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LETTER

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

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Abstract

Existing bottom-up emission inventories of methane from global oil and gas systems do not satisfactorily explain year-on-year variation in atmospheric methane estimated by top-down models. Using a novel bottom-up approach this study quantifies and attributes methane and ethane emissions from global oil and gas production from 1980 to 2012. Country-specific information on associated gas flows from published sources are combined with inter-annual variations in observed flaring of associated gas from satellite images from 1994 to 2010, to arrive at country-specific annual estimates of methane and ethane emissions from flows of associated gas. Results confirm trends from top-down models and indicate considerably higher methane and ethane emissions from oil production than previously shown in bottom-up inventories for this time period.

1. Motivation

Production of crude oil and natural gas gives rise to methane emissions, partly as a result of intended flaring and venting of associated gas released for security reasons during oil extraction, and partly due to unintended leakage along the production process chain from well head to upgrading and storage (IPCC 2006, volume 2, chapter 4). Existing bottom-up inventories of methane emissions from global oil and gas systems do not well explain the top-down trends in methane concentrations observed in the atmosphere (Kirschke *et al* 2013, Nisbet *et al* 2014, Hausmann *et al* 2016). This study recognizes that the emission factors that relate to venting and flaring of associated gas released during oil and gas extraction likely vary considerably across different oil and gas fields in the world, for geological as well as for managerial reasons (Satter *et al* 2007). A novel approach is used to quantify and attribute methane and ethane emissions from global oil and gas production, combining country-specific information from published sources with inter-annual variations in observed flaring of associated gas from satellite images, to arrive at country-specific annual estimates of methane and ethane emissions from flows of associated gas. The approach also allows for source attribution of methane emissions to oil or gas production, which has been considered difficult to achieve by top-down models because both sources release the same isotopes of methane (Brandt *et al* 2014). To further verify estimated methane emissions, corresponding ethane emissions from oil and gas production are derived in parallel. Compared to the atmospheric lifetime of 12 years for methane, ethane's shorter atmospheric lifetime of a few months, together with its sources being predominantly fossil in origin, make ethane a better tracker for year-on-year fluctuations in emissions from global oil and gas systems (Schwietzke *et al* 2014).

2. Method

2.1. Simulation of associated gas flows

Associated gas is a compound with a high methane content released at the well head as oil or natural gas is pumped to the surface. It is primarily generated during crude oil production and then referred to as associated petroleum gas (APG). Very limited amounts are released from natural gas wells (Johnson and Coderre 2011). The associated gas is flammable and must for security reasons be disposed of either through recovery, venting or flaring. If recovered, it can be reinjected to increase the well pressure or utilized as a

Table 1. Assumptions on the composition and heat value of APG used in simulations.

Hydro carbon	Russia and Former Soviet Union	Saudi Arabia and other Arabian and African countries producing a mix of conventional and heavy oil	Latin America	Canada	Default for rest of world	PJ energy per bcm of gas
	vol%	vol%	vol%	vol%	vol%	PJ/bcm
CH_4	81.0%	62.77%	50%	86%	86%	38
C_2H_6	5.5%	15.07%	5%	4%	4%	64
C_3H_8	6.6%	6.64%	5%	5%	5%	95
C_4H_{10}	4.0%	2.40%	5%	3%	3%	125
C_5H_{12}	1.4%	0.00%	0%	1%	1%	149
C_6H_{14} and heavier	0%	1.12%	0%	0%	0%	220
CO_2	0.5%	12%	35%	1%	1%	0
Other (N_2, H_2S etc)	1.0%	0%	0%	0%	0%	0
Sum	100%	100%	100%	100%	100%	
PJ per bcm	47.7	45.3	33.2	45.2	45.2	
References	Russian Energy 2015	Al-Saleh *et al* 1991	Elsenbruch 2010	Johnson and Coderre 2011; Ite and Ibok 2013		Demirel 2012

source of energy. As such, it can be utilized on site or transported to consumers provided the necessary gas pipeline infrastructure is in place (Hulbak and Røland, 2010).

This section describes the steps taken to simulate associated gas flows from every country in the world producing oil and/or gas in the period 1980 to 2012. A formal presentation of these steps is available in section SI-1 of the supplementary material.

