Atmospheric Environment 144 (2016) 111–123

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Estimating fugitive methane emissions from oil sands mining using extractive core samples

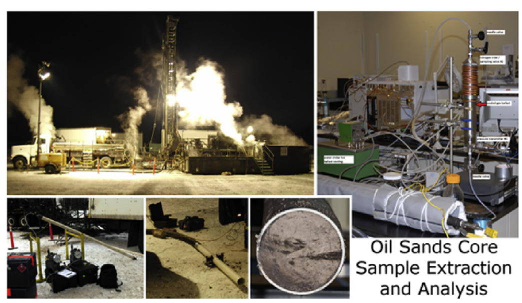
Matthew R. Johnson [a,*], Brian M. Crosland [a], James D. McEwen [a], Darcy B. Hager [b,†], Joshua R. Armitage [c], Mojgan Karimi-Golpayegani [c], David J. Picard [c]

[a] *Energy & Emissions Research Lab, Mechanical & Aerospace Engineering, Carleton University, Ottawa, ON, Canada*
[b] *Natural Resources Canada, CanmetENERGY-Devon, Devon, AB, Canada*
[c] *Clearstone Engineering Ltd., Calgary, AB, Canada*

HIGHLIGHTS

- Core samples were used to estimate fugitive CH_4 emissions from oil sands mining.
- Residual methane released when samples heated to relevant process temperatures.
- New emission factors imply 2015 mined Alberta oil sands fugitive $CH_4 \gtrsim$ 1.4–2.1 $MtCO_2e$.
- Routine drilling operations could be leveraged to improve emissions estimates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form
22 August 2016
Accepted 24 August 2016
Available online 26 August 2016

Keywords:
Oil sands
Fugitive emissions
Methane
Core sample
Mining
Emission factor

ABSTRACT

Fugitive methane emissions from oil sands mining activities are a potentially important source of greenhouse gas emissions for which there are significant uncertainties and a lack of open data. This paper investigates the potential of a control-system approach to estimating fugitive methane emissions by analyzing releasable gas volumes in core samples extracted from undeveloped mine regions. Field experiments were performed by leveraging routine winter drilling activities that are a component of normal mine planning and development, and working in conjunction with an on-site drill crew using existing equipment. Core samples were extracted from two test holes, sealed at the surface, and transported for off-site lab analysis. Despite the challenges of the on-site sample collection and the limitations of the available drilling technology, notable quantities of residual methane (mean of 23.8 $mgCH_4$/kg-core-sample (+41%/−35%) or 779 $mgCH_4$/kg-bitumen (+69%/−34%) at 95% confidence) were measured in the collected core samples. If these factors are applied to the volumes of bitumen mined in Alberta in 2015, they imply fugitive methane emissions equivalent to 2.1 $MtCO_2e$ (as correlated with bitumen content) or 1.4 $MtCO_2e$ (as correlated with total mined material) evaluated on a 100-year time horizon. An additional ~0.2 Mt of fugitive CO_2 emissions could also be expected. Although additional measurements at a larger number of locations are warranted to determine whether these emissions should be considered as additive to, or inclusive of, current estimates based on flux chamber measurements at the

* Corresponding author.
E-mail address: Matthew.Johnson@carleton.ca (M.R. Johnson).
† Dr. Darcy Hager died tragically in a motor-vehicle collision in July 2014. He is remembered as a generous collaborator and colleague.

http://dx.doi.org/10.1016/j.atmosenv.2016.08.073

mine face, these first-of-their-kind results demonstrate an intriguing alternate method for quantifying fugitive emissions from oil sands mining and extraction.

1. Introduction

Between 2008 and 2015, oil sands surface mining in Alberta, Canada increased by 45% from just over 400 Mt of mined material (containing 47 Mt of bitumen) in 2008 to 649 Mt of mined material (containing 75 Mt of bitumen) in 2015 (AER, n.d.). The continued expansion in mining operations has brought increased concern for environmental and climate issues specific to oil sands operations when compared to traditional oil and gas extraction methods. Such a comparison often requires comprehensive life cycle assessment to consider the potential range of emission sources and sinks as well as the various processes involved in the transformation of raw material into a useable end product (Bergerson et al., 2012; Brandt, 2012; Englander et al., 2013). Unfortunately, challenges in measurement and a lack of publicly available data on key sources complicate these types of analyses.

