Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012

Supplement

Lena Höglund-Isaksson

Air Quality and Greenhouse Gases Program

International Institute for Applied Systems Analysis

A-2361 Laxenburg

Austria

Email: hoglund@iiasa.ac.at

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SI-1: Steps in the simulation of associated gas flows

<u>Step1</u>: Reported information on associated gas flows and strategies to amend incomplete data

EIA (2015a) provides country-specific statistics on oil and gas production for 106 countries producing oil and/or gas in the period 1980 to 2012. The same source provides for 67 countries statistics on the volumes of associated gas reinjected and vented or flared in the period 1990 to 2012 (not complete time-series for all countries). From the same source the volume of associated gas recovered for utilization is derived as the difference between reported volumes of natural gas marketed and dry natural gas produced. The total volume of associated gas generated in a country *i* in year *t* is taken to be the sum of these three sources:

$$A_{it} = A_{it}^{reinjected} + A_{it}^{utilized} + A_{it}^{vent\&flare} \qquad \text{Eq. (1)}$$

Production of three different hydrocarbons were identified as possible sources for the generated associated gas; natural gas, heavy oil and conventional oil. Oil from oilsand is here not assumed to generate associated gas (Johnson and Coderre, 2011).

Hence, total associated gas generated can also be defined as the sum of associated gas generated from natural gas, heavy oil and conventional oil production, i.e.,

$$A_{it} = A_{it}^{gas} + A_{it}^{heavy} + A_{it}^{conv} \; . \qquad \text{Eq. (2)}$$

For the simulations of associated gas flows, the attribution of total associated gas generated to the respective types of hydrocarbons produced is performed as follows:

First, the associated gas released from natural gas production is derived as:

$$A_{it}^{gas} = \frac{a^{gas}}{h_i^{gas}} Q_{it}^{gas} \qquad \text{Eq. (3)}$$

where a_i^{gas} is the associated gas fraction for natural gas expressed in PJ associated gas generated per PJ dry natural gas produced,

h_i^{gas} is the country-specific heat value of natural gas produced in PJ per bcm, and

Q_{it}^{gas} is the production of dry natural gas in PJ.

Country-specific heat values of natural gas and natural gas production data are taken from EIA (2015a). A default associated gas fraction for natural gas production of 0.03% has been adapted from Johnson and Coderre (2011) and applied globally.

Second, the associated gas released from heavy oil production is derived as:

$$A_{it}^{heavy} = \frac{a^{heavy}}{h_i^{oil}}(1-\gamma^{conv})Q_{it}^{oil} \quad \text{Eq. (4)}$$

where a_i^{heavy} is the associated gas fraction for heavy oil expressed in PJ associated gas generated per PJ heavy oil produced,

h_i^{oil} is the region-specific energy content of APG in PJ per bcm (see Table 1 of main paper),

Q_{it}^{oil} is the total production of crude oil in PJ from EIA (2015a), and

γ_i^{conv} is the fraction of conventional oil produced out of the sum of conventional and heavy oil produced.

Country-specific heat values of oil produced are taken from EIA (2015a). A default associated gas fraction for heavy oil production of 5.1% has been adapted from Johnson and Coderre (2011) and applied globally.

Finally, the rest of total associated gas generated is attributed to conventional oil production, such that:

$$A_{it}^{conv} = A_{it} - A_{it}^{gas} - A_{it}^{heavy} \quad . \quad \text{Eq. (5)}$$

The reported data on associated gas is not complete for all countries and years. Information on associated gas for the period 1980 to 1989 is completely missing and for a number of countries the time-series from 1990 to 2012 is incomplete. For the purpose of completing the reported data, I derive country- and year-specific associated gas fractions for conventional oil and associated gas recovery rates assumed applicable to both heavy and conventional oil production. I.e., the derived associated gas fraction is:

$$a_{it}^{conv} = \frac{A_{it}^{conv} \times h_i^{oil}}{\gamma^{conv} \times Q_{it}^{oil}}, \quad \text{Eq. (6)}$$

and the derived associated gas recovery rate is:

$$r_{it} = \frac{\left(A_{it}^{reinjected} + A_{it}^{utilized}\right)}{\left(A_{it}^{heavy} + A_{it}^{conv}\right)}. \quad \text{Eq. (7)}$$

The two parameters a_{it}^{conv} and r_{it} are taken to be specific to a certain country and year. a_{it}^{conv} is likely to vary for different geological structures and with the age of individual oil wells (Satter et al., 2007). r_{it} is likely to vary for managerial reasons as the well management will have different ambition levels for recovery due to various economic and environmental concerns. To fill in missing information, the derived levels of the two parameters a_{it}^{conv} and r_{it} have been copied over from the nearest preceding year for which reported information is available. For the period 1980 to 1989, the derived parameter estimates for year 1990 (or nearest year with available data) have been kept constant for the entire period back to 1980.

In this way, the country- and year- specific characteristics of the associated gas generation and its flows are preserved in the completion of the dataset to the furthest extent possible. For countries with completely missing information about associated gas in published sources, default factors apply assuming 20% for the associated gas fraction for conventional oil and 90% for the associated gas recovery rate. Table SI-1.1 provides an overview of the number of countries in each year that produce oil and/or natural gas and the number of countries for which information on associated gas is available from published sources.

Table SI-1.1: Overview of completeness of reported data. Unit: number of countries for which reported data is available.

Year	Oil production	Dry natural gas production	Associated gas data in EIA (2015a) database	Associated gas information for Russia from Kutepova et al.(2011)	Satellite images of gas flares available from NOAA (2011)
1980	69	62	22	n.a.	n.a.
1981	70	64	22	n.a.	n.a.
1982	71	66	24	n.a.	n.a.
1983	73	68	37	n.a.	n.a.
1984	73	68	34	n.a.	n.a.
1985	74	69	34	n.a.	n.a.
1986	77	69	33	n.a.	n.a.
1987	76	69	37	n.a.	n.a.
1988	76	68	34	n.a.	n.a.
1989	76	69	34	n.a.	n.a.
1990	76	69	48	n.a.	n.a.
1991	78	70	51	n.a.	n.a.
1992	90	84	51	n.a.	n.a.
1993	93	83	54	n.a.	n.a.
1994	93	84	54	n.a.	56
1995	93	85	55	n.a.	54
1996	92	85	55	n.a.	56
1997	92	85	55	n.a.	58
1998	94	87	56	n.a.	59
1999	94	86	57	n.a.	60
2000	94	87	56	n.a.	59
2001	94	86	58	n.a.	59
2002	94	86	60	n.a.	60
2003	95	87	61	n.a.	60
2004	95	89	63	n.a.	60
2005	95	89	64	n.a.	61
2006	97	92	66	1	61
2007	97	92	67	1	61
2008	97	93	67	1	60
2009	97	94	67	1	60
2010	97	94	68	1	60
2011	98	95	68	n.a.	n.a.
2012	98	93	64	n.a.	n.a.

Step 2: *Attribution of associated gas flows to recovery, flaring and venting*

Once the associated gas fractions a_{it}^{conv} and the gas recovery rates r_{it} have been derived and completed for all countries and years, the associated gas generated but not recovered can be derived as the difference between the volumes of associated gas generated and the volumes recovered. This unrecovered associated gas must for security reasons be either flared or vented. As discussed in Section 2.1 of the main paper, I use fixed factors from a comprehensive Canadian study (Johnson and Coderre, 2011) on the venting to flaring ratio of unrecovered associated gas for natural gas and heavy oil production. If v^{gas}, v^{heavy}, and v^{conv} denote the assumed fractions of unrecovered associated gas that are vented instead of flared from natural gas, heavy oil, and conventional oil production, respectively, then the volumes of associated gas that go to recovery, flaring and venting, respectively, can be derived for each hydrocarbon source, i.e.,

$$A_{it}^{gas;vent} = A_{it}^{gas}\, v^{gas} \ , \qquad \text{Eq. (8)}$$

$$A_{it}^{gas;flare} = A_{it}^{gas}(1 - v^{gas}) \ , \qquad \text{Eq. (9)}$$

$$A_{it}^{heavy;vent} = A_{it}^{heavy}\left(1 - r_{it}\right) v^{heavy}, \qquad \text{Eq. (10)}$$

$$A_{it}^{heavy;flare} = A_{it}^{heavy}\left(1 - r_{it}\right)\left(1 - v^{heavy}\right) , \qquad \text{Eq. (11)}$$

$$A_{it}^{conv;vent} = \frac{a_{it}^{conv}\gamma^{conv}Q_{it}^{oil}}{h_{it}^{oil}}\left(1 - r_{it}\right)v^{conv} \text{ , and} \qquad \text{Eq. (12)}$$

$$A_{it}^{conv;flare} = \frac{a_{it}^{conv}\gamma^{conv}Q_{it}^{oil}}{h_{it}^{oil}}\left(1 - r_{it}\right)(1 - v^{conv}) \ . \qquad \text{Eq. (13)}$$

Note that some of the oil produced in Canada also derive from oilsands. This has been considered in the estimations, however, no associated gas generation is accounted for during extraction of oil from oilsands (Jonson and Coderre, 2011). All associated gas generated from oil production is taken to come from either conventional or heavy oil extraction.

Step 3: *Calibration to satellite image estimates of gas flares*

For the period 1994 to 2010 NOAA (2011) provides country- and year specific estimates of the volumes of gas flared based on satellite images. The estimates have been documented in Elvidge et al. (2009). In a later study Elvidge et al., (2016) estimate gas flares from satellite images for the 20 top-producing oil and gas countries in year 2012. In the latter study they attribute the flared gas volumes to upstream or downstream oil and gas activities. By taking the volumes of gas attributed to downstream activities in 2012 and scaling them by production of oil, I attribute some of the volumes of gas flared estimated from satellite images for the period 1994 to 2010 to downstream activities. The remaining gas volumes are assumed to come from upstream oil and gas activities.

Assuming the estimates of upstream flaring from satellite images are reasonably accurate, then the associated gas flared as deriving from reported data should match the satellite estimates of flaring, i.e.,

$$A_{it}^{NOAA} = A_{it}^{gas;flare} + A_{it}^{heavy;flare} + A_{it}^{conv;flare} \,. \qquad \text{Eq. (14)}$$

If this relationship does not hold and we believe it should, then adjustments must be made to one or more of the parameters derived from the reported data. I identify three possible candidates for parameters likely to cause differences in flaring volumes:

1. The associated gas fraction a_{it}^{conv} derived from reported associated gas as fraction of conventional oil produced may be under- or over-stated,
2. The fixed Canadian venting to flaring ratios v^{gas}, v^{gheavy}, and v^{conv} may not be applicable globally, or
3. The gas recovery rate r_{it} for oil production may be under- or over-stated.