The country- and year-specific features of the associated gas flows are captured through two key parameters; the associated gas fraction and the gas recovery rate. The associated gas fraction is derived as the ratio between associated gas generated and oil or gas produced expressed in energy content terms. It is expected to be country- and year-specific and primarily determined by geological conditions and well age (Satter *et al* 2007). Country-specific data on oil and gas production and volumes of associated gas recovered for reinjection, and vented or flared are taken from the US Energy Information Administration (EIA 2015a). Approximate estimates of volumes of associated gas recovered for utilization are taken to be the residual between volumes of marketed and dry natural gas produced. The total volume of associated gas generated is taken to be the sum of gas recovered, flared and vented. The energy content of associated gas is derived by considering the region-specific hydrocarbon compositions presented in table 1.

The gas recovery rate is derived as the fraction between the volumes of APG recovered and generated, expected to be country- and year-specific, and determined by managerial decisions, e.g. enhancing well pressure through gas reinjection or enhancing gas recovery for economic or environmental reasons.

The information on associated gas flows from EIA is incomplete with gaps in the time-series for some countries and completely missing data for 1980 to 1989 (see table SI-1.1 of the supplementary material). To preserve the country-specific features when filling data gaps, derived associated gas fractions and gas recovery rates have been copied from the nearest preceding year with available data and kept from year 1990 back to 1980. For Russia, Saudi Arabia and Kuwait, complementary information on associated gas from other published sources is used (see section SI-4 of the supplementary material), while for China and 38 countries with very limited production volumes, default assumptions apply assuming an associated gas fraction of 20% and a gas recovery rate of 90%. A sensitivity analysis is presented in section 3.3.

The associated gas fractions can be expected to differ for natural gas, heavy oil, and conventional oil production, respectively. Johnson and Coderre (2011) continuously measured recovery, flaring and venting of associated gas from 18203 oil and gas wells in the Canadian province of Alberta between 2002 and 2008. From detailed information provided for the year 2008 by Johnson and Coderre (2011), the author has derived associated gas fractions for conventional oil, heavy oil and natural gas, respectively, shown in table 2. The attribution of associated gas generation to natural gas and heavy oil production is made by adopting the Canadian fractions as fixed. The split of reported oil produced into heavy and conventional oil is described in section SI-3 of the supplementary material. Heavy oil is defined as oil with an American Petroleum Institute (API) gravity less than 22, with the exception for 'foamy' heavy oil produced in Latin and Central America, which has characteristics relevant for associated gas generation that makes it more similar to Canadian conventional than Canadian heavy oil (Dusseault 2001). Foamy heavy oil is therefore treated as conventional oil in the associated gas simulations (see section SI-4.2 of the supplementary material).

Table 2. Recovery, venting and flaring rates from oil and gas wells in the province of Alberta in 2008.

Variable	Source	Conventional oil	Heavy oil[c]	Natural gas
Production[a]	Johnson and Coderre (2011)	184 M barrels	214 M barrels	133 bcm
Associated gas fraction (% of production)	Derived by author from information in Johnson and Coderre 2011	35.5%[b]	5.1%	0.03%
Associated gas (% of associated gas)	Johnson and Coderre (2011, extracted from figure 1 and converted to fractions by the author)	100%	100%	100%
whereof recovered (% of associated gas)		97.1%	85.8%	0%
whereof flared (% of associated gas)		2.07%	1.74%	60%
whereof vented (% of associated gas)		0.85%	12.4%	40%
Venting ratio (% of flared/vented)	Derived by author from information in Johnson and Coderre 2011	29.1%	87.7%	40%

[a] In addition, the province of Alberta produced 264 M barrels of oil from oilsands in 2008.
[b] Not used in simulations. Instead, reported country-specific associated gas fractions and gas recovery rates were used for conventional oil.
[c] Johnson and Coderre mention in the text that this refers partly to crude bitumen but that '...in this context crude bitumen is believed to be predominantly heavy oil.'

Once attribution to natural gas and heavy oil production is completed, the remaining reported associated gas is attributed to conventional oil production to derive country- and year- specific associated gas fractions.

A serious limitation of the EIA data on associated gas flows is that only the sum of associated gas vented or flared is reported. Attribution to flared or vented is crucial for estimating methane and ethane emissions. In contrast to venting, flaring means almost all hydrocarbons in the gas oxidize to carbon dioxide. Johnson and Kostiuk (2002) measure an average combustion efficiency of 98% for gas flares. This is the flaring efficiency when the flaring device is up and running, however, Johnson and Coderre (2011, 2012) measured frequent instances of venting of associated gas with volumes of gas vented similar to those flared. To the author's knowledge, this is the only study available where the volumes of associated gas vented and flared have been measured industry-wide for a larger geographic area over a longer period of time. In the last row of table 2, the author has converted information on associated gas flows from Johnson and Coderre (2011) to 'venting ratios' by dividing the gas measured as vented by the volumes of gas not being recovered. Noteworthy, the fraction of unrecovered APG vented instead of flared is considerably higher for heavy than conventional oil. The Canadian Association of Petroleum Producers (CAPP 2002, p. 3–1) states that 'Because of the low volumes of gas associated with primary heavy oil casing gas, the gas is typically vented directly to atmosphere', which may offer an explanation. Because of a complete lack of measurements of venting ratios from other parts of the world, the Canadian ratios are applied globally. A sensitivity analysis is included in section 3.3.

