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Methane Emissions:
from blind spot to spotlight

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Executive Summary

Methane emissions can be defined as all releases of the gas – intentional or otherwise – that occur across the entire gas supply chain from exploration and production to final consumption. Releases of methane have long been seen by the industry as an unfortunate, if necessary, part of doing business. For safety reasons, unplanned gas escapes were avoided where possible, though a release to atmosphere was often the chosen option during maintenance and when dealing with minor distribution leaks. This mind-set was also evident in venting and flaring associated gas during oil production and the use of pressurised gas to operate valves and other equipment.

The economic cost of this activity was recognised but expenditure to reduce emissions often outweighed any benefit. Furthermore, many regulatory regimes included allowances for unaccounted for gas so operators could pass on the cost of emissions to consumers. The environmental impact of gas emissions was at best a minor consideration and in most cases an industry blind spot.

In wider environmental circles the impact of methane emissions – which come from a wide range of natural and anthropogenic sources – has received growing attention. Methane is a potent greenhouse gas (GHG) and whilst it degrades rapidly (it is sometimes referred to as a short-lived climate pollutant), the increased focus on shorter term environmental targets has raised its profile.

Global ambient methane levels have been rising and the coinciding growth in global gas production – and the rise of unconventional gas and hydraulic fracturing - led some to conclude that methane emissions from the natural gas industry were primarily responsible. This hypothesis received further support in 2016 when the US EPA published a major upgrade (subsequently partially reversed) in emission estimates from natural gas supply.

There has been a great deal of technical and scientific analysis of the level and impact of methane emissions. This, however, has not always led to greater consensus. At a general level, our understanding of the chemistry of the atmosphere, how this changes over time and the impact on temperature and climate is still evolving.

More specifically, whilst there is no shortage of academic studies of emissions from the oil and gas industry, these have used a wide range of estimation methods, data, and system definitions and boundaries. These approaches have resulted in a big variation in estimates of the magnitude of natural gas emissions. This state of affairs has been exacerbated by the lack of available or consistent data from the gas companies themselves. The gas industry's attempts to improve and standardise monitoring and reporting methane emissions have often resulted in arcane debates over data and impact. As a result, the hitherto, largely unchallenged, environmental credentials of natural gas as the "greenest" fossil fuel have been questioned by environmental groups and some government agencies. Even objective observers have suspected the worst, perhaps best exemplified by the Economist article of July 2016, `A dirty little secret'.

These issues were highlighted in Jonathan Stern's paper "The Future of Gas in Decarbonising European Energy Markets: the need for a new approach" (OIES, 2017) which flagged the risk that emissions of unburned methane in the supply chain could undermine the environmental case for gas. This paper examines the issues in more detail – primarily regarding the gas industry - but also recognising the wider context.

The key messages from the paper are:

- Whilst there are many data gaps and inconsistencies, most databases and studies support the view that the increase in global atmospheric methane in the last ten years was not a result of the increase in global gas production over this period. Many countries have reported a reduction in both the absolute and relative level of emissions from the natural gas sector. Furthermore, whilst the full chain effect of methane emissions reduces the environmental case for gas, it is still preferable to coal as a fuel for power generation.

- On the other hand, the lack of consistent and transparent data and a failure from industry players to articulate a coherent message on methane emissions has resulted in a data vacuum that has been filled by less rigorous, and in some cases self-serving, alternative conclusions. The gas industry has been increasingly active in countering this trend, both through greater efforts to reduce emission levels and in improved accuracy and transparency of data. The environmental case for gas is, however, in many policy maker's minds still likely to remain at best unclear.
- Several studies suggest that a global average emissions rate of between 1.5 - 2 per cent of sales gas across the entire supply chain is broadly correct, though some of this may be the result of oil production whilst a few estimates put the numbers much higher. Further action is required to confirm these numbers, to provide a consistent and proven database across the entire gas supply chain and for this to be reflected in government as well as industry statistics. Gas producing countries in particular, need to move quickly to ensure they are reporting updated and reliable numbers.
- Regulatory pressure on emissions control is likely to increase and companies should be prepared to meet greater reporting requirements and financial measures. At an operational level creating a "zero-emissions" mind-set remains a worthwhile objective.

The gas industry is still on a journey though the issue of methane emissions is clearly receiving much greater attention than hitherto. If the industry can build on the progress to date and deliver a clearer picture on the level of emissions and actions to address them, the arguments for gas displacing coal in power generation and oil products in transport become much stronger and the role for gas in a decarbonising economy more secure.

Contents

Figures

Tables

1. Introduction

This paper summarises the main issues relating to methane emissions and examines the various activities, underway and planned, to assess and reduce them. It attempts to take a wide ranging, non-specialist, overview that covers both the technical and scientific perspectives as well as operational and regulatory considerations.

The paper is structured as follows:

- The global picture for methane emissions and the part played by the energy sector
- Why controlling and reducing methane emissions is important.
- How methane emissions are measured and reported levels and sources for the energy and gas sectors
- How the impact of methane emissions is assessed
- The overall impact of methane emissions on the environmental case for natural gas
- Company and regulatory responses to the challenges of methane emissions

The paper looks at the issues globally, though a recurrent theme is the wide range of practices, regulatory controls, and data availability around the world. To provide greater granularity and illustrate some of the key points, two country profiles, focussing on the USA and Great Britain, have been included.

2. Methane emissions and why they are important

The growing atmospheric level of methane, from all sources, is shown in Figure 1. The rate of growth slowed up to 1999 and remained broadly constant during the period 2000 to 2007. From 2007 levels have increased and were estimated to be around 1,840 parts per billion (ppb) in 2015, up from 1,650 ppb in 1985[1]. This recent increase has been blamed by some on the rise in unconventional gas exploitation in North America[2] though as explained below there are more likely explanations.

It is important to note that methane does not persist in the atmosphere in the same way that CO_2 does. Methane undergoes chemical reactions in the atmosphere and degrades to CO_2 and water within ten years. The inclusion of this resultant CO_2 when assessing methane's overall impact is referred to as feedback and the degradation of methane in the atmosphere is known as a methane sink. If the amount of methane being absorbed through the sink effect exceeds the amount of methane emissions in each period, total levels of methane will fall.

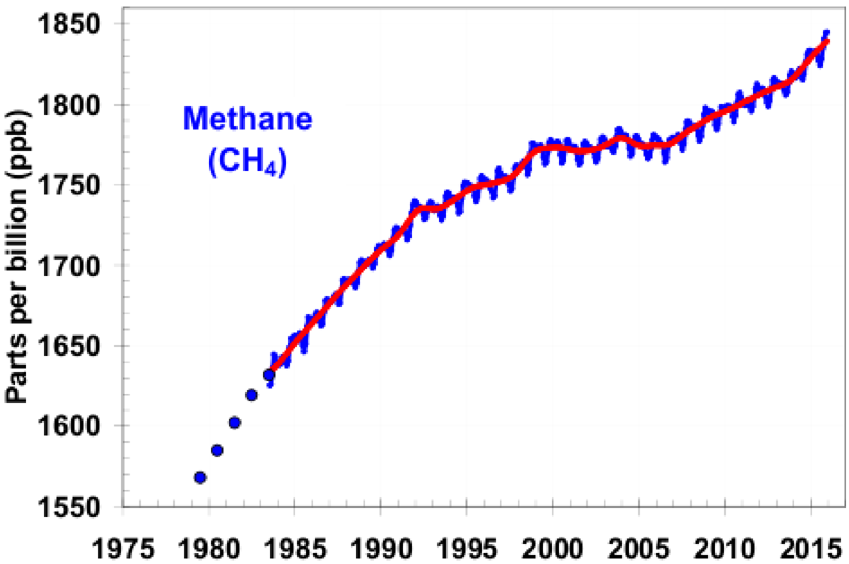
The global methane emissions and sinks, often referred to as a methane budget, are summarised in Figure 2. There are three main types of methane emissions:

- Biogenic – wetlands, rice paddies, cows, landfill, etc.
- Thermogenic – deriving from either natural seeps from fossil fuel or as a result of exploration and production (E&P) and coal mining activities
- Pyrogenic – the result of incomplete combustion of biomass (for example forest fires), biofuels, and fossil fuels

[1] NOAA Annual Greenhouse Gas Index https://www.esrl.noaa.gov/gmd/aggi/aggi.html
[2] https://phys.org/news/2016-12-surge-methane-emissions-threatens-efforts.html

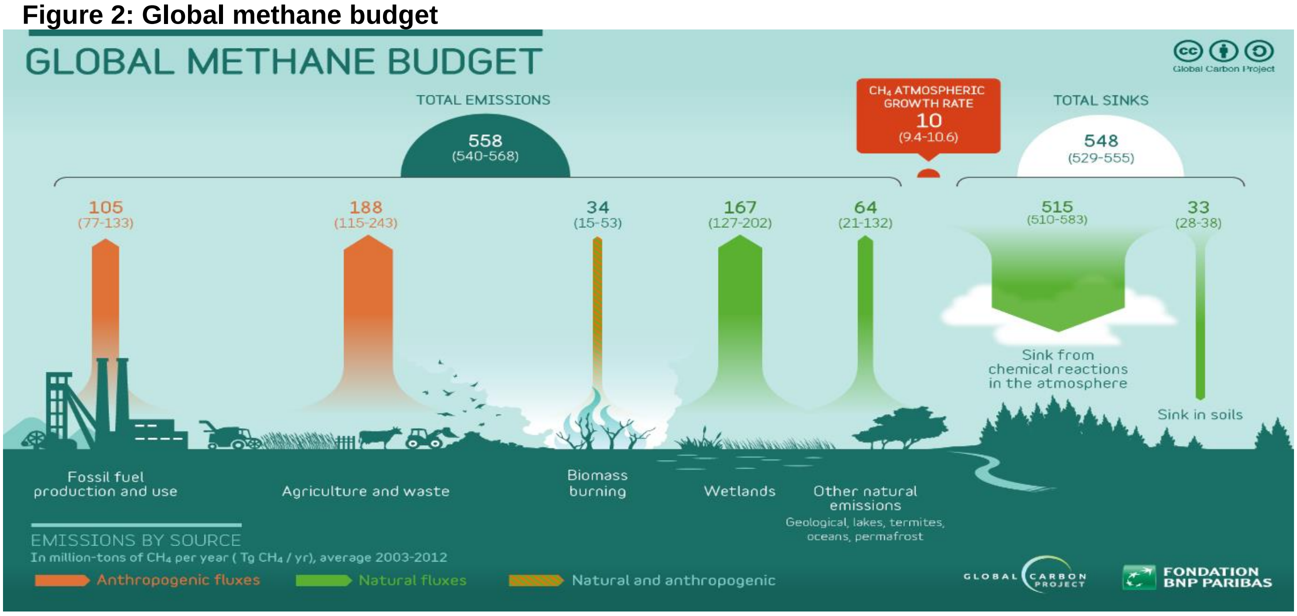
Within these categories, a distinction can be made between natural and anthropogenic sources. So, anthropogenic methane emissions from fossil fuels will in part be thermogenic and part pyrogenic. The Global Carbon Project[3] estimates that production and use from the fossil fuel sectors generate between 77 and 133 million tonnes of methane per year as shown in Figure 2. This figure illustrates the overall carbon budget for the period 2003-2012 showing both natural and anthropogenic sources and the impact of the methane sink which reduces, but does not eliminate, the growth in global methane emissions.