As the country-specific associated gas fractions are determined by external factors that are difficult to verify in any other way, I refrain initially from making adjustments to this parameter. To my (the author's) knowledge, the venting to flaring ratios measured at Canadian oil and gas wells by Johnson and Coderre (2011) are the only such measurements published. Without measurements of this parameter from other parts of the world, it is impossible to judge how representative they are for other regions. To refrain from speculations and in the hope that information will become available from other parts of the world in the future, I have kept the Canadian factors fixed in this study. The gas recovery rate is determined by managerial decisions at the wells and chosen here as the initial target parameter for calibration. Hence, the initial target is to find the gas recovery rate that satisfies an equilibrium between flaring volumes derived from reported data and estimated from satellite images, i.e.:

$$r_{it}^{calibr} = 1 - \frac{\left(A_{it}^{NOAA} - A_{it}^{gas;flare}\right)}{A_{it}^{heavy}(1-v^{heavy}) + A_{it}^{conv}(1-v^{conv})} \qquad \text{for all } 0 \leq r_{it}^{calibr} < 1. \qquad \text{Eq. (15)}$$

For countries and years for which $r_{it}^{calibr} < 0$, the flaring volumes will not match even when recovery rates are reduced to zero. For these observations -and only for them- I allow the total volume of associated gas generated from conventional oil production to exceed the reported volume until equilibrium between the flaring volumes derived from reported data and satellite images match. Hence, the volume of associated gas generated from conventional oil production then adjusts to:

$$A_{it}^{conv;calibr} = \frac{\left(A_{it}^{NOAA} - A_{it}^{gas;flare} - A_{it}^{heavy;flare}\right)}{(1-v^{conv})} \qquad \text{for all } r_{it}^{calibr} < 0. \qquad \text{Eq. (16)}$$

The respective volumes of gas vented and flared from conventional oil production becomes:

$$A_{it}^{conv;calib;vent} = A_{it}^{conv;calib}\ v^{conv} \qquad \text{Eq. (17)}$$

$$A_{it}^{conv;calib;flare} = A_{it}^{conv;calib}(1 - v^{conv})\ . \qquad \text{Eq. (18)}$$

The simulation of associated gas vented and flared from conventional oil production in Eq. (12) and (13) is reiterated using the calibrated recovery rates. Note that the data on gas flares estimated from satellite images only covers the period 1994 to 2010. The calibrated recovery rates obtained for year 1994 are therefore kept constant in years 1980 to 1993, while the calibrated rates obtained for year 2010 are kept constant for years 2011 and 2012.

SI-2. Detailed assumptions entering simulations of associated petroleum gas flows for year 2010

For transparency, this section shows in detail the information that enters the simulations of APG flows and subsequent methane and ethane emissions for year 2010 for a selection of countries producing at least 1000 PJ oil in that year. The first column of Table SI-2.1 presents country-specific assumptions about the relative contributions of different types of oil to total crude oil production, distinguishing between conventional oil (API>22^0), heavy oil (API<22^0), and oilsands. The second column presents assumptions about the fraction of crude oil produced off-shore (which is not used in simulations of associated gas flows but affects the emission factor for unintended leakage). Both the country-specific assumptions on the types of oil produced and the extent of off-shore production have been constructed by the author from information provided in the EIA Country Analysis Briefs (EIA, 2015b) and other sources (Meyer and Attanasi, 2003; Dusseault, 2001; Xiaofei et al., 2013; Santos et al., 2014). These assumptions are likely to be representative for oil production in the most recent years, however, due to lack of information on historical years, these assumptions have been kept constant throughout the analyzed period 1980 to 2012.

The third and fourth columns in Table SI-2.1 present the generation of APG as a fraction of the energy content of oil produced. The third column presents these fractions as they appear when derived directly from information provided in EIA (2015a) or, when unavailable, from EIA Country Analysis Briefs (2015b) or national sources (Kutepova et al., 2011). The fourth column presents the same fractions after calibration of the simulated volumes of associated gas flared to the volumes of gas flared estimated from satellite images by NOAA (2011).

The fifth column in Table SI-2.1 presents the fraction of APG recovered as it appears when derived directly from information provided in the EIA (2015a) database. The sixth column shows the same fraction after calibration of the APG recovery rate to match the simulated volumes of associated gas flared (from both oil and gas production) with the volumes of gas flared estimated from satellite images by NOAA (2011). As shown, globally 85 percent of APG generated is recovered for either reinjection or utilization when relying on the information published by EIA (2015a) and complementing with a national source for Russia (Kutepova et al., 2011), while the same fraction falls to 82 percent after calibration to volumes of gas flared as estimated from satellite images.

Table SI-2.1: Assumptions entering simulations of associated petroleum gas flows for year 2010. Table shows a selection of countries producing at least 1000 PJ oil in 2010.

Country	Assumptions entering simulations for year 2010					
	Types of hydrocarbon produced (% of crude oil production): conventional oil/ heavy oil/ oilsand	Off-shore production (% of crude oil production)	APG fraction for conventional oil in 2010		APG recovery rate 2010 (for conventional and heavy oil)	
	adapted from EIA (2015b)	adapted from EIA (2015b)	adapted from EIA (2015a)	after updates and calibration	adapted from EIA (2015a)	after updates and calibration
Azerbaijan	100/0/0	80%	25.7%	25.7%	90.1%	99.6%
Kazakhstan	100/0/0	20%	45.6%	45.6%	94.4%	84.3%
Russia	100/0/0	5%	17.0%	23%[b]	n.a.	53.7%[b]
Norway	100/0/0	100%	48.3%	48.3%	98.6%	99.0%
UK	100/0/0	100%	8.6%	8.6%	85.9%	79.5%
Algeria	90/10/0	0%	163.7%	163.7%	95.4%	94.5%
Egypt	100/0/0	10%	20.4%	20.4%	89.6%	62.5%
Libya	90/10/0	0%	17.9%	17.9%	74.1%	57.6%
Nigeria	100/0/0	20%	32.1%	32.1%	57.5%	44.3%
Angola	80/20/0	90%	11.5%	11.5%	26.5%	31.7%
Iran	100/0/0	33%	36.8%	36.8%	77.6%	81.1%
Iraq	100/0/0	0%	13.4%	13.4%	51.4%	20.3%
Saudi Arabia	85/15/0	20%	2.1%	20%[d]	n.a.	95.4%
Kuwait	100/0/0	0%	0.2%	20%[d]	n.a.	91.4%
Oman	100/0/0	0%	14.6%	14.6%	79.2%	58.7%
Qatar	100/0/0	0%	19.7%	19.7%	79.8%	84.1%
UAE	100/0/0	10%	24.4%	24.4%	96.6%	96.1%
Canada	40/10/50	11%	68.1%	68.1%	95.9%	92.5%
United States	100/0/0	7%	49.7%	49.7%	96.6%	98.2%
Mexico[a]	33/67/0	80%	2.4%	2.4%	n.a.	51.2%
Venezuela[a]	0/100/0	0%	29.9%	29.9%	87.0%	94.3%
Argentina[a]	20/80/0	0%	16.1%	16.1%	87.7%	96.2%
Brazil[a]	10/90/0	91%	7.3%	7.3%	76.6%	87.2%
Colombia[a]	5/95/0	0%	52.0%	52.0%	96.7%	97.2%
Ecuador[a]	50/50/0	0%	3.2%	5.6%[c]	n.a.	0%
China	100/0/0	15%	n.a.	20%[e]	n.a.	94.0%
Australia	100/0/0	100%	1.0%	2.0%[c]	n.a.	0%
India	100/0/0	80%	n.a.	2.7%	n.a.	30.3%
Indonesia	100/0/0	0%	34.9%	34.9%	67.4%	82.2%
Malaysia	100/0/0	100%	51.0%	51.0%	92.4%	89.3%
Rest of world	99/1/0	27%	35.6%	36.9%	75.3%	70.2%
World			32.5%	32.7%	84.7%	82.5%

[a] Due to its "foamy" characteristics, additional assumptions apply for Latin American heavy oil, see Section SI-4.2 for further details.

[b] Information reported for Russia to EIA (2015a) is incomplete, see Section 4.2.1 for further details.

[c] APG fractions adjusted upward to match simulated volumes of gas flared with flared volumes estimated from satellite images by NOAA (2011).

[d] APG fractions derived from EIA (2015a) statistics for Saudi Arabia and Kuwait are very small. Cross-checking with information available from EIA Country Analysis Briefs (EIA, 2015b) for Saudi Arabia, yield an APG fraction of about 20% in 2012. This fraction was used as representative for both Saudi Arabia and Kuwait for the entire analyzed period.

[e] No statistics reported for China to EIA (2015). A default associated gas fraction of 20% adopted whenever statistics are missing across all years for a country.

SI-3. Global and regional production patterns for crude oil and natural gas used in simulations

Figure SI-3.1 shows the development in global crude oil and dry natural gas production from 1980 to 2012 as used to drive methane and ethane emissions in the simulations. Country-specific information on the amounts of crude oil and dry natural gas produced are taken from the US Energy Information Agency (EIA, 2015a) international energy statistics for all 107 countries producing oil and/or gas in at least one year during the period 1980 to 2012. For the purpose of estimating methane emissions, it is of interest to split oil and gas production further by more detailed types of hydrocarbons. Further splits are therefore made to identify the amounts of conventional oil (API > 22º), heavy crude oil (API < 22º), crude oil extracted from oilsands, conventional natural gas, as well as the three unconventional natural gas types tight gas, coalbed methane (CBM), and shale gas. As the EIA international energy statistics (EIA, 2015a) does not provide production information in such detail, approximate country-specific fractions of conventional oil, heavy oil and oil from oilsands, respectively, have been constructed by the author as explained in Section SI-2. The relative fractions of the different types of unconventional gas produced have been taken from IEA (2011), where the fractions of tight gas, coalbed methane and shale gas are specified by country from year 2005 onwards. As no country-specific information prior to 2005 is found available for unconventional gas, no unconventional gas production is accounted for prior to that year. Figure SI-3.1 shows that crude oil production increased by 25 percent over the analyzed time period, while the production of natural gas more than doubled over the same period.