In a final step, the derived flaring volumes are calibrated to the volumes of gas flared estimated from satellite images. The latter use low light imaging data from the Defense Meteorological Satellite Program (DMSP) described in Elvidge *et al* (2009) with flare estimates downloaded from NOAA (2011). The satellite estimates are country- and year- specific and cover 61 countries with almost complete times-series from 1994 to 2010. To control for the contribution from downstream activities, gas flares are adjusted using information from Elvidge *et al* (2016) for year 2012 (see section SI-1 of the supplementary material).

If we accept the satellite estimates of gas flares as reasonably accurate (see section 3.3 for a discussion), the author identifies three parameters as plausible candidates for causing discrepancies in flaring volumes between the two sources; the reported volumes of associated gas generated and/or the reported gas recovery rates may be under- or over-stated, or the Canadian fixed venting ratios may not be applicable to other world regions. In the choice between these parameters, priority is initially given to keeping the reported volume of associated gas generated fixed since it depends on highly variable external factors that are difficult to verify in any other way. Venting ratios of unrecovered associated gas are likely to vary between countries but here held fixed, because the complete absence of information from other countries than Canada, makes it difficult to speculate about reasons for a regional variation. The gas recovery rate is primarily determined by managerial decisions and chosen as the most suitable parameter to target in the calibration. Hence, the initial target is to find the gas recovery rate that satisfies equilibrium between derived gas volumes flared and volumes flared estimated from satellite images. Should equilibrium not be attained with less than the calibrated recovery rate turning negative, then the total associated gas generated is allowed to increase until equilibrium is restored.

For Russia, the volumes of gas reported by Kutepova *et al* (2011) as flared or vented in 2006 to 2010 (see section SI-4.1 of the supplementary material) appear substantially under-reported. The total volume of APG generated is therefore allowed to increase provided it satisfies the fixed Canadian venting ratios. This is illustrated for year 2010 in figure 1. For the Former Soviet Union and Russia in the period prior to 2000, Evans and Roshchanka (2014) describe how venting was first significantly

