Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET™ Model

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1. Background

Life-cycle analysis of greenhouse gas (GHG) emissions of petroleum fuels pathways requires careful accounting of GHG emissions from both process fuel combustion and non-combustion activities associated with crude oil production, storage, transportation, refining operations, distribution of fuels and their end use by vehicles. CH4 emissions from Vented, fugitive, and incomplete flaring (VFF CH_4) and CO_2 emissions can be released to the atmosphere during crude oil production (US EPA 2014a). Argonne researchers previously estimated such emissions primarily based on the GHG emission inventory report by United States Environmental Protection Agency (EPA) and the volumetric amount of flared associated gas published by the National Oceanic and Atmospheric Administration (NOAA) (Wang 1996; Burnham et al. 2012) for incorporation into the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET™) model. We examined the GHG emissions estimates for both onshore and offshore petroleum production in the United States in 2012 as reported in EPA's latest GHG emission inventory report (US EPA 2014a), and compared them to the latest NOAA satellite remote sensing data on flare volumes (The World Bank 2014). The aim of this technical memorandum is to estimate the VFF CH_4 and CO_2 emissions per mmBtu of crude supplied to the U.S. market for incorporation in the GREET 2014 model. The scope of this memorandum includes the VFF CH_4 and CO_2 emissions associated with both U.S. and imported foreign crude oil production, except the VFF CH_4 and CO_2 emissions from Canadian oil sands production, which is provided in a separate document (Englander and Brandt 2014).

2. Data and methodology by the EPA

CH_4 emissions associated with crude oil production are released to the atmosphere as vented, fugitive, and undestroyed CH_4 from flaring. The EPA conducted comprehensive studies of CH_4 emissions from U.S. petroleum systems, and developed CH_4 emission factors for 33 venting and fugitive activities in crude oil production field operations (US EPA 2014a). On the other hand, the EPA approach estimates venting and fugitive CO_2 emission factors by multiplying existing CH_4 emissions factors by a conversion factor, which is the volumetric ratio of CO_2 content to CH_4 content for the particular stream. These volumetric ratios of CO_2 to CH_4 in emissions are presented in Table 1 for various activities. The amount of CO_2 in the crude oil stream changes as it passes through various equipment in the production operations. As a result, four distinct stages/streams with varying CO_2 contents are specified. The four streams are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil leaks downstream, and gas emissions from offshore oil platforms. The exception to this approach is the estimation of direct CO_2 emission factor from the flaring of associated gas (US EPA 2014a). Once the CH_4 and CO_2 emission factors are determined, the vented and fugitive CH_4 and CO_2 emissions from various petroleum production field activities are estimated using the corresponding activity data.

Table 1 Ratios of CO_2 to CH_4 volume in Emissions from petroleum production field operations

	Whole crude, post-separator	Associated gas	Tank flash gas	Offshore
CO_2/CH_4, by volume	0.052	0.020	0.017	0.004

EPA estimated the CH_4 emissions from flaring of associated gas by multiplying the total volume of flared associated gas by an estimated 98% flaring efficiency (i.e., assuming that 2% of the CH_4 in the associated gas is undestroyed CH4 that is released to the atmosphere). The CO_2 emissions from associated gas flaring, however, are not reported in the EPA's Emission Inventory Report.

3. Comparison of associated gas flared between the EPA and the NOAA data

EPA estimated the total volume of flared associated gas from various sources, including Energy Information Administration Monthly Energy Review and Interstate Oil & Gas Compact Commission Marginal Wells Report. We estimated that the total associated gas flared is about 0.52 billion cubic meters (BCM) by deduction from the undestroyed CH_4 emissions estimates by EPA and the chemical compositions estimates of the associated gas by the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) model shown in Table 2 (Brandt 2014). In addition, we estimated that the flared associated gas allocated to natural gas production by EPA is about 5.79 BCM (US EPA 2014a) based on the flaring CO_2 emissions (13,096 Gg) estimated by the EPA (US EPA 2014a) and the same associated gas chemical composition assumption that suggests a carbon content by mass of 70.3% and a density of 0.877 kg/m^3 as shown in Table 3. On the other hand, the NOAA satellite remote sensing data suggest a total flared associated gas volume of 7.1 BCM in the United States in 2011. Thus, the 2012 total flared associated gas suggested by the EPA is about 11% less than the 2011 NOAA data indicates. The EPA well-level data may be better representative of the actual flaring practices than the NOAA satellite flaring volume estimates that are directional rather than definitive (The World Bank 2014).Thus we adopted the EPA's estimation for CH4 emissions from flaring and estimated the flaring CO_2 emissions according to the flaring intensities suggested by the EPA.