Figure 1: Global methane levels



Source: NOAA https://www.esrl.noaa.gov/gmd/aggi/aggi.fig2.png

Figure 2: Global methane budget

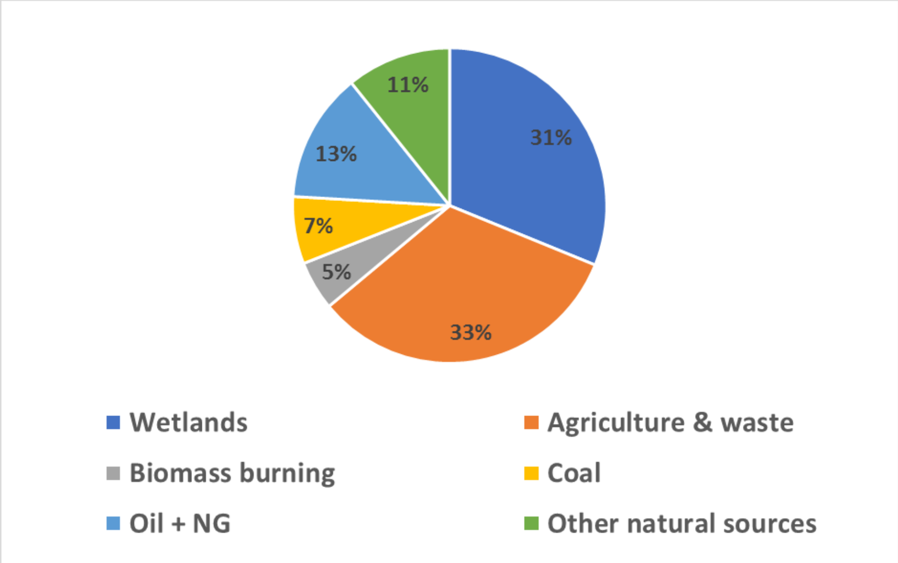


Source: Global Carbon Project

[3] http://www.earth-syst-sci-data.net/8/697/2016/essd-8-697-2016.pdf

A percentage breakdown of the main sources of methane emissions, averaged over the period 2003-2012, is shown in Figure 3. This gives a global share for oil and natural gas of 13 per cent and coal 7 per cent. The numbers in Figures 2 and 3 are based on a "bottom-up" calculation as part of the Global Carbon Project (see below).

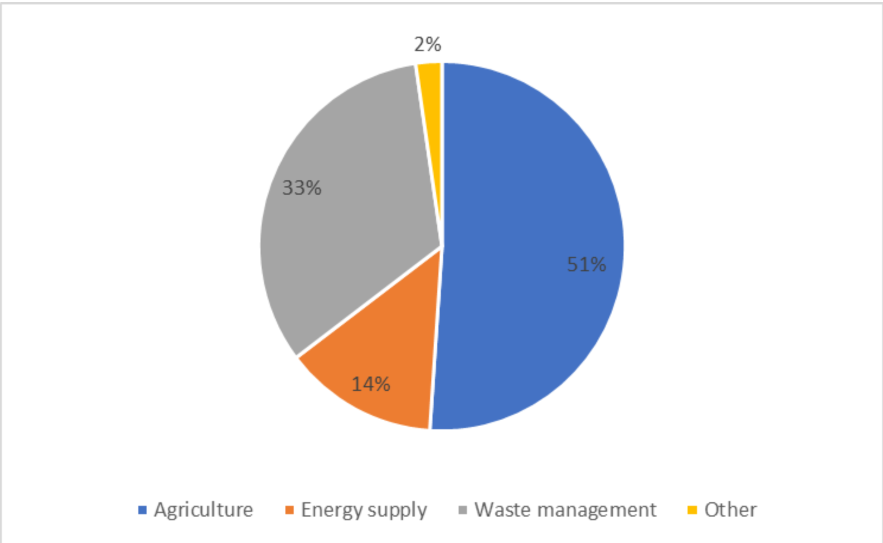
Figure 3: Global methane emissions by source 2003-2012 (bottom-up calculation)



Source: Global Carbon Project

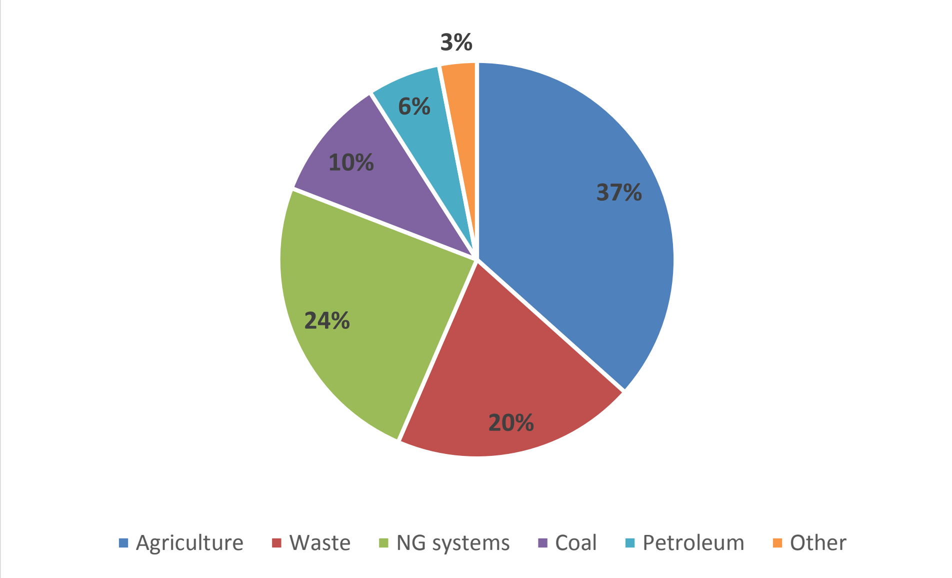
There are wide differences between countries both in terms of the level and source of methane emissions and the quality of reported data. Differences between sources is illustrated in Figures 4 and 5 which shows the breakdown in the US and UK respectively. The greater level of detail from the US and the high proportion arising from natural gas systems are particularly notable, suggesting that applying US experience of emissions to other systems may be inappropriate. These countries are considered in more detail in the country profiles.

Figure 4: UK Anthropogenic methane emissions by source (%), 2015



Source: UK BEIS 2017

Figure 5: USA Anthropogenic methane emissions by source (%), 2015



Source: US EPA 2017

Differences between countries in terms of data quality are discussed in the next section as is the issue of determining how much of the methane attributed to fossil fuels is produced as a direct result of natural gas exploitation. It is clear, however, that both coal and oil extraction also contribute to methane emissions. Coal mine methane (CMM) can be released during mining operations (including open cast mines) and through desorption during the crushing process. Li et al (2015) report that in 2010 estimated methane emissions from coal mines accounted for some 8 per cent of worldwide anthropogenic methane emissions. M. Saunois et al (2016) put coal's share higher, estimating that between 2003–2012 methane emissions from coal mining accounted for 12 per cent of worldwide anthropogenic methane emissions, or 34 per cent of total fossil fuel-related emissions of methane.

There are also significant methane emissions arising from oil production as described below.

The proportion of global methane emissions arising directly from natural gas exploitation and supply is therefore relatively small. This fact, however, is not an argument for complacency for several reasons:

- Methane is a much more potent greenhouse gas than CO_2 and emissions can have a disproportionate impact on the image of natural gas as a "green fossil fuel"
- Lack of attention to this issue in the past and consequent paucity of accurate data allows advocates of other energy sources to use data outliers to make their case vis à vis natural gas
- Unlike CO_2, methane has a market-derived monetary value. At average 2012 prices Larsen et al (2015) estimate that total industry emissions had a value of US$30 billion. There is therefore a clear incentive to minimise any wastage.
- There is a great deal the industry can do both to define the nature of the problem and to demonstrate concrete steps towards reducing emission levels.
- The industry has a generally good safety record though a more proactive measurement of methane leakage could help identify potentially dangerous leaks at an earlier stage and thus reduce the environmental impact.

- Whilst methane is a potent GHG it is also relatively short-lived in the atmosphere (less than ten years[4]), so reducing emissions would have an immediate benefit (Larsen et al, 2015). In addition, when compared with other key emitting sectors there are opportunities to reduce emissions relatively cheaply and effectively.

There are therefore many good reasons for addressing the issue of methane emissions though doing so is not without its challenges:

- In the past, preventing methane emissions was often not a high priority and given that the gas is lighter than air and potentially explosive in confined spaces, venting to atmosphere was often incorporated as a design feature to ensure safe operations.
- Some supply systems – particularly those offshore – were configured in such a way that retrofitting equipment to reduce emissions would be extremely costly even if it were practically possible.
- Regulatory arrangements allowing the cost of “own use gas” to be passed on to consumers encouraged wasteful practices such as using pressurised gas to actuate valves and to fuel inefficient compressors.

To summarise there are a wide range of sources for methane emissions and these can vary significantly between countries. The total level of emissions has been growing in recent years and regardless of whether these are due to increases in natural gas production there are good reasons for the industry to reduce methane emission levels. Industry attitudes and approaches have been changing for some time, but there is still no clear consensus about the best way to proceed. There is, however, broad agreement that the issues that need to be most urgently addressed, are measuring the extent of the emissions and to determine their impact. These are considered in the following two sections.

3. Measuring methane emissions

Methane emissions as a direct result of gas industry activity can be identified at each stage of the supply and delivery chain. Some of the emissions are deliberate or part of a system’s design. Examples include releasing well gas during production operations, the use of gas pressure to actuate valves, and emergency venting for safety reasons. Other emissions are unintentional (sometimes referred to as fugitive emissions) and usually proactively managed by the industry. These include leaks from pipelines, valves, joints, and accidental damage.

Natural gas reservoirs are either associated with oil or non-associated. Gas produced from the former is often a by-product with no opportunity for commercialisation and if it is not reinjected into the reservoir this gas is vented or more often flared. As a result, there can be significant methane emissions arising from oil production. Whilst flaring primarily results in the production of CO_2 there is nearly always some unburned methane as well. Where associated gas is used commercially, it is necessary to allocate methane emissions to both oil and gas production. Wherever possible, methane emissions associated with oil are excluded from this analysis, though in many cases it is not possible to distinguish between upstream sources of methane emissions.

Many studies have been undertaken to measure the extent of oil and gas industry related methane emissions. There are two broad approaches – top-down and bottom-up.

The top-down approach is based on measuring atmospheric concentrations of methane either at the surface using road vehicles or at higher altitudes by aircraft or satellite. The major issues with top-down measures are:

[4] 4th Assessment Report of the Intergovernmental Panel on Climate Change, 2007

- Extrapolating from point measurements to derive a figure for a larger region. Bruhwiler et al (2017) explain factors such as atmospheric variability, sampling biases, and choice of upwind background can make these estimates unreliable.
- Attributing global methane measurements to specific sources of emission. Estimates of emissions from the oil and gas sector have been achieved by various methods including determining the level of emissions from other sources and then subtracting these from the total, the use of "finger printing" techniques by measuring the presence of other gases such as ethane that are present in natural gas streams (Balcombe et al, 2015), or the use of carbon isotopes (Nisbet 2016, Schwietzke 2016).

The bottom-up approach measures emissions at a particular point in the supply chain and then extrapolates the data using sampling techniques. In the natural gas chain this would involve applying emission factors based on measurements of, for example, the number of production wells or kilometres of pipeline. This approach can generate inaccuracies if:

- the factors are out of date[5],
- the factors fail to reflect the wide variability across facilities (for example applying US distribution leakage rates to continental European systems),
- the number of facilities are miscounted
- the presence of possible so-called "super-emitters"[6] is ignored.

There are three major global inventories based on bottom-up analysis and each differs in their classification and regional breakdown[7]. In aggregate, bottom-up approaches tend to provide larger estimates of global methane emissions than top-down methods[8]. Given the range of approaches and the varying degree of proactivity across the industry there are understandably wide ranging estimates of the total amount of methane emissions by country and process.

