modified the original model to improve the accuracy of the WTC estimates. Then we performed a sensitivity analysis to identify sensitive inputs and ran a Monte Carlo simulation to determine the uncertainty ranges in each crude's WTC emissions.

2.1. Base case model

Since our focus is an uncertainty analysis, this paper only gives a brief overview of the FUNNEL-GHG-CCO&OS modules, hereafter jointly referred to as the F-1 model. Readers are encouraged to refer to the previously published work for additional details [12–16,23].

The F-1 bottom-up model uses engineering first principles to calculate energy use and emissions generated at each stage from raw material production to product end use.

Fig. 1 shows the seven main sub-processes within the model boundary.

The production stage includes drilling the wells, injecting fluids to maintain reservoir pressure, and lifting the crude to the surface. Surface processing includes crude stabilization, gas treatment, and water treatment. Unconventional crudes need to be either upgraded or mixed with diluent prior to being transported to the refinery. Crude is transported by a combination of pipelines and marine vessels to refineries where it is processed into gasoline, diesel, and jet fuel. The finished products are distributed to bulk terminals by pipelines, trains, barges, and tankers and then distributed to fueling stations by truck. The final stage is