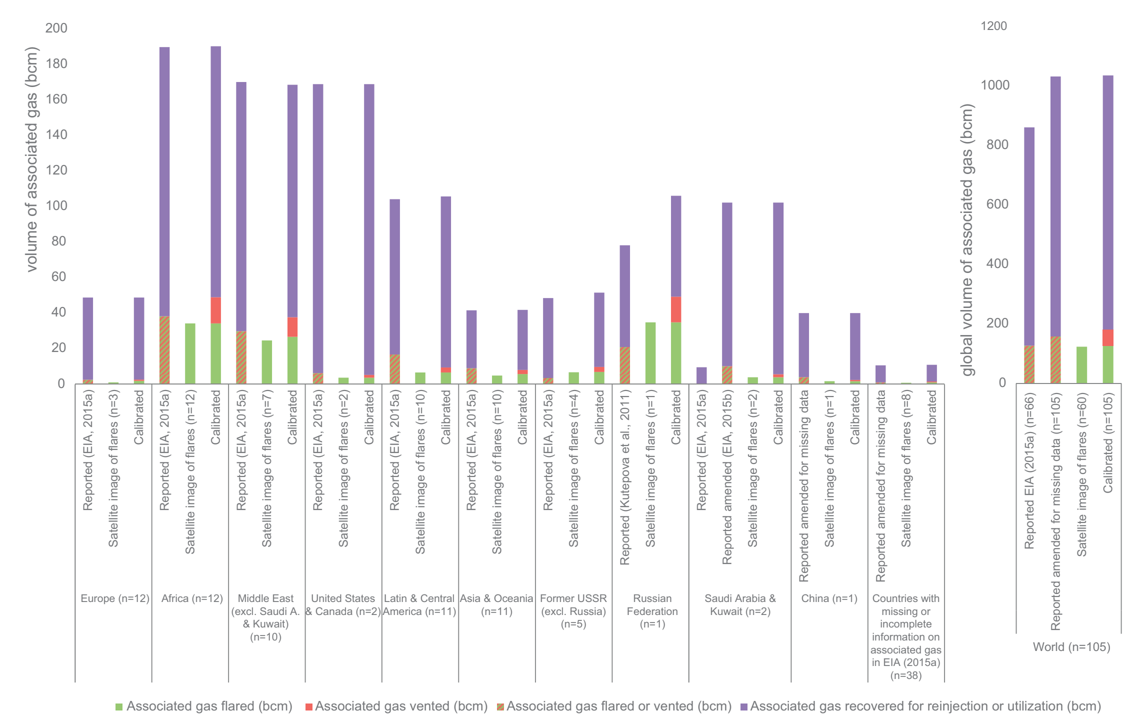

Figure 1. Associated gas flows in year 2010 as they appear from information reported to EIA (2015a), when amended for missing or incomplete information using default values or other information sources, and when calibrating the volumes of gas flared to satellite images of gas flared from upstream oil and gas activities. Unit: billion cubic meters (bcm).

reduced through increased flaring, followed by increased APG recovery. In a reference scenario it is assumed that 70% of APG generated in the Soviet Union was vented and 30% flared with a sensitivity analysis provided in section 3.3.

The calibration procedure is repeated for each country and year for the period 1994 to 2010 for which satellite estimates of gas flares are available. For the periods 1990 to 1994 and after 2010, the recovery rates derived for years 1994 and 2010, respectively, are kept constant. For the period 1980 to 1990, the 1994 levels of associated gas fractions and recovery rates have been kept constant.

Figure 1 illustrates the associated gas flows by world region for year 2010 as they appear from EIA (2015a) and other published sources, after amending for incomplete data, and after calibration. For transparency, all input and output data is displayed in a supplement dataset.

2.2. Methane and ethane emissions from associated gas flows

Methane and ethane emissions expressed in mass units have been derived from the simulated flows of associated gas by multiplying these with the volume fractions of methane and ethane contained in the associated gas, as presented in table 1. Conversions from volume to mass units assume 0.718 kg per m^3 for methane and 1.266 kg per m^3 for ethane (Smil 2015). To derive emissions from flaring, the volume of associated gas flared has been multiplied by a factor of 0.02 to reflect an average combustion efficiency of 98% for gas flares (Johnson and Kostiuk 2002).

2.3. Emissions from other oil and gas system sources

To complete the picture of methane and ethane emissions from oil and gas systems, emissions from intended flaring and venting of associated gas, must be complemented with emissions from unintended leakage of gas during oil and gas production, processing, transmission and distribution, e.g. leakage from compressor seals, well restimulation, and natural gas processing facilities (Johnson and Coderre 2012). Default emission factors for methane from these sources are available from IPCC (2006, volume 2, section 4.2, tables 4.2.4 and 4.2.5) and are reproduced in table SI-5.1 of the supplementary material. The median values of the presented ranges are adopted in a reference scenario with consideration taken to offshore or onshore production (see table SI-2.1 of the supplementary material). The IPCC guidelines do not provide leakage rates for unconventional gas production. For this purpose, a literature survey was conducted (see table SI-6.1 of the supplementary material). The range of measured methane leakage from shale gas extraction is wide and highly uncertain. In the reference scenario it is assumed that 2% of shale gas produced is lost through leakage with a sensitivity analysis provided in section 3.3. Estimates of global fugitive methane emissions from long-distance gas pipelines and consumer distribution networks have been adopted from Höglund-Isaksson (2012) for years 2005 and 2010, with extension to all years through scaling by production. The release of ethane emissions from unintended leakage is assumed to follow methane emissions in the same proportion as its relative prevalence in the associated gas (see table 1).