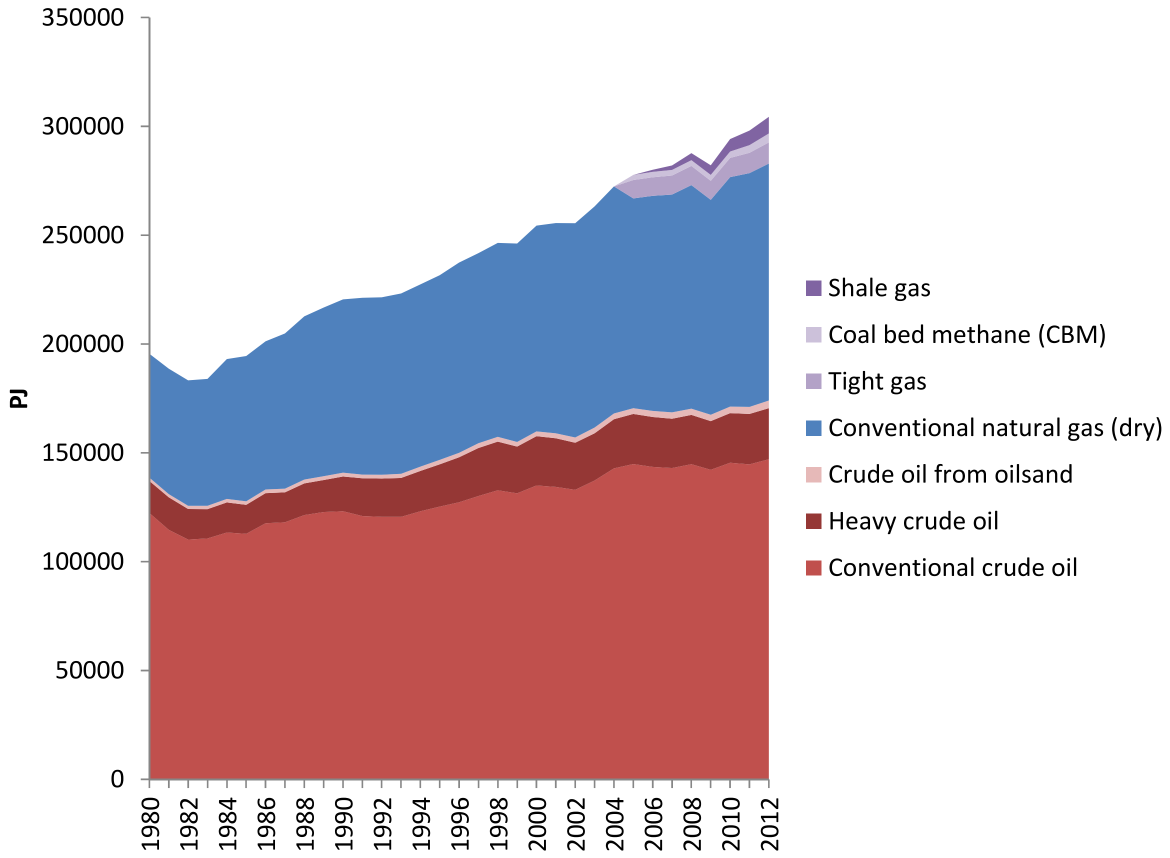

Figure SI-3.1: Global production of crude oil and natural gas by type of hydrocarbons 1980-2012.

Figure SI-3.2 shows production of crude oil and natural gas by world regions. A few major fluctuations in production levels are clearly visible at the regional scale. The sudden drop in oil production in the beginning of the 1980s in Saudi Arabia and other OPEC member countries reflects squeezes in supply undertaken in attempts to stabilize oil prices following the oil crises in the 1970s. The collapse of the Soviet Union in 1989 and 1990 meant that by the mid-1990s the region had seen crude oil production fall by 44 percent and natural gas production by 22 percent. The entire period from 1980 to 2012 displays strong increases in production in Africa, Latin America, and the Middle East outside of Saudi Arabia, while production in Europe peaked around the year 2000 and then dropped back to about the 1980 level by 2012. Oil and gas production in the United States declined by 23 percent between 1980 and 2005, but has since seen an increase in unconventional gas production putting the total energy content of oil and gas produced back at the 1980 level. It is possible that tight gas production, particularly in the United States and Canada, is underestimated for years prior to 2005 (and accordingly overestimated for conventional natural gas production) due to a lack of information in IEA (2011) on the amounts of unconventional gas produced prior to 2005.

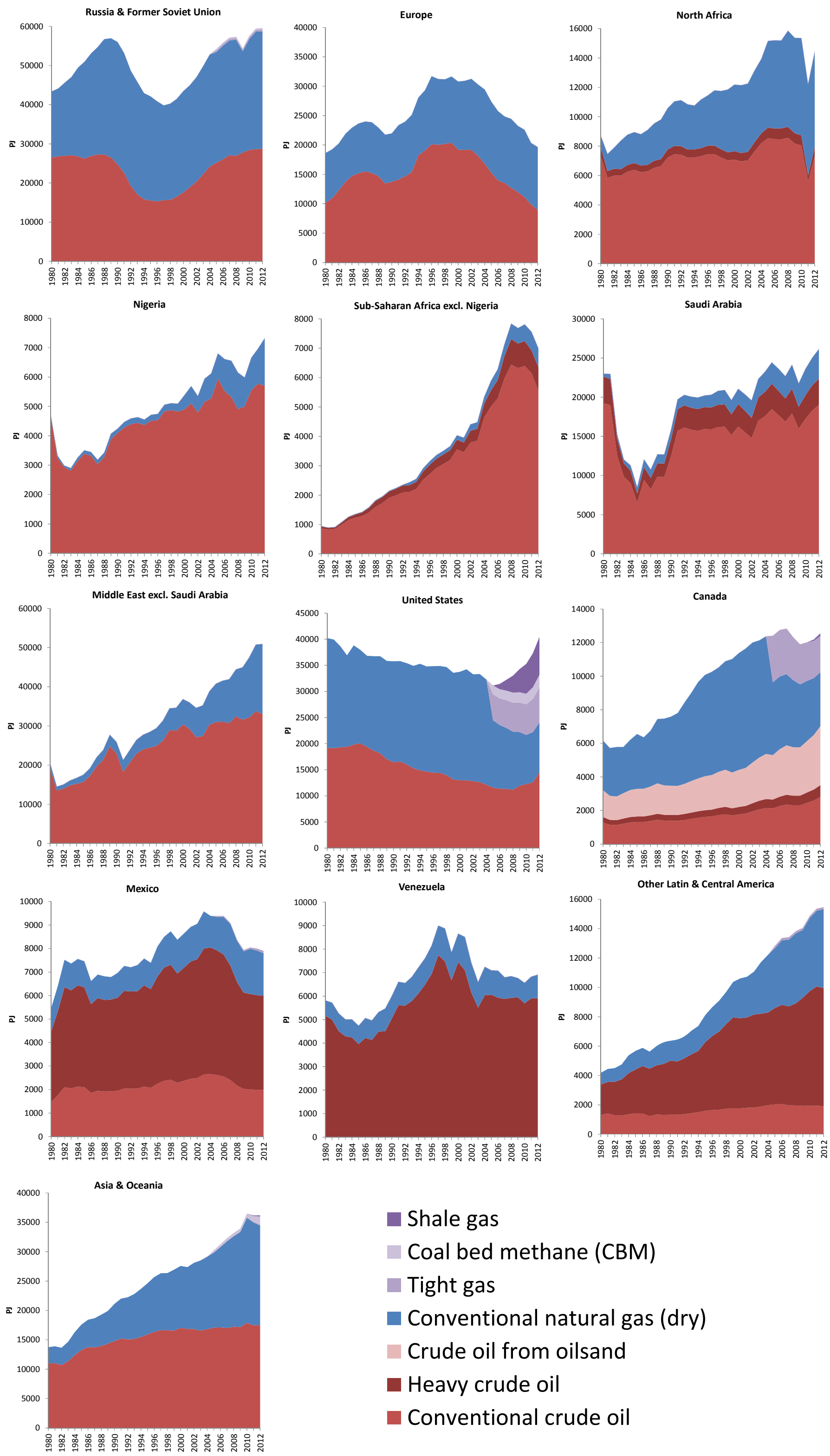

Figure SI-3.2: Oil and gas production (PJ) by world region and type of hydrocarbon as used to drive simulated associated gas flows. Note the difference in scales of the vertical axes.

SI-4. Region-specific considerations in the simulations of associated gas flows

The country-specific statistics on associated gas adopted from EIA (2015a) are incomplete or missing for a few key countries, which prompts for complementing this data with information from other sources. In addition, the application in the simulations of fixed factors for the fractions of unrecovered associated gas vented as opposed to flared based on the Canadian on-site measurements by Johnson and Coderre (2011), is a potential weakness of the analysis, however, necessary given the fundamental lack of information on these factors from other parts of the world. For some regions and periods, there are reasons to believe that the application of the Canadian-based fixed factors is particularly troublesome. This section discusses these information deficiencies at a regional level and how they have been addressed in the simulations of the associated gas flows.

SI-4.1. Russia

With Russia being the largest oil and gas producer in the world, the lack of consistent information on the quantities of associated gas generated, recovered and utilized presents a major source of uncertainty in the global estimates of methane emissions from oil and gas production. The EIA (2015a) statistics on associated gas generation in Russia is incomplete, reporting associated gas fractions corresponding to a few percentages of oil production and in absolute volume to a minor fraction of the flared volumes of associated gas picked up by NOAA (2011) from satellite images. In the simulations of associated gas flows for Russia, other sources than EIA (2015a) have been used. To understand the magnitudes of the overall generation of APG in Russia, information from Kutepova et al. (2011) was used. They report output of APG and APG utilization rates from 2006 to 2010 from all major oil producing companies in Russia (see the first ten columns of Table SI-4.1). Dividing the APG output by the APG utilization rate gives us a measure of the total volume of APG generated, which increases from 69.5 bcm in 2006 to 78.3 bcm in 2010. With such high recovery (i.e., utilization) rates, the volumes of gas flared or vented become relatively small at 19.1 bcm in 2006 and 21 bcm in 2010. Converting the volumes of APG generated to energy units (using heat value 47.656 PJ/bcm), the APG fraction falls to between 16 and 18 percent of the energy content of the oil produced (see fifth column of Table SI-4.2). However, there is an inconsistency between the low volumes of APG flared or vented that can be derived from the information provided in Kutepova et al. and the larger volumes of associated gas flared estimated by NOAA (2011) from satellite images. As shown in the sixth column of Table SI-4.2, flaring volumes estimated for Russia by NOAA amount to 50 bcm in 2006 and fall to 35 bcm in 2010. Being consistent with NOAA flaring volumes when applying the fractions of venting of unrecovered associated gas as reported by Johnson and Coderre (2011) and at the same time holding on to the volumes of APG recovered and utilized as reported for Russia by Kutepova et al., the total volume of APG generated would be considerably higher at 119 bcm in

2006 and 105 bcm in 2010 (see the seventh column of Table SI-4.2). With the higher level of APG generation, the corresponding APG fraction increases to 27 percent in 2006 and 23 percent in 2010, while recovery rates fall to 42 percent in 2006 and 54 percent in 2010. For the periods 1980 to 2005 and 2011 to 2012, a general assumption of APG generation corresponding to 25 percent of the energy content of oil produced has been adopted in the associated gas flow simulations for Russia and the Former Soviet Union.

