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2009 Environ. Res. Lett. 4 014005

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# Understanding the Canadian oil sands industry's greenhouse gas emissions

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Received 2 October 2008

Accepted for publication 30 December 2008

Published 20 January 2009

Online at [stacks.iop.org/ERL/4/014005](http://stacks.iop.org/ERL/4/014005)

## Abstract

The magnitude of Canada's oil sands reserves, their rapidly expanding and energy intensive production, combined with existing and upcoming greenhouse gas (GHG) emissions regulations motivate an evaluation of oil sands-derived fuel production from a life cycle perspective. Thirteen studies of GHG emissions associated with oil sands operations are reviewed. The production of synthetic crude oil (SCO) through surface mining and upgrading (SM&Up) or *in situ* and upgrading (IS&Up) processes is reported to result in emissions ranging from 62 to 164 and 99 to 176 kgCO<sub>2</sub>eq/bbl SCO, respectively (or 9.2–26.5 and 16.2–28.7 gCO<sub>2</sub>eq MJ<sup>-1</sup> SCO, respectively), compared to 27–58 kgCO<sub>2</sub>eq/bbl (4.5–9.6 gCO<sub>2</sub>eq MJ<sup>-1</sup>) of crude for conventional oil production. The difference in emissions intensity between SCO and conventional crude production is primarily due to higher energy requirements for extracting bitumen and upgrading it into SCO. On a 'well-to-wheel' basis, GHG emissions associated with producing reformulated gasoline from oil sands with current SM&Up, IS&Up, and *in situ* (without upgrading) technologies are 260–320, 320–350, and 270–340 gCO<sub>2</sub>eq km<sup>-1</sup>, respectively, compared to 250–280 gCO<sub>2</sub>eq km<sup>-1</sup> for production from conventional oil. Some variation between studies is expected due to differences in methods, technologies studied, and operating choices. However, the magnitude of the differences presented suggests that a consensus on the characterization of life cycle emissions of the oil sands industry has yet to be reached in the public literature. Recommendations are given for future studies for informing industry and government decision making.

**Keywords:** oil sands, life cycle assessment, greenhouse gas emissions, low carbon fuel standards, review

 Supplementary data are available from [stacks.iop.org/ERL/4/014005](http://stacks.iop.org/ERL/4/014005)

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## Nomenclature

AOSP Athabasca Oil Sands Project  
API American Petroleum Institute

bbl barrel  
bpd barrel per day  
CEPA Canadian Environmental Protection Act  
CH<sub>4</sub> methane  
CO<sub>2</sub> carbon dioxide

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CO <sub>2</sub> eq	carbon dioxide equivalent
CSS	cyclic steam stimulation
EIA	environmental impact assessment
ENGO	environmental non-governmental organization
g	gram
GHG	greenhouse gas
HHV	higher heating value
IS&Up	<i>in situ</i> and upgrading
kg	kilogram
km	kilometre
LCA	life cycle assessment
LCFS	Low Carbon Fuel Standard
LHV	lower heating value
m <sup>3</sup>	cubic metre
MJ	megajoule
Mt	megaton
N <sub>2</sub> O	nitrous oxide
ppm	part per million
RFG	reformulated gasoline
S	sulfur
SAGD	steam assisted gravity drainage
SCO	synthetic crude oil
SM&Up	surface mining and upgrading
SOR	steam-to-oil ratio
TTW	tank-to-wheel
WTR	well-to-refinery entrance gate
WTT	well-to-tank
WTW	well-to-wheel
yr	year

## 1. Introduction

High oil prices, growing demand, geopolitical tension, energy security, and diminishing conventional oil reserves in North America are increasing interest in domestically produced liquid fuels from unconventional fossil reserves. Canada's oil sands are one of the largest such reserves and consist of an amalgamation of bitumen, sand, and water buried in Northern Alberta. These oil reserves are second only to Saudi Arabia in quantity and represent 14% of global reserves (O&GJ 2004).

Two main methods are employed for oil sands recovery. Surface mining is used for shallower reservoirs (generally those buried less than 75 m below the surface) whereas *in situ* methods are applied for deeper ones. In *in situ* extraction, the bitumen is heated or diluted underground and then pumped to the surface. The majority of the extracted bitumen is upgraded into a lighter (lower viscosity), sweeter (lower sulfur content), and more valuable synthetic crude oil (SCO) and then refined, primarily into gasoline or diesel fuels. The remaining portion of bitumen (from *in situ* production) is directly processed into fuels in refineries that are able to accept raw bitumen feedstock. Although recovery methods generally fall into the above two categories, every oil sands project is distinct due to the differing characteristics of oil sands reservoirs, technology and operational choices, as well as continuing research and development.

In 2006, the production of SCO and non-upgraded bitumen from Alberta's oil sands totalled 1.2 million barrels per day (bpd) (CAPP 2008). Two joint ventures (the Athabasca Oil Sands Project (AOSP)<sup>5</sup> and Syncrude Canada Ltd) and one company (Suncor Energy Inc.) that utilize surface mining methods accounted for 70% of this production, mostly SCO, while a dozen *in situ* companies produced the remaining 30% as bitumen (CAPP 2008). Total production is increasing rapidly as a result of high current and expected future oil prices that draw significant investment in the sector and, as well, the success of existing projects. Production has been projected to reach 5 million bpd by 2030, supplying 16% of North America's oil demand (ACR 2004). By 2025, as much as 90% of Canada's crude oil production could originate from its oil sands resources (Centre for Energy 2007) compared to 43% in 2006 (CAPP 2008).

