Quantifying Fugitive Emission Factors from Unconventional Natural Gas Production Using IPCC Methodologies

IPCC TFI Technical Support Unit Inventory Internship

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Executive Summary

Continued advances in horizontal drilling techniques, when combined with a process known as 'hydraulic fracturing', are providing access to previously uneconomical natural gas resources. It is anticipated that these resources will play an increasing role in the global primary energy mix, with projections that the uptake will be exponential, growing from 145 billion cubic meters in 2010 to 975 billion cubic meters by 2035.

This study reviews available literature and data sources related to the fugitive emissions from the production of unconventional gas sources; Shale gas, Tight sands gas and Coalbed methane. Tier 1 (and Tier 2 for USA and Canada) emission factors are developed using IPCC good practice methodologies. Factors are developed for methane, carbon dioxide, non-methane volatile organic compounds and nitrous oxide for both developed and developing country scenarios. Using Monte Carlo analyses, expected values and uncertainty ranges for each emission factor are derived from the data retrieved through the literature review.

Emission factors and uncertainty ranges for the developed country scenario can be seen in Table E-1 below.

Category	Sub-category	Emission source	IPCC Code	CH4		CO2		NMVOC		N2O		Units of measure
				Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	
Gas Production	Conventional	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.3E-03	±100%	1.4E-05 to 8.2E-05	±100%	9.1E-05 to 5.5E-04	±100%	N/A	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	7.60E-07	±25%	1.20E-03	±25%	6.20E-07	±25%	2.1E-08	-10 to +1000%	Gg per 106 m3 gas production
	Shale Gas	Fugitives	1.B.2.b.iii.2	3.8E-04 to	±100%	1.4E-05 to	±100%	9.1E-05 to	±100%	N/A	N/A	
		Venting	1.B.2.b.i	5.8E-03	-100 to +500%	2.5E-04	-100 to +500%	7.8E-04	-100 to +500%	N/A	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	2.0E-04	-100 to +500%	2.8E-02	-100 to +500%	2.4E-05	-100 to +500%	9.0E-08	-100 to +500%	Gg per 106 m3 gas production
	Tight Sands	Fugitives	1.B.2.b.iii.2	3.8E-04 to	±100%	1.4E-05 to	±100%	9.1E-05 to	±100%	N/A	N/A	
		Venting	1.B.2.b.i	4.7E-03	-100 to +500%	1.5E-04	-100 to +500%	5.8E-04	-100 to +500%	N/A	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	1.0E-04	-100 to +500%	1.5E-02	-100 to +500%	1.3E-05	-100 to +500%	6.0E-08	-75 to +800%	Gg per 106 m3 gas production
	Coalbed Methane	Fugitives	1.B.2.b.iii.2	3.8E-04 to	±100%	1.4E-05 to	±100%	9.1E-05 to	±100%	N/A	N/A	
		Venting	1.B.2.b.i	1.6E-03	-100 to +500%	6.2E-05	-100 to +500%	2.0E-04	-100 to +250%	N/A	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	4.7E-05	-100 to +500%	8.2E-03	-100 to +500%	6.7E-06	-100 to +500%	3.9E-08	-50 to +800%	Gg per 106 m3 gas production

Table E-1: Proposed emission factors for production of Shale gas, Tight sands gas and Coalbed methane in developed countries with associated 95% confidence interval upper and lower limits (those for conventional natural gas production taken from Table 4.2.4 in Chapter 4, Volume 2 of the 2006 IPCC Guidelines are also included for comparison)

The results show that fugitive emissions arising from hydraulic fracturing activities are substantial when compared with typical conventional gas fugitive emissions. Mean life-cycle values for fugitive emissions from Shale gas, Tight sands gas and Coalbed methane are 133%, 100% and 36% higher respectively than those of conventional gas in the developed countries scenario as shown in Figure E-1. Developing countries show a similar scale of difference.

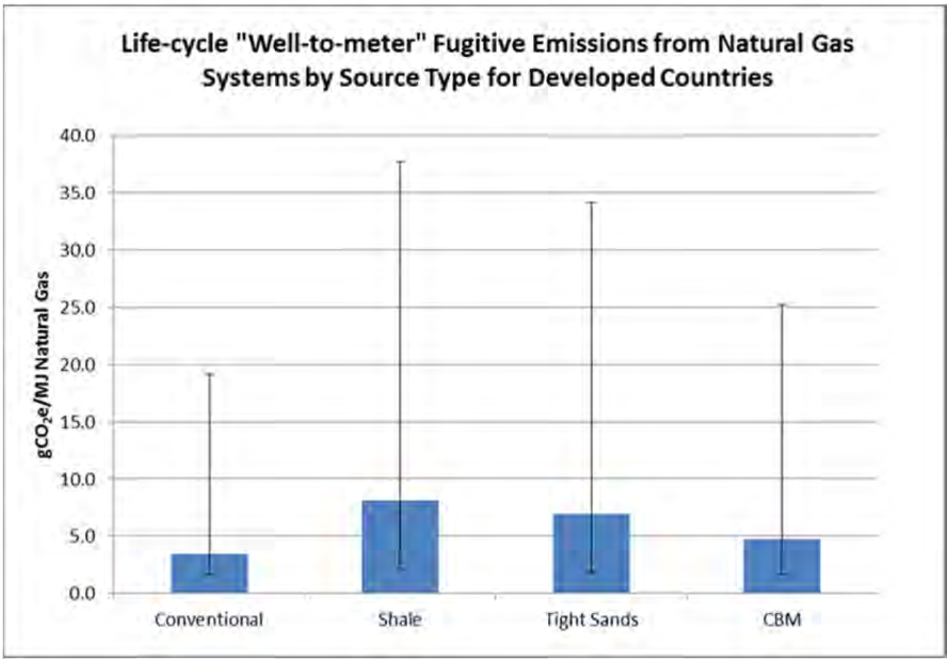

Figure E-1: Well-to-meter fugitive emissions for natural gas by source type in developed countries

In general the following conclusions can be drawn:

1) Fugitive emissions from completions and workovers of unconventional gas sources including Shale gas, Tight sands gas and Coalbed methane, are significant and the relevant emission factors should be added to the EFDB.

2) While the emission factors derived in this study are as accurate as possible, there is a deficit of measured and verified emissions data. Third party measurements to quantify fugitive emissions from unconventional (and conventional) gas sources would vastly improve the accuracy of the emission factors.

3) The scale of the difference in emissions between conventional and unconventional gas sources may be indicative of other types of unconventional fuel. In its current form the 2006 IPCC Guidelines do not address unconventional fuel types sufficiently and consideration should be given to amending the guidelines accordingly.

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Equations

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List of Acronyms

API	American Petroleum Institute
ANGA	America's Natural gas Alliance
CoV	Coefficient of Variation
EFDB	Emission Factors Database
EIA	Energy Information Administration (USA)
EPA	United States Environmental Protection Agency
EUR	Estimated Ultimate Recovery
GHG	Greenhouse Gases
GHGRP	Greenhouse Gas Reporting Program (EPA)
GRI	Gas Research Institute
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle assessment
MJ	Mega-joules (10^6 joules)
NGGIP	National Greenhouse Gas Inventories Program
PDF	Probability Density Function
QA	Quality Assurance
QC	Quality Control
REC	Reduced Emission Completion
TFI	Task Force on National Greenhouse Gas Inventories (IPCC)
tcm	Trillion Cubic Metres
TCO2e	Tonnes of Carbon Dioxide Equivalent

1 Introduction

1.1 Subject of Concern

Continued advances in horizontal drilling techniques, when combined with a process known as 'hydraulic fracturing', are providing access to previously uneconomical natural gas resources. Large reserves of this 'unconventional' natural gas (unconventional gas) have been identified and are distributed globally. It is projected that these sources will play an increasing role in the global primary energy mix, with projections that the uptake will be exponential.

From the limited amount of study that has been conducted on the subject, there is a general consensus that fugitive methane emissions from unconventional gas exceed those of conventional onshore sources (conventional gas), but there is some disagreement to the scale of the difference. Considering the increasing rate of extraction and the labelling of the fuel source as a 'transition fuel' between coal (and other high-emission fuels) and renewable sources of energy, the potential impact of unconventional gas on global greenhouse gas (GHG) emissions is significant. It is therefore a priority to reach a higher level of certainty with regard to the scale of these impacts so that well informed policy decisions can be agreed and implemented.

1.2 Unconventional Gas

Unconventional gas is defined by the International Energy Agency (IEA) as "*sources of gas trapped deep underground by impermeable rocks, such as coal, sandstone and shale. The three main types of 'unconventional' gas are: Shale gas (found in shale deposits); coal bed methane, or CBM (extracted from coal beds) and Tight sands gas (which is trapped underground in impermeable rock formations)*" (IEA, Glossary of Terms). These sources are mined using the hydraulic fracturing process whereby large volumes of water mixed with sand and chemicals are injected at high pressure into the formations causing fractures. This releases the trapped pockets of gas which can then flow into the well bore for collection. The process can be applied to either horizontally-drilled or vertically-drilled wells.

The IEA's *World Energy Outlook 2012* (IEA 2012a) estimates that Shale gas reserves alone are 200 trillion cubic meters globally (see Table 1 below), which accounts for nearly a quarter of total estimated natural gas reserves. Extraction was approximately 145 billion cubic meters in 2010 with anticipated increase in production to 975 billion cubic meters by 2035 (IEA, 2012b), resulting in the share of unconventional gas in total natural gas output rising from 14% to 32%.

Source	Unconventional Gas Reserves (tcm)	% of Total Estimated Natural Gas Reserves
Shale gas	200	25%
Coal Bed Methane	47	6%
Tight sands gas	81	10%

Table 1: Estimated Global Unconventional gas reserves (IEA, 2012a)

To date, only the USA has a well-established unconventional gas industry, which has seen unprecedented growth in recent years. Production grew 48% between 2006 and 2010 (IEA, 2011) and is projected to grow by a further 172% between 2010 and 2035 when it will make up 49% of natural gas production (IEA 2012a). Canada has also recently started commercial production.

Other major resources have been identified in a number of developed and developing countries around the world. The full extent and locations of unconventional gas sources is not completely understood. Figure 1 below shows the locations of confirmed Shale gas plays (gas fields). Outside of the USA and Canada, unconventional gas industries are predominantly still in the research and development stage and there is limited information available.

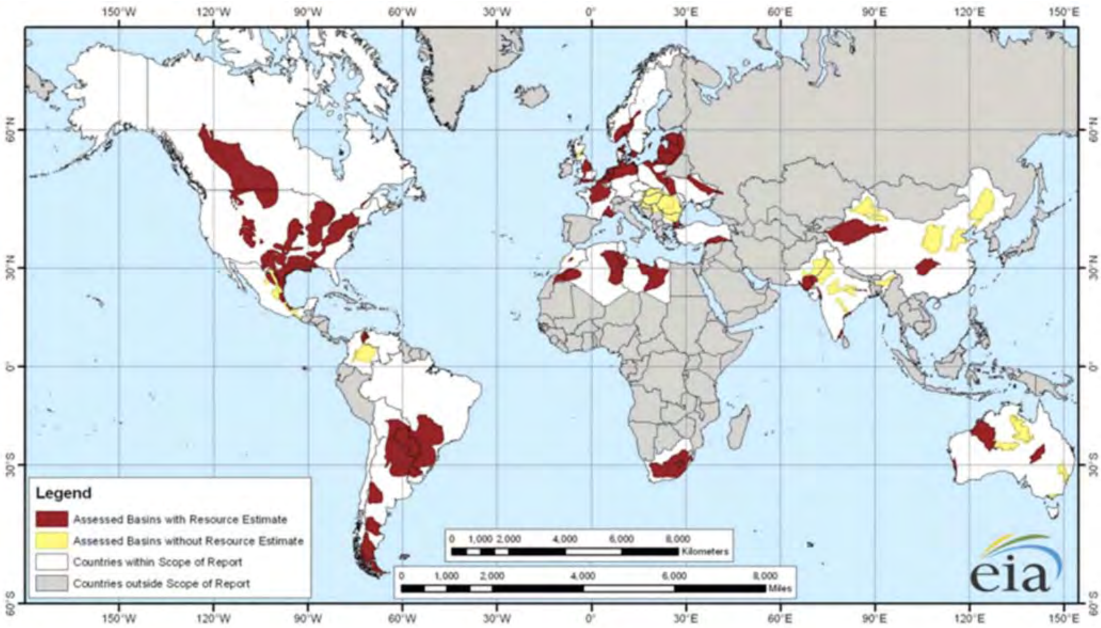


Figure 1: A map of known global Shale gas reserves (EIA, 2012)

The environmental impact of the extraction of unconventional gas sources has come under scrutiny and there remains significant uncertainty as to the scale of the effect. In terms of the potential impact on GHG emissions there is considerable on-going debate. One of the key issues is the level of fugitive emissions arising from the well development process. There are elements of unconventional gas extraction that do not pertain to the typical conventional process. Specifically, GHG emissions arising from the hydraulic fracturing process have significant uncertainties and are currently a source of considerable controversy.