Table SI-4.1: APG output and utilization rates as reported by Russian oil companies and presented in Kutepova et al., 2011 (p.15).

	APG output (bcm) (Kutepova et al., 2011)					APG utilization rate (% of APG) (Kutepova et al., 2011)					Derived APG generated (bcm)					Derived APG flared or vented (bcm)				
Oil company	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
1. Surgutneftegaz	15.6	15.0	14.8	14.0	13.9	94%	94%	95%	97%	96%	16.7	15.9	15.5	14.5	14.5	1.09	0.91	0.71	0.45	0.60
2. Rosneft	8.6	10.1	10.9	11.7	13.8	59%	60%	63%	67%	56%	14.6	16.7	17.2	17.5	24.6	5.98	6.65	6.35	5.76	10.76
3. TNK-BP	11.3	12.4	12.2	12.5	13.1	80%	68%	80%	84%	85%	14.2	18.1	15.3	14.8	15.5	2.86	5.73	3.13	2.31	2.38
4. Lukoil	6.7	7.6	7.4	8.2	8.6	75%	70%	71%	71%	77%	8.9	10.9	10.4	11.5	11.2	2.23	3.26	3.02	3.33	2.60
5. Gazprom Neft	4.5	4.9	4.6	4.3	4.4	45%	36%	47%	48%	55%	10.1	13.7	9.8	8.9	7.9	5.54	8.80	5.19	4.62	3.55
6. RussNeft	1.6	1.5	1.5	1.47[a]	1.5	71%	70%	61%	69%	70%	2.3	2.2	2.4	2.1	2.1	0.67	0.65	0.95	0.67	0.63
7. Slavneft	0.9	0.9	0.9	0.9	0.9	63%	68%	70%	71%	72%	1.5	1.4	1.3	1.3	1.2	0.56	0.43	0.39	0.37	0.33
8. Tatneft	0.7	0.7	0.8	0.8	0.8	95%	94%	95%	94%	95%	0.8	0.8	0.8	0.8	0.8	0.04	0.05	0.04	0.05	0.04
9. Bashneft	0.4	0.4	0.4	0.4	0.4	78%	82%	85%	86%	83%	0.5	0.5	0.4	0.4	0.5	0.11	0.08	0.07	0.06	0.09
Total Russia	50.4	53.6	53.4	52.8	57.3	73%	67%	73%	73%	73%	69.5	80.1	73.2	71.8	78.3	19.1	26.6	19.9	17.6	21.0

[a] No data for RussNeft was provided by Kutepova et al., 2011 for year 2009. For this assessment the 2009 value was replaced by the average values for 2008 and 2010.

Table SI-4.2: Information on Russian associated gas generation, utilization and flaring as reported in different sources of information.

	EIA (2015a)	Kutepova et al. (2011)		Derived from Kutepova et al. (2011)		NOAA (2011)	Results when calibrating flared gas to NOAA (2011), recovered gas to Kutepova et al. (2011), and venting and flaring of unrecovered APG consistent with Johnson and Coderre (2011)					
	Crude oil production	APG recovered	APG utilization rate	Derived APG generation	Derived APG fraction[a]	Associated gas flared	Derived APG generation	whereof AGP recovered	whereof AGP flared[b]	whereof AGP vented	Resulting APG fraction[a]	Resulting APG recovery rate
year	PJ	bcm	%	bcm	% of energy content of oil produced	bcm	bcm	bcm	bcm	bcm	% of energy content of oil produced	% of APG generated
2006	20939	50.4	72.6%	69.5	16%	50.0	119.2	50.4	49.2	20.1	27%	42.3%
2007	21369	53.6	66.9%	80.1	18%	52.3	125.4	53.6	51.5	21.0	28%	42.7%
2008	21187	53.4	72.9%	73.2	16%	42.0	110.8	53.4	41.1	16.8	25%	48.2%
2009	21501	54.2	75.5%	71.8	16%	46.6	118.3	54.2	45.9	18.7	26%	45.8%
2010	21951	57.3	73.2%	78.3	17%	35.2	105.2	57.3	34.3	14.0	23%	54.5%

[a] Heat content of Russian APG 47.656 PJ/bcm, see Table 1.

[b] APG flaring volumes consistent with NOAA estimates of gas flares after subtracting about 1 bcm per year to account for associated gas flared from natural gas extraction.

In the official reporting by Russia to the UNFCCC (2015), the implied methane emission factor for venting of associated gas is constant over the entire period 1990 to 2013 (10.35 kg CH_4 per 1000 m^3 oil produced), suggesting no development in venting and flaring patterns over the last two decades. It is known from other sources (PFC Energy and the World Bank, 2007; GGFR, 2013; Kutepova et al., 2011; Evans and Roshchanka, 2014) that such a development has taken place. Evans and Roshchanka (2014) describe how after the fall of the Soviet Union, venting first declined through increasing flaring and that since about 2005, flaring has been declining due to recovery and utilization of associated gas. The latter seems to be the result of government interventions. In a State of the Union address in April 2007, President Putin made recovery and utilization of associated gas a national priority, and in 2012, a fine was introduced on the release of polluting compounds from gas flares and venting of associated gas from oil production (Decree No.1148, Nov. 8 2012, of the Russian Federal Government). Hence, applying the default assumption from Johnson and Coderre (2011) of 29.1 percent of the unrecovered associated gas being vented instead of flared from conventional oil production would not reflect such a development. It would instead overstate the volume of gas recovered when calibrating recovery rates to match flaring to the satellite images of gas flares. Evans and Roshchanka (2014) do not provide any estimate of how high the venting fraction of unrecovered APG was before flaring started to increase and no other quantifications of this has been possible to find. What is known from the simulation results for the period 1994 to 2010, for which satellite images of gas flares are available, is that in 1994, about half of the APG generated was likely flared and half vented if no recovery of APG is assumed. As a Reference scenario for the situation in the Soviet Union up to year 1990 it is therefore assumed that there was no APG recovery and that 30 percent of the APG generated was flared while 70 percent was vented. As a sensitivity analysis, two alternative scenarios are created. In the first is assumed that 10 percent of the generated associated gas is flared while 90 percent is vented, and in the second scenario that 40 percent of the APG generated is flared while 60 percent is vented. The development in flaring and venting ratios between the assumed situation in 1990 and the calibrated ratios for 1994 is interpolated linearly in all three scenarios. Furthermore is assumed that over the period 1994 to 2000, the fraction of unrecovered APG flared successively increased to 71 percent, which is the level comparable to Canadian practice in 2002-2008 (Johnson and Coderre, 2011). Calibrating APG recovery rates to match flared volumes of APG to satellite images of gas flares for Russia from NOAA (2011) for years 1994 to 2010, result in recovered volumes of APG increasing from 5 bcm in 1994, to 21 bcm in 2000, and to 57 bcm in 2010. This corresponds to an APG recovery rate increasing from 7 percent in 1994, to 28 percent in 2000, and to 55 percent in 2010. The resulting associated gas flows for Russia and the former Soviet Union under the three alternative scenarios analyzed are illustrated in Figure SI-4.1.

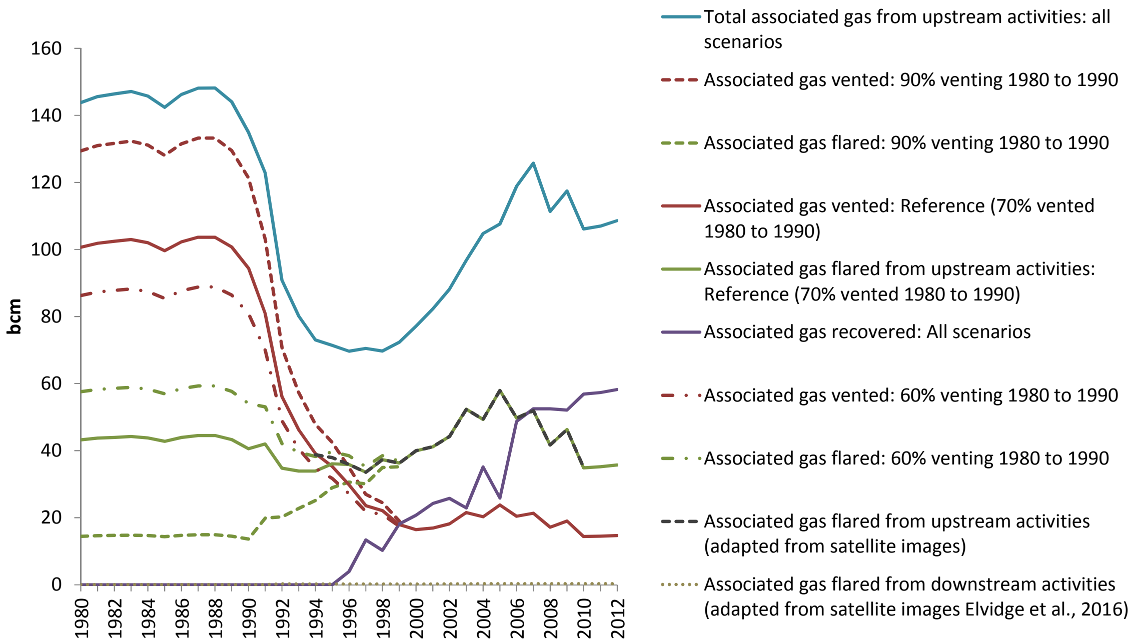

Figure SI-4.1: Simulation of associated gas flows in the Former Soviet Union (1980-1991) and within the Russian Federation (1992-2012) under different assumptions (60%, 70% or 90%) about the fraction of unrecovered APG that was vented instead of flared in the Soviet Union (1980 to 1990).