While oil sands development generates significant economic benefits, it is also the cause of much controversy due to its impacts on the environment, including high rates of fossil energy use and associated greenhouse gas (GHG) emissions. In spite of recent improvement in the GHG intensity of oil sands production (e.g., Suncor (2007) reported a 51% reduction between 1990 and 2006 attributed to technology and energy efficiency improvements), the cumulative emissions of the industry are of concern due to its rapid expansion. While the oil sands industry currently contributes a small fraction of Canada's GHG emissions (approximately 3%–4%) its emissions could grow to be similar in magnitude to those of the two largest contributing sectors (transportation: 190 Mt of CO<sub>2</sub> equivalent per year (MtCO<sub>2</sub>eq yr<sup>-1</sup>) and electricity and heat generation: 125 MtCO<sub>2</sub>eq yr<sup>-1</sup>) if left unchecked (Environment Canada 2007). However, such unrestricted growth is unlikely due to the Alberta and Federal governments recently adopting comparable industry GHG emissions targets in which large emitters must reduce their emissions by either improving their operation, purchasing emissions credits or investing in technology funds (CAPP 2008). Further, the Federal government's 'Turning the Corner' plan requires that oil sands projects, starting operations in 2012 and beyond, implement carbon capture and storage technologies (Environment Canada 2008). Additionally, regulations such as California's Low Carbon Fuel Standard (LCFS) have been proposed to reduce the life cycle GHG emissions intensity of transportation fuels sold in certain jurisdictions. The California LCFS will require fuel providers to ensure that the mix of fuels they sell into the California market meets, on average, a declining carbon intensity (Farrell *et al* 2007). These regulations present an additional challenge to the competitiveness of oil sands-derived fuels, which generally have higher production-related GHG emissions compared to conventional crude oil-derived fuels. Accurate emissions data for the full life cycles of the diverse oil sands-derived fuel production pathways are required to inform new regulations and GHG emissions management strategies.

There have been few life cycle studies of oil sands-derived fuel production pathways, as reported by Bergerson and Keith

<sup>5</sup> A joint venture among Shell Canada Ltd (60%), Chevron Canada Ltd (20%), and Marathon Oil Canada Corp. (20%).

(2006) in their literature review of oil sands environmental performance. While Bergerson and Keith concluded that completed studies have varying boundaries (what activities are/are not included) and resulting GHG emissions, they did not comprehensively analyse the results of the studies and the sources of their differences. McKellar *et al* (2008) reviewed prior life cycle studies of liquid fuels produced from oil sands as well as from conventional and other unconventional fossil fuel sources and found that the oil sands pathways, on a 'well-to-wheel' (WTW) basis, resulted in slightly higher GHG emissions (on the order of 5%–15%) than a conventional crude oil reference pathway. However, McKellar *et al* noted that further research was needed in order to better characterize all of the pathways. Due to its focus on various unconventional fossil fuel sources McKellar *et al* considered a subset of the studies examined in the current paper and completed a less detailed assessment of oil sands technologies.

The primary objective of this paper is to improve our scientific understanding of the life cycle GHG emissions associated with oil sands-derived fuel production pathways through: (1) completing a comprehensive review of prior life cycle studies and current life cycle models; (2) highlighting major differences in GHG emissions performance and elucidating the possible causes of such differences; and (3) providing guidance for future studies. This research aims to determine whether GHG emissions intensities from prior oil sands life cycle studies and current models are adequate for informing upcoming regulations and more broadly, stakeholder decision making.

## 2. Method

This research reviews publicly available studies (and models) that estimate GHG emissions from producing oil sands-derived fuels. Each study evaluated a different combination of fuels, pathways, and life cycle stages as well as employed different research methods and assumptions. In addition, the studies were produced at different levels of detail and for different purposes, making comparison of the studies challenging. To facilitate our analysis, the studies have been divided into two categories: 'well-to-refinery entrance gate' (WTR) studies focus on the bitumen extraction and/or the SCO production stages; WTW studies include the stages of the WTR category as well as refining and use of the fuel in a light-duty vehicle. Low sulfur reformulated gasoline (RFG) is the end product analysed in the WTW studies<sup>6</sup>. The oil sands production pathways included in the studies are designated as surface mining and upgrading (SM&Up), *in situ* and upgrading (IS&Up), and *in situ* without upgrading. A conventional crude oil reference pathway, included in some of the studies, is used for comparison. More detail on the methods used in

this analysis can be found in the supplementary information (available at [stacks.iop.org/ERL/4/014005](http://stacks.iop.org/ERL/4/014005)).

The 13 selected studies and their key characteristics are shown in table 1. GREET (2008) and GHGenius (2008) are two WTW models maintained by the US and Canadian governments, respectively. These models are intended to allow for comparisons of many fuel pathways and do not focus on oil sands pathways specifically. These models offer the option of relying on their default values for the oil sands and conventional oil pathways or user input of data. In this paper, all model results are generated based on the default values (except for the RFG definition in GREET (2008)—see footnote 6). Brandt and Farrell (2007) and Ordorica-Garcia *et al* (2007) are studies that result from academic research while McCann and Magee (1999), Furimsky (2003), Flint (2004) and McCulloch *et al* (2006) are consultants' studies. Flint (2004) also reported results of a McCann study not otherwise available. We refer to these results as 'McCann in Flint (2004)'. All of these studies focus on oil sands pathways. Shell (2007), Suncor (2007), Syncrude (2007), and CAPP (2008)<sup>7</sup> are studies completed by the industry with unimpeded access to operating data.

The boundaries of the WTR and WTW studies vary, as described in table 1. The studies generally accounted for the direct emissions of the activities associated with extraction, upgrading, refining, and use in the vehicle (the latter two applicable only to the WTW studies). Some studies also included one or more of the following emissions categories: indirect emissions over the supply chain (e.g., emissions associated with the production and transportation of the natural gas used in the process), venting, flaring, and fugitive releases. The construction and decommissioning of the oil sands facilities as well as the manufacture and disposal of the vehicles were generally outside of the scope of the studies. Excluding these activities has been common practice in life cycle studies to date, although it is not necessarily recommended for future studies of technologies with large infrastructure requirements such as the oil sands. With the exception of Ordorica-Garcia *et al* (2007) who considered only the construction and decommissioning of the on-site electricity generation and hydrogen production units (a relatively small portion of the complete infrastructure), none of the studies included construction or decommissioning of oil sands facilities. In addition, only the two WTW models reviewed (GHGenius (2008) and GREET (2008)) offer the option of including light-duty vehicle manufacture and/or disposal within the boundaries of the analysis.