A typical well will undergo multiple hydraulic fractures during the well development stage. During this stage, so-called ‘completion’ (also known as ‘flow-back’) of an unconventional gas well occurs. This is the stage at which, after the well has been hydraulically fractured, pressure causes an amount of the fracturing liquid (anywhere from 20 – 80%) and dissolved gases to return to the surface at the well head. The initial pressure and liquid content of this flow-back makes this fluid difficult to process so that it is not always economically or technically viable to recover the natural gas contained within the fluid. This may result in the venting or flaring of the gas which is predominantly composed of methane, a powerful GHG. Workovers (also known as re-fractures) involve principally the same process as hydraulic fracture and completion, but are carried out on existing wells where productivity has diminished. Any given well will thus undergo one completion and may or may not undergo multiple workovers, depending on its productivity and the availability of further gas resources in the rock formation. With the exception of completions and workovers, unconventional gas production, processing and transportation processes are considered consistent with those of onshore conventional gas.

Modern technology can allow for the capture of the gases contained within the flowback fluids during completions and workovers. This process is known as 'Reduced Emission Completions' (RECs) or 'Green Completions'. Deployment of these technologies is largely dependent on the financial incentive to do so and is not always of economic benefit to the mining operations.

1.3 USA and Canadian Unconventional Gas Industries

Unconventional gas was first mined on an economically viable scale in the USA in 1998. Since that time the scale of proven resources has grown significantly and now exceeds that of conventional gas (see Table 2 below). There has been rapid growth in the industry and the majority of the identified plays are now in production. The Canadian industry is now starting to follow in the USA's footsteps in exploiting unconventional gas sources, especially in the west of the country.

Conventional			Unconventional		
Onshore	Associated	Offshore	Tight	Shale	Tight Sands
25%	13%	7%	31%	16%	9%
44%			56%		

Table 2: USA natural gas reserves by type (NETL, 2011)

During this period of growth the USA Environmental Protection Agency (EPA) has been working to establish appropriate means of quantifying the associated GHG emissions. Based on the lack of verified data and information available, both the activity data and the relative emission factors have been subject to a large degree of uncertainty and debate. The most comprehensive study to date was conducted in partnership between the EPA and the Gas Research Institute (GRI) in 1992. The resulting report (EPA/GRI 1996) provided fugitive emission factors for the natural gas industry including estimates for conventional, unconventional, upstream and downstream sources. These figures have been in use until recently when some of the underlying assumptions were called into question. Subsequently the EPA has revised some of the figures including those for completions and workovers (EPA 2013).

In addition to the default emission factors used in USA national GHG reporting (EPA 2013), the EPA has started collecting industry-reported data through its legislated Greenhouse Gas Reporting Program (GHGRP). Under the mandate of Subpart W for 'Petroleum and Natural Gas Systems', which started in 2011, industry operatives with emissions over 25,000 TCO_2e are obliged to estimate and report their emissions on an annual basis. The initial results of this exercise have recently been made available to the public (EPA GHGRP 2013).

There are various other scientific initiatives underway throughout the USA to try and better estimate fugitive emission sources from the natural gas industry. These methods include technologies such as air-sampling and infrared imagery to measure the emissions. Initial results have indicated that current inventory techniques are significantly underestimating fugitive emissions. This may have serious consequences not only for the natural gas industry, but for the fossil fuel sector at large.

2 Background and Scope

2.1 Unconventional Gas and the IPCC Emissions Factor Database

The Intergovernmental Panel on Climate Change (IPCC) Task Force on National Greenhouse Gas Inventories (TFI) maintains an Emission Factors Database (EFDB) as part of the National Greenhouse Gas Inventories Programme (NGGIP). This database serves as an open-access repository of emission factors for use during GHG inventory compiling by users globally. The database is organized according to IPCC sectors and subsectors, categorised by sources of potential emissions. Within the Energy sector, there are subsectors relating to *Fuel Combustion Activities (1.A), Fugitive Emissions from Fuels (1.B)* and *Carbon Dioxide Transport and Storage (1.C)*. Default emission factors exist for fugitive emissions from the natural gas industry, however these factors pertain to conventional gas production and as yet, no emission factors have been included for fugitive emissions from unconventional gas. Similarly, there is no reference to unconventional gas in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2006 IPCC Guidelines).

The IPCC mechanism for prioritising various sources of GHG emissions and their related uncertainties is referred to as 'Key Category Analysis'. This quantitative and qualitative analysis considers the level, trend and uncertainty of any given GHG source or sink in order to qualify its importance in the context of any given inventory. By categorising these elements it allows inventory compilers to focus resources on the most relevant subcategories. When considering unconventional gas in this context, the emission source could be defined as a key category on a global scale given the existing level of production, the trend and the level of uncertainty of the related fugitive emissions. It is thus considered timely that fugitive emission factors for the production of unconventional gas be developed for inclusion in the EFDB.

2.2 Tier 1, 2 and 3 Emission Factors

The IPCC approach to developing GHG inventories is based on a three-tier system. Tiers are allocated to emission factors and activity data to categorize the level of rigour adopted in their development. The tiers are ordered in ascending complexity with the concept that that the higher the tier, the more accurate the reported activity data or emission factors are likely to be. In terms of emission factors; in general Tier 1 refers to a global default (least accurate), Tier 2 refers to a country-specific (moderate accuracy) and Tier 3 refers to a rigorous bottom-up analysis of localised factors and parameters (most accurate).

The natural gas industry qualifies as a 'Key Category' within a number of producing, exporting and importing states around the world. A significant amount of research and analysis has been undertaken to evaluate the level of fugitive emissions from conventional gas sources to allow for accurate inventorying. Guidance on the application of these emission factors is provided in the 2006 IPCC Guidelines[1]. Default Tier 1 emission factors for fugitive emissions from the conventional natural gas industry are included in both the 2006 IPCC Guidelines[2] and the EFDB, while there are also some Tier 2 factors for certain countries (including the USA and Canada).

[1] Volume 2, Chapter 4
[2] Volume 2, Chapter 4, Tables 4.2.4 and 4.2.5

2.3 Scope of Study

This study reviews available literature and data sources relative to fugitive emissions from the production of unconventional gas. Emission factors are developed consistent with IPCC good practice methodologies to arrive at Tier 1 and Tier 2 (USA and Canada) emission factors for Shale gas, Tight sands gas and Coalbed methane in both developed and developing country scenarios. The analysis also discusses the potential steps towards developing Tier 3 methodologies.

The IPCC defines fugitive emissions as "*intentional or unintentional releases of gases from anthropogenic activities. In particular, they may arise from the production, processing, transmission, storage and use of fuels, and include emissions from combustion only where it does not support a productive activity (e.g., flaring of natural gases at oil and gas production facilities)*" (IPCC 1996). When applying this definition to the production of natural gas, fugitive emissions are inclusive of unintentional leaks, intentional venting and flaring. Within the scope of this study venting and flaring of completion and workover gases are quantified and attributed to IPCC (IPCC 2006) source subsector 1.B.2.b (categorised by the following path: Energy → Fugitive Emissions from Fuels → Oil and Natural Gas → Natural Gas).

As discussed in Section 1.2, it is considered that the typical production, processing, storage, transport and distribution processes of conventional and unconventional gas sources are equivalent with the exception of completions and workovers of unconventional wells. Owing to this consistency, the emission factors for completions and workovers are compatible with existing emission factors for conventional gas such that they can be compiled as follows:

Equation 1: Basis for Emissions from Unconventional Gas Sources:

$$E_{unconv.} = E_{conv.} + E_{comps/works}$$

Where:

$E_{unconv.}$ = Fugitive emissions from unconventional gas sources

$E_{conv.}$ = Fugitive emissions from conventional gas sources

$E_{comps/works}$ = Fugitive emissions from completions and workovers

Based on this assumption, this study quantifies emissions from completions and workovers and applies them to emission factors already developed for fugitive emissions from conventional gas which can be found in the 2006 IPCC Guidelines[3].

Many literature sources identify a process known as 'liquids unloading' as an additional inconsistency between unconventional and conventional extraction processes as an activity (NETL 2011 and Burnham 2012) while other sources claim that it can occur in all well types (EPA 2012 and Howarth 2011). Considering the lack of clarity on this issue, it conservatively assumed that liquids unloading does occur in unconventional gas wells. It should be noted that fugitive emissions from liquids unloading has not received much attention and is poorly understood. This is considered further in Section 5.5 below.

[3] Volume 2, Chapter 4, Tables 4.2.4 and 4.2.5

The USA is the only country to have established a significant level of unconventional gas production and as such, is the only country about which literature and data specific to unconventional gas has been amassed. Therefore, this study reviews predominantly USA information and derives Tier 2 (country-specific) emission factors applicable to the USA. It is considered that in Canada the similar parameters, geological formations and technologies mean that the Tier 2 emission factors developed here are applicable. The assumption is made that these can also serve as Tier 1 emission factors for 'Developed Countries' on the basis that similar geological conditions, technology and resources can be expected. This is consistent with the 2006 IPCC Guidelines[4] for other natural gas systems. In the 'Developing Countries and Countries with Economies in Transition' scenario, it is assumed that similar geological conditions can be expected, but different assumptions need to be made regarding technology and resources.

There are significant differences in the factors that affect emissions from Shale gas, Tight sands gas and Coalbed methane source types. These arise from the differences in reservoir pressures which effect the potential emissions at completion and workover stages as well as the estimated ultimate recovery (lifetime productivity) of the wells. Consequently this study develops emission factors for each source type. It should be noted that considerably more research has been carried out on Shale gas compared to Tight sands gas or Coalbed methane which has an impact on data availability.

Consistent with the 2006 IPCC Guidelines, emission factors are developed for methane (CH_4), carbon dioxide (CO_2), non-methane volatile organic compounds (NMVOCs) and nitrous oxide (N_2O) for the production of each source type and in both developed and developing country scenarios.

[4] Volume 2, Chapter 4, Table 4.2.4

3 Methodology

3.1 Literature Review

Information and data used in this study is taken from the most recent sources available predominantly from USA literature (as previously discussed there are limited sources of information from other countries). Primary data is taken from reports and papers dating from 2010 to present (see Appendix 1). These sources were selected based on the quality of the information and to provide a balanced contribution from the scientific community, industry representatives and the environmental administration (EPA).

Unconventional sources of natural gas are still a relatively new fuel source and consequently there remains a shortage of verified data on the factors that affect fugitive emission levels. In order to overcome this issue a number of the assumptions used by scientists and industry representatives have been used as data points in this study. In these scenarios the data can be considered as 'Expert Judgement' as defined in the 2006 IPCC Guidelines[5]. Instances in which data from Expert Judgement is used are listed in Appendix 2.