One potentially important source of greenhouse gas emissions from oil sands development is methane gas originating within the mined material, which can be released to the atmosphere during mining, transport, and preparation of the oil sands ore, and bitumen extraction from the ore. Simpson et al. (2010) performed airborne measurements over the Alberta oil sands mining region and saw enhancements of up to 8% over expected background methane levels. Other airborne (Howell et al., 2014; Liggio et al., 2016) and satellite-based assessments (McLinden et al., 2012) have shown significant enhancements in NO_2, SO_2, and secondary organic aerosol concentrations. Gordon et al. (2015) described an improved method to infer facility emission rates based on airborne measurement and used CH_4 and SO_2 measurements as examples. Their method showed good agreement with industry-reported data for SO_2 emissions, though a similar comparison to industry-reported CH_4 emissions was not performed. They estimated the CH_4 emitted from the Canadian Natural Resources Limited (CNRL) Horizon oil sands mining and upgrading facility to be 4 t/h during the time of their flights. The CNRL Horizon site includes a surface oil sands mine, ~12 km^2 tailings pond, bitumen extraction plant, on-site bitumen upgrading facility, and associated infrastructure (CNRL, 2016).

Currently, only one value for fugitive emissions of methane due to oil sands mining operations can be found in the open literature. Bergerson et al. (2012) modeled life cycle greenhouse gas emissions of oil sands development and used a fugitive methane emissions intensity range of 3–24 kgCO$_2$e/m^3-bitumen for surface mining recovery and extraction. No measurement details were provided other than to state that the "data were collected under nondisclosure agreements with industry companies." In a separate study, Brandt (2012) used a value of ~3 gCO$_2$e/MJ-bitumen-mined, attributed to the 1990–2008 Environment Canada National Inventory Report (NIR) (Environment Canada, 2010), for the combined contribution of venting, flaring, and fugitive emissions resulting from oil sands mining (i.e. not specific to methane). Digitization of Figure. 2-12 in the NIR (Environment Canada, 2010) yields a precise value of 4.1 gCO$_2$e/MJ, of which 1.4 gCO$_2$e/MJ comes from "fugitives". Unfortunately, more recent NIR do not segregate fugitive emissions originating from mined and in situ oil sands production.

Though not published in the open literature, at least one additional data source is available. While the originating study (Clearstone Engineering Ltd., 1997) prepared for Syncrude Ltd. by Clearstone Engineering, Ltd., of Calgary, Alberta in 1997 is proprietary (and not available to the authors for use in the present analysis), its results have been summarized and reported elsewhere (Golder Associates Ltd. and Conor Pacific Environmental Inc., 1998; WorleyParsons, 2009). Measurements of methane emissions from the mine surface were performed using the Isolation Flux Chamber (IFC) method (Conen and Smith, 1998; Klenbusch, 1986), wherein an open-bottom enclosure is placed on the surface where a gas flux is to be measured. Purified air is then flowed through the enclosure at a known rate, allowing the flux of various gaseous species from the enclosed surface to be determined via measurement of species concentrations in the air leaving the chamber.

The study performed for Syncrude included measurements for three Syncrude mines (the North mine, the West Base Mine and the East Base mine). Average methane flux values for the month of July were 2274 kgCH$_4$/km^2/day with a standard deviation of 33%. Measurements were only made for the month of July, though the published reports (Golder Associates Ltd. and Conor Pacific Environmental Inc., 1998; WorleyParsons, 2009) noted use of a "mass transfer model" to estimate year-round emissions based on average ambient temperatures and windspeeds. Compared to July, emissions were estimated to be 35% lower in the colder winter months and 60% greater during the windier months of May and September. The year-round mean was estimated to be within 5% of the July value of 2274 kgCH$_4$/km^2/day.

Emissions from oil sands mining are also estimated in the GHGenius model for lifecycle assessment of transportation fuels (Natural Resources Canada, 2016). Documentation for this model ((S&T)^2 Consultants Inc., 2013) states that "Suncor and Syncrude did some monitoring of these emissions in the late 1990s," perhaps referring to the Clearstone study, while noting that these mine-face emissions data are not separately reported. Instead, the GHGenius model bases its mine-face methane emissions on "estimates … from environmental assessments made prior to the start of mining." The documentation tabulates values inferred from three such assessments (i.e., 360 L/t of bitumen for the Imperial Oil Kearl site and 480 L/t of bitumen for the Total Joslyn and the Shell Jackpine Expansion sites), and then states that the GHGenius model uses a mine-face methane emissions value of 480 L/t of bitumen without further discussion ((S&T)^2 Consultants Inc., 2013).

Since the 1997 Clearstone study, no direct measurements of methane fugitive emissions from oil sands mine faces have been found or referenced, although it is understood that on-site measurements are regularly conducted. Since 2014 on-site measurements have been required as described in a Government of Alberta Ministry of Environment and Sustainable Resource Development directive (ESRD, 2014) issued under their Climate Change Policy Program. The directive provides "a standard minimum procedure for flux chamber measurements to quantify area fugitive greenhouse gas emissions from mine faces and tailings ponds at oil sands mines." The directive requires all oil sands mining facilities that are regulated under the Specified Gas Emitters Regulation and Specified Gas Reporting Regulation to quantify area fugitive emissions including carbon dioxide and methane. The requirements of the directive were to be implemented in 2014 with initial compliance