For the above reasons, the boundary of the present WTR comparison is set to include the following: the operation of the oil sands projects, the transportation activities occurring during the extraction through to refining stages, and the activities associated with producing the electricity and natural gas inputs (including transportation activities) used in the oil sands projects. Reporting 'well-to-tank' (WTT) results is more common in examining the life cycle

<sup>6</sup> The WTW studies, with the exceptions of GHGenius (2008) and GREET (2008) do not provide information on the type of gasoline modelled. Among the large selection of fuels available in GHGenius, low sulfur RFG (30 ppm S) was selected by default, being characteristic of the Canadian market. This fuel's properties were input into GREET (for comparability purposes) in generating results for the GREET pathway documented in this study (the fuel properties used differ slightly from a US low sulfur RFG base case).

<sup>7</sup> The Canadian association of petroleum producers (CAPP) represents the upstream Canadian oil and natural gas industry.

**Table 1.** Study category, data characteristics, and sources.

Study/ Model	Type of Study	Target Year	Project-Specific Results	Pathways				LCA Stages						Included in LCA Boundary					Sources of Oil Sands Data
				Surface Mining & Upgrading	In Situ	In Situ & Upgrading	Conv. Crude	Recovery & Extraction	Upgrading [primary technology]	Transport to Refinery	Refining	Distribution Storage Dispensing	Vehicle Use	Electricity Supply Chain	Natural Gas Supply Chain	Venting & Flaring	Fugitive: Leaks	Fugitive: Tailings Ponds	
<b>"Well-to-Refinery Entrance Gate" Category</b>																			
CAPP 2008	I	2006		√	√			√	√ [C&H]					√	NI	Flaring only			Average of oil companies data (disaggregated data not available)
Flint 2004	C			√	√	√		√	√ [Ø]					√		NI	NI	√	N/A
McCulloch <i>et al</i> 2006	C		√	√	√	√		√	√ [Ø]					NI	NI	√	√	√	Publicly available data from oil companies
Orderica-Garcia <i>et al</i> 2007	A	2003	√	√	√			√	√ [C&H]					√	√				Publicly available data from oil companies & literature
Shell 2007 (AOSP)	I	2006	√	√				√	√ [H]					√	NI	NI			Company data
Suncor 2007	I	2006	√	√	√			√	√ [C]					√		√	√	√	Company data
Syncrude 2007	I	2006	√	√				√	√ [C&H]					NI	NI	NI	NI	NI	Company data
<b>"Well-to-Wheel" Category</b>																			
Brandt and Farrell 2007	A		√	√		√		√	√ [C&H]	Incomplete	√	√	√	Incomplete	Incomplete	NI	NI	NI	Publicly available data from oil companies & GREET model
Furimsky 2003	C		√	√				√	√ [C&H]		√					Flaring only			Data from theoretical literature (no project specific data)
GHGenius 2008	M	2008+		√	√	√	√	√	√ [C&H]	√	√	√	√	√	√	√	√	√	Data mostly from CAPP, CIEEDAC, and oil companies public reports
GREET 2008	M	2007+		√	√	√	√	√	√ [Ø]	√	√	√	√	√	√	NI	√	NI	Data from ACR 2004
McCann and Magee 1999	C	1995 & 2005		√			√	√	√ [C&H]	√	√	NI	√	√	√	NI	NI	NI	N/A
McCann in Flint 2004	C			√	√		√	√	√ [Ø]	√	√	NI	√	NI	NI	NI	NI	NI	N/A

Notes:

- AOSP: Athabasca Oil Sands Project; CAPP: Canadian Association of Petroleum Producers; CIEEDAC: Canadian Industrial Energy End-use Data and Analysis Centre; Conv. Crude: conventional crude oil.
- Type of study. A: academic paper; C: consulting report; I: industry report; M: "well-to-wheel" model.
- √: data/stage included.
- NI (Not Indicated): unknown whether data/stage included or not.
- Incomplete: data/stage is not included in several pathways considered in the study. The data/stage is included only when Brandt and Farrell (2007) use results from the GREET model.
- Blank cells: data/stage not included (or not applicable).
- N/A: source of data Not Available.
- Primary upgrading technologies. C: coking; H: hydrocracking; C&H: combination of coking and hydrocracking; Ø: unknown whether both technologies (coking and hydrocracking) are considered.

performance of transportation fuels as a WTR approach neither characterizes the fuel production portion of the life cycle, nor accounts for the range in quality of SCO being produced or the related range of energy requirements during the refining phase. The latter approach is also problematic in making a consistent comparison to conventional crude oil pathways, which also differ in composition and refining energy requirements to arrive at the same end products. However, WTR is chosen for our analysis as the majority of the studies (7 of 13) stopped at this process stage. In addition, the WTR results provide insight into the production phase of oil sands development, which helps to identify areas for potential improvements.

The WTW comparison boundary includes all the previous activities as well as those occurring during the refining operation, the upstream activities associated with the electricity and natural gas used in refining, the transportation activities from refining to distribution, and the use of the produced fuel in a light-duty vehicle. Land use and carbon capture and storage are not considered in this paper.

The remainder of this section discusses the steps taken to ensure reasonable comparability of the studies (while identical system boundaries were the initial goal, it was not possible to rigorously adjust many of the differences due to the lack of detailed documentation in most studies).

The metric examined in this paper is GHG (including CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) emissions, expressed in grams (g) of CO<sub>2</sub>eq. For the WTR comparison, the functional unit is one barrel (bbl) of marketable product, SCO for SM&Up and IS&Up, bitumen for *in situ* extraction alone, and crude oil for the baseline conventional oil. The WTR results are also presented as gCO<sub>2</sub>eq per megajoule (MJ) of marketable product in the supplementary information. For WTW, the functional unit is one kilometre (km) driven in a gasoline powered light-duty vehicle. Unit conversions are made, where necessary, to present study results on the bases of these functional units.

The properties of conventional crude oil, SCO, and bitumen (e.g., API gravity, hydrogen to carbon ratio, sulfur content) resulting from different production processes applied to different reservoirs vary substantially. These properties dictate how much additional upgrading/refining will be required later in the life cycle in order to process the petroleum product to end products such as gasoline or diesel. However, only GHGenius (2008), GREET (2008), and Flint (2004) included some of these data. As a result, the oil properties defined in GHGenius are used by default throughout this research (except for SCO in Flint and conventional crude oil in GREET).