3.2 Screening for Bias

Following a detailed review of the relevant literature, the available information was scrutinised to determine applicable datasets and to try to eliminate sources of bias. It was identified that a number of papers utilised the same EPA data source for emissions from completions before applying various assumptions for other variables affecting the level of emissions. In order to utilise all of this data, the data and assumptions identified in the literature were disaggregated from their sources and categorised according to the variables (detailed in Section 3.3 below). This approach allows for maximum use of available data while minimising potential bias from potentially polarised assumptions in any given study. It also ensures double-counting of EPA data is avoided.

A significant amount of the data available in published literature is derived from industry reported figures. For the most part this data is deemed permissible, especially in light of the lack of third party measurements. One exception for the use of industry reported data was made for estimated ultimate recovery (EUR - the lifetime productivity of a well), which was not included on the basis that such data can be subject to inflation by industry for financial reasons and is thus considered a potential source of bias.

3.3 The Model

When considering fugitive emissions from any natural gas sources, the most effective means of calculating net emissions for establishing emission factors involves the following general approach:

Equation 2: Net Fugitive Emissions from Natural Gas Operations:

$$E_{net} = E_{pot.} - E_{mit.}$$

Where:

$E_{net.}$ = Net fugitive emissions

[5] Volume 1, Chapter 2

$E_{pot..}$ = Total potential fugitive emissions[6]

$E_{mit.}$ = Mitigated fugitive emissions (i.e. gas captured through abatement technologies)

This concept is expanded to apply its principals specifically to unconventional gas production. In order to maintain consistency with the 2006 IPCC Guidelines, emission factors for venting and flaring are derived separately. The emissions of a GHG 'i' are calculated using the following equations:

Equation 3: Emissions from Venting:

$$E_{i,fugitive} = \frac{y_i \cdot \left[M_{pot,comp} \cdot \left(1 - REC_{comp}\right) \cdot X_{comp,vent} + M_{pot,work} \cdot N_{work} \cdot \left(1 - REC_{work}\right) \cdot X_{work,vent}\right]}{EUR}$$

Equation 4: Emissions from Flaring:

$$E_{i,flaring} = \frac{\left[M_{pot,comp} \cdot \left(1 - REC_{comp}\right) \cdot X_{comp,flare} + M_{pot,work} \cdot N_{work} \cdot \left(1 - REC_{work}\right) \cdot X_{work,flare}\right] \cdot \left[(1 - FE) \cdot y_i + FE \cdot CEF_i\right]}{EUR}$$

Where:

$E_{i,venting}$ = Venting emissions factor for gas *i* as a result of completion and workover activities for unconventional gas wells (g/MJ or $Gg/10^6m^3$)

$E_{i,flaring}$ = Flaring emissions factor for gas *i* as a result of completion and workover activities for unconventional gas wells (g/MJ or $Gg/10^6m^3$)

$M_{pot.comp.}$ = Total potential natural gas emissions from completion activities (g or Gg)

$M_{pot.work.}$ = Total potential natural gas emissions from workover activities (g or Gg)

$N_{work.}$ = Number of well workovers during well lifespan

REC_{comp} = Ratio of natural gas captured by REC technology during completions

REC_{work} = Ratio of natural gas captured by REC technology during workovers

$X_{comp,flare}$ = Ratio of natural gas not captured by REC technology that is flared during completions (i.e. $X_{comp,flare} = 1 - X_{comp,vent}$)

$X_{work,flare}$ = Ratio of natural gas not captured by REC technology that is flared during workovers (i.e. $X_{work,flare} = 1 – X_{work,vent}$)

$X_{comp,vent}$ = Ratio of natural gas not captured by REC technology that is vented during completions (i.e. $X_{comp,vent} = 1 - X_{comp,flare}$)

[6] One of the most common sources of data used to estimate potential fugitive emissions from completions in the various studies reviewed is from the amounts of gas reported as captured when using REC technology. The volume of recovered gas is assumed to be that which would have escaped in the absence of abatement technology. Some industry representatives have questioned the legitimacy of using this measurement technique to estimate emissions and described it as counter-intuitive (based on the fact that the gas in question was captured and not vented). In this regard it must be emphasised that in using this data, the emissions are strictly defined as 'potential emissions' and irrespective of abatement technologies that can be applied to mitigate the net (actual) emissions.

$X_{work,vent}$ = Ratio of natural gas not captured by REC technology that is vented during workovers (i.e. $X_{work,vent} = 1 - X_{work,flare}$)

FE = Flaring destruction efficiency (i.e. fraction of the gas that leaves the flare partially or fully burned). Typically, a value of 0.995 is assumed for flares at refineries and a value 0.98 is assumed for those used at production and processing facilities.

y_i = Mass fraction of the associated gas that is composed of substance *i* (i.e., CH_4, CO_2 or NMVOC).

CEF_i[7] = Combustion emission factor for gas *i* from flaring (Gg of gas *i*/Gg of associated natural gas flared). Refer to the IPCC emission factor database (EFDB), manufacturer's data or other appropriate sources for the value of this factor.

EUR = Estimated ultimate recovery from the gas well (MJ or $10^6 m^3$)

The data extracted from the literature reviews for each source type were converted to common units and applied to these equations using the assumptions and statistical approach outlined in Sections 3.4 and 3.5 below.

3.4 Assumptions

Emissions from the three source types of unconventional gas are derived through a combination of itemised and common variable inputs as listed in Table 3. Information relating to the geological conditions in Shale gas, Tight sands gas and Coalbed methane (i.e. data regarding potential emissions and EUR) wells is itemised. No disaggregated data is available for the level of mitigation by source type. There is no information to suggest that the prevalence of these measures differ between the source types so the inputs derived are considered common between them.

Itemised Variables	Common Variables
Completion potential emissions	Completions REC rate
Workover potential emissions	Completions flaring rate
Number of workovers	Workovers REC rate
Estimated Ultimate Recovery	Workovers flaring rate

Table 3: List of itemised and common variables for the development of Shale gas, Tight sands gas and Coalbed methane fugitive emissions

When applying Equations 3 and 4 to a population of wells it should be noted that for REC rates (REC_{comp} *and* REC_{work}), the input should be the product of expected capture rates with the technology in place and the prevalence of RECs in industry (i.e. the average capture rate from a gas well population including wells where REC technology is not utilized).

[7] CEF is usually used to stand for "Carbon Emission Factor", but it stands for "Combustion Emission Factor" in this report.

The results derived from USA literature provide Tier 2 emission factors for the USA (and Canada). The assumption is made that these factors are appropriate for application as Tier 1 emission factors for other developed countries, consistent with the 2006 IPCC Guidelines[8] approach to fugitive emissions.

In order to estimate Tier 1 emission factors for developing countries, different assumptions regarding the level of mitigation (i.e. the common variables listed in Table 3 above) are made to account for the differing levels of technology, resource and knowledge. In these cases it is assumed that no REC technology is used and that all completion and workover potential emissions are either vented or flared. The upper limit of the range for flaring has been set to equal the mean value derived for developed countries, with the lower limit set to 0%. This approximation is made in the absence of available industry data from developing countries, deemed consistent with the 2006 IPCC Guidelines[9] approach to fugitive emissions in developing countries. Using the assumption that similar geological conditions for each source type can be expected regardless of the location, variables contributing towards the level of potential emissions ($M_{pot.comp.}$ and $M_{pot.work.}$) were kept consistent with those developed from USA data.

No data was identified for potential emissions from workovers ($M_{pot.work.}$) by source type. To fill this data gap, surrogate data is used (consistent with the 2006 IPCC Guidelines[10]). Workover potential emissions from uncategorized sources is available (EPA GHGRP 2013, US EPA 2013), which is applied to the appropriate 'pressure group' ratio derived from potential emissions from completions as follows:

Equation 5: Workover Potential Emissions Estimation:

$$M_{pot,work,source} = \left(\frac{M_{pot,comp,source}}{M_{pot,comp,all\ sources}}\right) \times M_{pot,work,all\ sources}$$

Where:

$M_{pot.work,source}$ = Total potential natural gas emissions from workover activities for a given source type (e.g. Shale gas)

$M_{pot.comp,source}$ = Total potential natural gas emissions from completion activities for a given source type (e.g. Shale gas)

$M_{pot.comp,all\ sources}$ = Total potential natural gas emissions from completion activities for all unconventional source types

$M_{pot.work,all\ sources}$ = Total potential natural gas emissions from workover activities for all unconventional source types

In this way emissions from workovers for a particular source type are proportional to the emissions from completions for that source type. The level of emissions is also pro-rated using data from all sources so that the relative difference in emissions between completions and workovers is taken into consideration.

[8] Volume 2, Chapter 4, Table 4.2.4
[9] The approach taken in the development of emission factors listed in Volume 2, Chapter 4, Table 4.2.5
[10] Volume 1, Chapter 5, Section 5.3

3.5 Statistical Analysis

Probability density functions (PDFs) were assigned to each of the data sets before a Monte Carlo analysis[11] was applied to combine each contributing dataset and derive an expected value and uncertainty range for each variable (input). These input variable PDFs were subsequently put through a further Monte Carlo cycle using Equations 3 and 4 to derive the emission factors and related uncertainties. The input PDFs can be found in Appendix 3. IPCC adopts a 95% confidence interval limit in defining uncertainties and this is applied in this study.

For datasets with sufficient sample sizes, normal or lognormal PDFs were assigned using a best-fit algorithm available in the software package. For smaller sample data sets, PDFs were selected using best judgement. These were assigned as follows:

1. Normal distributions were used for symmetrical samples
2. Lognormal distributions were assigned for positively skewed samples
3. Triangular distributions were applied in instances where only expected values, maximums and minimums were provided

For the majority of variables, sufficient data is available to derive acceptable PDFs for the variables listed. The exception was information related to workovers for which there is limited data (as described in Section 3.4 above). In order to develop uncertainty ranges for this variable ($M_{pot.work.}$), a PDF was developed using emissions from all sources (EPA GHGRP 2013, US EPA 2013) and then applied to the expected value for each source type, as calculated using Equation 5.

3.6 Time Series Considerations

The 2006 IPCC Guidelines[12] identify the issue of time series consistency as a key consideration when developing emission factors or emission inventories. In order to determine the applicability of the emission factors developed in this study to be used over time series from this point forward and to consider the frequency at which factors should be reviewed, an analysis of the time variability of the variables that contribute to fugitive emissions from unconventional gas is detailed in Table 4 below. This lists the variables and potential considerations for their applicability to a time series consistent emission factor. It should be noted that for all of the variables there should be an opportunity to reduce the level of uncertainty over time as more survey information and better technologies become available.

Taking the considerations from Table 4 into account, as the various unconventional gas industries evolve, it will improve accuracy if a Tier 3 approach to fugitive emissions is developed. This will allow for updated emission factors which will better reflect improvements in technology.

[11] Monte Carlo analysis uses pseudo-random model input samples generated in reference to a probability density function. After 100 simulations of 10,000 iterations each the model output, mean, standard deviation, percentiles etc. are statistically inferred.
[12] Volume 1, Chapter 5

Variable	Time Series Considerations
Potential fugitive emissions ($M_{pot.comp.}$ and $M_{pot.work.}$)	Given the definition of potential emissions used in this study, there are no changes anticipated. There is however significant opportunity to improve the accuracy of this variable.
Reductions in emissions through application of reduced emission completions/workovers ($REC_{comp.}$ and $REC_{work.}$)	In the USA and Canada, it is considered that the prevalence of RECs will increase over time. The EPA has placed a legal requirement on the use of REC technology for the majority of unconventional gas wells (excluding some low pressure formations) from 2015 onwards through the New Source Performance Standards (NSPS). It is also considered that the technology used for RECs will improve over time increasing the level of captured gas.
Reductions in emissions from flaring ($X_{flare.comp.}$ and $X_{flare.work.}$)	It is anticipated that as environmental considerations develop into policy, there will be an increase in the prevalence of flaring in the natural gas and associated industries.
Estimated ultimate recovery	As hydraulic fracturing technology improves, it is possible that higher EUR levels may be realised.
Combustion emission factors for CO2, CH4 and N2O (CEF_i)	No significant changes anticipated.
Natural gas composition (y_i)	No significant changes anticipated.