SI-4.2. Latin America

Oil producing countries in Latin America (i.e., Venezuela, Brazil, Colombia, Ecuador, Peru, Argentina, Chile and Bolivia) hold 61% of the recoverable reserves of heavy oil in the world (USGS, 2003). The oil produced is almost entirely of a high density expressed as API gravity below 22^0. The characteristics of the Latin American heavy oil differs from other heavy oils in the world in that its viscosity is lower than usual despite the high density (Dusseault, 2001; Xiaofei et al., 2013). This characteristic is often referred to as "foamy" oil because of the many gas bubbles that are trapped in the extracted oil, which contributes to enhancing its flowability and also reduces the volumes of free gas released (Xiaofei et al., 2013; Santos et al., 2014). Dusseault (2001) compares the characteristics of Venezuelan heavy oil to Canadian heavy and conventional oil and finds that the amounts of gas solved in the oil are "extremely similar" and yet the mobility of the Venezuelan heavy oil is 2 to 3 times higher than that of Canadian heavy oil. Hence, in terms of viscosity the ranges found for Venezuelan heavy oil deposits show more similarities to Canadian conventional oil than to Canadian heavy oil wells.

The specific characteristics of the Latin American heavy oil raises particular concerns about the applicability of the Canadian-based default factor used in the simulations for the generation of APG as fraction of the energy content of oil produced (adapted from Johnson and Coderre, 2011). Unfortunately, it has not been possible to find corresponding direct measurements for APG generation at Latin American heavy oil wells. In absence of additional information, the assumption made for the simulations of associated gas flows is that the heavy oil produced in Latin and Central American countries (Argentina, Brazil, Bolivia, Colombia, Chile, Ecuador, Mexico, Peru, Suriname and Venezuela) is more similar in terms of gas release to Canadian conventional than Canadian heavy oil and therefore treated in the simulations as if it were conventional oil produced.

SI-4.3. Middle East

When deriving the APG fractions from data reported to EIA (2015a) for Saudi Arabia and Kuwait, these turn out to be particularly small, corresponding to 0.02 and 0.2 percent of oil produced, respectively. By using information available from EIA Country Analysis Briefs (2015b) for Saudi Arabia, it is possible to derive an APG fraction of about 20 percent for the year 2012. This APG fraction was used as representative for Saudi Arabia and Kuwait for the entire analyzed period.

SI-4.4. China

No statistics on associated gas was reported for China to EIA (2015a). A default APG fraction of 20 percent was applied for China as well as for all oil-producing countries for which reported statistics on associated gas is completely missing (which except for China is the case mostly for countries producing relatively small quantities of oil and gas). The application of these default factors do not have a significant impact on global results since China’s oil production corresponds to about 5 percent of global cumulative oil production over the period 1980 to 2012, and the sum of the cumulative production for the other countries for which default factors were applied amounts to about one percent of the cumulative global oil production over the entire period (see Section 3.3 of the main paper).

SI-5. Methane emission factors for unintended leakage from oil and gas production.

Table SI-5.1 presents methane emission factors for unintended leakage for conventional and unconventional sources of oil and gas.

Table SI-5.1: Methane emission factors for unintended leakage from oil and gas production. Sources: IPCC (2006), Vol. 2, Tables 4.2.4 and 4.2.5 for oil and conventional natural gas production. Sources for unconventional gas are presented in Table SI-6.1.

		Developed countries		Developing/ transitional countries	
		This study	IPCC (2006) range	This study	IPCC (2006) range
		Gg CH_4/ PJ	Gg CH_4/ PJ	Gg CH_4/ PJ	Gg CH_4/ PJ
Oil production	Conventional oil on-shore	0.06	0.00004 to 0.094	0.12	0.00004 to 1.5
	Heavy oil on-shore	0.1863	0 to 0.3726	0.3726	0.1863 to 3.066
	Conventional and heavy oil off-shore	0.000015	0 to 0.00003	0.000015	0.000013 to 0.00013
	Oilsands	0.0542	0.0135 to 0.095	0.0542	0.018 to 0.135
Gas production	Conventional gas on-shore	0.06	0 to 0.12	0.12	0.1 to 2.15
	Conventional gas off-shore	0.00974	0 to 0.0195	0.00974	0.0058 to 0.034
	Unconventional: tight gas	0.326[a]	n.a.	0.326[a]	n.a.
	Unconventional: coal bed methane	0.114[a]	n.a.	0.114[a]	n.a.
	Unconventional: shale gas	0.85[a]	n.a.	0.85[a]	n.a.

[a]For references for unconventional gas leakage, see subsequent Section.

SI-6. Literature survey of unintended leakage from production of unconventional gas

Table SI-6.1 presents a survey of leakage rates measured from extraction of unconventional gas at different US locations. As shown, the range of leakage rates measured from shale gas extraction is very wide ranging from 1 to 17 percent of the gas produced. In the reference scenario, the assumption of an average leakage rate of 2 percent is adopted for shale gas, while 5 percent is adopted in an alternative scenario to show the sensitivity of this assumption in particular for emissions from oil and gas production in the USA. For tight gas and coal bed methane (CBM), the assumptions adopted are 1.63 and 0.57 percent average leakage rates, respectively.

Table SI-6.1: Literature survey of methane leakage from conventional and unconventional natural gas production.

Reference	Regional scope of emission factors	Upstream (excl. gas transmission and distribution)			
		Conventional	Shale	Tight	CBM
		% of gas produced			
Kirchgessner, 1997	USA	0.52%	n.a.	n.a.	n.a.
Howarth et al., 2011	USA & Russia	0.31% to 2.36%	2.21% to 4.26%	n.a.	n.a.
Skone et al., 2011 (current technology)	USA	1.06% (1.64% on-shore & 0.19% off-shore)	1.61%	1.63%	0.57%
Skone et al., 2011 (new technology)	USA	0.68% on-shore & 0.18% off-shore	1.61%	1.63%	0.57%
Petron et al., 2012	Colorado Front Range	n.a.	n.a.	2.3-7.7%	n.a.
Cathles, 2012a and Cathles et al., 2012b	USA	0.52% to 0.62%	"Comparable to conventional"		
Allen et al., 2013	USA (nationwide)	0.42%			
Karion et al., 2013	Uintah county, US	6.2 to 11.7%		n.a.	n.a.
Caulton et al., 2014	Marcellus shale PA, USA	n.a.	3% to 17%	n.a.	n.a.
Schneising et al., 2014	Bakken and Eagle Ford formations, USA	n.a.	10.1% ± 7.3% 9.1% ± 6.2%	n.a.	n.a.
Peischl et al., 2015	Haynesville, Fayetteville, Marcellus, PA, USA	n.a.	1.0-2.1%, 1.0-2.8%, 0.18-0.41%	n.a.	n.a.
This study	Global	0.52% (range 0.03% to 0.72%)	2% (or 5%)	1.63%	0.57%

SI-7. Simulated volumes of associated gas flows by world regions

Figure SI-7.1 shows simulated volumes of associated gas generated, recovered, vented and flared by world region over the period 1980 to 2012. Findings indicate that the collapse of the Soviet Union meant a sudden drop in oil production from 26500 PJ to 13200 PJ between 1988 and 1996, which translates into a simulated generation of associated gas halving from almost 150 bcm in 1988 to 86 bcm in 1996. Due to a lack of information about associated gas flaring and recovery in Russia in years preceding 1994 (and discussed in Section SI-4.1), the simulated recovery, flaring and venting patterns for the early years of the analyzed period are highly uncertain. From 1994 onwards, the calibration of recovery rates to match flaring with NOAA (2011) satellite images of gas flares indicate a steady increase in the recovery rate in Russia and the Former Soviet Union states from about 11% in the mid-1990s, 31% in 2005 and 63% in 2010. With increased recovery in Russia, gas flaring in the entire Former Soviet Union declines from 68 to 42 bcm between 2005 and 2010, while gas venting declines from 28 to 17 bcm over the same period.

The calibration of recovery rates to match flared volumes of associated gas with the satellite images of gas flares in years 1994 to 2010 indicate that recovery rates are high, i.e., close to or exceeding 90% in most countries by 2010. With such high rates of recovery, only very limited volumes of associated gas are flared and vented. Nigeria and most countries in sub-Saharan Africa appear to have increased recovery rates from very low levels over the analysed period, however, still in 2010 simulated recovery rates hoover around 50% which suggests scopes for further improvements. With higher recovery rates, less associated gas will be flared or vented, thereby contributing to the release of lower emissions of methane and ethane.

Figure SI-7.2 shows simulated as well as reported associated gas flows when countries have been grouped according to data availability. As shown in the upper right graph, for 67 countries reporting associated gas information to the EIA (2015a) database for at least one year, the simulated and reported volumes of associated gas generated are quite close in magnitude, in particular for the later part of the time period. The same can be said for the volume of associated gas recovered. The upper left graph compares the volumes of associated gas simulated for the Former Soviet Union states (including Russia) with the volumes reported to EIA (2015a) and by Kutepova et al. (2011) for the Russian Federation for the years 2006 to 2010. Although the volumes of associated gas recovered matches for the later years of the analyzed time period, the considerably higher simulated than reported volume of associated gas generated indicate underreporting of associated gas generation. The lower left graph shows a similar pattern with likely underreporting to EIA (2015a) of associated gas volumes generated for Saudi Arabia and Kuwait.