Table 1 shows the difference between the two approaches. The discrepancies between the two methods regarding fossil fuel emissions are relatively small. A recent study by Schweitzke et al (2016) used isotopes to separate naturally occurring methane emissions from those arising from the industry. This suggested that fossil fuel industry emissions were higher than previous estimates at 156 MT of CH_4/year ($\pm$ 24) though natural gas emissions had fallen dramatically. The study allocated emissions to each sector generating an approximate split of coal (50 per cent), natural gas (40 per cent) and oil (10 per cent)[9], and reported that the level of emissions per unit of production in the natural gas industry had fallen from nearly 8 per cent in the mid-1980s to just over 2 per cent in the late 2000s and early 2010s. Nisbet et al (2016) also examined the isotopic evidence to conclude that observed atmospheric methane increases between 2007 and 2014 were predominantly caused by biogenic methane emissions and that fossil fuels had not been the dominant cause.

[5] Costello, 2015
[6] Balcombe et al p 58.
[7] Saunois, 2016, p 703.
[8] This is primarily due to greater levels of uncertainty surrounding emissions from wetland and other natural sources (Saunois)
[9] Supplementary information, Figure 10

Table 1: Estimated methane emissions by source and method (million tonnes of CH_4 / yr)

Source	Top-down		Bottom-up	
	Mid-point	range	Mid-point	range
Wetlands	167	127-202	185	153-227
Agriculture & waste	188	115-243	195	178-206
Biomass burning	34	15-53	30	25-35
Fossil Fuel prodn & use	105	77-133	121	114-133
Of which: Coal	n/a	n/a	41	26-50
Oil + NG	n/a	n/a	79	69-88
Other natural	64	21-132	199	104-297
Total	558	54-568	736	596-884

Source: M. Saunois et al.: The global methane budget 2000–2012

The most comprehensive review of emissions estimates specific to the gas industry has been undertaken by the Sustainable Gas Institute (Balcombe et al 2015) which reviewed in detail 250[10] papers. This study reported that total methane emissions across the whole supply chain ranged from 0.2 per cent to 10 per cent of produced methane with a mean and median across the estimates of 2.2 per cent and 1.6 per cent respectively. The mean of 2.2 per cent is the same as that reported by Schweitzke (2016) described above.

The SGI study highlighted a wide range of approaches to data collection and publication, and many apparent anomalies. This is a particular issue in producing countries where data is often absent or highly aggregated. Differences between countries in terms of data quality are primarily a factor of a country's status[11] under the UN Framework Convention on Climate Change (UNFCCC). Larsen et al (2015) note that only Annex 1 countries are required to report emissions on an annual basis separated by source. Non-Annex I countries report much less frequently with significant lags in data[12]. China for example has issued leakage data based on 2005 measurements. This shows very low rates compared to other countries with similar gas production and processing structures, applying US leakage rates to Chinese gas production figures would increase the latter's overall methane emissions by 6 times.

Even in countries with comprehensive data collection systems there can be significant variations in estimates of methane emissions from the natural gas industry. In 2016, the US EPA greenhouse gas inventory (EPA, 2016) reported a 12 per cent upward revision in methane emissions from natural gas systems in 2013. This increase was, according to the IEA (2016), primarily a result of applying rates of fugitive emissions to increased estimates of the number of wells and other equipment. The latest report (EPA, 2017) records a downward revision of 6 per cent for the same year.

Table 2 shows reported methane emissions from the oil and gas sector for oil and gas producers in both Annex 1 and non-Annex 1 countries with the year of reporting shown. These countries reportedly account for at least 60 per cent of global methane emissions from oil and gas production – and approximately 55% of oil and gas production. The reporting year can vary widely and there are also some notable omissions – Iraq for example. The Table also shows a rate of emissions that is calculated on the basis of tonnes of methane per tonne of oil equivalent oil and gas production.

[10] 54 per cent of these were US studies

[11] Countries are either Annex 1 (developed) or non-Annex 1 (developing/in transition) see http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php

[12] See http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf for details of the emissions factors that are to be applied

Table 2: Methane emissions from the oil and gas sector in major producing countries (where reported)

	Million T CH_4	Reporting Year	Oil and gas production (Mtoe)	CH_4 emissions rate (%)
Russia	25.29	2015	1058.3	2.4%
USA	8.09	2015	1272.0	0.6%
Uzbekistan	3.63	2005	54.0	6.7%
Venezuela	1.81	1999	183.8	1.0%
Canada	1.72	2015	349.8	0.5%
Iran	1.72	2000	245.4	0.7%
India	1.56	2010	85.6	1.8%
Mexico	1.53	2013	194.2	0.8%
Ukraine	1.15	2012	35.0	3.3%
UAE	1.00	2005	178.7	0.6%
Algeria	0.99	2000	145.8	0.7%
Nigeria	0.97	2000	116.2	0.8%
Turkmenistan	0.95	2010	48.9	1.9%
Azerbaijan	0.55	2012	57.4	1.0%

Source: UNFCCC, BP World Energy Statistics. Oil and gas production is for the reporting year shown.

Tables 3 and 4 highlight the range of emissions for selected Annex 1 countries under the UNFCCC[13]. There are some clear anomalies within these tables. For example, levels of gas industry emissions in the Netherlands seem low whilst those for Romania and Ukraine seem high. Some of these anomalies are due to differences in methods for determining emissions between countries – some will use direct measurements whilst others such as Russia and Ukraine use UNFCCC recommended emission factors as part of the reporting process. It should be noted that in the case of Russia, Gazprom reports a significantly lower figure[14] than those reported via the National Inventory Report and shown in Tables 3 and 4. Differences in the total emissions from natural gas in the two tables are also likely to arise from different approaches to recording and allocating emissions from upstream venting and flaring and downstream consumption. Finding ways of improving the consistency of this data is an area that requires further research.

[13] http://unfccc.int/ghg_data/items/3800.php
[14] See DBI, 2016 p 39 and http://www.igu.org/sites/default/files/4-%20Romanov.pdf

Table 3: Methane emissions from the energy sector for selected Annex 1 countries in 2015 (Thousand tonnes of methane)

	Oil	Gas	Venting or Flaring	Solid fuels	Total
Australia*	5	290	-	1,212	1,510
Canada	295	483	944	46	1768
France	2	44	1	1	48
Germany	9	193	0	124	326
Italy	12	182	3	2	199
Netherlands	1	13	12	-	26
Poland	4	35	50	676	765
Romania	99	185	92	40	416
Russia	13,304	5,376	6,608	2,450	27,738
Spain		26	2	6	34
Turkey	11	80	19	49	159
Ukraine*	5	1,141	-	943	2,090
UK	7	154	41	55	257
USA	1,595	6,497	IE	2,692	10,784

Source: UNFCC http://di.unfccc.int/detailed_data_by_party

Note: * 2012 numbers, IE Included elsewhere

Table 4: Methane emissions from the natural gas sector in selected Annex 1 countries in 2015 (Thousand tonnes of methane)

	E&P	Transmission	Distribution	Other	Total	Rate **
Australia*	42	12	172	0	226	0.2%
Canada	104	46	38	295	483	0.2%
France	0	24	20	-	44	0.1%
Germany	1	76	89	27	193	0.2%
Italy	9	31	142	-	182	0.2%
Netherlands	0	7	6	-	13	Neg
Poland	16	6	13	-	35	0.1%
Romania	138	7	20	20	185	1.2%
Russia	1164	3715	497	-	5376	0.6%
Spain	0	2	24	-	26	0.1%
Turkey	2	24	54	-	80	0.1%
Ukraine*	75	54	433	575	1137	1.4%
UK	3	2	149	-	154	0.1%
USA	4709	1349	439	-	6497	0.5%

Source: UNFCC http://di.unfccc.int/detailed_data_by_party, BP World Energy Statistics

Note: * 2012 numbers, ** the rate is the level of reported emissions as a percentage of either the country's reported 2012 natural gas production or consumption, whichever is greater.

Table 5 shows how methane emissions from the energy sector as reported to the UNFCCC for Annexe 1 countries have evolved since 1990. The numbers are not directly comparable as there have been changes in reporting methods over the period though the marginal downward trend for natural gas is apparent.

Table 5: Methane emissions from the energy sector for Annex 1 countries: 1990-2015 (Thousand tonnes of methane)

Source	1990	2000	2010	2015
Oil	15,571	10,454	14,883	15,360
Natural Gas	16,063	14,301	13,587	13,433
Venting and Flaring	7,343	5,402	7,412	7,777
Solid Fuels	11,883	7,668	7,321	6,415
Other	222	83	61	43
Total	51,082	37,906	43,264	43,027

Source: UNFCC http://di.unfccc.int/detailed_data_by_party

The SGI study provides a comprehensive review of methane emissions separated by stage and source in the natural gas supply chain. Five stages were identified with a range of sources within each stage. This taxonomy has been adapted to expand the downstream stages and is shown in Table 6, along with a brief description.

Table 6: Main sources of methane emissions in the natural gas supply chain

Stage	Source	Example
Pre-production	Drilling and Hydraulic Fracturing	Shallow gas encountered whilst drilling vented to atmosphere
	Well completion	Gas vented during the completion process
Extraction	Flaring (non-routine)	Unburned methane
	Liquids unloading	Gas vented during the process
	Workovers	Intentional venting during workover
	Fugitive	Equipment leaks
Processing	Flaring (non-routine)	Unburned methane
	Fuel	Unburned methane
	Fugitive and vent	Equipment leaks
Transmission, Storage & Distribution	Fuel	Unburned methane in compressor engine
	Fugitive	Corroded metallic mains
Utilisation	Leakage and methane slip	Unburned methane in NGV engines and domestic and industrial appliances

Note: Shading indicates a potentially major source of emissions

An additional dimension to the categories listed in Table 6 is the concept of super-emitters – these are specific points on the system that are responsible for disproportionately large volumes of gas leakage. These are normally located upstream but could occur in pipelines or storage facilities. In some cases, super-emitters may be a consequence of system design - for example, large volumes of gas being vented as a safety measure. More usually, however, they occur following a catastrophic failure, malfunction or operational error (see below).

Upstream

In the upstream stages of natural gas production, the most prominent sources of methane emissions are:

- Flow back emissions during completion (see below)
- Fugitive emissions from gathering pipelines and stations
- Liquids unloading – this seems to be a particular issue in older, onshore US wells where liquids accumulate in the well as a result of declining flow rates and need to be pumped out. This process typically results in methane escaping from the system[15].

Flaring (resulting in small amounts of unburned methane) and venting are also prominent sources of methane emissions though these primarily arise from the associated gas from oil production that is not gathered and so are not a direct result of natural gas production and supply. Indeed, it is assumed that if gas is flared as part of the gas supply operation it is usually being done as a safety measure during a maintenance operation.

Upstream methane emissions in the US have grown in recent years and this has been linked, amongst other things, to increases in onshore gathering lines and field booster stations (EPA 2016) in line with the rapid increase in shale gas production. Stern (2017) has noted that in the minds of politicians and the media, emissions from upstream operations are directly connected with unconventional gas and hydraulic fracturing. A 2011 paper (Howarth et al) concluded that because 3.6 - 7.9 per cent of shale gas escaped into the atmosphere it had a larger GHG footprint than coal if used in power generation, although more recent US EPA reports (2016) suggest that the evidence is

[15] See Balcombe et al, 2015 p 11 for a description of the various causes of emissions during the liquids unloading process.

less clear cut. Balcombe et al (2015, p22) point out that, based on US data, the highest reported levels of emissions from well completions come from secondary assessments based on models that have used either unsuitable or unverified data including excessively high levels of assumed gas flows. Direct or primary measurements do show that some unconventional wells have higher levels of emissions, although those adopting “reduced emission techniques” (for example by capturing gas that would otherwise be vented - also referred to as “green completions”) are below the levels reported for conventional wells. The numbers are summarised in Table 7.

