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Life cycle assessment of greenhouse gas emissions from Canada's oil sands-derived transportation fuels

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ABSTRACT

A comprehensive LCA (life cycle assessment) for transportation fuels (gasoline, diesel, and jet fuel) derived from Canada's oil sands was conducted, and all the current possible pathways from bitumen extraction to use in vehicles were explored. Authors, in earlier studies, have presented the energy consumption and GHG (greenhouse gas) emission results for individual unit operations-recovery, extraction, upgrading and refining. The LC (life cycle) inventory data for the current LCA study were obtained from theoretical model named FUNNEL-GHG-OS (**FUN**damental E**N**gineering Princip**LE**s- based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in the **O**il **S**ands), developed from fundamental engineering principles. The impact of the cogeneration of electricity in oil sands recovery, extraction, and upgrading on the LC GHG emissions of gasoline was explored. LC WTW (well-to-wheel) GHG emissions range from 106.8 to 116 g-CO_2equivalent/MJ of gasoline, 100.5 to 115.2 g-CO_2equivalent/MJ of diesel, and 96.4 to 109.2 g-CO_2equivalent/MJ of jet fuel, depending on the pathway. Combustion emissions (64.7%–70.3%) are the largest constituent of WTW emissions for gasoline production; recovery (through surface mining and steam assisted gravity drainage) forms 7.2%–16% depending on the LC production process of gasoline.

1. Introduction

With the technologies available today, bitumen from the oil sands can be produced via surface mining and in situ recovery. CSS (Cyclic steam stimulation) and SAGD (steam assisted gravity drainage) are most widely used in situ recovery methods in which steam is used as stimulant to reduce viscosity of bitumen and pump it to the surface [1]. About 20% of Alberta's oil sands are recoverable by surface mining; the remaining 80% are too deep for mining and require in situ extraction techniques [2]. In 2012, total in situ production accounted for 52% of the total crude bitumen production and surface mining for the rest [3]. In situ bitumen production has been increasing at a higher rate than has mined bitumen. In 2012, all crude bitumen from mining and a small portion (about 7%) of bitumen produced from in situ was upgraded[1] to SCO (synthetic crude oil), yielding 329 million barrels of upgraded bitumen [4]. Upgraded bitumen formed 52% of the total crude bitumen in 2012 [4].

There is cautioned growth in the oil sands industry due to rising interest in global carbon management. Of all the economic sectors, the transportation fuels sector has attracted the most interest recently. This is due to the fact that the transportation sector is the second largest source (after electricity) of GHG (greenhouse gas) emissions, accounting for 28% of total GHG emissions in the U.S and 26% of the total GHG emissions in Canada [5,6]. The high GHG intensity of the transportation sector has resulted in regulations such as the LCFS (Low Carbon Fuel Standard) and the European Fuel Quality Directive that demand a 10% reduction in life cycle GHG (greenhouse gas) emissions from transportation fuels by 2020 [7,8]. In 2007, the Alberta government passed the SGER (Specified Gas Emitters Regulations) to legislate GHG emissions reduction for large industrial facilities (those emitting over 100,000 tonnes of CO_2e per year) to reduce their carbon emissions by 12% from the 2003–2005 baseline [9]. These regulations use a life cycle assessment approach to calculate the carbon footprint of transportation fuels sold.

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[1] In the process of upgrading, bitumen is fractionated or chemically treated to yield a higher value product. This is achieved either through thermal cracking (coking) or hydrogen based cracking (hydroconversion) [1,19].

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A LCA (life cycle assessment) is a powerful tool that measures and regulates the environmental performance of different fuel systems that may be interrelated. An LCA helps in assessing direct and indirect environmental impacts of a fuel system. The strength of an LCA lies in the fact that it allows policy makers to assess the impacts of a fuel on all affected sectors rather than shifting the impact from one sector to other. The policies mentioned above use the LC (life cycle) approach to regulate the emissions from transportation fuels as this approach is helpful to reduce overall GHG emissions. An LCA may not become part of a particular jurisdiction's regulations if there is a comprehensive policy on GHG emissions across all regions and sectors of society [10], but because not all regions and sectors have these policies, the use of the LC approach to reduce overall GHG emissions is justified.

Significant contributions in the field of LCA of crude oils have been made by Keesom et al. [11] and Rosenfeld et al. [12]. These studies present LC emissions from conventional and non-conventional crudes imported to the U.S. [12] and used data from specific companies to perform the LCA. Though Keesom et al. [11] performed the LCA based on a developed theoretical process model, the authors provide very little information about data sources and inputs to the model. Neither sources [11,12] modeled all the possible bitumen LC pathways in the oil sands. The GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation)[2] model [13], maintained by the Argonne National Laboratory, and GHGenius[3] [14], maintained by Natural Resources Canada, have been widely discussed and used to construct oil sands pathways. Charpentier et al. [15] and Brandt [16] reviewed the results from these models along with other studies and found inconsistencies in the results reported due to variations in system boundaries, data quality, methods, and documentation. Whereas Charpentier et al. [15] called for additional research for better characterization of oil sands technologies and pathways, Brandt [16] recommended modeling emissions of process specific configurations. Bergerson et al. and Charpentier et al. [17,18] document the development of GHOST, a LCA model for oil sands-derived pathways. The database inventory for this model is based on confidential data from industry and mainly focuses on upstream emissions from the oil sands instead of an entire well-to-wheel LCA.