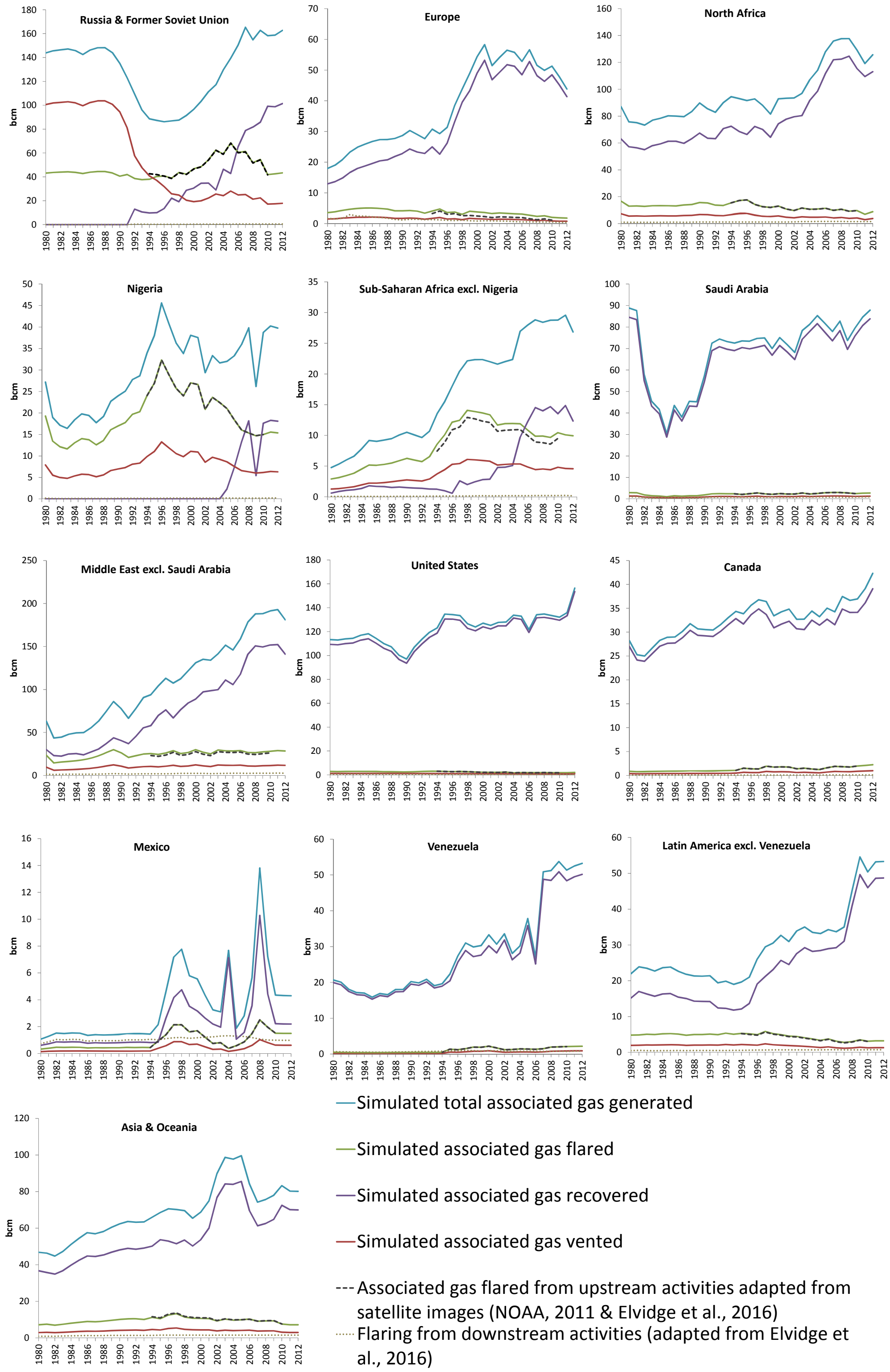

Figure SI-7.1: Simulated associated gas flows by world region. Note the difference in scales of the vertical axes.

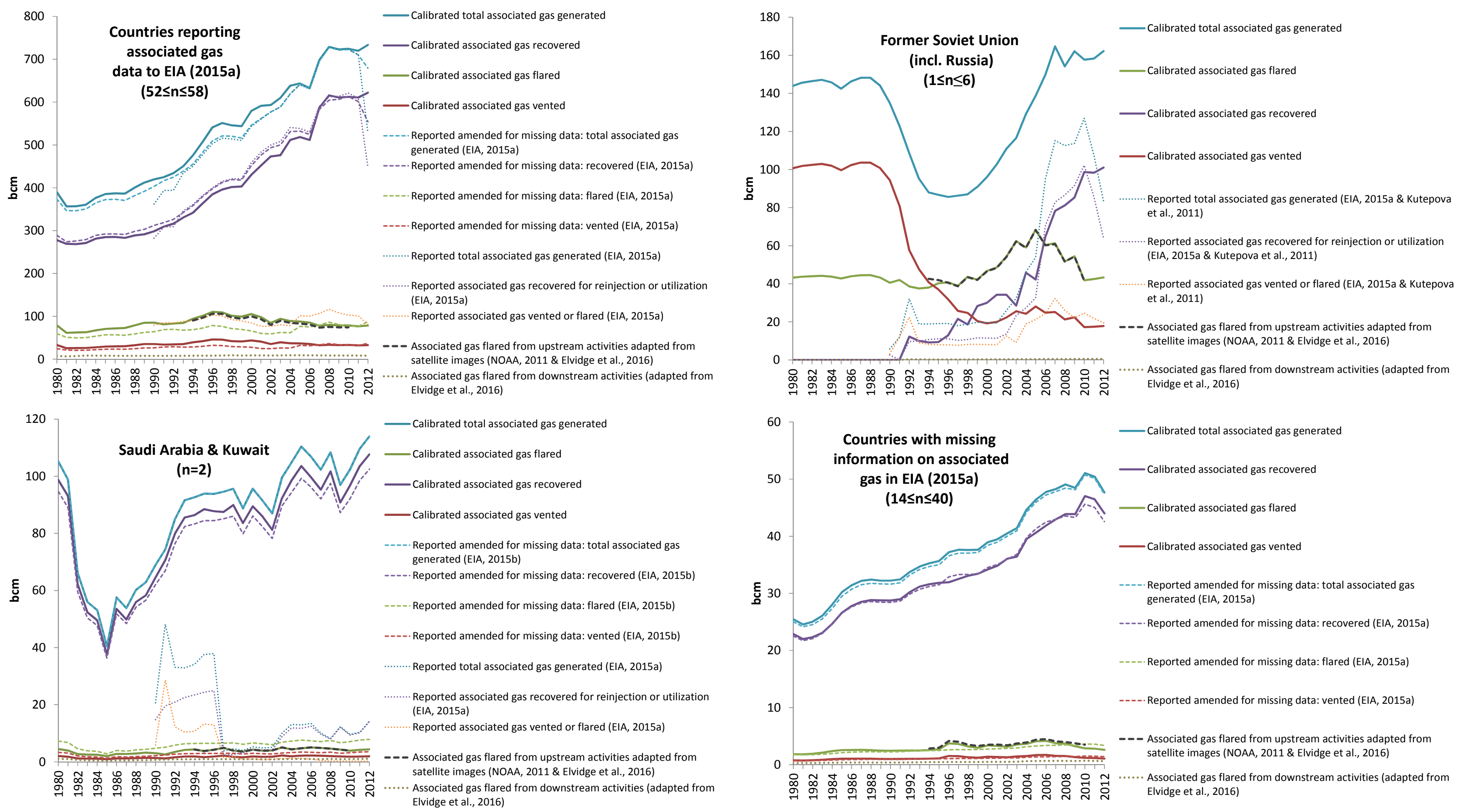

Figure SI-7.2: Reported, reported amended for missing information, and calibrated associated gas flows with countries grouped by data availability.

SI-8: Simulated ethane emissions from oil and gas production by world regions

Figure SI-8.1 presents the regional contribution to global ethane emissions from oil and gas production by world regions as they follow from country-specific simulations of associated gas flows. A similar pattern is shown over time as for methane emissions (see Figure SI-9.1), however, the relative contribution from the Soviet Union and Russia is less pronounced because of a low ethane content of 5.5 percent relative the ethane content of on average 15 percent in APG from Saudi Arabia and also assumed representative for other Arabian and African countries producing a mix of conventional and heavy oil (Al-Saleh et al., 1991). For other parts of the world, the average ethane content of APG is assumed to be about 5 percent (Johnson and Coderre, 2011; Ite et al., 2013; Russian-Energy, 2015; Elsenbruch, 2010).

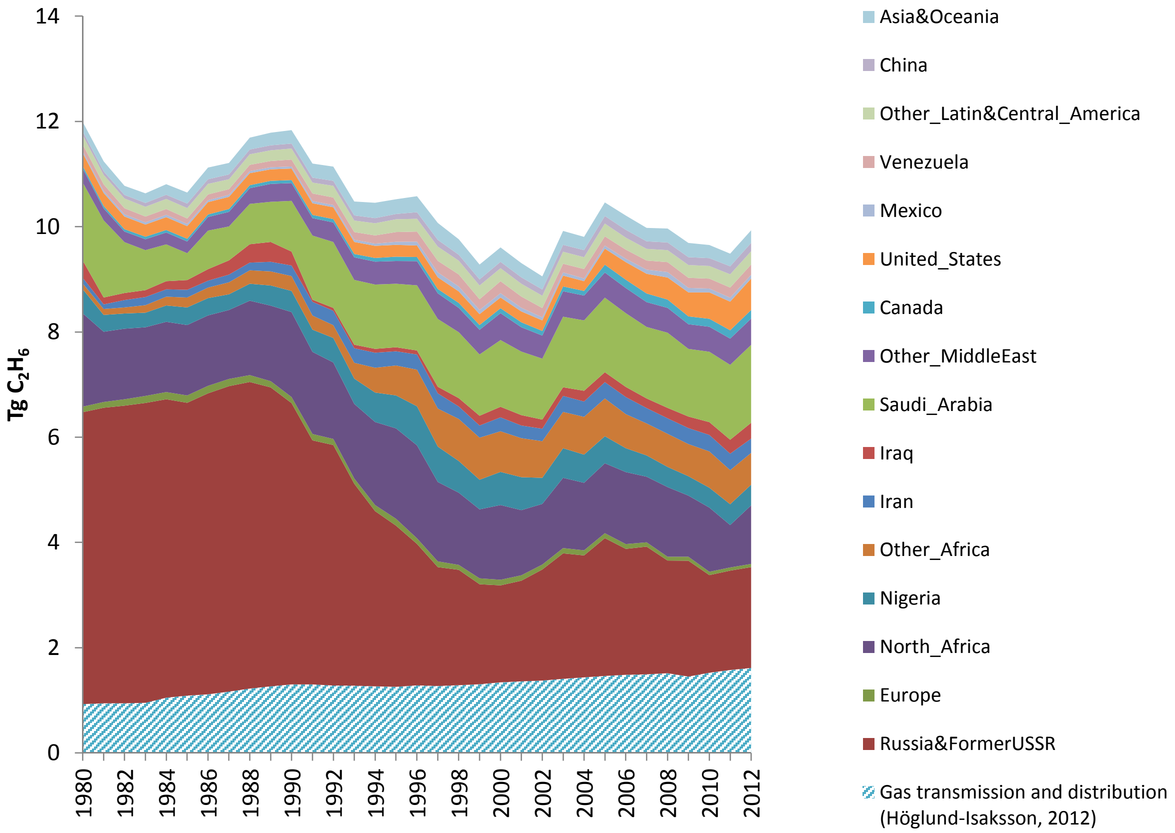

Figure SI-8.1: Simulated ethane emissions from global oil and gas systems 1980 to 2012 by world region.