Table 7: Methane emission estimates from well completions

Well Type	**Assessment method**	**Average methane emissions (‘000m^3/completion)**
Conventional	Primary	4.9
	Secondary	0.9
Unconventional – reduced emission completion	Primary	3.0
	Secondary	39.3
Unconventional – non-reduced emission completion	Primary	11.9
	Secondary	606.0

Source: Balcombe et al, SGI 2016

LNG

LNG liquefaction, shipping and regasification processes are relatively carbon-intensive compared to pipeline transportation. There is, however, not much evidence to suggest that these stages have a higher percentage of methane emissions than the rest of the gas supply chain. This is an area where more measurement and greater transparency would be beneficial. (Balcombe et al, 2015 p 35)

Transmission

Methane emissions during the transmission stage (which includes long-distance transportation) would appear to arise primarily from above ground installations such as compressors and pressure regulation stations where equipment type, age, and maintenance levels can be crucial and from maintenance and repair operations. Sources can also include venting from pneumatic controllers which are actuated by pipeline pressure. Emissions arising during repair operations can be an issue if the gas in pipelines is vented to the atmosphere prior to work commencing. In 2015 Gazprom reported 1.3 million tonnes of methane emissions of which 77 per cent arose from venting during repairs (Gazprom, 2016, p22). This source of emissions is being reduced by using portable compressors to pump the gas forward using nitrogen, rather than venting it.

High pressure pipelines are typically closely monitored both by telemetry and above ground surveys, and large scale leakage is expected to be minimal. Leakage rates can vary widely however. A recent DBI study (2016) assessed leakage rates for Russian export gas transiting Ukraine as 0.38 per cent of sales gas whilst a European transmission operator reports a reduction in measured pipeline leakage rates from 0.024 per cent of sales gas to 0.01 per cent after a major repair programme carried out between 2015 and 2017.

Storage

Underground gas storage is likely to have similar characteristics to transmission with fugitive emissions most likely to be the result of outdated or leaking compressors and surface valves. However, the presence of a very large volume of high pressure gas creates the potential for a super-emitter in the event of a catastrophic failure. A striking example of this was the Aliso Canyon storage facility which suffered a well pipe casing failure resulting in an uncontrolled escape of gas between October 2015 and February 2016. Nearly 100,000 tonnes of methane escaped[16].

[16] http://www.bbc.co.uk/news/science-environment-35659947

Distribution

In gas distribution, the most prominent source of methane emissions is normally from older metallic mains. These typically arise from holes or cracks in iron mains or from leaking joints where the original seals are no longer effective. This is a particular issue in the USA and UK which still have a large number of metallic mains (see Country profile) but may be of less concern where distribution pipelines are predominantly polyethylene. Some US studies[17] have indicated relatively high levels of leakage from plastic pipes though this experience is not replicated in Europe. Discussions with UK companies, where operating pressures may be lower, suggests that whilst there may be some permeation through the walls of older pipes, most leaks from plastic pipes occur because of poor quality jointing and installation techniques that can be reduced with an effective performance and acceptance testing system[18].

One area where plastic pipelines are more susceptible to causing emissions is as a result of interference damage (this may in part explain the high US leakage numbers). This is where a third party accidentally damages a gas pipeline whilst excavating. The nature of polyethylene pipes is that they are susceptible to fracturing if struck forcefully and can therefore emit large volumes of gas – particularly in the case of medium pressure pipelines. Minimising the possibility of interference damage is therefore an important component of a leakage reduction strategy.

Other emission sources at the distribution stage can include metering and regulating stations and intentional venting during operations. In most countries, leaks in customer services and meters are dealt with as a priority due to safety considerations though where retail meter installations are located away from the property (as in many parts of the US) these can also be a cause of sustained leakage.

The explosive property of methane means that gas leaks from distribution systems are attended to quickly, although this does not always mean the leaks are repaired quickly. Leaks are typically prioritized according to safety criteria and those that do not present a hazard are deferred or reprogrammed. This can result in venting to the atmosphere for prolonged periods. In California in 2015, repairs to 22,156 reported gas leaks were carried over to 2016. (Charkowicz et al – more details in the US Country profile).

Gas consumption

It is to be expected that methane emissions downstream of the meter would normally be insignificant as any leaks would be treated as a priority for repair. The UNFCC statistics show a number of anomalies: although many countries report zero or very low proportions of leakage from consumer premises, Russia identifies that 26 per cent of emissions from natural gas supply are from consumer (mainly industrial) premises and both Romania and Ukraine report 51 per cent. These very high numbers could be due to data collection anomalies[19] though high leakage rates from inefficient district heating and other large scale plant cannot be ruled out. Figures from the USA cite an average of 0.3 per cent of metered methane escaping from power plants[20].

One growing area of potential emissions is 'methane slip' in the transport sector where gas-fired engines are not able to fully combust all the methane and this escapes to the atmosphere. Thinkstep (2017) estimates this to be in the region of 0.13 - 0.16 per cent of the mass of gas consumed. This amount should be reduced as engine designs are adapted specifically for natural gas as a fuel, though dual fuel engines are still likely to be susceptible to some degree of methane slip. The same study estimates methane emissions of 0.05 - 0.2 per cent during fuel dispensing.

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[17] Lamb et al (2015 – see Country profile).

[18] http://www.smarternetworks.org/Project.aspx?ProjectID=1622#downloads

[19] Analysis in the UK of the industrial processes, residential and business sectors showed the main sources were coal used in the manufacture of bricks, household composting, and accidental fires.

[20] https://www.purdue.edu/newsroom/releases/2017/Q1/estimates-of-emissions-from-natural-gas-fueled-plants-much-too-low,-study-finds.html

In conclusion, there has been progress on several fronts in identifying, recording, and monitoring methane emissions in the gas supply chain, and some of the initiatives are summarised in Section 5. There is, however continuing concern over the quality and consistency of data. Factors explaining these differences include:

- Differing definitions of sources - for example, flaring gas in association with oil production being allocated to the gas industry
- Different methodologies for the calculation and application of emissions factors
- Top-down and bottom-up methane emissions measurements
- The application of different global warming potential values
- Conversion factors (density, gross calorific value, etc.)
- Pipeline distances (for example, route kilometres versus pipe kilometres)

Providing accurate, and accepted, data for the natural gas value chain remains a major problem in many countries and this in turn distorts the debate over the impact of methane emissions from the gas industry which is considered in the next section.

4. The impact of methane emissions

The second key issue relates to impact. It is clearly important to be able to develop a levelised metric for all greenhouse gases (expressed in CO_2 equivalents) to compare their comparative impact on the climate. Methane is a much more potent greenhouse gas than the equivalent quantity of CO_2: at the time of emission, the instantaneous climate forcing impact of methane is between 100 and 120 times greater although it decays rapidly over time, oxidising to CO_2 after around twelve years on average. After 100 years, its impact (over and above the resulting CO_2 product) is virtually zero. CO_2 on the other hand accumulates in the atmosphere and remains there almost indefinitely.

The time horizon is therefore crucial in order to assess the comparative impact of methane on the atmosphere. The most common approach is to calculate the average global warming potential (GWP)[21] over a 100-year horizon which generates a GWP of 28[22], whilst a 20-year horizon increases this to 84. The former number has been adopted by the IPCC.

This approach, however, is not without its critics. Whilst it is outside the scope of this paper to go into details, it is certainly the case that to use the higher GWP factors for methane as a means of comparing fossil fuel options is potentially misleading. The rationale for the 100-year time horizon is that it is more appropriate for assessing the relative merits of investments designed to reduce greenhouse gas emissions overall, although as Balcombe et al (2015) point out, the choice of time horizon may vary depending on the nature of the policy question being considered. There is the risk that by focussing too much on short-lived climate pollutants such as methane, which will have little impact on the warming experienced by future generations, the longer-term temperature reduction goals which can only be achieved through CO_2 reduction will be jeopardised. Pierrehumbert[23], amongst others, notes that GWPs do a very poor job of representing the reversible/irreversible dichotomy between methane and CO_2.

To counter these drawbacks, it has been argued that a more appropriate environmental metric to use is Global Temperature Change Potential (GTP) which uses assumptions to translate the radiative forcing measured by GWP into actual temperature change. GTP measures the absolute change in

[21] For a detailed definition of GWP see the glossary. The comparison of with $CO_2$is on a weight not volume basis
[22] This is before feedback. After feedback the figure is 34.
[23] https://dotearth.blogs.nytimes.com/2013/08/01/two-climate-analysts-fault-gas-leaks-but-not-as-a-big-warming-threat/?_php=true&_type=blogs&_php=true&_type=blogs&_r=2 See also see Solomon et al 2012

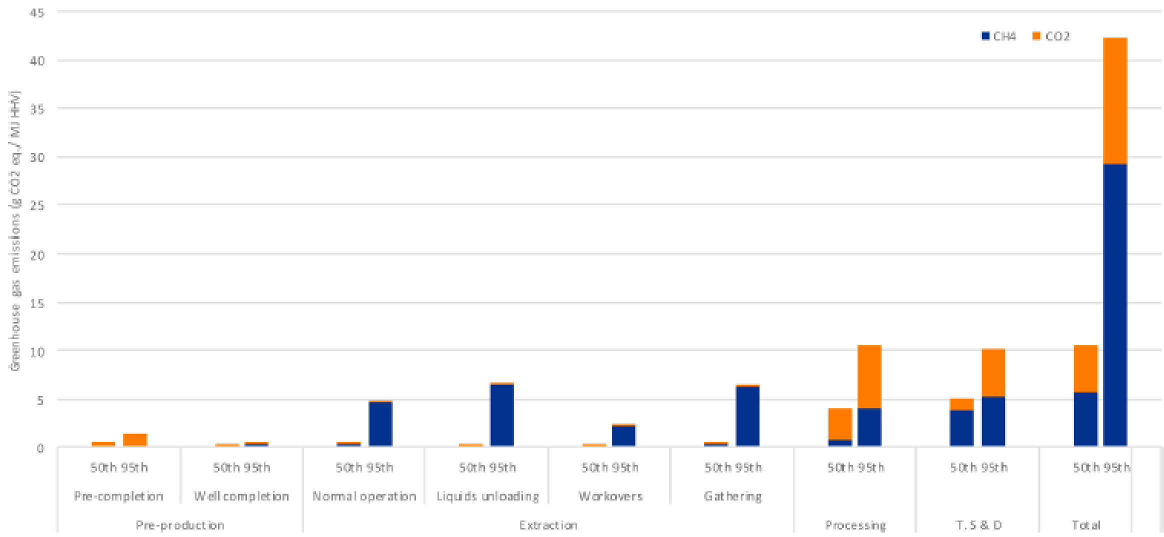
global mean surface temperature at the end of a defined time frame, arising from a specific emission, relative to the temperature change due to the emission of an equal amount of CO_2[24]. The IPCC 5th Assessment Report (AR5)[25], states that the GTP approach is more suitable for policies targeting a defined future temperature change as it answers the question, “What will the temperature change be in year X as a result of certain GHG emissions?” The GTP of methane after 100 years is around 6 (or 13 with feedback) though this time horizon does not take into account the short-term warming impact of methane which could be significant. It is also clear that our understanding of the impact of methane in the atmosphere is still evolving. There is widespread scientific debate surrounding the uncertainty of the influence of methane on both climate change and the formation of ozone, together with several explanations for past trends in atmospheric CH_4. To take just one example of how our understanding is evolving, there is now scientific evidence (Pohlmana et al, 2017) that methane seeps from the ocean actually contribute to climate cooling.

5. Methane leakage and the decarbonisation agenda

A previous study (Le Fevre, 2014) has described in detail how the relative environmental performance of different fuels should incorporate the entire life-cycle of the fuel from production to combustion including extraction, separation and treatment, transportation, refining and distribution, and utilization. This is usually referred to as the well to wheel (WTW) or well to wire carbon intensity (CI) depending on the end use. The pre-utilization phases (well to tank or WTT) typically cover CO_2 emissions from gas processing and the energy to transport the gas, as well as emissions of methane from each stage of the system.