Although the WTW studies reviewed in this research reported vehicle-use ('tank-to-wheel', TTW) GHG emissions, for our comparison, a common light-duty vehicle TTW result was substituted for those utilized in the studies. This modification is made in order to emphasize GHG emissions differences associated with fuel production rather than those resulting from differing vehicle assumptions, e.g., fuel consumption (the latter of which are not the focus of this paper). The TTW result selected is that of GHGenius (2008) default RFG vehicle, a spark ignition internal combustion engine light-duty vehicle with a fuel consumption of 9.6 l/100 km.

Only two studies reviewed (Furimsky (2003) and Flint (2004)) considered the impacts of switching process energy, from natural gas to heavier feedstock. This substitution requires further analysis but is not discussed in the present paper. Other potentially important issues (such as assumptions about cogeneration, allocation/co-product credits, etc) that may differ among the studies are not discussed in the studies and therefore, steps could not be taken with respect to comparability in this regard.

### 3. Results and discussion

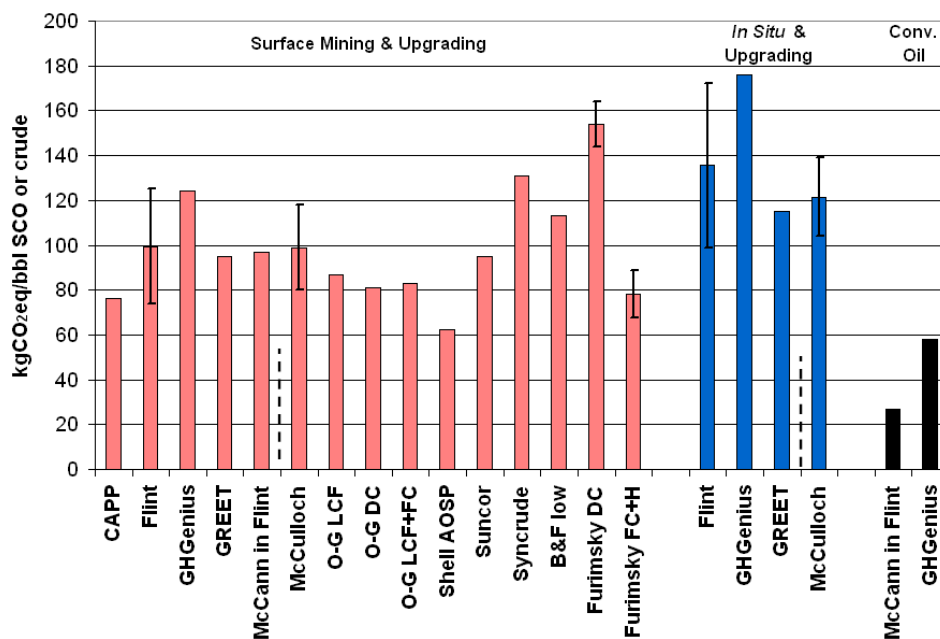
The reviewed studies have made contributions to the literature and public knowledge as they made progress in estimating GHG emissions resulting from varying subsets of the life cycle activities involved in selected oil sands operations. While each study has its strengths, gaps in documentation, limited transparency as well as incomplete and sometimes poor quality data make it challenging to elucidate sources of differences in the studies' results and to determine the likelihood that these results are representative of actual industry life cycle emissions.

All 13 studies include SM&Up pathways while eight also include *in situ* extraction (no upgrading) and four studies incorporate IS&Up pathways as well. Seven studies focused on specific projects while the others aimed to provide generic results to characterize a pathway (e.g., SM&Up). These latter studies either calculated a range of results or attempted to capture the characteristics of the entire industry. Brandt and Farrell (2007) and McCulloch *et al* (2006) are considered project-specific because, although both studies provided ranges of emissions values, these ranges resulted from calculations using project-specific data. Flint (2004) is considered generic by default due to the study not containing sufficient documentation to classify it otherwise.

Table 1 shows that many of the studies did not include all life cycle stages and that in some cases it is not clear which stages have been included. Most studies did not calculate supply chain and fugitive emissions (or did so incompletely) nor did they fully include emissions from flaring, venting, and what appear to be 'secondary' stages: transport to refinery, distribution, storage, and dispensing. The relative contributions of emissions from the various life cycle activities are discussed in sections 3.1 and 3.2. The WTR results for the SM&Up and IS&Up are discussed in the text while those for *in situ* (no upgrading) are provided in the supplementary information. The WTW results for all three pathways are included in the text.

#### 3.1. 'Well-to-refinery entrance gate': synthetic crude oil production from surface mining and upgrading and *in situ* and upgrading

The WTR GHG emissions resulting from SCO production reported in the studies as well as the minimum and maximum results from the baseline conventional crude oil production are shown in figure 1. The GHG emissions associated with producing SCO through SM&Up and IS&Up range from 62