SI-9. Simulated methane emissions from oil and gas production by world regions

Figure SI-9.1 shows the regional contribution of methane emissions to global methane emissions from oil and gas systems between 1980 and 2012 as resulting from the simulations of associated gas flows. After a small decline in the beginning of the 1980s following supply contractions by OPEC member countries, global methane emissions from oil and gas systems increase from 107 to 120 Tg CH_4 per year between 1982 and 1989, this time primarily driven by oil production increases in the Soviet Union. The dominating contribution of methane emissions from oil and gas production in the Soviet Union prior to 1990 stands out as exceptional, as well as the rapid decline in emissions following its collapse. This can offer a potential explanation to the slowdown in the growth of average methane concentration in the global atmosphere observed by top-down models for the period 1990 to 2005 (Nisbet et al., 2014).

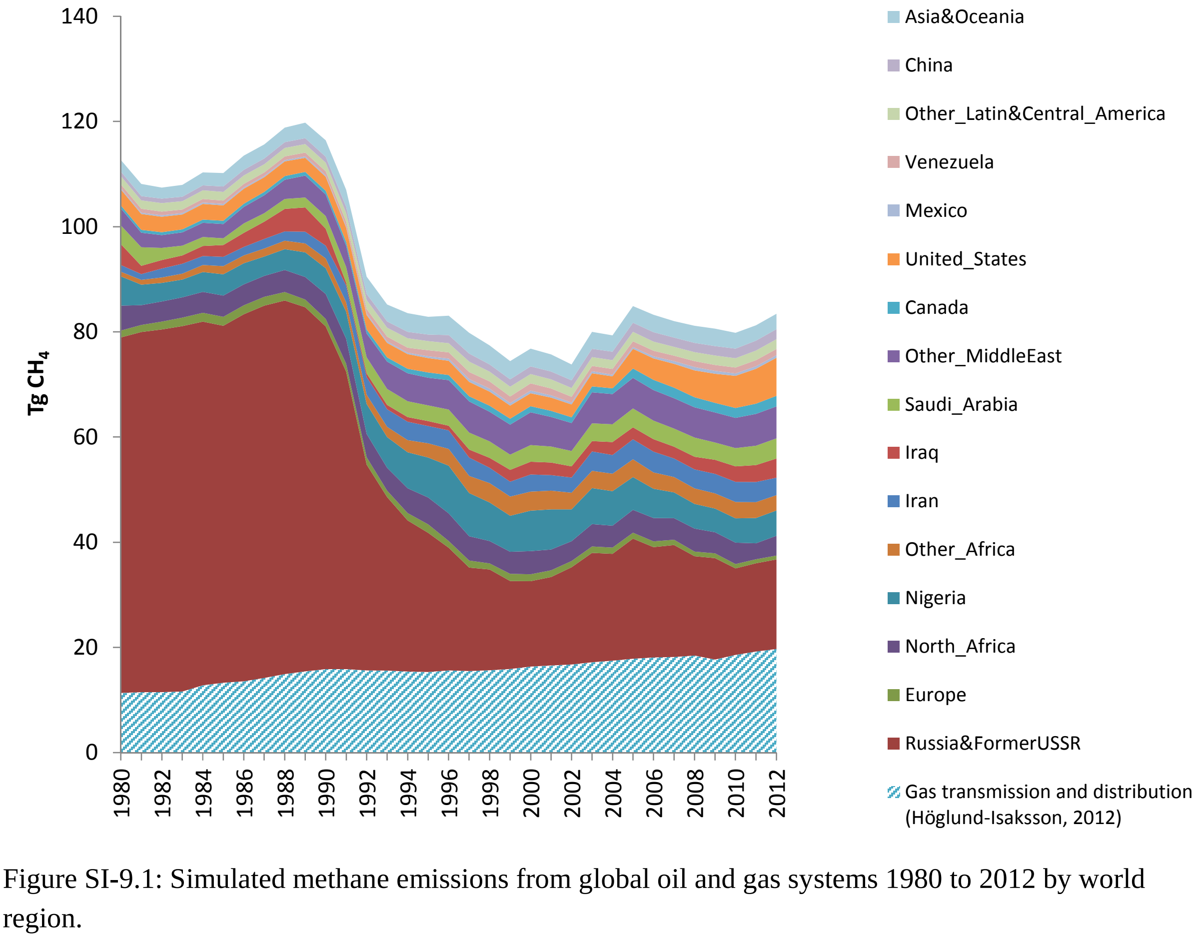

Figure SI-9.1: Simulated methane emissions from global oil and gas systems 1980 to 2012 by world region.

Figure SI-9.2 shows the contribution of different sources to methane emissions from oil and gas production (without downstream emissions) by world region. With the fall of the Soviet Union in 1990, annual emissions from Russia and the Former Soviet Union states decline rapidly from about 70 Tg CH_4 to 25 Tg CH_4 by the mid-1990s. Oil production in Europe and Sub-Saharan Africa is primarily off-shore and methane emissions from unintended leakage are therefore very low. Saudi Arabia is estimated to primarily emit emissions from unintended leakage because APG recovery rates are found to exceed 90 percent and emissions from APG venting are therefore relatively low. The United States and Canada emit relatively modest amounts of methane from APG venting and unintended leakage, however, depending on the actual leakage rate of shale gas extraction, methane emissions from this source risk increasing overall methane emissions from oil and gas production considerably in these countries. E.g., if the leakage rate from shale gas extraction is 2 percent of gas produced, US methane emissions from oil and gas systems increase from 2.2 to 6.1 Tg CH_4 between 2004 and 2010, while if the leakage rate is 5 percent, the same emissions increase to 9.4 Tg CH_4 in 2010. Performing more measurements to reduce the uncertainty presently surrounding leakage from shale gas extraction is urgently needed to better understand US methane emissions from oil and gas production (Brandt et al., 2014). Estimates of Canadian methane emissions from oil and gas production reveal the importance of the assumption about unintended leakage from tight gas extraction. With a leakage rate of 1.63 percent of tight gas produced (Skone et al., 2011), about half of Canadian methane emissions from oil and gas production come from tight gas production in recent years. Note that due to a lack of information on the production of unconventional gas in years preceding 2005, it is possible that methane emissions from unconventional sources are here underestimated for these years for the United States and Canada.

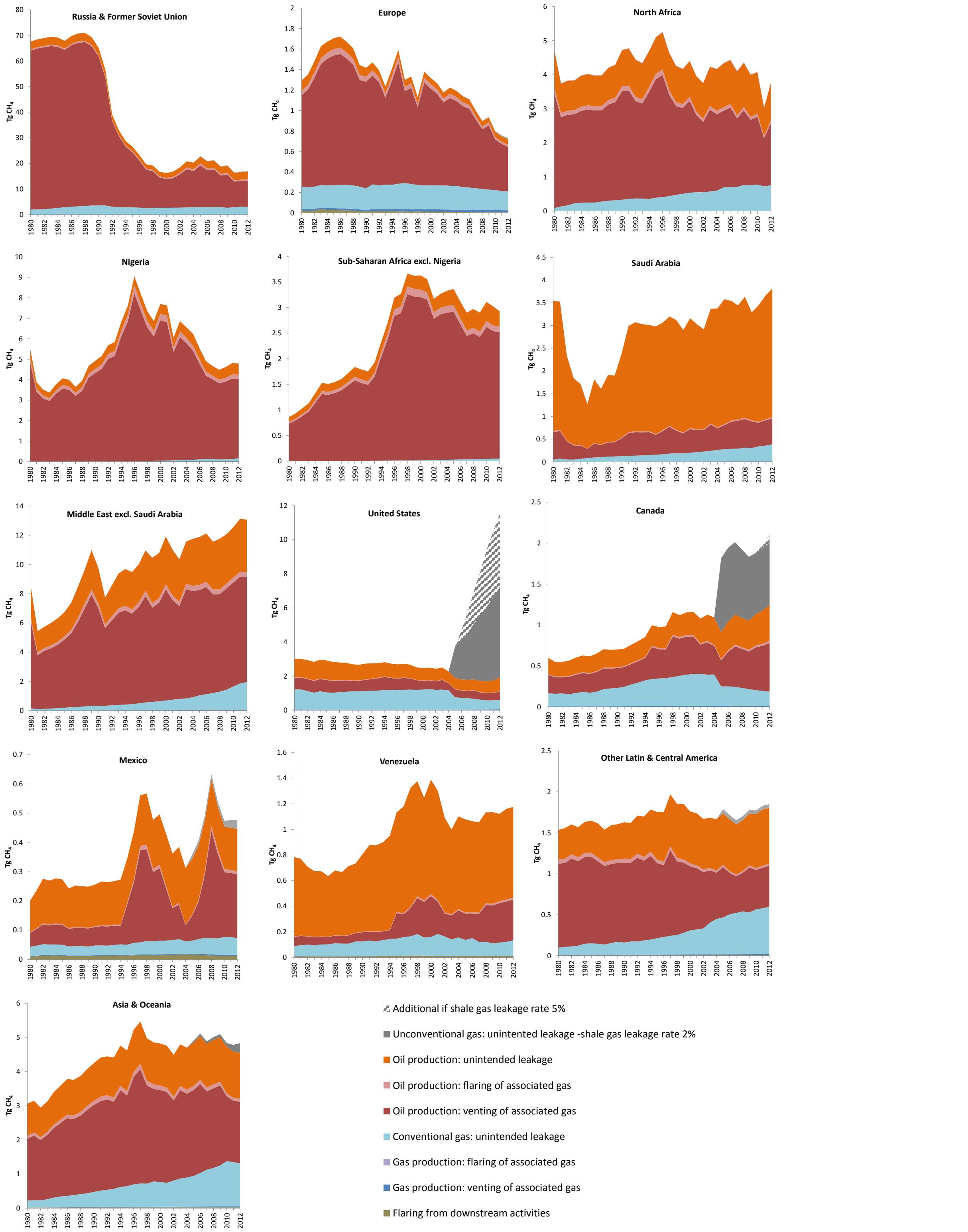

Figure SI-9.2: Simulated methane emissions from oil and gas production (without downstream emissions) by world region. Note the difference in scales of the vertical axes.