Table 4: Time series consistency considerations for variables affecting fugitive emissions from unconventional gas

3.7 Uncertainty

The 2006 IPCC Guidelines[13] suggest two approaches to quantifying uncertainty in the estimation of emissions/removals of greenhouse gases.

Approach 1 is an error propagation methodology which uses simple standard equations to establish the uncertainty in multiplication and addition/subtraction derived quantities. This approach is acceptable in a situation where the coefficient of variation (CoV) of a PDF is less than 0.3 and where it is symmetrical. In the case of fugitive emissions from unconventional gas this approach was deemed insufficient based on the facts that:

1) A number of variables had CoVs in excess of 0.3,
2) The majority of the PDFs were asymmetric and
3) The emission source is likely to be a 'Key Category' and warrants a more detailed investigation and more accurate uncertainties.

On this basis Approach 1 was not applied.

Approach 2 is a more rigorous methodology which involves a Monte Carlo simulation. This applies a category-by-category assessment of uncertainty through the use of defined PDFs by variable to determine non-normal uncertainty ranges. This approach has been applied to the emission factors developed in this study using the *@Risk* software.

[13] Volume 1, Chapter 3, Section 3.2

A number of considerations were taken to reduce the uncertainty as far as possible, consistent with the 2006 IPCC Guidelines[14]:

1. **Improving conceptualisation**: key variables affecting the emission factors were identified in the literature reviews to create a common framework that best utilises available data.
2. **Improving models**: the model was created consistent with the identified variables and the data extracted from the literature has been parameterised accordingly. This disaggregation approach reduces the potential for bias from literature and allows for better identification of 'outlying' data.
3. **Improving representativeness**: disaggregation of the data also increased the sample data population to allow for better representation of measured and Expert Judgement data points. PDFs were applied to the various data populations individually using best judgement in order to most accurately represent expected values and related uncertainties.

Further details of the strategies used to deal with different causes of uncertainty are listed in Appendix 4.

3.8 Quality Control Procedures and Limitations

The 2006 IPCC Guidelines[15] set out a detailed approach to quality assurance (QA) and quality control (QC). The process is designed to minimise uncertainty and maintain integrity in the emission factors and activity data associated with GHG inventories such that the outcomes:

i. *contain neither over- nor under-estimates so far as can be judged,* and
ii. *reduce uncertainties as far as practicable*

In this study a rigorous QC process was adopted to ensure data sources, assumptions and calculations were examined carefully.

The potential emissions data ($M_{pot.comp.}$ and $M_{pot.work.}$) is based on secondary information and deemed not to have gone through sufficient QA/QC procedures. The literature containing the data has however been subject to peer review (with the exception of the EPA data) and so to that extent has been verified.

In the unconventional gas scenario there are no other IPCC process-derived emission factors for comparison. Comparisons are drawn between emission factors derived in this study and those estimated in other scientific papers and publications as part of a precision test detailed in Section 5.3.

[14] Volume 1, Chapter 3, Section 3.1.6
[15] Volume 1, Chapter 6

4 Results

4.1 Tier 1 Emission Factors for Unconventional Gas Sources in Developed Countries (Tier 2 for USA and Canada)

Emission factors for Shale gas, Tight sands gas and Coalbed methane for developed countries are listed in Table 5 below, together with those for unconventional natural gas production taken from Table 4.2.4 of Chapter 4, Volume 2 of the 2006 IPCC Guidelines. Associated 95% confidence intervals are included in the 'Uncertainty' column[16].

As discussed in previous sections of this report these emissions contribute solely to the Production category (as defined by the IPCC) and are considered as appropriate Tier 1 emission factors for developed countries and Tier 2 emission factors for USA and Canada.

The results show a significant contribution of fugitive emissions from completion and workover activities when compared to conventional sources of natural gas. As would be expected given the different pressure conditions, Shale gas shows the highest level of emissions followed by Tight sands gas and Coalbed methane. Uncertainty ranges are positively-skewed consistent with the lognormal input PDFs.

Figure 2 gives a life-cycle (including production, processing, transport and storage and distribution) comparison of conventional gas default emission factors with those of Shale gas, Tight sands gas and Coalbed methane by GHG.

4.2 Tier 1 Emission Factors for Unconventional Gas Sources in Developing Countries and Countries with Economies in Transition

Emission factors for Shale gas, Tight sands gas and Coalbed methane for developing countries and countries with economies in transition are listed in Table 6 below, together with those for unconventional natural gas production taken from Table 4.2.5 of Chapter 4, Volume 2 of the 2006 IPCC Guidelines. Associated 95% confidence intervals are included in the 'Uncertainty' column (as with Table 5).

In the developing countries scenario there is a significant contribution of emissions from venting gases (CH_4 and NMVOCs) during completions and workovers, but the contribution from flaring products (CO_2 and N_2O) is less substantial. This result is expected due to the lower level of flaring (i.e. a higher proportion is vented).

Figure 3 gives a comparison in the same format as Figure 2 but for the developing countries scenario. The relative effect of completions and workover emissions on total emissions is less pronounced than in the developed countries scenario due to the higher baseline emissions (i.e. emissions from conventional gas production).

[16] Rounded up/down (to ± 10, 20, 40, 50, 75, 100, 200, 250, 500, 800 or 1,000%) depending on the magnitude of the value, consistent with the approach in the 2006 IPCC Guidelines; Volume 2, Chapter 4, Table 4.2.4

Category	Sub-category	Emission source	IPCC Code	CH4		CO2		NMVOC		N2O		Units of measure
				Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	
Gas Production	Conventional	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.3E-03	±100%	1.4E-05 to 8.2E-05	±100%	9.1E-05 to 5.5E-04	±100%	N/A	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	7.60E-07	±25%	1.20E-03	±25%	6.20E-07	±25%	2.1E-08	-10 to +1000%	Gg per 106 m3 gas production
	Shale Gas	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.3E-03	±100%	1.4E-05 to 8.2E-05	±100%	9.1E-05 to 5.5E-04	±100%	N/A	N/A	Gg per 106 m3 gas production
		Venting	**1.B.2.b.i**	**5.8E-03**	**-100 to +500%**	**2.5E-04**	**-100 to +500%**	**7.8E-04**	**-100 to +500%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**2.0E-04**	**-100 to +500%**	**2.8E-02**	**-100 to +500%**	**2.4E-05**	**-100 to +500%**	**9.0E-08**	**-100 to +500%**	Gg per 106 m3 gas production
	Tight Sands	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.3E-03	±100%	1.4E-05 to 8.2E-05	±100%	9.1E-05 to 5.5E-04	±100%	N/A	N/A	Gg per 106 m3 gas production
		Venting	**1.B.2.b.i**	**4.7E-03**	**-100 to +500%**	**1.5E-04**	**-100 to +500%**	**5.8E-04**	**-100 to +500%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**1.0E-04**	**-100 to +550%**	**1.5E-02**	**-100 to +500%**	**1.3E-05**	**-100 to +500%**	**6.0E-08**	**-75 to +800%**	Gg per 106 m3 gas production
	Coalbed Methane	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.3E-03	±100%	1.4E-05 to 8.2E-05	±100%	9.1E-05 to 5.5E-04	±100%	N/A	N/A	Gg per 106 m3 gas production
		Venting	**1.B.2.b.i**	**1.6E-03**	**-100 to +500%**	**6.2E-05**	**-100 to +500%**	**2.0E-04**	**-100 to +250%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**4.7E-05**	**-100 to +500%**	**8.2E-03**	**-100 to +500%**	**6.7E-06**	**-100 to +500%**	**3.9E-08**	**-50 to +800%**	Gg per 106 m3 gas production

Table 5: Proposed emission factors for production of Shale gas, Tight sands gas and Coalbed methane in developed countries with associated 95% confidence interval upper and lower limits (those for conventional natural gas production taken from Table 4.2.4 in Chapter 4, Volume 2 of the 2006 IPCC Guidelines are also included for comparison)

Category	Sub-category	Emission source	IPCC Code	CH4		CO2		NMVOC		N2O		Units of measure
				Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	Value	Uncertainty (% of Value)	
Gas Production	Conventional	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.4E-02	-40 to +250%	1.4E-05 to 1.8E-04	-40 to +250%		-40 to +250%	NA	N/A	Gg per 106 m3 gas production
		Flaring	1.B.2.b.ii	7.6E-07 to 1.0E-06	±75%	1.2E-03 to 1.6E-03	±75%	6.2E-07 to 8.5E-07	±75%	2.1E-08 to 2.9E-08	-10 to +1000%	Gg per 106 m3 gas production
	Shale Gas	Fugitives	1.B.2.b.iii.2	3.8E-04 to	-40 to	1.4E-05 to	-40 to		-40 to	NA	N/A	Gg per 106 m3 gas
		Venting	**1.B.2.b.i**	**1.8E-02**	**-75 to +500%**	**6.9E-04**	**-75 to +500%**	**2.0E-03**	**-75 to +500%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**1.7E-04**	**-200 to +500%**	**3.0E-02**	**-100 to +500%**	**2.5E-05**	**-150 to +500%**	**2.2E-07**	**-40 to +1000%**	Gg per 106 m3 gas production
	Tight Sands	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.4E-02	-40 to +250%	1.4E-05 to 1.8E-04	-40 to +250%		-40 to +250%	NA	N/A	Gg per 106 m3 gas production
		Venting	**1.B.2.b.i**	**7.8E-03**	**-75 to +500%**	**9.3E-05**	**-75 to +500%**	**2.0E-03**	**-75 to +500%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**9.0E-05**	**-200 to +500%**	**2.1E-02**	**-100 to +500%**	**1.5E-05**	**-100 to +500%**	**1.9E-07**	**-40 to +1000%**	Gg per 106 m3 gas production
	Coalbed Methane	Fugitives	1.B.2.b.iii.2	3.8E-04 to 2.4E-02	-40 to +250%	1.4E-05 to 1.8E-04	-40 to +250%		-40 to +250%	NA	N/A	Gg per 106 m3 gas production
		Venting	**1.B.2.b.i**	**4.8E-03**	**-75 to +300%**	**1.9E-04**	**-50 to +500%**	**6.5E-04**	**-50 to +500%**	**N/A**	**N/A**	Gg per 106 m3 gas production
		Flaring	**1.B.2.b.ii**	**5.0E-05**	**-200 to +500%**	**1.5E-02**	**-100 to +250%**	**1.0E-05**	**-100 to +500%**	**1.7E-07**	**-20 to +1000%**	Gg per 106 m3 gas production

Table 6: Proposed emission factors for production of Shale gas, Tight sands gas and Coalbed methane in in developing countries and countries with economies in transition with associated 95% confidence interval upper and lower limits (those for conventional natural gas production taken from Table 4.2.5 in Chapter 4, Volume 2 of the 2006 IPCC Guidelines are also included for comparison)