**Figure 1.** ‘Well-to-refinery entrance gate’ greenhouse gas emissions of synthetic crude oil production-per bbl basis. Notes: (1) kgCO<sub>2</sub>eq: kilograms of carbon dioxide equivalent; bbl: barrel; SCO: synthetic crude oil; Conv. oil: conventional oil; OG: Ordorica-Garcia *et al* (2007); LCF: LC-fining; DC: delayed coking; FC: fluid coking; H: hydrocracking; AOSP: Athabasca Oil Sands Project; B&F: Brandt and Farrell (2007). (2) Results on a per MJ basis are reported in figure S2 in the supplementary information. (3) Oil sands results in kgCO<sub>2</sub>eq/bbl SCO; conventional oil result in kgCO<sub>2</sub>eq/bbl crude. (4) Only the minimum and maximum conventional oil results are shown in the figure due to space limitations. Other results are those of GREET (2008) and Brandt and Farrell (2007) at 33 and 30 kgCO<sub>2</sub>eq/bbl crude, respectively. (5) For each pathway, the dashed line separates generic (left) and project-specific (right) results. (6) Error bars: Flint (2004) low result for upgrading up to 34° API with natural gas and high result for upgrading up to 40° API using the heavy fraction of the barrel as upgrading energy feedstock; McCulloch *et al* (2006) low and high emissions scenarios; Furimsky (2003) current operation (high result) and potential improvements (low). (7) Only GHGenius (2008) and Flint (2004) provide API gravities of the crudes. GHGenius’ default API gravities for SCO, bitumen, and conventional oil are assumed for the other studies if required, mainly to convert results from these studies into the common functional unit (see the supplementary information). (8) GHGenius results are from ((S&T)<sup>2</sup> 2008). For the IS&Up pathway, it is assumed that half of the production results from steam assisted gravity drainage (SAGD) and the other half from cyclic steam stimulation (CSS). (9) Shell (2007) AOSP results have been converted from kgCO<sub>2</sub>eq/bbl of bitumen to kgCO<sub>2</sub>eq/bbl of SCO assuming a SCO/bitumen volumetric ratio of 1.02. (10) It is highly probable that Brandt and Farrell (2007) results refer to the lower heating value (LHV) of the fuel since LHV is the default option in the GREET model. These results are converted to higher heating values (HHV) using factors calculated from GREET (2008). Brandt and Farrell’s ‘high emissions’ oil sands scenario is not included since it could not be validated by the authors. (11) Furimsky (2003) results are CO<sub>2</sub> emissions only (rather than CO<sub>2</sub>eq). (12) Suncor (2007) is included so the figure shows company results from the three currently operating surface mining and upgrading projects but the result shown is a blend of Suncor’s mining and *in situ* pathways’ performance. Both pathways are reported together and could not be disaggregated. The *in situ* operations account for ~15% of Suncor’s total oil production. (13) McCann and Magee (1999) results are not included in this comparison because they are expressed in metric tons of CO<sub>2</sub>eq per cubic metre of transportation fuel and could not be converted into the common unit of comparison.

to 164 and 99 to 176 kgCO<sub>2</sub>eq/bbl SCO, respectively (or 9.2–26.5 and 16.2–28.7 gCO<sub>2</sub>eq MJ<sup>-1</sup> SCO, respectively), compared to 27–58 kgCO<sub>2</sub>eq/bbl (4.5–9.6 gCO<sub>2</sub>eq MJ<sup>-1</sup>) of crude for conventional oil production (the number of significant digits reported and the variation of the latter results are both discussed in the supplementary information). The higher GHG emissions intensity associated with SCO compared to conventional oil production primarily results from the higher fossil fuels used to extract bitumen and to upgrade it into a lighter and more valuable product such as SCO.

The above ranges of results for the SCO production pathways are wide. While some of the variation is caused by each project having a distinct reservoir and using different technologies that naturally result in different levels of GHG emissions, some of the studies report quite dissimilar results for the same project or combination of projects (as will be discussed subsequently). Therefore, one cannot definitively conclude that one pathway (SM&Up or IS&Up)

is less GHG intensive than the other based on existing studies. The results for conventional crude oil production also show significant variation, with the maximum value (58 kgCO<sub>2</sub>eq/bbl crude for GHGenius (2008)) being more than 100% higher than the minimum (27 kgCO<sub>2</sub>eq/bbl crude for McCann in Flint (2004)). These results are further discussed in the supplementary information, which includes the recommendation that additional investigation is required to resolve these differences.

The range of results is wider for SM&Up than for IS&Up in part because more SM&Up technologies are evaluated and also because this pathway has been investigated for a longer period of time in a larger number of studies. In addition, there are three large-scale SM&Up projects (those of AOSP, Suncor, and Syncrude) currently operating compared to a single integrated IS&Up project in its start-up phase (OPTI/Nexen’s Long Lake Project). Other *in situ* producers ship their bitumen either to independent upgraders such as

that of Husky Energy Inc. in Lloydminster, Saskatchewan, or to their own upgraders that primarily process surface mined bitumen (e.g., Suncor). In both cases, multiple bitumen feedstocks are blended together, making it challenging to allocate resulting GHG emissions to the different feedstocks. Moreover, the required information is generally confidential.

For the IS&Up pathway results, the differences may, in part, be due to different steam-to-oil ratios (SORs) being assumed. The SOR is a measure of the efficiency of oil production processes based on steam injection. It is the volume of steam required to produce one unit volume of oil. In current *in situ* processes, the steam requirements are one of the most critical factors determining energy consumption and associated GHG emissions. An SOR increase of 0.5 is approximately equivalent to an additional six cubic metre (m<sup>3</sup>) of natural gas being used to produce a barrel of bitumen (NEB 2006), which generates an additional 10 kgCO<sub>2</sub>eq/bbl. Oil companies generally aim for an SOR of 2.5 but few projects have achieved this ratio (NEB 2006). GHGenius assumes SORs of 3.2 and 3.4 for *in situ*-produced bitumen extracted through Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS), respectively<sup>8</sup> ((S&T)<sup>2</sup> 2008), but, unfortunately, no other IS&Up study reported the assumed SOR. While ranges of SORs for both processes are discussed in (S&T)<sup>2</sup> (2008), no detailed explanation or reference justifies the default SOR values in GHGenius. Although it is not possible to quantify the extent of the impact of this critical parameter on the study results, differences reported in figure 1 are such that the variation cannot be solely attributed to the SOR assumptions. Further insights are provided on SOR in the section on WTR results for the *in situ* (without upgrading) process in the supplementary information.

Differences in methods, system boundaries, and data sources used in the studies may also explain some of the SM&Up and IS&Up result differences illustrated in figure 1. The nature of the data used for the analyses varies significantly from theoretical literature values to project-specific material and energy balances. Details on the data used by the oil companies in their own studies are generally undisclosed while third-party studies usually have access only to less recent (potentially outdated) publicly available information such as the environmental impact assessment (EIA) of a project. The EIA is submitted to the regulatory authorities during the design phase of the project and repeatedly amended during the project pre-operational and operational phases. As a result, the completed project can be quite different from that presented in the original EIA.

Further details on the individual studies are discussed in the supplementary information to provide additional insights into differences in the WTR results. The main findings are reported below.