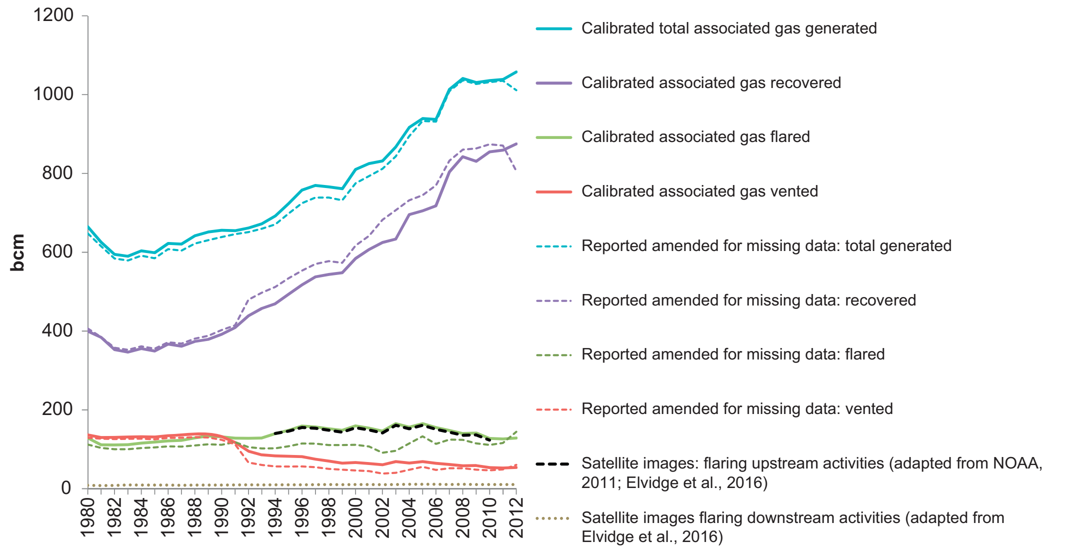

Figure 2. Amended reported and calibrated volumes of global associated gas generated, recovered, flared and vented. Note that the sum of volumes of associated gas recovered, flared and vented add up to the total volume of associated gas generated. Unit: billion cubic meters (bcm).

3. Results

3.1. Simulated associated gas flows

Figure 2 shows simulated associated gas flows from global oil and natural gas production when using the approach described in section 2.1. Corresponding illustrations by world regions are presented in section SI-7 in the supplementary material. Simulation results suggest 665 billion cubic meters (bcm) associated gas was generated globally in 1980, dropping to 590 bcm in 1983 following a squeeze in oil supply from Middle East countries in response to repercussions of the second oil crisis. Since the mid-1980s the estimated associated gas volumes increase, passing 1000 bcm in 2007. Global rates of recovery for associated gas are estimated to have increased from 60% to 83% between 1990 and 2010. Over the same period, global flaring of associated gas generated declined from 20% to 12%. In parallel, global venting of associated gas generated is estimated to have declined from 20% to 5%. Due to simultaneous increases in global oil production, the volumes of gas flared increased from 131 to 165 bcm between 1990 and 2005, thereafter falling back to about 130 bcm annually as gas recovery increased. Between 1990 and 2010, the volume of vented associated gas is estimated to have fallen from 132 to 53 bcm. To illustrate the calibration effect, figure 2 also shows the global volumes of associated gas generated, recovered, and vented or flared as they follow from amended reported data before calibration. The impact of calibration on associated gas flows are illustrated by country groups in figure SI-7.2 in the supplementary material.

3.2. Simulated ethane and methane emissions

Figures 3 and 4 present the ethane and methane emissions from global oil and gas systems consistent with the calibrated associated gas flows presented in figure 2. To display the effect of calibration, the emission estimates that would have resulted from amended reported data without calibration are shown as dotted lines.

Figure 3 shows that the simulated level of ethane corresponds reasonably well to top-down estimates of the atmospheric ethane budget by Aydin *et al* (2011). They estimate that global ethane emissions peaked around 1980 at about 16 to 17 Tg ethane per year and declined to about 12 to 13 Tg per year by the turn of the century. After subtracting between 1 and 4 Tg ethane for biomass burning and biofuel use, Aydin *et al* attribute about 12 to 16 Tg ethane in 1980 and about 8 to 12 Tg ethane in 2000 to fossil fuel sources (illustrated by the vertical range between the two black diamonds in figure 3). The findings of this study of 12 and 9.6 Tg ethane from oil and gas systems in 1980 and 2000, respectively, fall within these ranges. If the assumption about venting in the Soviet Union were 90% instead of 70% of APG generated, global ethane emissions from oil and gas systems in 1980 would be 13.4 Tg ethane (illustrated by a grey dashed line in figure 3), which is still within the range suggested by Aydin *et al* and may indicate that global venting in this period is underestimated in the simulations. Perhaps venting was higher in other World regions too during this period. Simpson *et al* (2012) made top-down estimates of the global atmospheric ethane budget and found emissions declining from 14.3 to 11.3 Tg ethane between 1984 and 2010 (illustrated as black crosses in figure 3). The estimates of 10.8 Tg ethane in 1984 and 9.7 Tg ethane in 2010 found in this study are reasonably consistent with their estimates, if attributing 3.5 and 1.6 Tg ethane, respectively, to other sources than fossil fuels.