In addition to domestic crude oil production, which accounted for 49.1% of the total crude oil consumption in 2012, the U.S. imported the remaining crude oil from Canada, Mexico, Middle East, Latin America, Africa, and rest of the world, as shown in Table 4. In particular, we differentiated the relative shares of Canadian oil sands and Canadian conventional oil production to estimate the VFF CH4 emissions associated with Canadian conventional oil production. Table 5 shows the oil sands receipts by the Petroleum Administration for Defense Districts (PADDs)

(Canadian Association of Petroleum Producers 2014). Furthermore, we explored the shares of Canadian oil sands and conventional crude imports of the total crude inputs to the U.S. refineries as shown in Table 6. As mentioned earlier, the VFF CH4 emissions for Canadian oil sands were estimated and documented elsewhere (Englander and Brandt 2014).

Table 2. Chemical composition of associated gas flared and vented during crude oil production

	Volumetric percentage
N_2	2
CO_2	6
C1	84
C2	4
C3	2
C4	1
H_2S	1

Table 3. Density (g/m^3), total carbon content, and the CO_2 and CH_4 contents by weight of associated gas flared and vented during crude oil production according to OPGEE

	OPGEE
Density, g/m^3	877
Total Carbon %	70.3%
CO2, wt%	13.4%
CH4, wt%	68.4%

Table 4. Crude oil mix in the U.S. in 2013 (EIA, 2014).

	U.S.	Imports					
		Canada	Mexico	Middle East	Latin America	Africa	Others
Crude oil domestic production and import[a]	2,719,584	941,236	310,402	730,192	549,484	234,711	55,455
Shares	49.1%	17.0%	5.6%	13.2%	9.9%	4.2%	1.0%

a: in thousand barrels per year

Table 5. The oil sands receipts by the Petroleum Administration for Defense Districts (PADDs)

	2013			2020		
	SCO[a]	Heavy crude[b]	Total oil sands	SCO	Heavy crude[c]	Total oil sands
PADD1	0	0	0	0	0	0
PADD2	252	1,144	1,190	200	1,670	1,705
PADD4	28	189	183	44	220	242
PADD5	34	30	59	67	77	137
PADD3	0	0	0	0	0	0
U.S.	314	1,363	1,431	311	1,967	2,084

a: Synthetic crude oil;
b: 82% of this heavy crudes including oil sands heavy and conventional heavy are oil sands heavy (Canadian Association of Petroleum Producers 2014);
c: 90.1% of this heavy crudes including oil sands heavy and conventional heavy are oil sands heavy (Canadian Association of Petroleum Producers 2014).

Table 6. The shares of imported Canadian oil sands and conventional oil of the U.S. total inputs to refineries in 2013 and 2020

	2013	2020
U.S. total inputs to refineries [MBPD]*	15,181	15,313
Total oil import from Canada [MBPD]	2,579	3,430
Oil sands share of total input to U.S. refineries	9.4%	13.6%
Conventional oil share of total input to U.S. refineries	7.6%	8.8%

* MBPD = 1000 bbl per day

Unlike the United States, there are no bottom-up available estimates of VFF GHG emissions from crude oil production in other countries or regions that are available to us. The only information for foreign oil wells is the volume of associated gas flared in the top 20 flaring countries as reported by NOAA. Table 7 shows that the top 20 flaring countries accounted for 121 of the world's total of 140 BCM in 2011, with the flaring intensity in m^3/bbl differing significantly among countries.

Table 7 shows that the U.S. flaring intensity reported by NOAA was about 3.4 m^3/bbl. When the flaring intensities of foreign countries are aggregated on their crude oil shares weighted average basis, the weighted average flaring intensity was about 3.8 m^3/bbl. Thus, the flaring GHG emissions in foreign countries are comparable to those in the U.S. Despite the probable differences in actual flaring and venting practices in oil fields among different countries and regions, we assumed that foreign crudes have the same VFF CH_4 and CO_2 emission factors as those for the U.S. crudes.

4. Results

For vented and fugitive CH_4 and CO_2 emissions, we adopted the EPA's estimates using a bottom-up Tier 2 approach for 12 activities associated with crude oil production. We note that the fugitive CH_4 and CO_2 emissions accounted for a minor portion of the total VFF emissions. The emission factors adopted by the EPA for many of these activities or equipment operations were expressed in standard cubic feet of CH_4 emissions per activity or equipment, e.g., 54,795 standard cubic feet of CH_4/platform for offshore platforms in shallow water, but without indicating the quantity of oil production per activity or equipment. Thus we were unable to estimate the emissions per mmBtu of crude produced from each activity or equipment operation directly. Hence, we applied another approach, shown in Equation (1), to estimate the average vented and fugitive CH_4 and CO_2 emissions per mmBtu of crude produced.

$$EF_{ANL} = \frac{\sum_i (EF_{EPA,i} \times A_i)}{(P \times LHV)} \tag{1}$$

Where: $EF_{EPA,i}$ is the EPA emission factor of CH_4 or CO_2 for activity or equipment item i;

A_i is the activity data or equipment count for activity or equipment item i;

P is the total crude oil production in barrels;

LHV is the lower heating value of crude oil in mmBtu per barrel, which is 5.446 mmBtu/barrel (Argonne National Laboratory 2014);

and EF_{ANL} is the ANL estimated emission factor of CH_4 or CO_2 in gram per mmBtu of crude production.