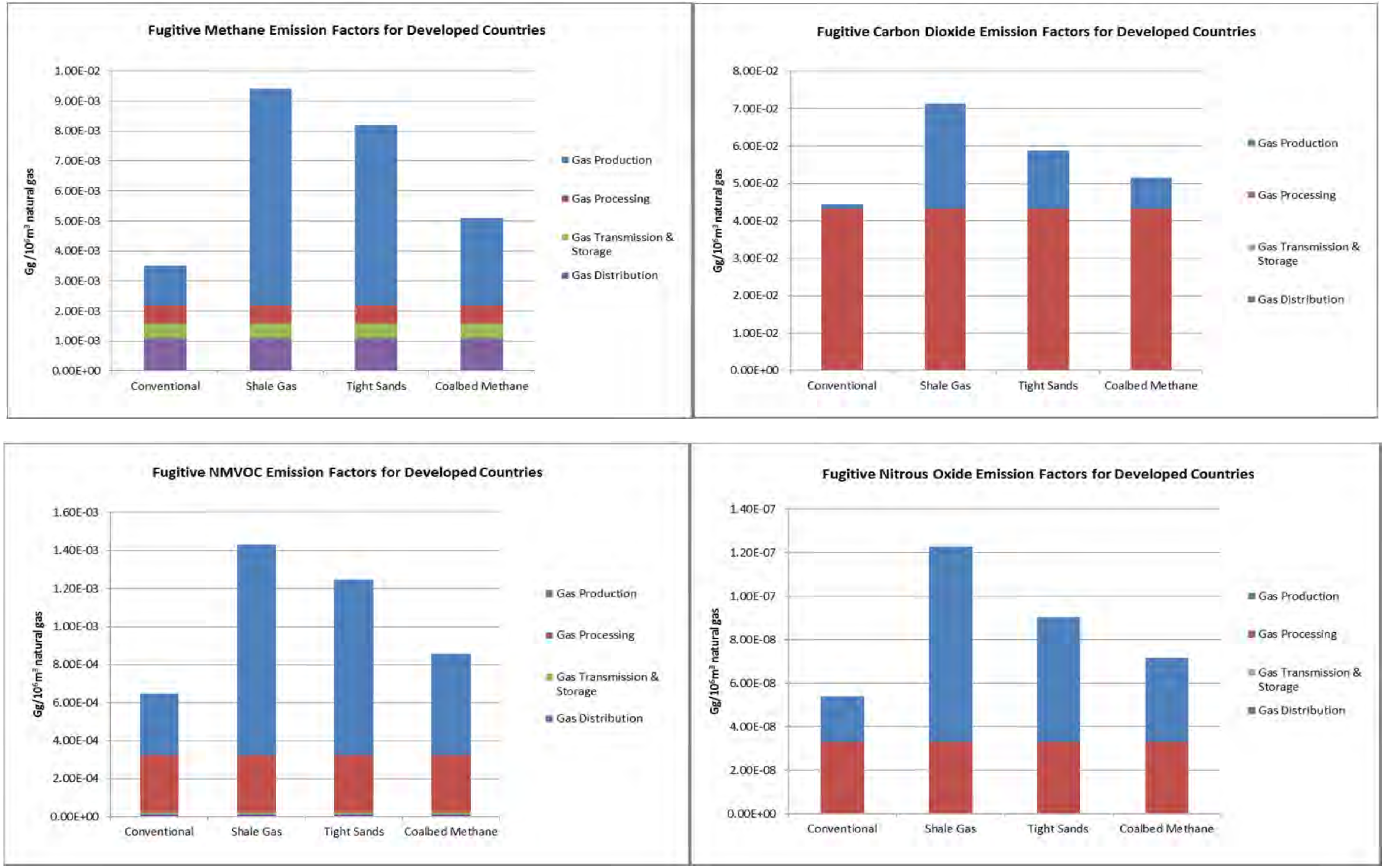


Figure 2: Fugitive emission factors for CH_4, CO_2, NMVOCs and N_2O by IPCC category for conventional gas, Shale gas, Tight sands gas and Coalbed methane in developed countries

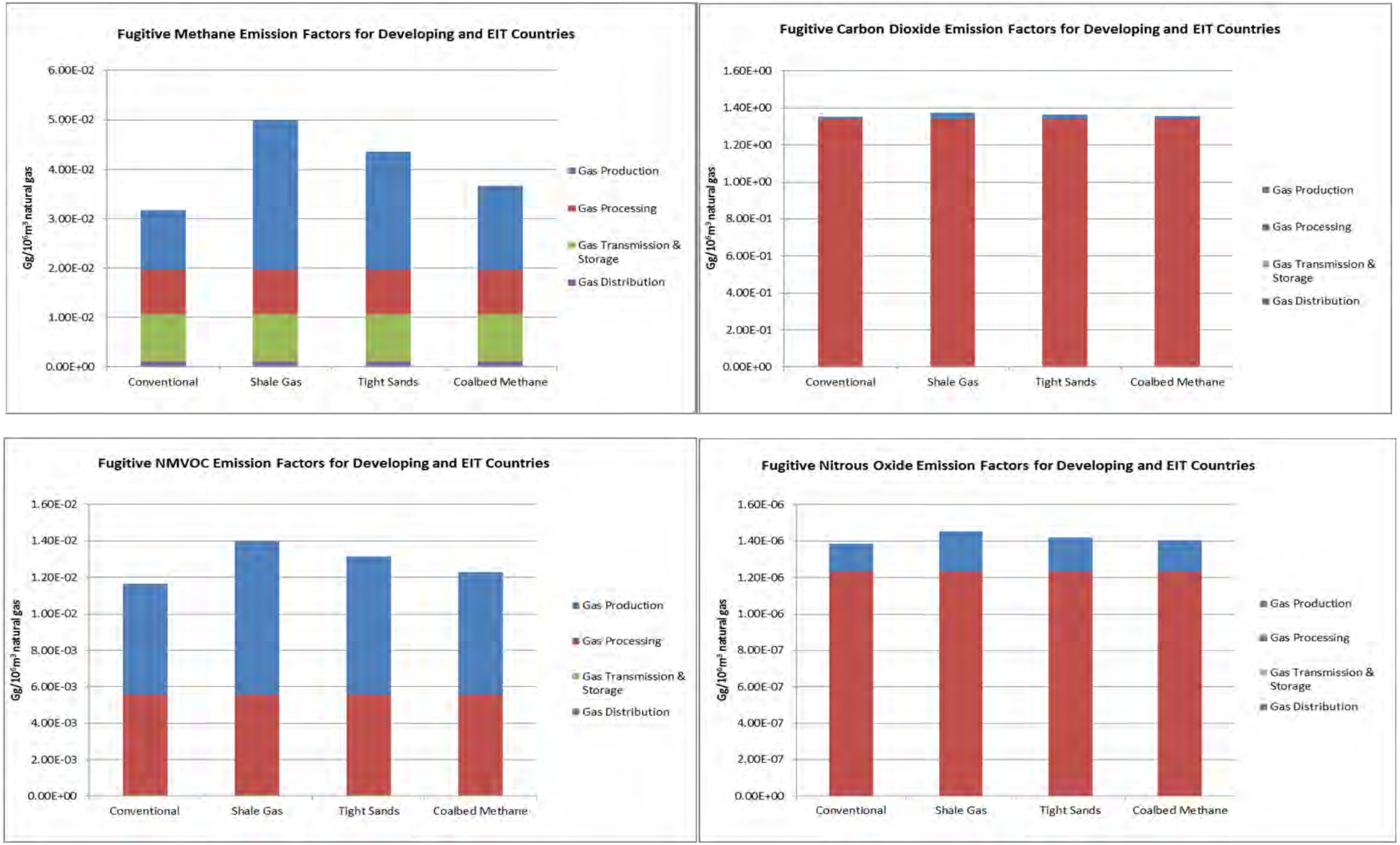


Figure 3: Fugitive emission factors for CH_4, CO_2, NMVOCs and N_2O by IPCC category for conventional gas, Shale gas, Tight sands gas and Coalbed methane for developing countries and countries with economies in transition

5 Discussion

5.1 Life-cycle Assessment of Fugitive Emissions from Conventional and Unconventional Gas Sources

By adding IPCC defaults for conventional gas processing, transport and storage and distribution (from the 2006 IPCC Guidance[17]) to the emission factors derived for production, a 'well-to-meter' life-cycle analysis of fugitive emissions has been estimated. These estimates with associated uncertainty ranges are shown in Figure 4 below. The comparison indicates that fugitive emissions from venting and flaring of natural gas during completion and workover events is significantly higher than that of conventional sources. The mean values for Shale gas, Tight Sands gas and Coalbed methane are 133%, 100% and 36% higher respectively than those of conventional gas in developed countries.

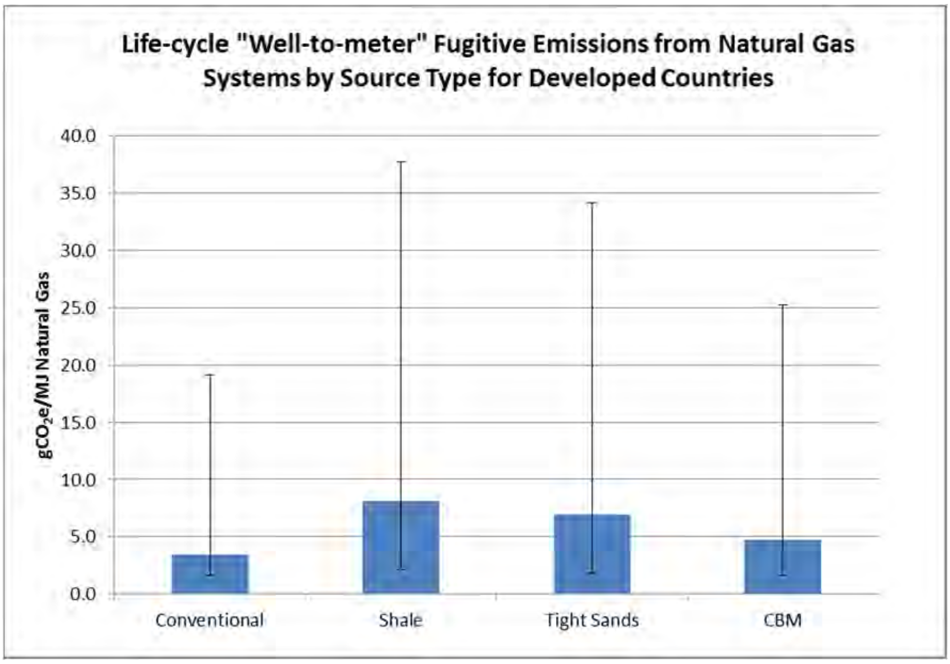


Figure 4: Life-cycle well-to-meter fugitive emissions[18] for natural gas by source type in developed countries

5.2 Uncertainty Analysis

The main contributing factors to the level of uncertainty are the ranges for potential emissions ($M_{pot.comp.}$ and $M_{pot.work.}$) and EUR as can be seen in the sensitivity analysis in Figure 5 below. Reducing the uncertainty associated with these parameters would have a significant effect on the overall uncertainty of the derived emission factors.

