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Energy consumption and greenhouse gas emissions in upgrading and refining of Canada's oil sands products

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A model-FUNNEL-GHG-OS (**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 fundamental engineering principles was developed to estimate the specific energy consumption and GHGs (greenhouse gas emissions) for upgrading bitumen to produce SCO (synthetic crude oil). The model estimates quantity of SCO produced, the consumption of hydrogen, steam, natural gas and power in two different upgrading operations, namely delayed coking and hydroconversion. Hydroconversion upgrading is more energy and GHG (433.4 $kgCO_2eq/m^3$ of bitumen) intensive than delayed coker upgrading (240.3 $kgCO_2eq/m^3$ of bitumen) but obtains a higher yield of SCO. This research explores bitumen pathways in oil sands – upgrading bitumen to SCO, followed by transporting and refining SCO as compared to transporting and refining dilbit. The energy consumption, GHG emissions and volume of transportation fuels obtained from refining of different oil sands feeds has been investigated. Refining of oil sands products produce 7.9 to 15.72 gCO_2eq per MJ of refined product. Refining of SCO to transportation fuels produces 41% and 49% less emissions than dilbit and bitumen respectively.

1. Introduction

Unconventional oil resources such as oil sands in Canada have gained a lot of attention due to limited conventional oil resources and ever increasing energy demand. The oil sands in Alberta, one of the Provinces in Canada, with 170.2 billion barrels, are the third largest proven oil reserves in world after Saudi Arabia and Venezuela [1]. Production of crude bitumen from Alberta oil sands was almost 1.9 million barrels per day in 2012, 54% of which was upgraded to synthetic crude oil [2].

Bitumen production is projected to increase to 3.8 million barrels per day by 2022 [3]. The growing oil sands industry faces tough decisions as to how to develop this resource further, whether to upgrade bitumen to SCO within the province or to blend it with lighter hydrocarbons to produce dilbit [4]. This decision is further made difficult by the climate policies such as the LCFS (Low Carbon Fuel Standard) [5], the European Fuel Quality Directive [6] and the Alberta SGER (Specified Gas Emitter Regulation) [1] adding strict regulation for reducing GHG (greenhouse gas) emissions. These regulations call for appropriate quantification and assessment of life cycle GHG emissions from these oil resources.

The bitumen recovered and extracted in SAGD (Surface Mining or Steam Assisted Gravity Drainage) is highly dense, viscous and high in sulfur content [7]. All the refineries in North America do not have capability to refine heavy feeds. So to access more markets and ease the transportation, the Canadian crude is upgraded to produce "SCO" (synthetic crude oil). Bitumen is fractionated or chemically treated to yield a higher value product through a process known as upgrading. The aim of upgrading process is to obtain a high quality substitute to crude oil known as SCO or may be limited to reduce the viscosity of product to allow its shipment by pipeline without adding a solvent [8]. Upgrading of the highly viscous and hydrogen deficient bitumen consumes substantial amounts of energy, making it a GHG (greenhouse gas) intensive process. On the other hand, dilbit requires less energy during initial blending [4]. SCO or dilbit is transported to refineries via pipeline. Pipeline transport of heavier feeds such as dilbit requires more energy than SCO [9]. Refining of SCO requires less energy than refining of dilbit and yields different products [10–12]. So it becomes necessary to quantify the emissions in the unit operations of upgrading, transportation and refining so as to compare the bitumen pathways and make informed decisions.

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Nomenclature

GHG	greenhouse gas
SCO	synthetic crude oil
gCO_2eq	grams of carbon-dioxide equivalents
MJ	mega joule
bbl	barrel
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
LHV	lower heating value
SMR	steam methane reforming
NG	natural gas
DHT	diesel hydrotreating
KHT	kerosene hydrotreating
NHT	NAPHTHA hydrotreating
HCD	hydrocracking
FCC	catalytic cracking
SGP	saturated gas plant
UGP	unsaturated gas plant
HYD	hydrogen production

Large scale commercial upgrading technologies comprise either thermal cracking-coking technologies or hydrogen based cracking-hydroconversion technologies [8,12,13]. Of the total bitumen volume upgraded in Alberta, 30% goes through hydroconversion [14]. The quality and characteristics of the product produced depend on the technology chosen. Selection of upgrading technology is primarily based on type of product required and other secondary considerations are capital cost, cost of fuels along with catalysts, coke production, operating complexity and experience, production expandability, constructability and maintainability [14]. The GHG impact of these technologies may not been considered earlier as important factor in selection of the technology but it is gaining importance due to increasing environmental awareness and strict regulations imposed by policy makers.