Figure 4 presents corresponding estimates of global methane emissions from oil and gas systems.

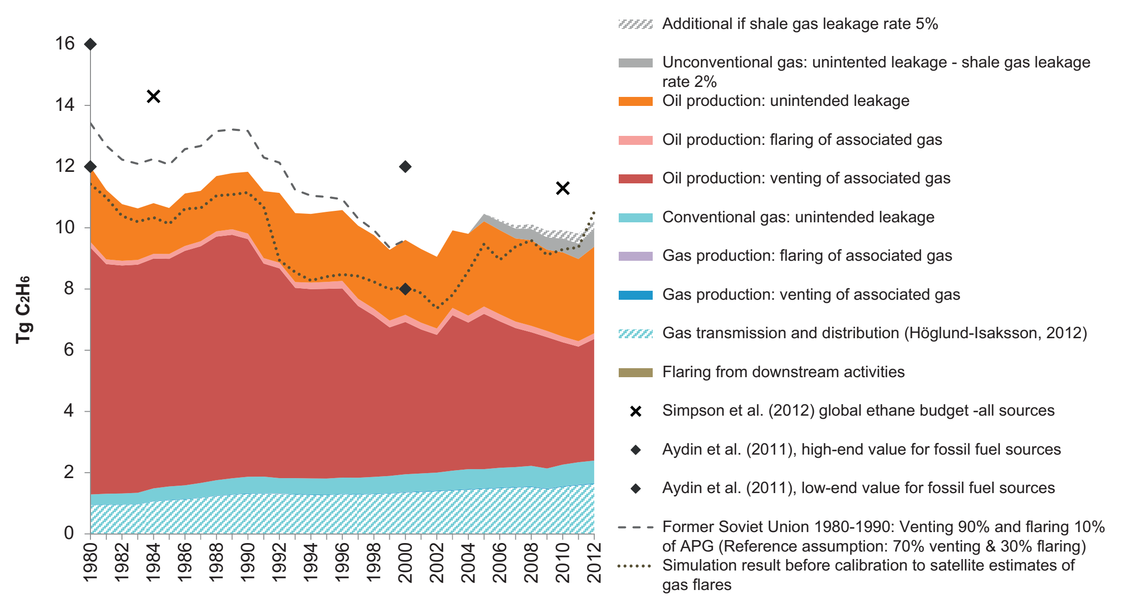

Figure 3. Simulated ethane emissions from global oil and gas systems 1980 to 2012 by emission source.

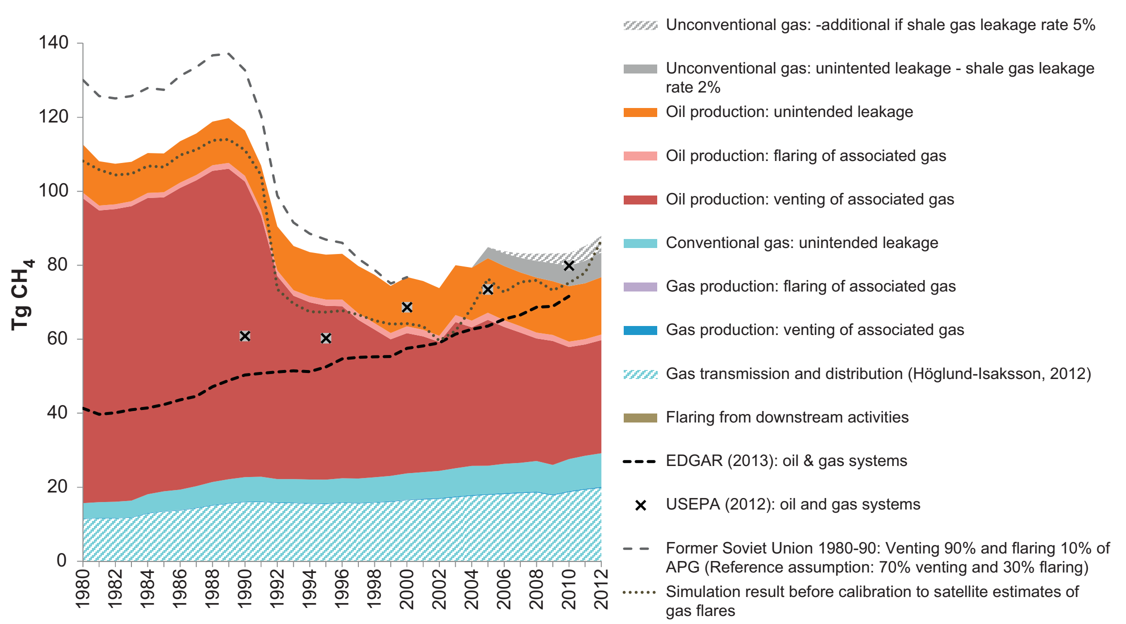

Figure 4. Simulated methane emissions from global oil and gas systems 1980 to 2012 by emission source.