[17] Volume 2, Chapter 4, Table 4.2.4

[18] Using 100-year global warming potentials (GWPs) of 25 for CH_4, 1 for CO_2, 3.4 for NMVOCs (weighted average) and 298 for N_2O consistent with IPCC Fourth Assessment Report (AR4) and supplementary data

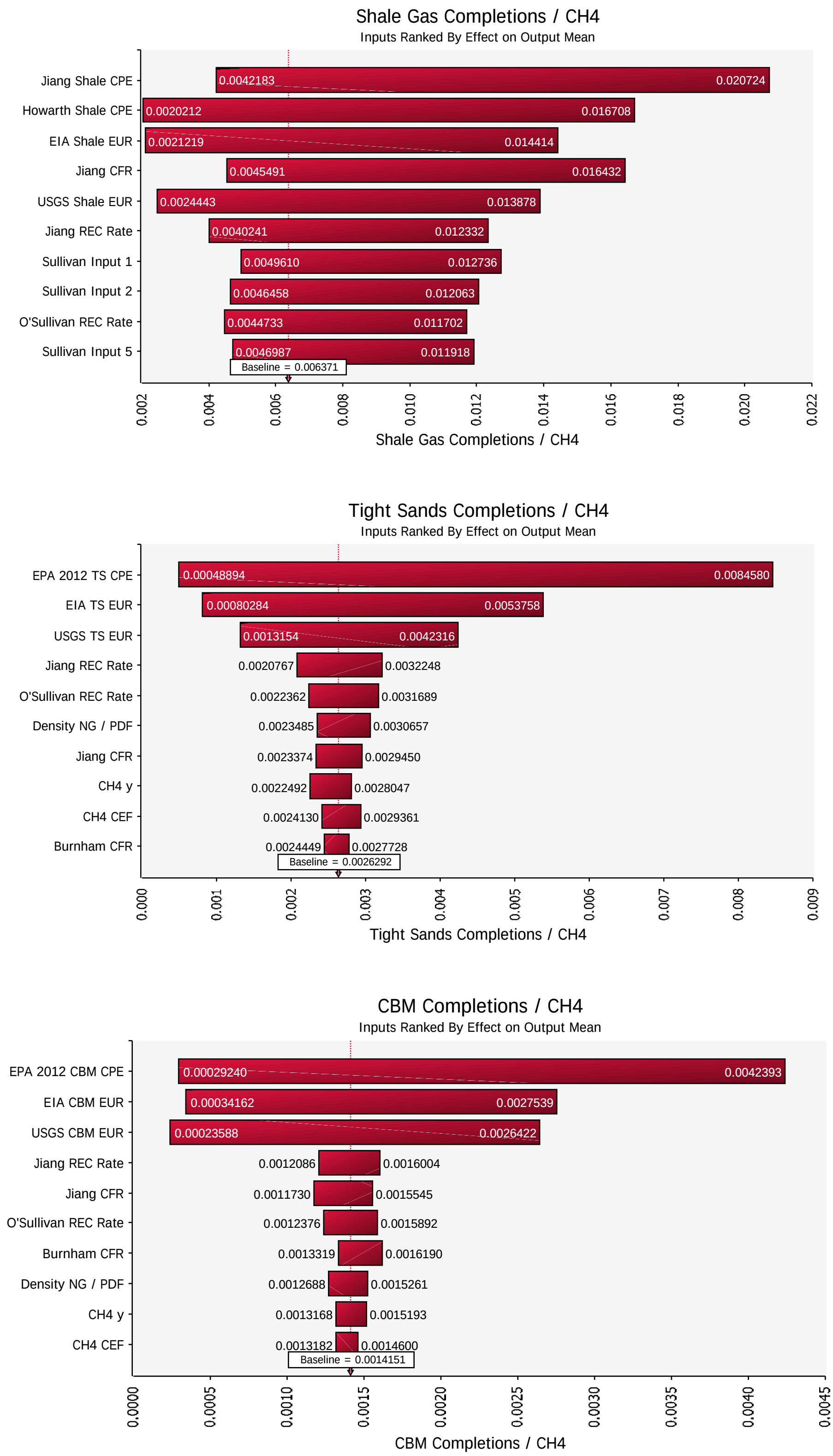


Figure 5: Sensitivity charts for total CH4 fugitive emissions arising from Shale gas, Tight sands gas and Coalbed methane with input variables and datasets ranked by effect on output mean

Figure 5 also indicates the significance of the lack of completion potential emissions data for Tight sands gas and Coalbed methane. The data available (from EPA) is a limited sample size which subsequently increases the uncertainty range (resulting in the large effects demonstrated from 'EPA

2012 TS CPE' and 'EPA 2012 CBM CPE'). By increasing the sample size for these variables (i.e. retrieving more data), uncertainty could be reduced.

Further sensitivity charts can be found in Appendix 5 in which similar opportunities to reduce uncertainty can be identified.

5.3 Precision

A comparison of the proposed emission factors developed within this study with those that have been developed in other studies can provide an insight into the level of precision among factors. The 2006 IPCC Guidelines[19] defines precision as *"Agreement among repeated measurements of the same variable. Better precision means less random error."* Figure 6 compares the emission factors developed in this study with those found in other peer-reviewed literature (Weber *et al.* 2012). This serves as a quality control procedure as well as providing a sense of precision among studies. With disagreement among the level of emissions from the various studies of a factor of more than 9, it is clear that the emissions estimates developed are collectively imprecise. This is an indication that the lack of third party measured and verified emissions data from natural gas operations is a significant issue.

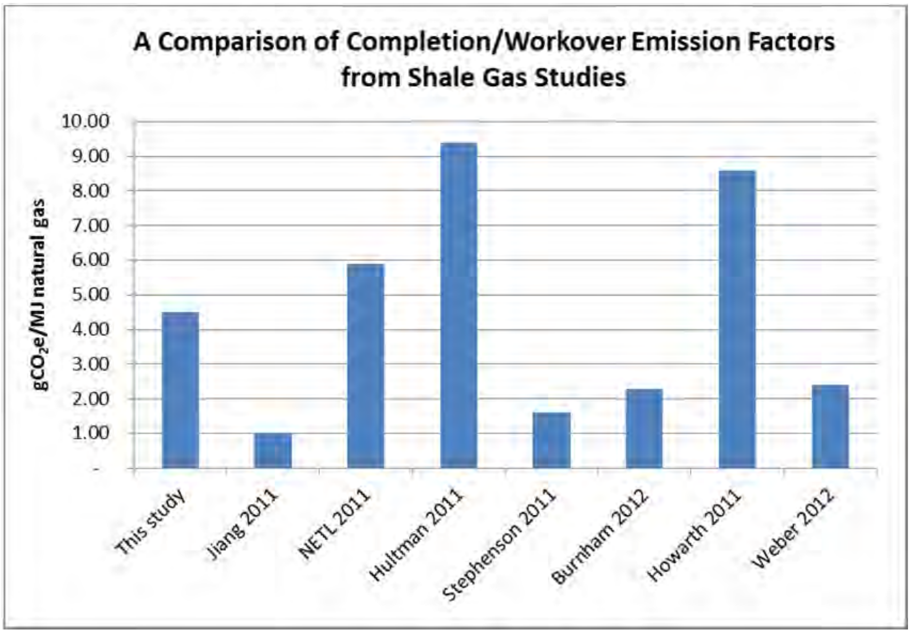


Figure 6: A comparison of fugitive emission factors for Shale gas from completion and workover activities

5.4 Emerging Research and Potential Consequences

There is still a large degree of uncertainty surrounding the issue of fugitive emissions from natural gas production, processing, transport and distribution, both conventional and unconventional. The estimations still rely largely upon the EPA/GRI data published in 1996 which has been supplemented with some updates as the industry has matured. The most significant concern is that the data is based on engineering calculations and/or approximately measured volumes but as yet there has not been a comprehensive study to measure and verify emissions from a wide variety of wells.

[19] Volume 1, Chapter 3, Page 3.7

Technology has recently been developed whereby air sampling and infrared photography can now offer a more accurate means of measuring and verifying these fugitive emissions. A study undertaken by National Oceanic and Atmospheric Administration (NOAA) measured atmospheric methane concentrations in the Denver-Julesberg basin in Colorado (Petron et al. 2012). The findings of this analysis indicated that methane emissions were four orders of magnitude higher than that estimated through the inventorying process. The Authors acknowledge it is difficult to assign the exact source of the methane based on the varied fossil fuel activity in that basin, however, the chemical signature indicated that *"the ambient molar ratios are lower than what could be expected from condensate tank flashing emissions alone, indicating that most of the CH_4 emissions observed came from the venting of raw natural gas."* This result has raised great concern (Tollefson 2012), not only to estimated emissions of fugitive methane but to the inventorying process at large.

The University of Texas along with NOAA and various other partners are currently undertaking a detailed study of fugitive methane emissions from the natural gas industry which will be the first of its kind as is scheduled for publication in 2013.

5.5 Recommendations for Further Work

With the rapidly evolving global unconventional gas sector, it is considered that further research is necessary to allow for more accurate GHG reporting. The following is a list of issues that with further research would improve the accuracy of fugitive emission factors from unconventional gas sources.

1) **Liquids unloading** - emissions from the liquids unloading process in both conventional and unconventional gas wells are poorly understood (as described in Section 2.3). The number and type of wells that require liquids unloading is not clear. The prevalence of mitigation technologies (such as plunger lifts) is also subject to significant uncertainty. Further research and measurement/verification of emissions is required to better understand this emission source.
2) **Measurement (sampling) analysis** - measured and verified emissions data collected by third-party organisations (using technology as described in Section 5.4) are needed to improve the accuracy and confidence of fugitive emission factors for natural gas.
3) **Update IPCC default EFs for NG** - existing IPCC fugitive emission factors for the natural gas industry are still largely based on the 1996 EPA/GRI study. These emission factors may be outdated and consideration should be given to updating the IPCC default factors, especially considering the significant increase in natural gas consumption that has been projected.
4) **Reporting by pressure of play** - in order to improve the emission factors developed and move towards a Tier 3 approach, consideration should be given to categorising the pressure of the unconventional gas 'plays'. This will allow for improved accuracy and reduced uncertainty for potential emissions ($M_{pot.comp.}$ and $M_{pot.work.}$) which can have a significant impact on reducing the uncertainty ranges of the emission factors developed in this study, as indicated by the sensitivity analysis in Section 5.2.
5) **Reporting by EUR of play** – in order to improve the emission factors developed and move towards a Tier 3 approach, consideration should be given to categorising the expected EUR by unconventional gas 'plays'. Improving EUR accuracy can have a significant impact on reducing the uncertainty of the emission factors developed in this study, as indicated by the sensitivity analysis in Section 5.2.

6 Conclusion

In general the following conclusions can be drawn:

1) Fugitive emissions from completions and workovers of unconventional gas sources including Shale gas, Tight sands gas and Coalbed methane, are significant and the relevant emission factors should be added to the EFDB.

2) While the emission factors derived in this study are as accurate as possible, there is a deficit of measured and verified emissions data. Third party measurements to quantify fugitive emissions from unconventional (and conventional) gas sources would vastly improve the accuracy of the emission factors.

3) The scale of the difference in emissions between conventional and unconventional gas sources may be indicative of other types of unconventional fuel. In its current form the 2006 IPCC Guidelines do not address unconventional fuel types sufficiently and consideration should be given to amending the guidelines accordingly.

Appendix 1

Primary Information Sources

1. API/ANGA 2012: Characterizing Pivotal Sources of Methane Emissions from Natural gas Production
   An industry survey conducted using various data sources questioning the EPA approach to GHG emission inventorying techniques, particularly from liquids unloading and re-fractures rates.

2. Burnham et al 2012: Life-cycle greenhouse gas emissions of Shale gas, natural gas, coal, and petroleum
   LCAs of Shale and conventional gas GHG emissions using EPA default data with various assumptions applied.

3. Howarth et al 2011: Methane and the greenhouse gas footprint of natural gas from shale formations
   LCA assessment of GHG emissions from Shale gas compared with conventional gas and coal using data reported from industry.

4. Hultman et al 2011: The greenhouse impact of unconventional gas for electricity generation
   LCAs of shale and conventional gas GHG emissions using EPA default data with various assumptions applied.

5. Jiang et al 2011: Life cycle greenhouse gas emissions of Marcellus Shale gas
   LCA of Shale gas emissions in the Marcellus play using data provided by Pennsylvania Department of Environmental Protection and New York State Department of Environmental Conservation Data

6. NETL 2011: Life Cycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production
   Top-down LCA of natural gas sources using EPA default emission factors and other industry figures and assumptions.

7. O'Sullivan et al 2012: Shale gas production: potential versus actual greenhouse gas emissions
   Analysis of fugitive emissions from Shale gas well completion using data reported from 4,000 wells.

8. Stephenson et al 2011: Modeling the Relative GHG Emissions of Conventional and Shale gas Production
   LCA of unconventional gas sources using EPA default data with various assumptions applied.

9. US EIA 2012: Assumptions to the Annual Energy Outlook 2012
   Assessment of EUR forecasting based on statistical analysis of existing well resource depletion.

10. EPA GHGRP 2013: Reported Subpart W Data
    Emissions data reported through EPA's GHGRP.

11. EPA 2013: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011
    Emission factors and inventory assumptions used in the development of the 2013 National Inventory Report for the period 1990 to 2011.

12. USGS 2010: Assembling Probabilistic Performance Parameters of Shale-Gas Wells
    Assessment of EUR forecasting based on statistical analysis of existing well resource depletion.