Both GHGenius (2008) and GREET (2008) rely on the processes' energy balances to calculate emissions intensities. Different boundaries and sources of data explain some of the variations in results. For the SM&Up pathway, both models

do not include the AOSP project, despite its significant market share. In addition, the energy balance in GREET appears to omit the diesel fuel used in mining and the coke used in upgrading, hence the lower emissions intensity compared to GHGenius. The average SM&Up and IS&Up results of Flint (2004), which presents a series of production scenarios and a range of results to characterize the industry, are consistent with other studies' results but some of his scenarios present some surprising discrepancies. The results of Brandt and Farrell (2007) and McCulloch *et al* (2006) also fall within the range of the other studies, but it is not possible to determine whether the emissions factors they provided characterize the whole industry or just the selected projects they analysed. Due to confidentiality issues, the results published by the companies themselves tend to lack transparency in calculations and product definition, making these studies difficult to interpret and compare. On the other hand, while independent project-specific studies published by third parties tended to discuss system boundaries and data sources in more detail, relying on public data, which tend to be less recent and of lower quality, could impact the quality of the results. Finally, the results from Furimsky (2003), the only life cycle study selected that used data from the theoretical petrochemical literature are not consistent with those reported by the industry.

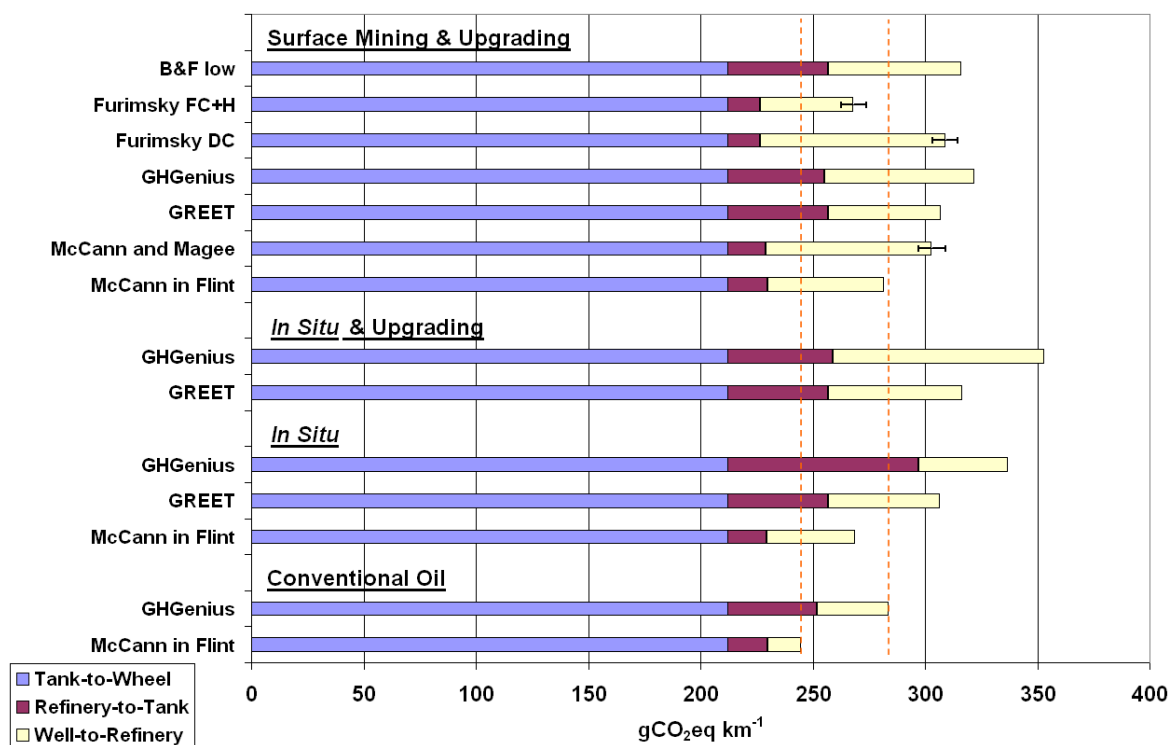
### 3.2. 'Well-to-wheel' comparison of the pathways

The WTW GHG emissions of the oil sands and conventional oil pathways are shown in figure 2.<sup>9</sup> Table S2 in the supplementary information shows additional details, numerical values, and assumptions supporting the WTW results. On a WTW basis, the ranges of GHG emissions associated with producing RFG<sup>10</sup> with current SM&Up, IS&Up, and *in situ* technologies, and utilizing the fuel in a light-duty vehicle are 260–320, 320–350, and 270–340 gCO<sub>2</sub>eq km<sup>-1</sup>, respectively, compared to 250–280 gCO<sub>2</sub>eq km<sup>-1</sup> for RFG from conventional oil. These ranges of results are generally consistent with those reported in McKellar *et al* (2008). The differences between pathways are much smaller on a WTW basis than on a WTR or WTT basis due to the large-vehicle-use component of GHG emissions included in the WTW results. Considering all the pathways in the present analysis, the vehicle-use phase (TTW) emissions account for 60%–80% of the WTW emissions. These results corroborate general knowledge in the field that the majority of the WTW GHG emissions occur during the TTW phase when conventional internal combustion engine vehicles are assumed. This holds

<sup>9</sup> The only study included in figure 2 that was not included in the WTR discussion is that of McCann and Magee (1999). Compared to the results of the more recent study, McCann in Flint (2004), done by the same consulting firm and utilizing what appears to be the same methodology, the WTW results of the SM&Up scenarios in McCann and Magee for the years 1995 and 2005 are, respectively, 19% and 15% higher than the SM&Up result of the more recent study. Unfortunately, no explanatory information could be located to better understand the differences in the studies.

<sup>10</sup> As explained in footnote 6, the low sulfur RFG (30 ppm S) defined in GHGenius (2008) was selected by default, parameters in GREET (2008) were adapted accordingly, and the fuels modelled in the other WTW studies for which no information is provided were assumed to be equivalent to the GHGenius RFG.

<sup>8</sup> The *in situ* and IS&Up results for GHGenius (2008) reported in the present paper assumed that half of the *in situ*-produced bitumen is extracted through SAGD and the other half through CSS, resulting in an average SOR of 3.3.