An example of how methane and CO_2 emissions occur across the gas supply chain is shown in Figure 6. This analysis, from Balcombe et al (2016), is an update of the 2015 SGI study (Balcombe, 2015) and shows the median and 95th percentile based on the most recent and reliable data. The wide difference between the median and upper estimate demonstrates the variability in the data but also the likelihood that most supply chains exhibit relatively low emissions.

Figure 6: Estimated median and 95th percentile GHG Emissions for the natural gas supply chain



Source: Balcombe et al, 2016

[24] https://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/koldmedier-med-lag-gwp/low-gwp-news/vilket-matt-ska-vi-anvanda-for-koldmediernas-klimatpaverkan-1.473500
[25] https://www.ipcc.ch/report/ar5/

The issues with data and disputes over the impact of emissions of methane described above can result in an information vacuum. This has allowed some consultants and environmental lobby groups to paint a particularly disadvantageous picture for natural gas, often based on sparse or misapplied data. For example:

- In March 2016, a press release issued by the environmental lobby group Transport and Environment stated, "Gas-powered trucks and buses will always result in higher overall GHG emissions ……. because the lower exhaust emissions are undone by higher emissions and methane leakage during the extraction, production and transport of gas." [26]
- A study for the European Commission by Exergia (EC, 2015) concluded that the carbon intensity of natural gas was some 50 per cent higher than previous studies due to the underestimation methane leakage rates[27].
- UK environmental lobby group, Help Rescue the Planet, has used questionable assumptions regarding methane emissions from US fracking to argue that the supposed benefit of natural gas over coal should be reversed and that "this is an absolutely key point for decision makers contemplating the future of energy generation in the UK".[28]

There are also reasons other than lack of data explaining why methane emissions may be overstated. These include:

- the inappropriate use of broad based emission factors, for example applying US distribution factors to European systems or extrapolating on the basis of worst-case estimates
- Allocating methane emissions from oil production to natural gas
- Using outdated numbers that fail to take account of improvements in assets and processes that are reducing absolute levels of leakage

There is no doubt that the treatment of methane emissions can have an important impact on interfuel comparisons. Balcombe et al (2015) note that a typical gas fired power station will produce total life cycle emissions of between 400 and 600 grams of CO_2eq per kWh of electricity generated. Methane emissions at a rate of 2.2 per cent are equivalent to 92 grams of CO_2 per kWh so represent a significant element of total emissions. The comparison with coal fired power is shown in Table 8.

A key point from Table 8 is that whilst methane emissions may reduce the environmental case for gas, it is still preferable to coal or lignite even without taking account of the supply chain emissions associated with those fuels. This comparison is based on a 100-year methane GWP of 34. It should be noted that the environmental harm caused by additional methane emissions is a transitory effect whilst the additional CO_2 from coal burn is one that will persist for centuries[29].

A life cycle assessment of gas and coal supply chains in the EU and Asia was undertaken by CIRAIG for Total (2016). This analysis included the upstream emissions in the coal supply chain. The results of the base case are summarised in Figures 7 and 8 confirming the differentials shown in Table 8. Figure 8 also illustrates the proportion of methane in total emissions for each chain illustrating that it is as common in coal production as it is in gas. The CIRAIG study also undertook various sensitivity analyses. This showed that in the case of Utica shale production, fugitive emissions would have to

[26] https://www.transportenvironment.org/press/natural-gas-vehicles-expensive-ineffective-way-cut-car-and-truck-emissions-%E2%80%93-not-%E2%80%98bridge-fuel%E2%80%99

[27] The DBI study (2016) discussed in this paper concluded that methane emissions for supplies to Germany were around 40 per cent less than those quoted in the Exergia study.

[28] https://helprescuetheplanet.com/2016/03/14/we-stand-by-our-conclusions-on-methane-emissions-and-fracking/

[29] See Pierrehumbert quoted in https://dotearth.blogs.nytimes.com/2013/08/01/two-climate-analysts-fault-gas-leaks-but-not-as-a-big-warming-threat/?_php=true&_type=blogs&_php=true&_type=blogs&_r=2

reach 11 per cent (against an assessed level of 1 per cent) in order to reach emissions parity with hard coal in Europe.

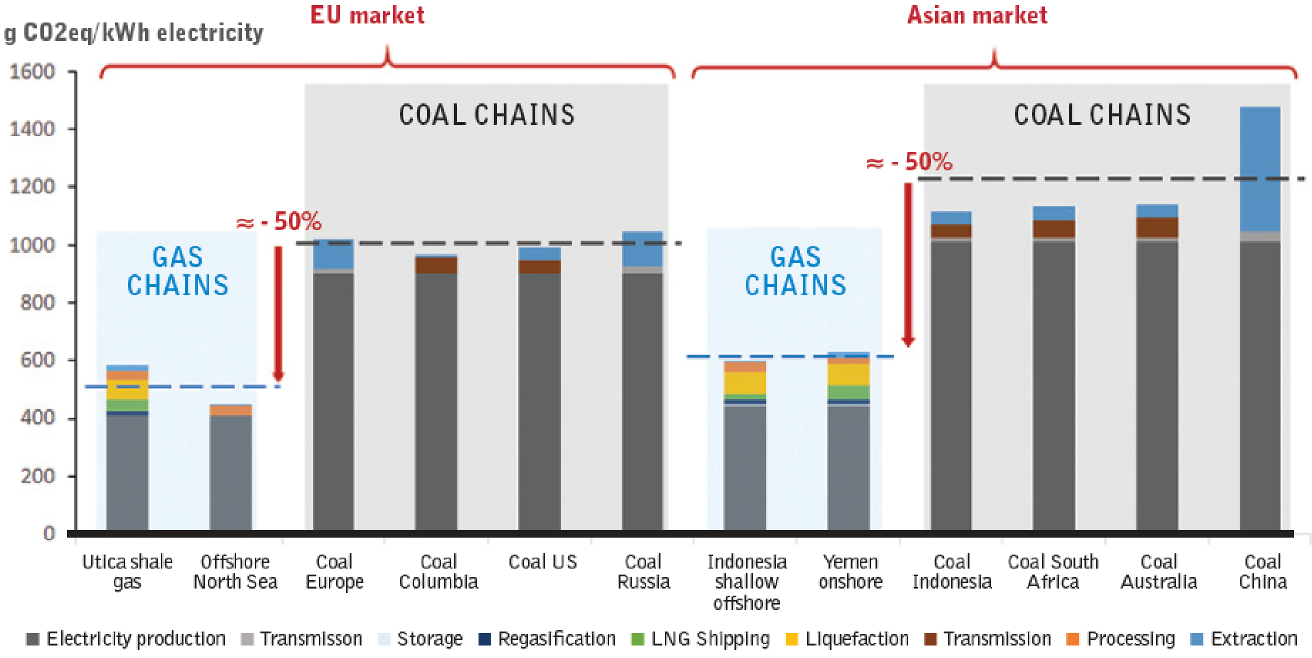
Table 8: Comparative emissions for fossil fuel generation

Fuel		**grams of CO_{2eq} per kWh CH_4 GWP=100**	
Gas	Supply chain*	No LNG	LNG
		92	175
	Combustion	350	350
	Total	442	525
Coal	Combustion only	850	
Lignite	Combustion only	1,200	

*CH_4 and CO_2 emissions for the full supply chain. Split between CH4/CO2 is 60%/40% for non-LNG and 44%/56% with LNG

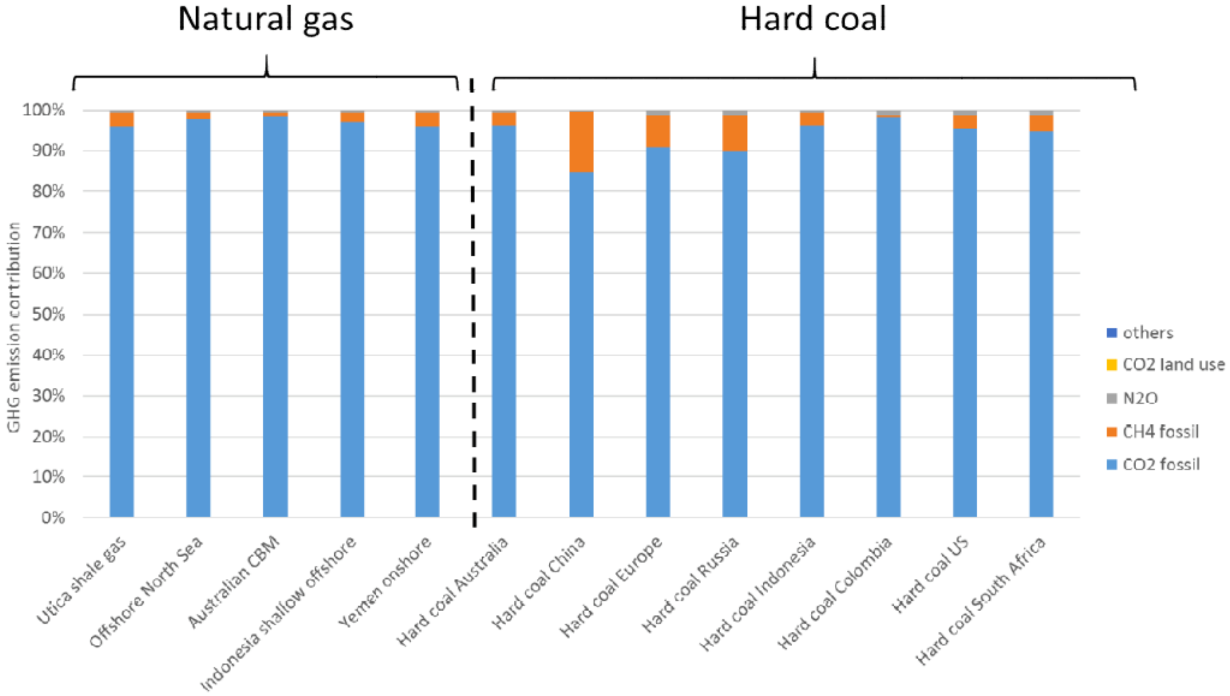
Source: Balcombe 2015, EIA, DBI 2016 and author's estimates

Figure 7: Lifecycle GHG Emissions for selected supply chains, GWP=100



Source: CIRAIG 2016

Figure 8: Contribution of different GHG emissions to total life cycle assessment, GWP=100



Source: CIRAIG 2016

Analysis by Thinkstep (2017) for the Natural Gas Vehicles Association has assessed the total well to tank (WTT) emissions for an EU based CNG vehicle as 12.5 g CO_2 eq/MJ of which 3.4g CO_2 eq/MJ (27 per cent) is due to methane emissions. These are assessed as 45 per cent arising from production, processing and liquefaction, 32 per cent from transmission, distribution and storage, 15 per cent from LNG feedstock transportation, and 8 per cent from dispensing. For an LNG vehicle, the total well to tank (WTT) emissions are 19.9 g CO_2 eq/MJ of which 5.4g CO_2 eq/MJ (27 per cent) is due to methane emissions with 78 per cent arising from production, processing and liquefaction.

When emissions downstream of the tank are considered, the total well to wheel (or well to wake in the case of shipping) emissions picture is shown in Table 9 with an indication of the proportion arising from methane emissions. These metrics are shown in terms of CO_2 equivalent per kilometre in the case of road vehicles and per kwh (namely the amount of engine power produced) for shipping. Methane emissions account for between 6 - 8 per cent of total GHG emissions in road transport and between 8 -18 per cent in marine.

Table 9: Well to Wheel/Wake GHG emissions for different fuels

Mode	Petrol	Diesel	CNG		LNG	
			Total	Of which methane	Total	Of which methane
Car CO_2eq/km	169	140	131	7.7	-	
HGV CO_2eq/km	-	1074	908	54.0	912	69.0
Mode	Fuel Oil	Marine diesel	LNG 4-stroke	Of which methane	LNG 2-stroke	Of which methane
Marine CO_2eq/kwh	742	750	662	120	589	49

Source: Thinkstep (2017). Note figures for LNG HGVs are based on HPDI engines and for LNG shipping on dual fuel engines.