Table 7. Flaring intensities by country and the U.S. crude share by country reported by NOAA

	Flaring, billion cubic meters[a]	Crude oil production, 1000 bbls[b]	Flaring intensity, m3/bbl crude	Crude share[c]
U.S. Domestic	7.1	2,060,398	3.4	49.1%
Canada	2.4	941,236	2.5	17.0%
Mexico	2.1	310,402	6.8	5.6%
Middle East				
Iraq	9.4	959,582	9.8	2.2%
Saudi Arabia	3.7	4,111,454	0.9	8.7%
Oman	1.6	325,174	4.9	0.02%
Egypt	1.6	262,317	6.1	0.03%
Iran	11.4	1,538,098	7.4	0.0%
Qatar	1.7	706,784	2.4	0.0%
Latin America				
Venezuela	3.5	908,573	3.9	9.9%
Africa				
Nigeria	14.6	932,388	15.7	1.6%
Algeria	5	679,982	7.4	0.2%
Angola	4.1	656,958	6.2	1.3%
Libya	2.2	183,035	12.0	0.3%
Other countries/regions				
Russia	37.4	3,737,293	10.0	0.3%
Kazakhstan	4.7	597,999	7.9	0.0%
China	2.6	1,586,649	1.6	0.0%
Indonesia	2.2	373,169	5.9	0.1%
Uzbekistan	1.7	38,751	43.9	0.0%
Malaysia	1.6	228,481	7.0	0.0%
Rest of the world	19	10,920,777	1.7	3.6%

a: 2011 data from NOAA;

b: 2011 data from EIA;

c: 2013 data from EIA.

With the information on the U.S. crude oil production in 2012, which was 2,378 million bbls (United States Energy Information Administration 2014), we estimated the vented and fugitive CH_4 and CO_2 emission factors from U.S. crude oil production, as shown in Tables 8 and 9.

Table 8. Vented and fugitive CH_4 emission factors for various activities and equipment operations for crude oil production in 2012

Activity/Equipment	Emissions, Gg	Emission factors, g/mmBtu
	Vented emissions	
Oil Tanks	267	20.6
Pneumatic Devices, High Bleed	337	26.0
Pneumatic Devices, Low Bleed	98.4	7.6
Chemical Injection Pumps	50	3.9
Vessel Blowdowns	0.285	0.02
Compressor Blowdowns	0.187	0.01
Compressor Starts	0.419	0.03
Stripper wells	14.2	1.1
Well Completion Venting	0.222	0.02
Well Workovers	0.074	0.01
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	556	43.0
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	53.42	4.1
	Fugitive Emissions	
Oil Wellheads (heavy crude)	0.014	0.001
Oil Wellheads (light crude)	24	1.8
Separators (heavy crude)	0.012	0.001
Separators (light crude)	9.86	0.8
Heater/Treaters (light crude)	10.4	0.8
Headers (heavy crude)	0.008	0.0006
Headers (light crude)	3.30	0.3
Floating Roof Tanks	0.159	0.01
Compressors	1.81	0.1
Sales Areas	1.54	0.1
Battery Pumps	0.271	0.02
Pressure Relief Valves	0.132	0.01
Well Blowouts Onshore	2.85	0.2
	Voluntary Reductions	
Voluntary Reductions	**-45**[a]	-3.5
Aggregated	**1,387**	**107**

a In the 2014 inventory, EPA has moved the following reduction activities from the natural gas systems to the petroleum systems

Table 9. Vented and fugitive CO_2 emission factors for various activities and equipment operations for crude oil production in 2012

Activity/Equipment	Emissions, Gg	Emission factors, g/mmBtu
	Vented Emissions	
Oil Tanks	350	27.1
Pneumatic Devices, High Bleed	18.8	1.45
Pneumatic Devices, Low Bleed	5.49	0.42
Chemical Injection Pumps	2.79	0.22
Vessel Blowdowns	0.016	0.001
Compressor Blowdowns	0.01	0.001
Compressor Starts	0.023	0.002
Stripper wells	0.793	0.06
Well Completion Venting	0.012	0.001
Well Workovers	0.004	0.0003
Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	10	0.77
Offshore Platforms, Deepwater oil, fugitive, vented and combusted	0.96	0.07
	Fugitive Emissions	
Oil Wellheads (heavy crude)	0.001	0.0001
Oil Wellheads (light crude)	1.34	0.10
Separators (heavy crude)	0.001	0.0001
Separators (light crude)	0.55	0.04
Heater/Treaters (light crude)	0.475	0.04
Headers (light crude)	0.184	0.01
Floating Roof Tanks	0.023	0.002
Compressors	0.101	0.01
Sales Areas	0.219	0.02
Battery Pumps	0.039	0.003
Pressure Relief Valves	0.019	0.001
Well Blowouts Onshore	0.159	0.01
Total vented and fugitive CO_2	**392**	**30.2**