Cumulatively over the period 1980 to 2012, this study estimates a release of 3047 Tg methane, whereof 74% from oil production and 26% from gas production, transmission and distribution. With a global warming potential for methane of 34 times that of CO_2 over 100 years including climate-carbon feedbacks (IPCC 2013, WG1, table 8.7), this is equivalent to 104 Pg CO_2 eq. Venting of APG turns out a major source of methane emissions. Due primarily to a combined effect of a drop in oil production following the collapse of the Soviet Union and an increase in flaring instead of venting of unrecovered associated gas, global methane emissions from oil and gas systems drop by a third between 1990 and 2000. This offers a possible explanation to the slowdown in the atmospheric methane concentration between 1990 and 2005 observed by top-down models (Nisbeth *et al* 2014). The decline after 1990 observed for methane is not as pronounced for ethane, because the ethane content of Russian APG is smaller than for major oil producers in the Middle East (see table 1). Figure 4 shows an increase in methane emissions from unconventional gas expansion in recent years. With leakage rates for shale gas between 2% and 5%, the increase in emissions from unconventional sources is of about the same magnitude as the decrease in global emissions from extended APG recovery. Hence, unless the shale gas leakage rates assumed here are understated, this study does not provide clear evidence for recent shale gas expansion as explanation for the increase in the atmospheric methane concentration observed by top-down models for the period 2007 to 2012 (Hausmann *et al* 2016).

Figure 4 compares the results of this study with global bottom-up inventories of methane from oil and gas systems by EDGAR v.4.2 (2013) (shown as a dashed black line from 1980 to 2010) and USEPA (2012) (shown as black crosses in five year intervals from 1990 to 2010) (see also Höglund-Isaksson *et al* 2015). The estimate of cumulative emissions in this study is 73% higher than the estimate by EDGAR (2013) for the same time period. On an annual basis, estimates in 1990 are almost double in this study than estimated by USEPA (2012) and 16% higher in 2010. The significant differences in bottom-up estimates can be explained by the consideration taken in this study to country-specific circumstances in the generation and management of associated gas. Such considerations have not been made in the inventories by EDGAR and USEPA, which apply default emission factors globally that derive from direct measurements representative for North America, alternatively apply implied emission factors as reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC) (USEPA 2012, Olivier *et al* 2012). Section SI-10 in the supplementary material provides a comparison of emission factors for year 2010 between this study, other global inventories and national reporting to the UNFCCC. Sections SI-8 and SI-9 in the supplementary material present global ethane and methane emission estimates by world regions.

3.3. Uncertainty

There are several sources of uncertainty present in the analysis. First, there is uncertainty in the quality of the reported data on associated gas volumes. In general, reported data have many different sources of uncertainty that are difficult to verify and quantify. Second, there is uncertainty in the volumes of gas flared as estimated from satellite images, which has been discussed in Elvidge *et al* (2009, 2013, 2016). Elvidge *et al* (2009) do not report a global uncertainty range that includes Russia for the estimates used here for years 1994 to 2010. With improved technology, Elvidge *et al* (2016) estimate for year 2012 a global gas volume flared at 143 (±13.6) bcm, whereof 129 (±12.2) bcm from upstream oil and gas activities. This means an uncertainty range of ±9.5%. The simulated volume of gas flared from upstream activities in 2012 is 129 bcm also in this study, with corresponding methane emissions estimated at 83 Tg CH_4. With an uncertainty range for flaring of ±9.5%, the simulated effect on methane emissions from upstream activities in 2012 is between 5.7% and +2.7%. This gives an indication of how methane emission estimates from upstream activities are affected by the uncertainty present in the satellite estimates of gas flares.