Whilst the environmental case for natural gas remains broadly positive compared to other fossil fuels, reducing methane emissions could further enhance its prospects. Furthermore, the scope for disinformation is such that gas companies cannot afford to ignore the issue. The next section describes some of the initiatives that are underway.

6. Methane emissions from a company perspective – work to date

Companies along the supply chain have increasingly recognised that the emission of methane is an issue that needs to be tackled in terms of data transparency and reporting. Furthermore, there is likely to be little argument from most gas companies that best practice should include minimising methane emissions wherever possible. However, the dilemma to be faced is that there are some circumstances where reducing or eliminating methane emissions is not economically justifiable and there could be a mismatch between this and a societal view of the cost of methane leakage. Hausman[30] suggests that whilst methane leakage does represent a cost to companies, the incentive to fix the problem is much less than the social cost, which he puts at US$27/mmbtu, of the emissions.

Gas companies active in the upstream and elsewhere in the gas supply chain have taken several steps both jointly and independently. Joint initiatives include:

- The Oil and Gas Climate Initiative (OGCI). Objectives include improving methane data collection and selecting and deploying cost-effective methane management technologies[31]
- IPIECA[32], the global oil and gas industry association for environmental and social issues, provides guidance on reporting direct methane emissions as a common reporting element
- The International Gas Union (IGU) has a task force addressing the methane challenge[33] to follow on from its report (IGU, 2012) recommending a number of best practices to reduce methane emissions.
- Marcogaz, the technical association of the European gas industry, has a methane emissions working group and is collaborating with the European Gas Research Group (GERG) on the development of proposals for a Europe-wide set of methane emission estimation methods (MEEM)[34] based on data from different companies. Marcogaz is also producing a "Best Practices" document which includes the best available technology to reduce methane emissions.
- The UNECE Group of Experts on Gas is working on a Model Framework for Reducing Methane Emissions along the Gas Value Chain[35].
- In the US, the Natural Gas Star Methane Challenge program[36] provides a mechanism for oil and gas companies to make specific and transparent commitments to reducing methane emissions.
- Also in the US, the downstream natural gas initiative[37] is a group of leading natural gas utilities (including National Grid US and PG&E) collaborating to address key technical, regulatory, and workforce challenges affecting methane emission reduction opportunities from the natural gas distribution segment. This includes improving data and sharing best practice.

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[30] https://theconversation.com/why-utilities-have-little-incentive-to-plug-leaking-natural-gas-63092
[31] http://www.oilandgasclimateinitiative.com/climateinvestments
[32] http://www.ipieca.org/news/ipieca-s-work-on-methane/
[33] http://www.igu.org/news/igu-council-workshop-measure-document-and-reduce-gas-industry%C2%B4s-commitment-managing-methane
[34] http://www.dbi-gut.de/emissionen.html
[35] https://www.unece.org/fileadmin/DAM/energy/se/pdfs/nat_gas/geg/geg4_March2017/Item_5.1_-_Foster_-_UNECE_Model_Framework_on_Reducing_Methane_Emissions_xxxWeb.pdf
[36] https://www.epa.gov/natural-gas-star-program/natural-gas-star-methane-challenge-program
[37] http://www.mjbradley.com/content/downstream-natural-gas-initiative

- Various industry partnerships with governments and NGOs such as the Climate and Clean Air Coalition and the Oil & Gas Methane Partnership

Individual companies have improved transparency and many now publish detailed environmental reports. A selection is summarised in Table 10. Whilst these reports provide aggregate data, the general lack of detailed breakdown (for example by country) still leaves the industry exposed to charges of inadequate reporting.

Table 10: Examples of environmental reporting by major gas companies

Company	Report
Shell	In 2016, methane emissions contributed less than 5 per cent of Shell's GHG emissions on a CO_2-equivalent basis. More than 60 per cent of reported methane emissions in 2016 came from flaring and venting in upstream operations.
BP	Its Annual Sustainability report [38] publishes methane emissions. Calculates methane intensity[39] at around 0.2 per cent. Introduced green completions in onshore US wells and is replacing pressure-operated equipment.
Enagas	Publishes an annual carbon footprint report on its website which details the proportion of methane emissions as a percentage of total GHG emissions.
Gazprom	Annual Ecology report[40] recording methane emissions split by company. Targeted reduction of methane emissions during repair.

Companies have also developed a range of technical solutions covering gas leak detection, process and equipment redesign to eliminate emissions, and have targeted replacement programmes. Some examples are shown in Table 11 and in the country profiles.

Table 11: Examples of technical solutions introduced to reduce methane emissions

Sector	Example
All sectors	New technology to detect and swiftly repair leaks but also to get a better understanding of the data. LDAR programmes using infrared cameras to identify and repair fugitive leaks Improved techniques such as Flame Ionisation Detector to quantify fugitive leaks Review of training and processes to establish a "no emissions" culture
Upstream	Green completions Reduction/elimination of venting and flaring Capturing methane during liquids unloading
Transmission & Distribution	Proactive monitoring of high risk super-emitters – storage sites, processing facilities, and compressors Forward pumping using portable compressors during maintenance operations Increased survey cycles, use of telemetry, and pressure monitoring Pipeline replacement programmes Replace gas driven compressor engines with electric ones Proactive corrosion repair Replacement of devices operated by pipeline pressure Targeted inspections

[38] https://www.bp.com/content/dam/bp/en/corporate/pdf/sustainability-report/group-reports/bp-sustainability-report-2016.pdf
[39] Methane emissions as a percentage of marketed gas production
[40] Gazprom 2016

To summarise company performance has improved both in terms of reporting and reducing the level of methane emissions. There are also a number of pan-industry initiatives that are beginning to bear fruit though there are still many gaps and inconsistencies and scope for more proactive approaches. For example, greater efforts from gas importers to determine the level of emissions from their suppliers would be beneficial. The range and inconsistency of approaches means there remains a strong interest by, and a role for, government and other regulatory agencies. This is considered in the next section.

7. Methane emissions from a regulatory perspective – sticks and carrots

Restricting the amount of natural gas that is released to the atmosphere has long been a feature of many government and regulator's policies for both safety and environmental reasons. In the upstream the focus has been on restrictions on the venting and flaring of natural gas during the production process. In the downstream sector, safety legislation puts strict requirements on gas pipeline companies to deal swiftly with gas escapes, though as noted above this can include a requirement to "make safe" that might not actually stop emissions in the short-term.

Growing awareness of the wider environmental ramifications of methane emissions has led governments to take more proactive and specific measures. Developments on the legislative front have occurred in the following countries (see also country profiles):

- the USA where the EPA has increased reporting requirements
- Russia, which is currently the only country in Europe that has regulation on methane. In Russia methane is treated as both a GHG and an atmospheric pollutant and legislative treatment to restrict methane emissions was introduced in 2009[41]. This legislation was primarily directed at limiting the flaring of associated gas but includes widespread reporting requirements and fines for methane emissions (Carlarne et al, 2016). It is to be noted that there is a separate GHG reporting system based on activity levels and international IPCC co-efficients. Methane emissions reporting is based on actual measurements which result in lower reported levels of methane emissions.

In the EU, there is no specific legislation aimed at methane emissions. There was some pressure to include methane within the National Emission Ceilings Directive (NECD) which would have introduced a country level cap. This move was successfully resisted by the agricultural lobby though the Commission may still submit legislative proposals to reduce methane emissions[42]. These emissions are also indirectly addressed through various waste and agriculture regulations such as the Landfill Directive.

In the downstream, traditional treatment by regulators has focussed on unaccounted for gas (UAG)[43]. This term covers a wide range of factors including variations in calorific value, metering inaccuracies and theft, as well as leakage. In many cases regulated utilities were compensated for these amounts and so the incentive to try and reduce emissions was limited. The liberalisation of markets has led to greater focus in this area and a requirement for the precise causes of UAG to be identified and minimised. It has also been recognised that passing costs on to consumers is inequitable; Costello (2013) reports that the Pennsylvania Public Utility Commission has estimated that gas customers may be paying as much as US$131 million annually for UAG.

Regulators have turned increasingly towards incentive regimes, and other measures have evolved to encourage/enforce greater attention to the issue – particularly where companies can take active measures to reduce losses. Examples include:

[41] http://government.ru/docs/all/108250/

[42] http://data.consilium.europa.eu/doc/document/ST-10493-2016-INIT/en/pdf

[43] Sometimes referred to as "lost and un-accounted for" (LAUF) gas. See Costello 2013.

- Incentives to replace metallic mains
- Enhanced data reporting requirements – this alone can have a beneficial impact on leakage reduction
- Funding for technical innovations aimed at reducing emissions

Nevertheless, some disincentives may still exist. For example, rate base regulatory systems encourage the replacement of mains but may not incentivise operating expenditure to fix non-hazardous leaks.

In conclusion, a combination of incentives, mandating and monitoring is likely to provide the most efficient and effective approach to minimising emissions.

8. Conclusions

This paper has sought to put the issue of methane emissions from the natural gas industry into a global context and highlight the key issues of measurement and impact. It has identified how the issue might shape the role of natural gas within the broader carbonisation agenda and the various actions that industry and regulators are taking.

The main conclusions from this study are:

- There has been a significant increase in the measured amount of global atmospheric methane since 2006. Over this period global gas production has increased by around 2.4% annually though there is no evidence that the increase in atmospheric methane levels is a result of this increase. Indeed, many countries have reported a reduction in both the absolute and relative level of emissions from the natural gas sector.
- Estimating an accurate figure for global methane emissions from the natural gas industry remains a work in progress. Several studies suggest that a global average of between 1.5 - 2 per cent of gas across the entire supply chain is broadly correct though some of this may be the result of oil production whilst a few estimates put the numbers much higher. There are significant gaps and inconsistencies in the data picture - particularly in some major producing countries.
- There also appears to be a significant gap in some countries between government reporting of methane emissions using standard UNFCCC emission factors and templates, and the more accurate assessments provided by companies and other organisations within these countries. These gaps and inconsistencies add to the level of confusion and distrust over industry reporting.
- The issue of methane emissions is now on the agenda of most gas companies though responses are still varied and data provision is inadequate. There is general recognition that best practice should include minimising methane emissions wherever possible, and many initiatives have been pursued to good effect, though there may be circumstances where removal is not economically justified. There is likely to be a continuing gap between some groups' view of the societal cost of methane leakage and the commercial cost of eliminating methane emissions completely.
- The industry has much to gain from an increase in transparency. The absence of data will lead some agencies and competing fuels to postulate misleadingly high estimates and these, in the absence of information to the contrary, will achieve purchase in some quarters. Furthermore, the absence of comprehensive and reliable data is hampering efforts by the industry to be part of the debate. Studies such as the recent Thinkstep report demonstrate what can be achieved in terms of data consistency and transparency. Greater efforts from gas importers to determine and publish the level of emissions from their suppliers would be also be beneficial.
- The inappropriate use of broad brush emission factors and disputes over the impact of methane emissions on global warming has led to a confusing picture of the relative environmental merits of

natural gas versus other fuels. The lack of a common accounting and reporting standard (which could also apply to other sectors such as coal and agriculture) is also unhelpful.