We estimated a flaring CH_4 and CO_2 emission factor of about 0.5 and 89.4 g/mmBtu of the U.S. crude oil produced, respectively, based on the volume of the associated gas flared at a flaring efficiency of 98%, which was about 0.52 BCM as estimated above, and based on the physical properties of the associated gas shown in Table 3. Table 10 summarizes the VFF CH_4 and CO_2 emission factors based on the EPA Report. With our assumption that foreign crudes have the same VFF CH_4 and CO_2 emission factors as those for the U.S. crudes, the total VFF CH_4 and CO_2 emission factors were estimated at 108 and 120 g/mmBtu, respectively, of all the crude oil processed in the U.S. refinery market in 2012. These estimates have been incorporated in GREET 2014.

Table 10. Vented, flaring, and fugitive CH_4 and CO_2 emission factors from U.S. crude oil production

	VFF CH_4, g/mmBtu of crude	VFF CO_2, g/mmBtu of crude
Venting emission factor	103	30
Flaring emission factor	0.5	89
Fugitive emission factor	4	0.2
Total VFF emission factor	**108**	**120**

5. Discussion

The EPA allocated a majority of flared volume of associated gas from oil and gas production in the U.S. to the natural gas production without consideration to the relative ratio of the oil and gas production by energy. Better clarification on the EPA data and methodology to draw the boundary between oil and gas production is warranted to accurately allocate the flares between crude oil production and natural gas production.

With the increase in shale oil and shale gas production, the previous EPA Tier 2 emission factors may be less representative of the VFF CH4 and CO2 emissions from hydraulically fractured well completions. Efforts to develop new emission factors for this source can improve the estimates of VFF emissions to be consistent with current industry practice. The newly compiled GHG emission reporting database called Greenhouse Gas Reporting Program (GHGRP) by the EPA provides facility-level information on GHG emissions from the oil and gas industry, among others, and can be helpful for updating the information on emissions from hydraulically fractured well completions, particularly when GHGRP starts to report activity data in 2015 (US EPA 2014b). Studies focusing on initial production data from Bakken, Eagle Ford, and other shale oil and shale gas fields can also help bridge the data gap. Despite a recent significant drop in foreign crude oil importation in the U.S., the VFF emissions of foreign crudes with high quality data from direct measurement and observations of venting, flaring, and fugitive activities associated with foreign crude oil production remains an outstanding issue to be addressed.

References

Argonne National Laboratory. 2014. "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model." https://greet.es.anl.gov.

Brandt, Adam. 2014. "OPGEE: The Oil Production Greenhouse Gas Emissions Estimator." https://pangea.stanford.edu/researchgroups/eao/research/opgee-oil-production-greenhouse-gas-emissions-estimator.

Burnham, Andrew, Jeongwoo Han, Corrie E. Clark, Michael Wang, Jennifer B. Dunn, and Ignasi Palou-Rivera. 2012. "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum." *Environmental Science & Technology* 46 (2): 619–27. doi:10.1021/es201942m.

Canadian Association of Petroleum Producers. 2014. "2014 Crude Oil Forecast, Markets and Transportation." http://www.capp.ca/forecast/Pages/default.aspx.

Englander, J, and A Brandt. 2014. "Oil Sands Energy Intensity Analysis for GREET Model Update." https://greet.es.anl.gov/publication-lca-update-oil-sands.

The World Bank. 2014. "Estimated Flared Volumes from Satellite Data, 2007-2011." http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTOGMC/EXTGGFR/0,,contentMDK:22137498~menuPK:3077311~pagePK:64168445~piPK:64168309~theSitePK:578069,00.html.
United States Energy Information Administration. 2014. "Crude Oil Production." http://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm.
US EPA, Climate Change Division. 2014a. "U.S. Greenhouse Gas Inventory Report." Reports & Assessments,. Accessed September 17. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html#fullreport.
———. 2014b. "Greenhouse Gas Reporting Program Home | US Environmental Protection Agency." Policies & Guidance. Accessed September 21. http://www.epa.gov/ghgreporting/.
Wang, M. 1996. "GREET 1.0 - Transportation Fuel Cycles Model: Methodology and Use." https://greet.es.anl.gov/publication-c4z3r4c2.