13. Wrap Phase III 2008: Development of Baseline 2006 Emissions from Oil and Gas Activity
    An industry survey carried out by WRAP to estimate emissions from Oil and Gas activities in the western U.S. focussing on NOx, CO, VOCs, PM and SOx.

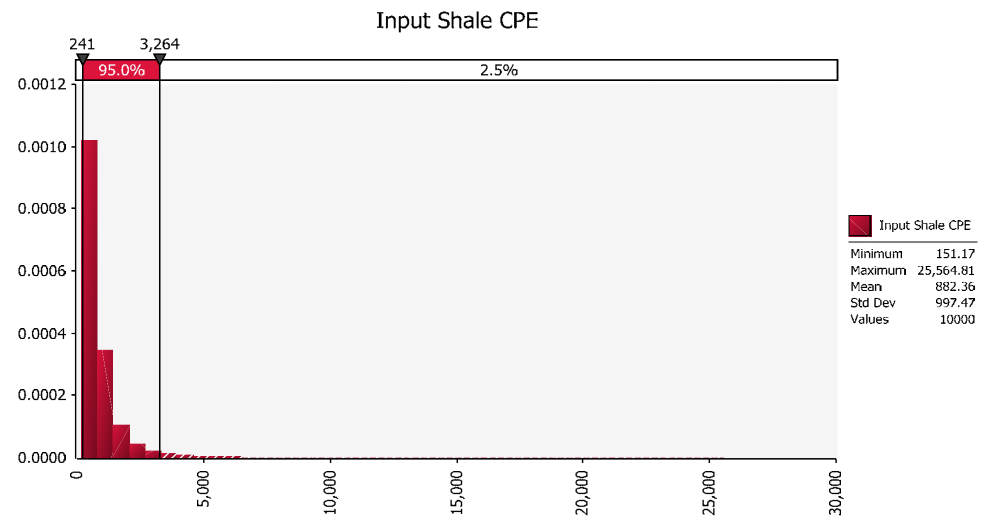
Appendix 2

Datasets and Expert Judgement Sources Used

Variable	Data Sources	Data type	Published
Shale gas Completion Potential Emissions	1) EPA 2013 2) Jiang 3) O'Sullivan 4) Howarth	Industry reported Industry reported Industry reported Industry reported	2013 2011 2012 2011
Tight sands gas Completion Potential Emissions	1) EPA 2013	Industry reported	2013
Coalbed methane Completion Potential Emissions	1) EPA 2013	Industry reported	2013
Completion REC Net Capture Rate (net of prevalence and capture rate)	1) EPA 2013 2) Jiang 3) O'Sullivan	Industry reported Expert judgement Expert judgement	2013 2011 2012
Completions flaring rate	1) EPA 2013 2) Jiang 3) O'Sullivan 4) Burnham 5) EPA S/P W	Industry reported Expert judgement Expert judgement Expert judgement Industry reported	2013 2011 2012 2012 2013
Workovers per lifespan	1) API/ANGA 2) EPA 2013 3) NETL 4) Hultman 5) API/ANGA	Survey Industry reported Expert judgement Expert judgement Survey	2012 2013 2011 2011 2008
Workover potential emissions	1) EPA 2013 2) EPA S/P W	Industry reported Industry reported	2013 2013
Workover REC Net Capture Rate (net of prevalence and capture rate)	1) EPA S/P W	Industry reported	2013
Workovers flaring rate	1) EPA S/P W	Industry reported	2013
Estimated ultimate recovery	1) O'Sullivan 2) USGS 3) EIA	Expert judgement Detailed analysis Detailed analysis	2012 2010 2012
Well lifespan	1) O'Sullivan 2) Hultman 3) Burnham	Expert judgement Expert judgement Expert judgement	2012 2011 2012
Combustion emission factors	1) IPCC 2006	Detailed analysis	2006
Natural gas composition	1) IPCC 2005	Detailed analysis	2005

Appendix 3

Input Variable Probability Density Functions

<table>
<tr><th>Variable</th><th>PDF</th></tr>
<tr><td>Shale gas Completions Potential Emissions ($M_{pot,comp}$)</td><td>


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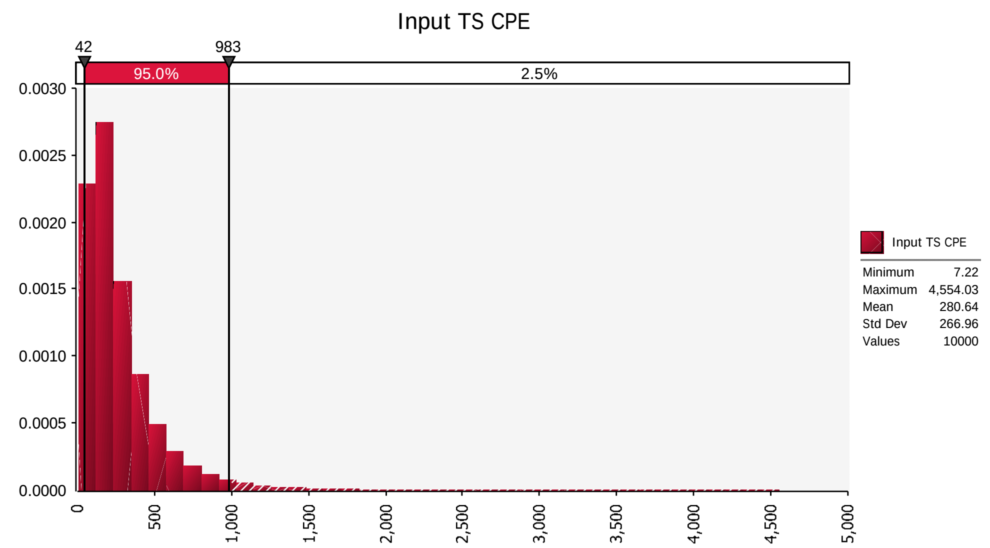
<tr><td>Tight sands gas Completions Potential Emissions ($M_{pot,comp}$)</td><td>


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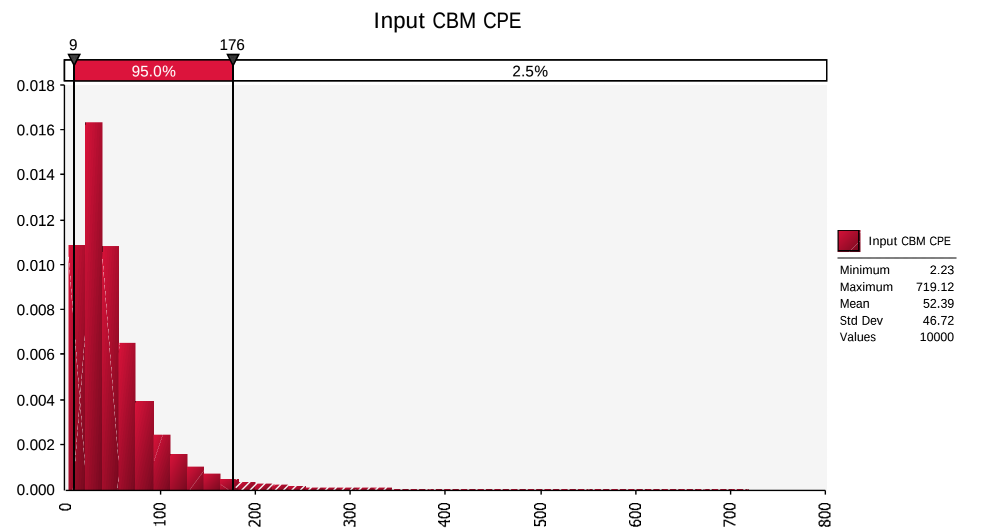
<tr><td>Coalbed methane Completions Potential Emissions ($M_{pot,comp}$)</td><td>


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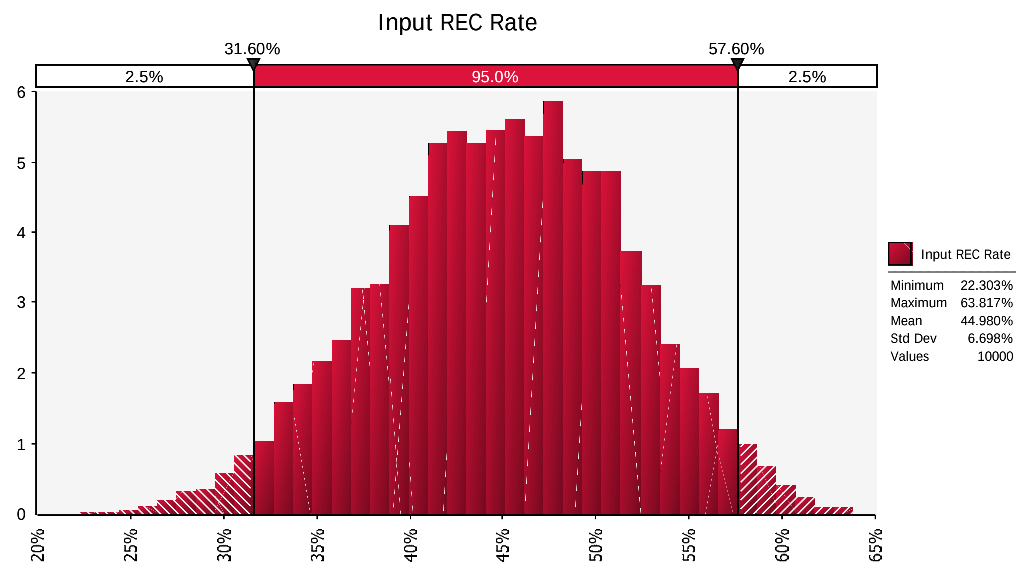
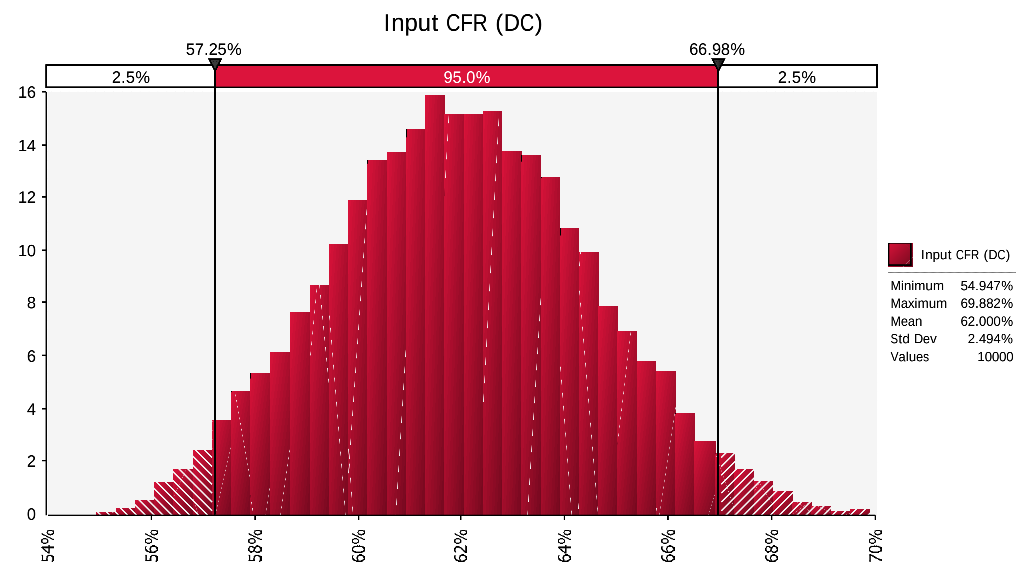
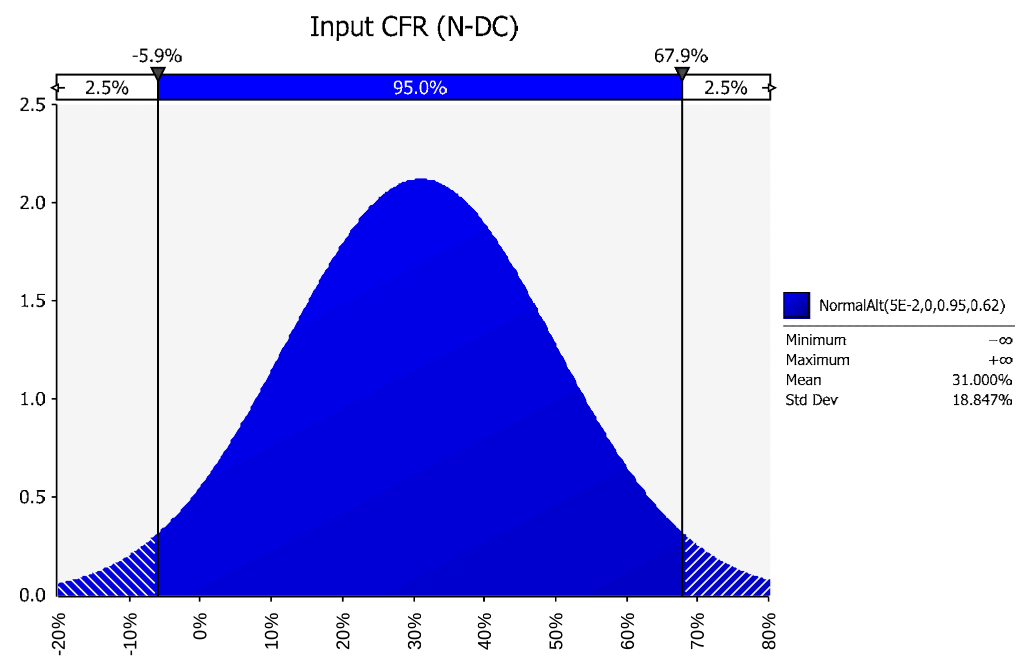
Reduced Emissions Completions Capture Rate (REC_{comp})