- There would appear to be broad agreement that the GWP potential for methane should be assessed on a 100-year basis making methane between 28 and 34 times more potent than the equivalent amount of CO_2. There is a case for using Global Temperature Potential rather than GWP as a comparator as it measures the temperature outcome at a particular point in time, though it would tend to understate the short-term warming impact of methane. The depth of understanding on the true impact of methane emissions on climate change is still evolving and policy decisions based on short-term benefits may be unwise.
- Whilst the full chain effect of methane emissions reduces the environmental case for gas, it is preferable to coal as a fuel for power generation on a full well to wire basis using the 100-year assessment. The case for gas in transport is less clear cut and improvements in engine and fuel delivery performance will be necessary to demonstrate the benefits in GHG terms though gas has other important benefits[44].
- It is possible that upstream emissions are most prevalent in low output onshore wells, for example during liquids unloading. The hydraulic fracturing of some shale wells has probably resulted in high emissions levels though there are no apparent reasons why unconventional gas developments should have a higher rate of emissions than any other type of gas well.
- The country profiles illustrate the ways in which regulatory interventions can be productive as a means of standardising data collection and publication requirements and in developing an appropriate mix of incentives. A combination of incentives, mandating, and monitoring is likely to provide the most efficient and effective approach to minimising emissions.
- Risk-based assessment of potential super-emitters could see an increased requirement for real-time monitoring of salt cavity storage and similar assets. More broadly, a better understanding of the conditions that are likely to precipitate super-emissions could enable better identification and more targeted responses.

Methane emissions influence but do not undermine the environmental case for gas. If the industry can build on the progress to date and deliver a clearer picture on the level of emissions and actions to address them, the arguments for gas displacing coal in power generation and oil products in transport become much stronger.

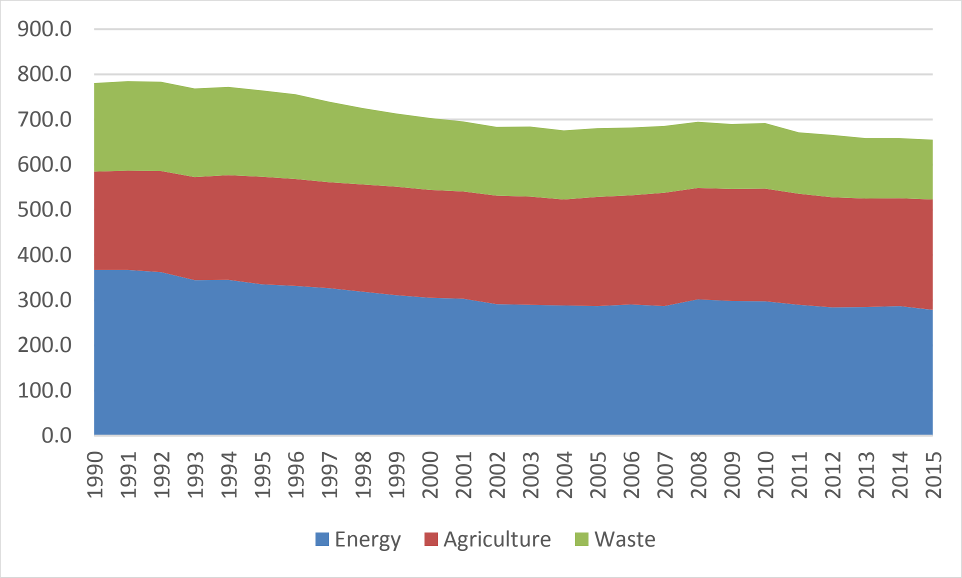
[44] Natural gas has clear advantages in terms of reduced pollution of Sox, Nox and PM

US Country Profile

Extensive data collection and state-led regulation.

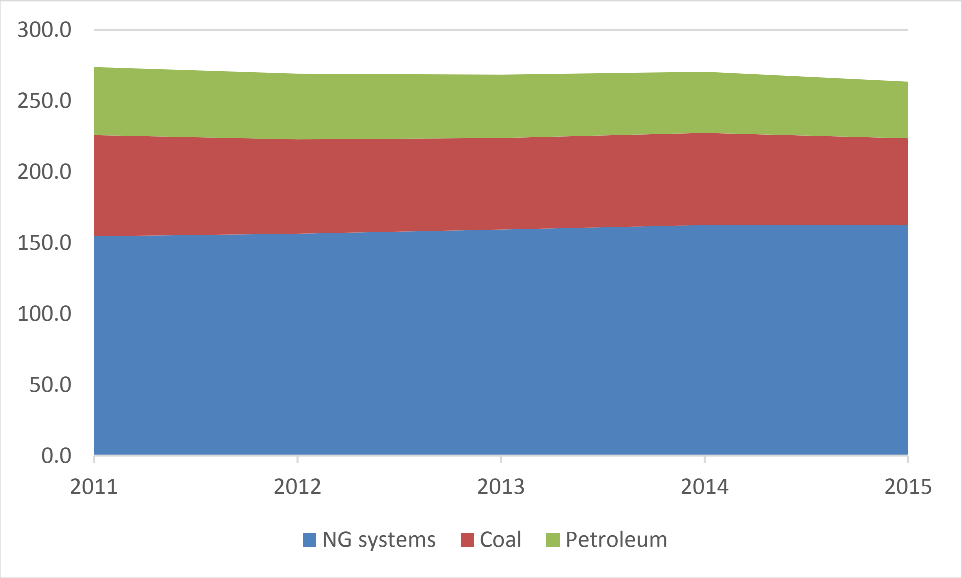
The US has, until recently at least, been relatively proactive in promoting efforts to measure, report, and reduce methane emissions. Figures 1 and 2 summarise the breakdown of sources and how these have evolved over time.

Figure 1: Main sources of anthropogenic methane emissions (Million tonnes of CO_2eq) 1990-2015



Source: US EPA

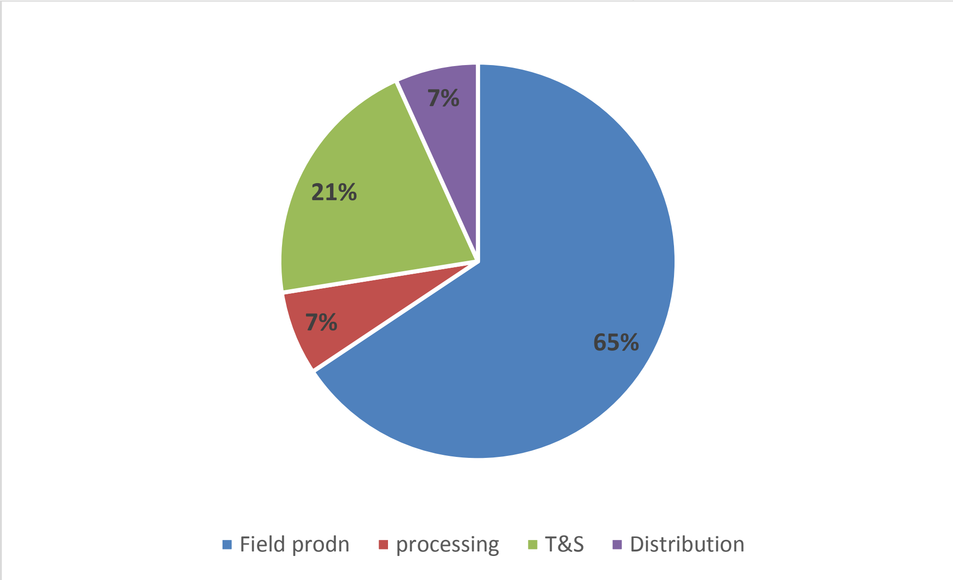
Figure 2: Main sources of methane emissions from energy systems (Thousand tonnes of methane) 2011-2015



Source: US EPA

The natural gas industry claims to have made good progress in this area pointing out that production rose by 39 per cent between 1990 and 2013 during which time methane emissions fell by 12 per cent. However, as Figure 2 shows emissions have remained fairly static in the past five years. This was due to increased gas production which countered the effects of new technologies, pipeline replacements, and voluntary efforts by producers and pipeline and distribution companies (Costello 2015).

Figure 3: Main sources of methane emissions from natural gas systems 2015

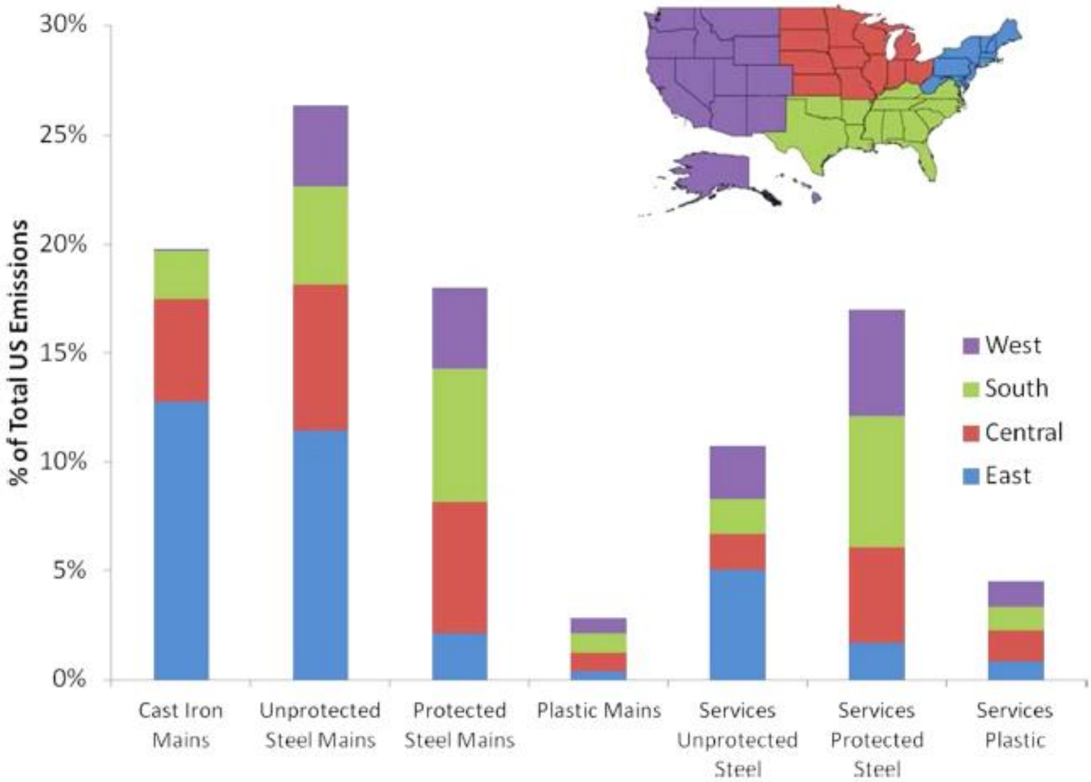


Source: US EPA

Figure 3 shows the main sources of emissions from natural gas systems and the significant share that is attributed to upstream production, although it is understood that these figures include unburned methane from flaring associated gas from oil production. The other main emissions sources in the upstream arise from deliberate venting from production wells during liquids unloading or for safety or operational reasons, leaks from gathering stations, and pneumatic controllers and pressure relief valves. Growth in methane emissions in the US are linked to increases in the absolute number of wells, gathering facilities, and in-field booster stations. Outside the upstream sector the most common source of leaks are compressor stations and distribution pipelines.

A multi-utility study published in 2015 (Lamb et al) collected data on distribution system emissions from 13 different gas companies. As shown in Figure 4 this study demonstrated that most downstream leaks came from metallic mains and services.

Figure 4: Sources of methane leaks in distribution companies (per cent)



Source: Lamb et al 2015

In March 2014, the Obama Administration released a report entitled Strategy to Reduce Methane Emissions. This was followed in January 2015 by a series of measures aimed at reducing these emissions from the oil and gas sector by 40 - 45 per cent from 2012 levels by 2025 (The White House 2015). The Trump Administration has since announced that it intends to overturn rules relating to the reporting and control of methane emissions on federal lands and in March, the EPA withdrew its 2016 information request. In May 2017, however, these moves were defeated in the Senate[45].

Whilst efforts to control methane emissions at a federal level may have stalled, state initiatives have made some headway. In California, for example, a 2014 regulation (SB 1371) places higher duties on utilities regarding leak identification and quantification, as well as switching the cost of unmetered gas from the consumer to the utility. A detailed analysis of the utility sector's performance arising from this regulation (Charkowicz et al, 2017) concluded that reliance on emissions factors was not an acceptable long-term strategy for measuring leakage rates and actual measurements should be applied wherever possible.