SI-10. Implied methane emission factors for oil and gas production –a comparison to published sources

Tables SI-10.1 and SI-10.2 present implied methane emission factors for crude oil and natural gas production as they follow for year 2010 from the simulations of associated gas flows performed in this study and in comparison to implied emission factors from other published sources. As shown in Table SI-10.1, the implied emission factor for global oil production is in this study estimated at 0.28 Gg CH_4 per PJ crude oil produced. This is at the higher end of the range of 0.02 to 0.35 Gg CH_4 per PJ suggested by IPCC (2006, Vol. 2, Tables 4.2.4 and 4.2.5) as default. It is also considerably higher than the global average emission factor of 0.13 Gg CH_4 per PJ oil produced used in the EDGAR v4.2 (2013) inventory. These differences can be referred to the use of different methodological approaches for deriving the implied emission factors, where EDGAR rely on a global application of default emission factors based on existing measurements from North American oil and gas fields (Olivier et al., 2012). Table SI-10.1 also presents implied emission factors reported by countries to the UNFCCC. It is noteworthy that Russia has recently increased the implied emission factor for methane from oil production in year 2010 by about ten times between the 2014 and 2015 submissions (UNFCCC 2014; 2015). In the 2015 submission the implied emission factor is 0.86 Gg CH_4 per PJ oil produced, which is 69 percent higher than the implied emission factor of 0.51 Gg CH_4 per PJ derived in this study for Russian crude oil production.

Table SI-10.2 shows that this study estimates the implied global emission factor for natural gas production in 2010 to 0.12 Gg CH_4 per PJ gas produced. This is within, but at the lower end, of the range from 0.07 to 0.41 Gg CH_4 per PJ gas produced suggested by IPCC (2006, Vol. 2, Tables 4.2.4 and 4.2.5) as default. Noteworthy is that between the 2014 and 2015 submissions to the UNFCCC (2014; 2015), Russia increased the implied emission factor for methane from natural gas production in year 2010 from 0.10 to 0.31 Gg CH_4 per PJ gas produced. The latter is higher than the implied emission factor of 0.12 Gg CH_4 per PJ gas produced derived in this study for Russian natural gas production in the same year.

Note that no comparison with the USEPA (2012) is possible as they do not report global emission estimates separately for oil and gas production.

Table SI-10.1: Implied emission factors for oil production sources in year 2010 as estimated in this study and in comparison to other published sources. Table shows a selection of countries producing at least 1000 PJ crude oil in 2010.

Reference	Country/ Region	Implied emission factors for oil production sources in year 2010			
		Venting of associated gas from oil production	Flaring of associated gas from oil production	Unintended leakage from oil production	Total emission factor for oil production sources
		Gg CH_4 per PJ crude oil produced in 2010			
Implied emission factors simulated in this study	Azerbaijan	0.0034	0.0002	0.0240	0.0276
	Kazakhstan	0.2622	0.0128	0.0960	0.3710
	Russia	0.3783	0.0184	0.1140	0.5107
	Norway	0.0185	0.0009	0.000015	0.0195
	UK	0.0677	0.0033	0.000015	0.0710
	Algeria	0.2249	0.0109	0.1453	0.3810
	Egypt	0.2857	0.0139	0.1080	0.4076
	Libya	0.2082	0.0093	0.1453	0.3628
	Nigeria	0.6821	0.0332	0.0960	0.8113
	Angola	0.2318	0.0086	0.0171	0.2575
	Iran	0.2654	0.0129	0.0804	0.3587
	Iraq	0.4068	0.0198	0.1200	0.5467
	Saudi Arabia	0.0256	0.0011	0.1263	0.1530
	Kuwait	0.0670	0.0033	0.1200	0.1902
	Oman	0.2284	0.0111	0.1200	0.3596
	Qatar	0.1167	0.0057	0.1200	0.2424
	UAE	0.0366	0.0018	0.1080	0.1464
	Canada	0.0847	0.0039	0.0621	0.1507
	United States	0.0341	0.0017	0.0558	0.0916
	Mexico	0.0364	0.0018	0.0240	0.0622
	Venezuela	0.0540	0.0026	0.1200	0.1767
	Argentina	0.0193	0.0009	0.1200	0.1402
	Brazil	0.0295	0.0014	0.0108	0.0418
	Colombia	0.0326	0.0016	0.1200	0.1542
	Ecuador	0.1754	0.0085	0.1200	0.3039
	China	0.0471	0.0023	0.1020	0.1514
	Australia	0.0790	0.0039	0.000015	0.0829
	India	0.0736	0.0036	0.0240	0.1012
	Indonesia	0.2415	0.0118	0.1200	0.3733
	Malaysia	0.2130	0.0104	0.000015	0.2234
	Rest of world	0.4108	0.0200	0.0833	0.5141
	World	0.180	0.0086	0.089	0.278
Other global inventories	EDGAR v4.2 (2013) global in year 2010	n.a.	n.a.	n.a.	0.131
	IPCC (2006) Tier 1, Vol. 2, Tables 4.2.4 and 4.2.5.[a]	0.086	0.0012	0.097	0.184
	IPCC (2006) Tier 1 Low end[a]	0.022	0.0003	0.001	0.023
	IPCC (2006) Tier 1 High end[a]	0.151	0.0021	0.194	0.347
National reporting of Annex 1 countries to UNFCCC	Russia (v2, 2015 submission)	0.279	0.0084	0.573	0.861
	Russia (2014 submission)	0.036	0.0077	0.040	0.084
	Kazakhstan (v1.3, 2014 submission)	0	0.00026	0.002	0.0027
	Norway (v3.1, 2014 submission)	0.0041	0.0000025	0.002	0.0063
	UK (v1.3, 2014 submission)	0.0021	0.0023	0.00074	0.0051
	Canada (v1.1, 2014 submission)	0.110	0.0006	0.042	0.152
	United States (v1.1, 2014 submission)	(no separate reporting by source)			0.113
	Australia (v3, 2015 submission)	0.040	0.016	0.003	0.059

[a] Global weighted average using IPCC default factors when adopting the assumptions from this study for fractions of conventional/heavy oil produced, off-shore/on-shore production, and developed/developing countries.

Table SI-10.2: Implied emission factors for natural gas production sources in year 2010 as estimated in this study and in comparison to other published sources. Table shows a selection of countries producing at least 1000 PJ natural gas in 2010.

Reference	Country/ Region	Implied emission factors for gas production sources in year 2010			
		Venting of associated gas from gas production	Flaring of associated gas from gas production	Unintended leakage from gas production[a]	Total emission factor for gas production sources
		kt CH4 per PJ dry gas produced in 2010			
Implied emission factors simulated in this study	Russia	0.0019	0.000058	0.1183	0.120
	Turkmenistan	0.0020	0.000058	0.0318	0.034
	Uzbekistan	0.0020	0.000058	0.0318	0.034
	Netherlands	0.0022	0.000058	0.0097	0.012
	Norway	0.0019	0.000058	0.0097	0.012
	United_Kingdom	0.0018	0.000058	0.0097	0.012
	Algeria	0.0018	0.000058	0.1200	0.122
	Egypt	0.0019	0.000058	0.1090	0.111
	Nigeria	0.0019	0.000058	0.0979	0.100
	Iran	0.0019	0.000058	0.0836	0.086
	Saudi_Arabia	0.0019	0.000058	0.0979	0.100
	Oman	0.0019	0.000058	0.1200	0.122
	Qatar	0.0018	0.000058	0.1200	0.122
	United_Arab_Emirates	0.0019	0.000058	0.1090	0.111
	Canada	0.0019	0.000058	0.1604	0.162
	United_States	0.0019	0.000058	0.2140	0.216
	Mexico	0.0019	0.000058	0.0406	0.043
	Argentina	0.0019	0.000058	0.1385	0.141
	Trinidad_and_Tobago	0.0019	0.000058	0.1200	0.122
	China	0.0019	0.000058	0.1107	0.113
	Australia	0.0018	0.000058	0.0212	0.023
	India	0.0019	0.000058	0.0334	0.035
	Indonesia	0.0018	0.000058	0.1200	0.122
	Malaysia	0.0019	0.000058	0.0097	0.012
	Pakistan	0.0023	0.000058	0.1200	0.122
	Thailand	0.0020	0.000058	0.1200	0.122
	Rest of world	0.0019	0.000058	0.0859	0.088
	World	0.0019	0.000058	0.1151	0.117
Other global inventories	EDGAR v4.2 (2013) global in year 2010	(not reported separate for gas production)			n.a.
	IPCC (2006) Tier 1, Vol. 2, Tables 4.2.4 and 4.2.5.[b]	n.a.	0.000015	0.242	0.242
	IPCC (2006) Tier 1 Low end[b]	n.a.	0.000011	0.073	0.073
	IPCC (2006) Tier 1 High end[b]	n.a.	0.000017	0.412	0.412
National reporting of Annex 1 countries to UNFCCC	Russia (v2, 2015 submission)	0	0.00006	0.311	0.311
	Russia (2014 submission)	0.000	0.00064	0.101	0.102
	Kazakhstan (v1.3, 2014 submission)	n.a.	n.a.	0.226	0.226
	Norway (v3.1, 2014 submission)	0	0.00016	0	0.00016
	UK (v1.3, 2014 submission)	0.0074	0.00074	0.00145	0.010
	Canada (v1.1, 2014 submission)	0.033	0.00005	0.043	0.075
	United States (v1.1, 2014 submission)	(no separate reporting by source)			0.131
	Australia (v3, 2015 submission)	0.021	0.0012	0.015	0.037

[a] Assuming leakage rate for shale gas is 2% of natural gas produced.

[b] Global weighted average using IPCC default factors when adopting assumptions of this study for off-shore/on-shore production, developed/developing countries, and conventional/unconventional gas.

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