There is little research on estimating LC GHG emissions of transportation fuels from oil sands pathways. FUNNEL-GHG-OS[4] (**FUN**damental E**N**gineering Principl**E**s- based Mode**L** for Estimation of **G**reen**H**ouse **G**ases in the **O**il **S**ands), based on engineering first principles (i.e. using the basic equations of mass and energy balance), is developed to estimate the energy consumption and GHG emissions in surface mining, SAGD (steam assisted gravity drainage), and upgrading operations in the oil sands and is detailed in previous work [1,19]. The main objective of this paper is integration of the energy consumption and GHG emissions results for various oil sands operations, which were mathematically estimated by authors in earlier studies [1,19]. This paper presents the results of a comprehensive WTW (well-to-wheel) LCA of oil sands-derived transportation fuels – gasoline, diesel and jet fuel while exploring all the possible bitumen pathways from extraction to end use in vehicles. Further it adds to the knowledge base for conducting a comprehensive LCA of transportation fuels derived from Canada's oil sands.

The LC of transportation fuels starts with the recovery of crude from the resource, which in the oil sands means bitumen production via surface mining or SAGD. After the initial extraction of bitumen from the ore, bitumen is either upgraded to superior crude oil (known as SCO) or transported to refineries as dilbit, which is made by mixing a diluent in bitumen. The feed to refineries is processed and converted to transportation fuels, which are then moved to market to be consumed in vehicles. These steps are detailed in Fig. 1. The figure shows the different unit operations that bitumen goes through from recovery and extraction to the point of combustion in vehicles. WTW (Well-to-wheel) emissions refer to emissions associated with all the operations from initial production of crude to the combustion of transportation fuel in vehicles. WTT (Well-to-tank) emissions refer to the emissions upstream of the vehicle tank, i.e., WTW without the combustion emissions. TTW (Tank-to-wheel) constitutes only combustion emissions.

2. Methodology

Essential procedures in identifying and assessing the environmental impact of transportation fuels in their LC include defining the system boundaries, functional units, and allocation methods as well as collecting and processing relevant LCI (life cycle inventory) data, followed by an impact assessment [20].

2.1. Goal and scope

The primary goals of this LCA are:

- To use the GHG emissions obtained from the developed theoretical models to quantify the LC emissions of transportation fuels from oil sands products (SCO and bitumen).
- To explore and compare the LC GHG emissions in different bitumen LC pathways.
- To identify the processes with the highest GHG emissions in the production of transportation fuels.
- To add to the knowledge base in the comparison of the GHG intensity of oil sands products to that of conventional crudes.

The scope of this study encompasses all the processes throughout the entire LC from recovery and extraction of bitumen from its resource to the use of transportation fuels in vehicles.

2.1.1. System boundary

Fig. 2(A–F) presents the system boundaries for the LCA of transportation fuels from oil sands products. The boundaries include the burden of all inputs in recovery, extraction, transportation, upgrading, dispensing, and combustion of fuels. Fig. 2(A–F) shows that throughout the LC pathway more than one product are formed. Coke is formed in upgraders, whereas both coke and fuel oil are formed as co-products in refineries along with the major products gasoline, diesel, and jet fuel. Coke and fuel oil are set inside the system boundary implying that the burden required to produce them is borne by major products (diesel, gasoline, and jet fuel). The excess cogenerated electricity in the oil sands that is exported to the Alberta grid is considered outside the system boundary and is appropriately credited.

Along with the direct emissions from the combustion of process fuels, the system boundary encloses the upstream emissions to recover and transport these process fuels. For example, the net

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[2] GREET is a spreadsheet based model that contains energy use and GHG emissions to build the different vehicle fuel combinations for full vehicle or fuel life cycle (Wang, M., 2012).

[3] GHGenius is a spreadsheet model that calculates the GHG emissions from extraction of fuel to when it is converted to motive power. It assess a wide variety of fuels and technologies in respect to life cycle energy use, GHG emissions, and cost effectiveness ((S&T)[2], 2012). GHGenius differs from GREET in its methodologies, assumptions and data sources.

[4] FUNNEL-GHG-OS is a spreadsheet model to calculate the energy consumption and GHG emissions in oil sands building different life cycle pathways based on specific project parameters (Nimana et al., 2015a&b).