The report also contained some detailed analysis of how gas leaks are graded and dealt with. Leaks are identified and assessments made as a result of a survey – pipeline surveys are typically performed every five years. Grading of leaks, in common with many gas distribution operations, is based on actual or potential hazard. In California, there are three categories as shown in Table 1.

[45] http://www.salon.com/2017/05/11/republicans-buck-donald-trump-on-the-climate-senate-blocks-repeal-of-obama-era-rule-on-methane-emission/

Table 1: Gas leak categories and occurrence in California in 2015

Category	Description	Percentage of total
1	leaks that represent an existing or probable hazard to persons or property and require prompt action.	25%
2	leaks that are not hazardous at the time of detection but justify a scheduled repair based on potential for a future hazard	16%
3	leaks that are not hazardous at the time of detection and can reasonably be expected to remain non-hazardous	59%

Source: Charkowicz et al, 2016

It should be noted that the grade 3 leaks described in Table 1 can be carried over year after year. In 2015, 19,491 leaks were repaired whilst 22,156 (mostly grade 3 leaks) were carried over to 2016[46]. Emissions from open grade 3 leaks accounted for 78 per cent of distribution mains leakage. The report shows, however, that in California meter assemblies are a more significant source of emissions than graded leaks. This may be more of an issue in the US than elsewhere as US gas meters tend to be located in front yards away from the property so may be less susceptible to regular monitoring.

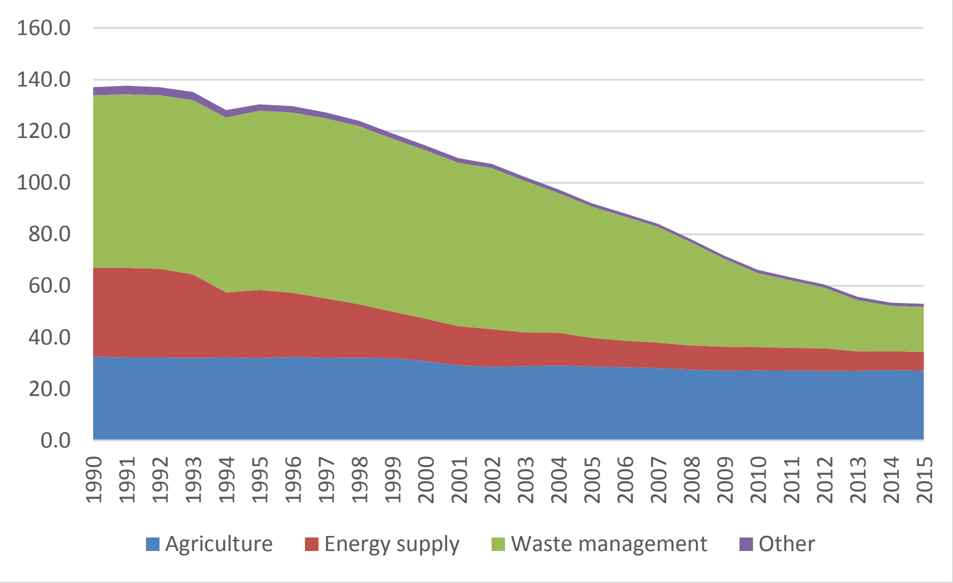
[46] HEET, an energy NGO in Massachusetts, maps unrepaired gas leaks in the state. They reported unrepaired leaks at the end of 2014 and 2015 as 18,624 and 15,749 respectively.
https://www.heetma.org/squeaky-leak/natural-gas-leaks-maps/

UK Country Profile

Incentive based regulation

Government statistics for the UK (BEIS, 2016) show that methane represents most non-CO_2 GHG emissions. The agriculture sector accounts for slightly over half of all methane emissions, while the waste management sector accounts for around 30 per cent. The remaining methane emissions are largely attributed to fugitive energy emissions which arise from natural gas leakage, operational and closed coal mines, and solid fuel transformation. Figure 1 shows that the level of emissions from the energy sector have declined significantly in recent years along with those from waste management[47].

Figure 1: UK methane emissions by source 1990 to 2015 (M tonnes of CO_{2e})



Emissions from the energy sector have fallen due to the reduction in coal mining and the replacement of old metallic mains in the gas distribution network (Brown et al, 2017).

Data on methane (and other) emissions in the upstream sector is collected via the Environmental and Emissions Monitoring System (EEMS)[48]. Methane emissions amounted to 41,200 tonnes during 2015[49]. Venting accounted for 53 per cent of this amount with a further 34 per cent due to unburned gas during flaring operations[50]. There has been some criticism of the accuracy of the data collected via EEMS which is understood to be primarily based on top down estimates rather than actual measurements. This is an area where greater transparency would be helpful.

There are tight controls on venting and flaring and this is primarily carried out on oil-producing platforms – though venting increased in 2015 in line with higher gas production. Most venting is likely to occur on older platforms where the costs of elimination would render production uneconomic.

Leakage from the gas distribution network is the largest source of anthropogenic methane outside of the agriculture and waste sectors, comprising approximately 7 per cent of all CH_4 emissions.

[47] This is due to methane recovery systems being installed at land fill sites.
[48] https://www.gov.uk/guidance/oil-and-gas-eems-database
[49] To put this into some context the Elgin gas leak in 2012/2013 emitted some 6,000 tonnes of methane. See https://www.theguardian.com/business/2015/dec/22/oil-company-total-fined-1m-north-sea-gas-leak
[50] UK OIL & GAS Environment report 2016 (https://cld.bz/qgAn4xr/1) The methane from flaring is assumed to be 2 per cent

For safety reasons the replacement of ageing metallic gas mains has been a priority for the gas distribution sector since the late 1970s though absolute levels of replacement were around 2,500 km per year[51]. In 2002, following three fatal incidents arising from mains leakage, the replacement programme was accelerated after an enforcement policy from the Health and Safety Executive (HSE). Records showed that there were approximately 101,000 kilometres of iron mains within 30 metres of properties which could be a risk to people[52]. The HSE considered it reasonable to expect the industry to replace these over a 30-year period. The regulatory price control arrangements for the gas distribution networks (GDNs) included provision for the mains replacement programme with some incentives for outperformance. However, the programme does not target high leakage pipes per se, just those seen as presenting the highest safety risk. GDNs appear to be making good progress with most recently reported figures showing annual replacement levels at around 4,200 kms[53].

There is a separate regulatory arrangement to encourage leakage reduction via two incentives[54]:

- The Shrinkage Incentive acknowledges that 95 per cent of shrinkage is caused by pipeline leaks. GDNs receive a payment based on the gas commodity price for exceeding agreed targets. In 2015-16 the GDNs earned £3.1 million via this mechanism
- The Environmental Emissions Incentive (EEI) is a further payment to GDNs with a payment based on the government's non-traded carbon value for reducing methane emissions below their leakage targets. In 2015-16 the GDNs earned £17 million via this mechanism.

The regulator also allows expenditure to be recovered on agreed innovation schemes, some of which are aimed at reducing emissions.

To continue leakage reduction from remaining metallic mains the GDNs have employed or experimented with various approaches including[55]:

- System pressure control to reduce pressure during periods of low demand
- Targeted sealants for leaking joints using aerosol sealants, robots, or gas polymerisation
- Advanced gas detection techniques
- Analysis of the type of polyethylene pipe leaks/failures

GDNs have also sought to employ best practice from elsewhere including other sectors, such as the water industry, which have experience of dealing with pipeline leaks.

[51] http://www.hse.gov.uk/research/rrpdf/rr888.pdf
[52] http://www.hse.gov.uk/gas/supply/mainsreplacement/irongasmain.htm
[53] http://www.energynetworks.org/assets/files/news/publications/GAS%20FAST%20FACT%20CARDS%20-%20ALL.pdf
[54] https://www.ofgem.gov.uk/system/files/docs/2017/02/riio-gd1_annual_report_2015-16_0.pdf
[55] More details are on the Energy Networks Association portal http://www.smarternetworks.org/site.aspx

Glossary

- Bcm: one billion cubic metres.
- Bcma: one billion cubic metres per annum.
- CCGT: Combined cycle gas turbine power station
- CNG: compressed natural gas, made by compressing natural gas (which is mainly composed of methane [CH4]), to less than 1% of the volume it occupies at standard atmospheric pressure. It is a fossil fuel substitute for gasoline (petrol), diesel, or propane/LPG.
- CO_2: Carbon dioxide
- CO_2-eq: Carbon Dioxide-Equivalent Emissions
- CH_4: Methane
- Conventional Gas: Natural gas produced from an underground reservoir other than shale gas, tight gas or coal bed methane.
- ENTSOG: The European Network of Transmission System Operators for Gas
- EPA: Environmental Protection Agency – A US Government Agency
- EU Emissions Trading System: A cap and trade system under which participating EU Member States allow qualifying CO2 emitting installations to trade CO2 permits. The number of CO2 permits are limited by agreed caps on CO2 emissions at the Member State level.
- Flaring: The combustion of emissions of methane, usually deliberate as a result of operations
- Fugitive emissions: Leaks from pipelines and other facilities (i.e. unplanned emissions, see venting)
- GDNs: gas distribution networks
- GHG: Greenhouse Gas
- GTP: Global Temperature Change Potential: the ratio between the global mean surface temperature change at a given future time horizon (TH) following an emission (pulse or sustained) of a compound *x* relative to a reference gas *r* such as CO_2
- GTP_{100}: Global Temperature Change Potential at a 100-year time horizon
- GWP: Global Warming Potential, a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). It is important to note that the comparison is based on weight (1 tonne of CO_2 versus 1 tonnes of CH_4) and not on a molecule or volume basis.
- GWP_{100}: Global Warming Potential over a 100-year time horizon
- IEA: International Energy Agency
- IPCC: Intergovernmental Panel on Climate Change
- JRC: Joint Research Centre (of the European Commission)
- kWh: Kilo Watt Hour
- LAUF: Lost and unaccounted for gas
- LCA: Life Cycle Assessment
- LNG Terminal: Facility for importing ship borne LNG. Normally the LNG is stored at the terminal before regasification and injection into the transmission system.

- LNG: Liquefied natural gas, natural gas liquefied by cooling to minus 162 degrees Centigrade
- Methane slip: CH4 emissions from the dispensing or incomplete combustion of natural gas in transportation
- Mmbtu: Million British thermal units
- MT: Million Tonnes
- MTPA: Million Tonnes per annum
- MTOE: Million Tonnes of oil equivalent
- MWh: A unit of energy equivalent to a Megawatt of power over the duration of one hour.
- N_2O: Nitrous oxide
- NO_x: A mixture of various nitrogen oxides as emitted by combustion sources
- NTS: The National Transmission System – GB's high pressure gas grid.
- Ofgem: The Office of Gas and Electricity Markets, the GB gas and electricity regulator
- PE: Polyethylene
- PM: Particulate matter - microscopic emissions from diesel engines that have been shown to cause breathing difficulties and to have a carcinogenic effect
- RF: Radiative Forcing - the measurement of the capacity of a gas to contribute to climate change
- Shale Gas: natural gas formed in fine-grained shale rock (called gas shales) with low permeability in which gas has been adsorbed by clay particles or is held within minute pores and micro fractures.
- Super emitters: A source of large scale fugitive emissions
- TSO: Transmission System Operator
- TTW: Tank-To-Wheels, emissions from burning a fuel in a vehicle
- TWh: A unit of energy equivalent to a Terawatt of power over the duration of one hour.
- UAG: Unaccounted for gas
- Venting: Deliberate emissions of methane as a result of operations
- WTT: Well-To-Tank, emissions from producing and distributing a fuel (starting from the primary energy resource), including vehicle refueling
- WTW: Well-To-Wheels, emissions from the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle. Can also refer to Well-to-Wire for fuel used in power generation

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