The two most prominent North American life cycle models in this area are GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) [15] maintained by Argonne National Laboratory and GHGenius [16] maintained by Natural Resources Canada. Oil sands pathways can be constructed using these models, but there is no method in these models to estimate the specific energy consumption in the oil sands operations. In the refinery operation, these models do not show the effects of crude quality on energy consumption and GHG emissions. Hence it is not possible to estimate energy consumption and GHG emissions for a particular kind of feed refined in a specific refinery, using these life cycle models. This research is aimed at addressing these gaps in knowledge.

Two earlier studies [11,12] present life cycle GHG emissions from conventional and non-conventional crudes performing a comparative analysis of production of transportation fuels in the U.S. These studies do not calculate project specific energy consumption and GHG emission based on technical parameters. Another work [17] studied the upgrading and refining operation GHG emissions for oil sands based on certain project data. Rahman et al. studied extraction, recovery and refining of five different conventional crude oils which are refined in the North America but did not consider the oil sands-based oil [18,19]. These results have limitations as these cannot be modified to evaluate emissions for a different project. Some studies [10,20,21] have looked into the effects of crude quality and refinery configuration for different feeds. These studies are limited to refinery operation and do not analyze the upgrading and refinery operations on a common platform to study the effects obtaining end products from oil sands feeds.

Charpentier et al. [22] and Bergerson et al. [23] report the range of energy consumption and GHG emissions in oil sands based on confidential data from industry. The results are therefore specific to those projects hence cannot be used for calculation of project specific energy consumption and GHG emissions based on quality of feed and technical parameters of the project. Brandt [7] and Charpentier et al. [24] performed a comparative analysis of GHG emissions in each oil sands operation as reported by earlier studies and life cycle models. Whereas Charpentier et al. [24] called for additional research for better characterization of oil sands technologies and pathways, Brandt [7] recommended modeling GHG emissions of process specific configurations.

Oil sands produce a variety of feeds such as SCO, dilbit and bitumen that are refined to transportation fuels. Each feed depending on its characteristics consumes different amount of energy and emits different GHG emissions. Refining of oil sands feeds end up in different useful end products. So this makes it necessary to study upgrading and refining operations together to compare the net energy consumption and GHG emissions on similar platform. The variety of feeds and technology in oil sands makes each project unique in its energy consumption and GHG emissions. This uniqueness demands the estimation of energy consumption and GHG emissions for each individual project.

This paper presents a detailed data intensive model named FUNNEL-GHG-OS (FUNdamental ENgineering PrinciplEs-based ModeL for Estimation of GreenHouse Gases in the Oil Sands) based on fundamental engineering principles to mathematically estimate project and process specific energy consumption and related life cycle GHG emissions for an upgrading operation in oil sands. FUNNEL-GHG-OS model conducts a comprehensive LCA (life cycle assessment) of transportation fuels from oil sands, within the framework of ISO (International Standard Organization) standards [25]. The system boundary includes all the bitumen pathways possible in oil sands. The oil sands recovery and extraction pathways have been modeled in Refs. [26,27], whereas in this paper the upgrading and refinery pathways for oil sands feeds have been modeled. The impact category analyzed in the LCA is the global warming potential. As the results of LCA depend on the quality of data used in analysis, FUNNEL-GHG-OS performs engineering calculations to provide quality data for LCA.

Two most widely used technologies for upgrading in oil sands – delayed coking and hydroconversion have been analyzed. This research further evaluates the energy consumption and GHG emissions for upgrading bitumen and refining of SCO, dilbit and bitumen feeds on a common platform. A process model [28] built in Aspen HYSYS has been used to study the refining operation. The GHG emissions reported for the unit operations include 1) direct emissions from the combustion of fuel on site and 2) upstream emissions associated with recovery, processing, and transportation of these fuels. The paper does not include the fugitive, venting and flaring, equipment, and land-use emissions. The coke produced in upgrading and refinery operations is assumed to be stockpiled.

2. Methodology

2.1. Functional unit

The functional unit used for life cycle assessment of oil sands-derived fuels is one unit volume of crude feed input to upgraders and refineries. The metric used for presenting the life cycle GHG emissions is kg-CO_2eq per unit volume of crude feed. The emissions also include the effects of other GHGs such as CH_4 and N_2O. However, the results are also presented in g-CO_2eq per MJ (megajoule)