**Figure 2.** ‘Well-to-wheel’ greenhouse gas emissions of oil sands pathways. Notes: (1) gCO<sub>2</sub>eq km<sup>-1</sup>: grams of carbon dioxide equivalent per kilometre driven; DC: delayed coking; FC: fluid coking; H: hydrocracking; B&F: Brandt and Farrell (2007). (2) Only the minimum and maximum conventional oil results (noted as dashed lines) are shown in the figure due to space limitation. Missing results are GREET (2008), Brandt and Farrell (2007), and McCann and Magee (1999) at 275, 273, and 256 gCO<sub>2</sub>eq km<sup>-1</sup>, respectively. (3) Error bars: Furimsky (2003) current operation (high result) and potential improvements (low); McCann and Magee (1999) 1995 scenario (high result) and 2005 scenario (low). (4) A common ‘tank-to-wheel’ (TTW) result for the four pathways is assumed: GHGenius (2008) TTW result for reformulated gasoline used in the model’s default vehicle (i.e., a spark ignition internal combustion engine light-duty vehicle with a fuel consumption of 9.6 l/100 km). (5) The complete list of assumptions and the disaggregated results are detailed in table S2 in the supplementary information.

true even for the oil sands pathways with the highest WTR emissions. The high TTW emissions are due to the high carbon content of the fuel and because much of the energy of the fuel is lost due to inefficiencies in internal combustion engine vehicles.

The ranges of results for the three oil sands pathways show the divergence and limitation of current oil sands literature results. Unlike the WTR results, surprisingly, the low-end WTW results for the SM&Up pathway (McCann in Flint (2004) and fluid coking and hydrocracking in Furimsky (2003)) and *in situ* pathway (McCann in Flint (2004)) are lower than the WTW result in GHGenius (2008) for RFG-derived from conventional oil. However, McCann in Flint (2004) reports lower WTW results from conventional crude oil than does GHGenius (and the other studies reviewed that included this pathway) and therefore, in all individual studies, the oil sands pathway results are higher than those of the conventional crude baseline pathways. The studies reviewed reported wide and differing ranges of conventional oil results, suggesting that this pathway also deserves further study. However, as noted earlier, it is not discussed in detail since the focus of the current study is on oil sands pathways.

The low-end oil sands results occur in part due to differing assumptions in the studies about the refining stage of the life cycle. The refining GHG emissions results of McCann

and Magee (1999), McCann in Flint (2004), and Furimsky (2003) for the SM&Up pathway are generally consistent (14–18 gCO<sub>2</sub>eq km<sup>-1</sup>) but are less than half of those reported in GHGenius (2008) and GREET (2008)<sup>11</sup>. For the *in situ* pathway, the refining emissions differences across the studies are even greater than those for the SM&Up pathways, with the refining emissions of McCann in Flint (2004) and GREET (2008) reported to be 70% and 30% lower, respectively, than those of GHGenius (2008). These differences are in part explained by the major limitation of most of the refining modules in the studies in that they do not integrate the characteristics of the crude (viscosity, carbon content, sulfur content, etc) into the refining variables and therefore assume that the same emissions are associated with refining a light Saudi crude and a heavy sour bitumen from *in situ* extraction even though the latter would require more refining energy and emit more GHGs. In 2007, the capability of the refining model in GHGenius was improved so that it considers the API gravity and the sulfur content of the feedstock when calculating energy use and emissions from this stage of the life cycle (2007). In GREET (2008), the user has the option to modify the refining

<sup>11</sup> The low-end refining results in McCann and Magee (1999) and McCann in Flint (2004) reported for the conventional crude oil pathway suggest that McCann and Magee did not assume a low sulfur gasoline end product and that these first results were not updated in McCann in Flint.

efficiency. While these capabilities are good first steps, the refining process is complex and significantly impacts GHG emissions performance. Further improvements in this area are needed in future studies.

In all three pathways, SM&Up, IS&Up, and *in situ*, the recovery, extraction, upgrading (where included), and refining activities are responsible for the vast majority of WTT emissions, as expected. Emissions associated with other activities (e.g., transportation, flaring) are reported to be small (maximum 6 gCO<sub>2</sub>eq km<sup>-1</sup> for any single activity as per table S2 in the supplementary information). Nevertheless, there is considerable variation in the few results for these activities that are provided; differences are up to an order of magnitude. The sum of these 'secondary' emissions suggest that they may contribute more significantly to the total WTW GHG emissions than is indicated in the studies reviewed.

#### 4. Conclusions and recommendations for future oil sands life cycle studies

This review of oil sands life cycle based studies highlights characteristics of the studies and examines the GHG emissions intensities of the fuel production pathways. Potential sources of differences in the studies and in their resulting GHG emissions are discussed where study documentation permitted.

Overall, the WTR GHG emissions intensity ranges presented for the SM&Up and IS&Up pathways, as well as for the conventional crude oil pathway are broad. On a WTR basis, while the studies reported that producing SCO from SM&Up and IS&Up resulted in higher GHG emissions than producing conventional crude oil, one cannot conclude which of the SM&Up or IS&Up pathways generally result in lower GHG emissions. Based on our discussion of the studies, their inconsistencies, and gaps, one cannot be sure that the ranges presented reflect current oil sands WTR performance. This analysis also demonstrates that a WTR comparison between oil sands projects as well as to conventional crude projects is not sufficient for a consistent comparison and therefore it is recommended that the refinery component be included in future studies.

When the refining and large TTW components are added to the WTR components of selected studies, the resulting WTW ranges are relatively small. However, when comparing the WTW oil sands pathway results with those of conventional crude oil, the low-end oil sands results fall into the range of the conventional crude oil pathways reported in the studies. While this is probably due to inconsistencies in the modelling in the studies, it is not inconceivable that an oil sands pathway may perform better than a conventional oil pathway, under certain circumstances. For example, it may be possible that an oil sands project with high feedstock quality and minimum extraction and upgrading energy requirements (or low carbon energy inputs) results in lower GHG emissions than a conventional oil project with a low production rate, steam enhanced stimulation, heavy flaring and long transport distance from extraction to market. Therefore, it is important that the oil sands and conventional crude pathways be investigated in more detail. The previous discussion shows that statements

such as, 'the oil sands are three times as greenhouse gas intensive as regular oil' (Arsenault 2008), 'oil production in Algeria or in the North Sea is three times less polluting than from Alberta's oil sands' (Cardinal 2008), and 'well-to-wheels carbon footprint was [is] only 15% higher than conventional oil' (Macalister 2008) could be misleading given that they are based on these types of studies. Definitive conclusions about the relative GHG emissions performance of the different oil sands pathways cannot be drawn with the ranges of results presented in this paper.