Third, to bridge information gaps a number of assumptions have been made throughout the analysis, which could potentially have significant impacts on resulting estimates of methane and ethane emissions. To analyze the relative importance of these assumptions, their impacts on global ethane and methane emissions from oil and gas systems have been estimated when varying the default assumptions within reasonable ranges, as presented in table 3. As shown, the assumptions with the largest potential effect of uncertainty on estimated methane and ethane emissions are the application of the Canadian venting ratios as default to all countries and years, the uncertainty surrounding the associated gas flows from foamy heavy oil in Latin and Central America, and the adoption of IPCC default emission factors for unintended leakage. The latter uncertainty range for ethane is larger than for methane because the IPCC high-end emission factor is considerably higher for developing than developed countries and some developing countries have a relatively large ethane content in the APG (see table 1). Improved certainty in these assumptions requires a considerable extension of the generation and publication of direct measurements from oil and gas production in different parts of the world. The uncertainty range for the venting ratios in the Soviet Union 1980 to 1990 converts into −8% to +15% for global methane emissions from oil and gas systems over that period. Uncertainty surrounding the leakage rate for shale gas production in the year 2012 has a relatively limited effect (−2% to +5%) on emissions at a global scale. Uncertainty due to default assumptions adopted for China and other countries not reporting associated gas information does not have a significant effect on global emissions due to the limited production quantities of these countries. Likewise, the uncertainty introduced through adoption of fixed associated gas fractions for natural gas and heavy oil has a small effect on estimated methane and ethane emissions.

4. Discussion

Understanding the magnitudes of methane emissions and how they attribute to different human activities is crucial for the design of effective methane reduction strategies. By making use of as much country-specific information as available from published sources, this study provides more insights into the regional- and temporal- distribution of historical methane emissions from oil and gas production than previously found by bottom-up inventories. These have tended to apply emission factors globally that derive from measurements representative for North American oil and gas fields.

Table 3. Sensitivity analysis of assumptions.

Assumption	Reference scenario	Low	High	Resulting uncertainty range: effect on global cumulative emissions 1980–2012 from oil and gas systems	
				Methane	Ethane
Default assumptions for China and 38 countries without reported information on associated gas. Default APG fraction and recovery rate refer to conventional oil production.	APG fraction: 20% Recovery rate: 90%	10% 95%	30% 85%	−0.07% to +0.05%	−0.05% to +0.04%
Fraction of unrecovered APG vented instead of flared	Conventional oil: 29.1% Heavy oil: 87.7%	20% 60%	40% 95%	−12% to +16%	−14% to +18%
Fixed associated gas fractions for natural gas and heavy oil extraction	Natural gas: 0.03% Heavy oil: 5.1%	0.003% 2%	0.3% 10%	−2.1% to +0.8%	−2.8% to +0.8%
Latin and Central American 'foamy' heavy oil: APG generation and venting ratios	Treated as Canadian conventional oil production	Same as Reference scenario	Treated as Canadian heavy oil production	0% to +7.8%	0% to +12%
Fraction of unrecovered APG vented instead of flared in the Soviet Union 1980–1990	70%	60%	90%	−4.2% to +7.0% (−8% to +15% in 1980-90)	−2.9% to +5.7% (−6% to +12% in 1980–90)
Shale gas upstream leakage rate	2%	1%	5%	−0.2% to +0.6% (−2% to +5% in 2012)	−0.1% to +0.4% (−1.2% to +3.6% in 2012)
Unintended leakage rates for oil and conventional gas production	Median of IPCC (2006)	IPCC low-end applied globally	IPCC high-end applied globally (30% of high-end for developing countries)	−16% to +35%	−32% to +54%

The results of this study show much closer consistency between bottom-up and top-down estimates of global ethane emissions from fossil sources than existing bottom-up inventories. A considerably higher release of methane and ethane emissions from global oil and gas systems is found in this study for the period 1980 to 2012 with oil production coming out as a much larger contributor than natural gas production. This finding could have important policy implications for the evaluation of climate effects of different fossil fuels. Also, the dramatic decline estimated for vented methane emissions from oil production following the fall of the Soviet Union, offers a possible explanation to the slowdown in the atmospheric methane concentration between 1990 and 2005 observed by top-down models. The estimated increase in methane emissions from unconventional gas extraction in recent years is largely offset by increased recovery of associated petroleum gas and does not offer an explanation for recent increases in atmospheric methane observed by top-down models. Although the inclusion of country-specific parameters in this study offers improvements over existing global emission inventories, large uncertainty prevails. Particularly desirable to reduce uncertainty would be access to more direct measurements from different parts of the world on unintended leakage as well as venting ratios for unrecovered associated gas. Close cooperation between industry and the scientific community will be crucial to make such measurement results available.

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