Studies were found to vary in their boundaries, data quality, methods, and documentation. The studies have different strengths and weaknesses although there are a number of common issues that were discussed. The most complete and up-to-date studies have informed stakeholders of key issues associated with oil sands-derived fuel production and are a good starting point for future research. Based on our review, GHGenius (2008) has the most current and comprehensive oil sands pathways. The version of the model reviewed in this paper was released in August 2008 and the oil sands data has been improved compared to that in prior model versions. GHGenius could be further improved, however, with more transparency and better justification of default values. A significant advantage of both GREET (2008) and GHGenius is that they are valuable 'accounting tools' in that a user may input their own data and is not restricted to values in the model. In spite of this, additional research (data collection and model development) is needed in order to better characterize current and emerging technologies so as to inform industry and government decision making. Constructing reliable life cycle models of oil sands pathways is challenging for a variety of reasons, including limited data availability (and the proprietary nature of industry data), the rapid expansion of the industry, the unique and complex nature of each oil sands project, and the evolving technologies being applied in the industry. These challenges are reflected in the ranges of results presented in this paper but do not explain them all.

The uncertainties and inconsistencies discussed above are of concern for upcoming LCFS, which have binding life cycle based emissions targets and have large amounts of product sales, profits, and fines at issue. For these regulations to achieve their intended objectives, an improved understanding is needed of uncertainties in life cycle assessment (LCA) methods associated with transportation fuels, as well as uncertainty and variability in oil sands data so as to accurately portray oil sands pathways compared to a conventional crude baseline. Failure to acknowledge and resolve these issues will result in not achieving the intended regulatory outcomes, even though the 'letter of the law' may still be met. A concerted effort is needed to develop validated life cycle models that produce verifiable results sufficiently refined for supporting sound scientific and public policy decision making. A task force of industry, government, ENGO, consultancy, and academic representatives should be created to advise the development of a common platform for oil sands life cycle studies and to devise a plan to ensure that quality data are available for the studies, while respecting firm competitiveness. Based on our review, we highlight

the following key issues needing critical attention from industry, government, and the scientific, engineering, and policy research communities:

*Study documentation.* Future oil sands WTW studies should emphasize complete and transparent documentation. Guidance in this regard can be obtained from the International Organization for Standardization's 14048 technical specifications covering the documentation of life cycle data (ISO 2002).

*Generalizability of results.* Studies that aim to calculate a representative average GHG emissions intensity or a range of intensities for a single pathway such as SM&Up should consider a series of representative projects in developing such estimates and use common boundaries and methodologies to ensure their comparability.

*Data availability for current oil sands technologies.* The availability of high quality data must be addressed while ensuring that company competitiveness is not compromised. We suggest the usage of the data collected by the federal government under section 71 of the Canadian Environmental Protection Act (CEPA 2007). This idea is developed further in the supplementary information.

*Assessment of emerging technologies.* Once the intensities for current oil sands pathways are in place and reliable, it will be important to facilitate the investigation of the potential benefits (and/or tradeoffs) that could be generated by emerging technologies that the industry is investigating. Further analysis is required to assess the implications of switching from natural gas to 'bottom of the barrel' feedstock as well as different extraction approaches such as *in situ* combustion.

*Study boundaries.* Maintaining consistent boundaries in oil sands studies is key. Inputs and discharges associated with all direct (on-site) and major indirect (off-site) activities over the supply chain should be included, as well as transport activities. Construction and demolition of oil sands facilities should be investigated and, where warranted, should be included in life cycle studies.

*Accounting, allocation, and credit procedures.* Emissions intensities can be significantly impacted by the allocation and crediting methods applied to by-products and co-products (e.g., coke, sulfur, cogenerated electricity surplus). There has been little attention to these issues in the literature, hence the lack of prior discussion in this paper. However, thorough treatment of these issues will be required in future studies.

*Product properties.* Key product properties such as API gravity and sulfur content must be documented in studies. 'More highly upgraded products' should receive appropriate recognition.

*Uncertainty.* Model and parameter uncertainties associated with oil sands pathways should be clearly documented and reported quantitatively when supporting data are available. Both GHGenius (2008) and GREET (2008) have the capability of specifying probability distributions for input variables and running associated stochastic simulations. However, uncertainty results will only be as robust as the input data and assumed distributions (or ranges).

*Updating.* An explicit adaptive management strategy is needed whereby, as the state-of-the-art advances, new information is incorporated into the LCA framework or the regulatory

decision making process. Emphasizing an iterative and transparent process in LCFS, and more broadly in future studies, is key so that pathways may be updated in a straightforward manner.

We acknowledge that life cycle studies of oil sands pathways are complex, vary with technologies employed, reservoirs, etc, and that completing and documenting thorough and transparent studies is a challenge. However, key drivers are raising the bar with respect to acceptable life cycle studies. The life cycle field is well prepared to meet this challenge as the quality of studies has, on average, improved dramatically over the past 15 years with advances in theory, science, available data, and attention to more transparent and complete documentation. It is recommended that the research community develop common approaches for estimating oil sands pathway metrics to improve overall study quality, facilitate comparisons of results, and, importantly, to provide key inputs into decision making that has the potential to improve the life cycle environmental performance of the industry.

## Acknowledgments

We thank Natural Resources Canada, the Natural Sciences and Engineering Research Council, the Ontario Government Early Researcher Award, and the AUTO21 Network Centre of Excellence for financial support; Professor David Keith and Sarah Jordaan of the University of Calgary, and Martina Betkova and Jennifer McKellar of the University of Toronto for research support.

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