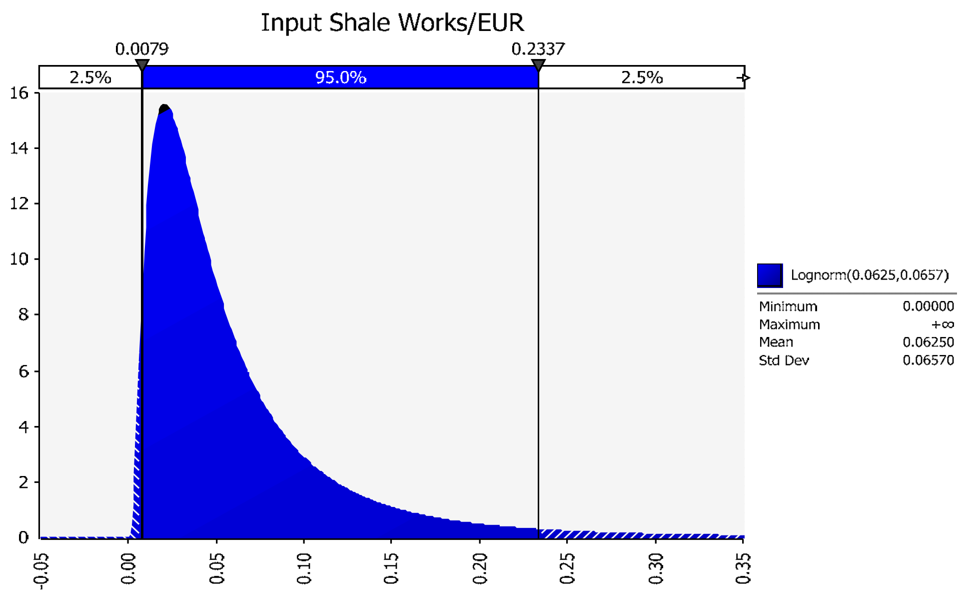
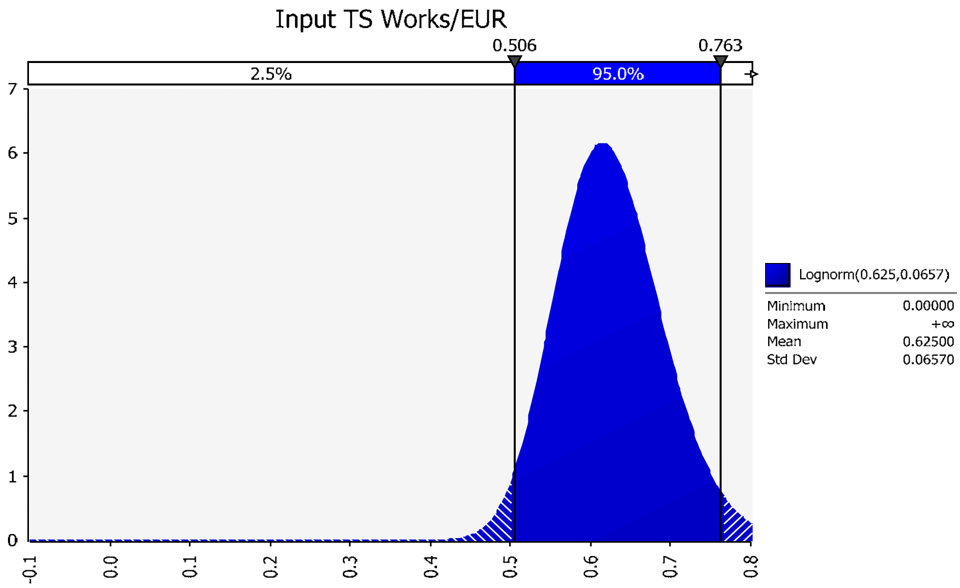
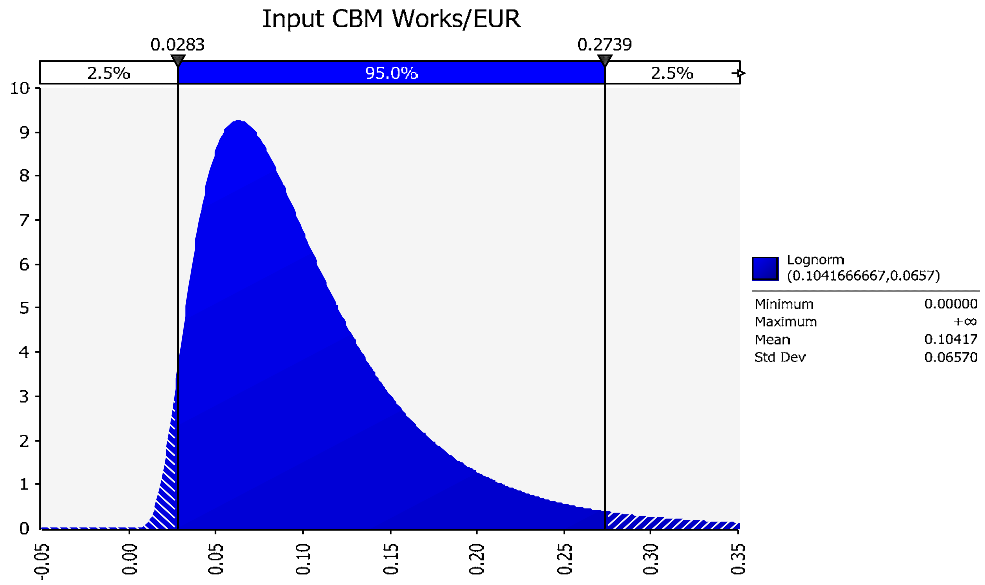


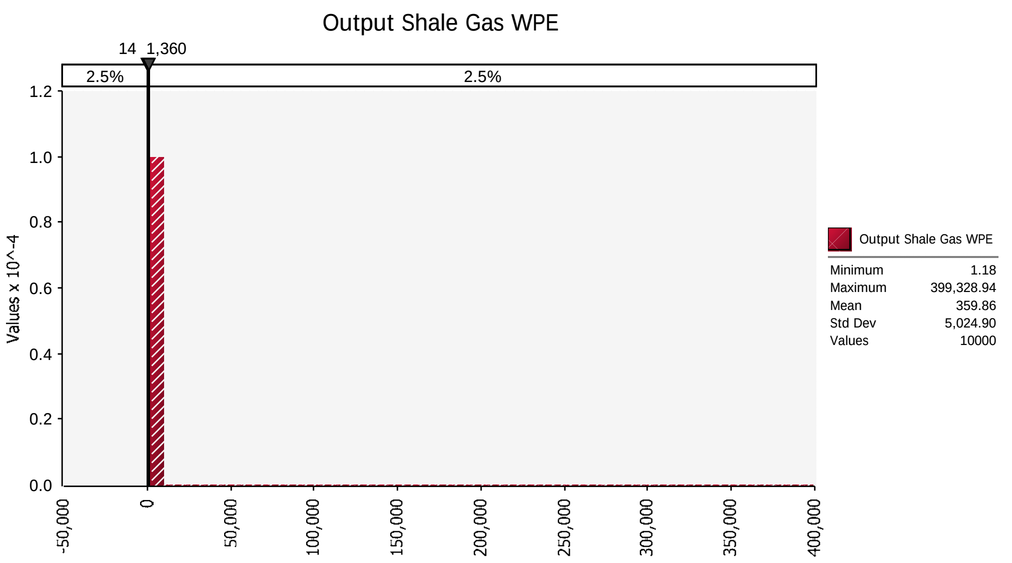
Developed Countries Completions Flaring Rate ($X_{comp,flare}$)



Non-Developed Countries Completions Flaring Rate ($X_{comp,flare}$)



Shale gas Workovers per Lifespan (N_{work})	
Tight sands gas Workovers per Lifespan (N_{work})	
Coalbed methane Workovers per Lifespan (N_{work})	

<table>
<tr><td>Shale gas Workover Potential Emissions ($M_{pot,work}$)</td><td>
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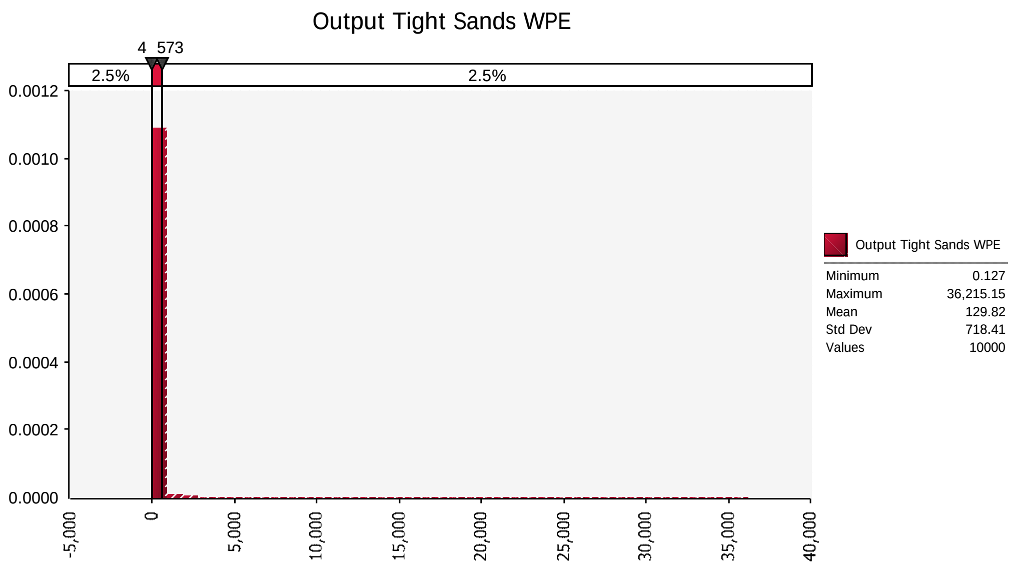
<tr><td>Tight sands gas Workover Potential Emissions ($M_{pot,work}$)</td><td>
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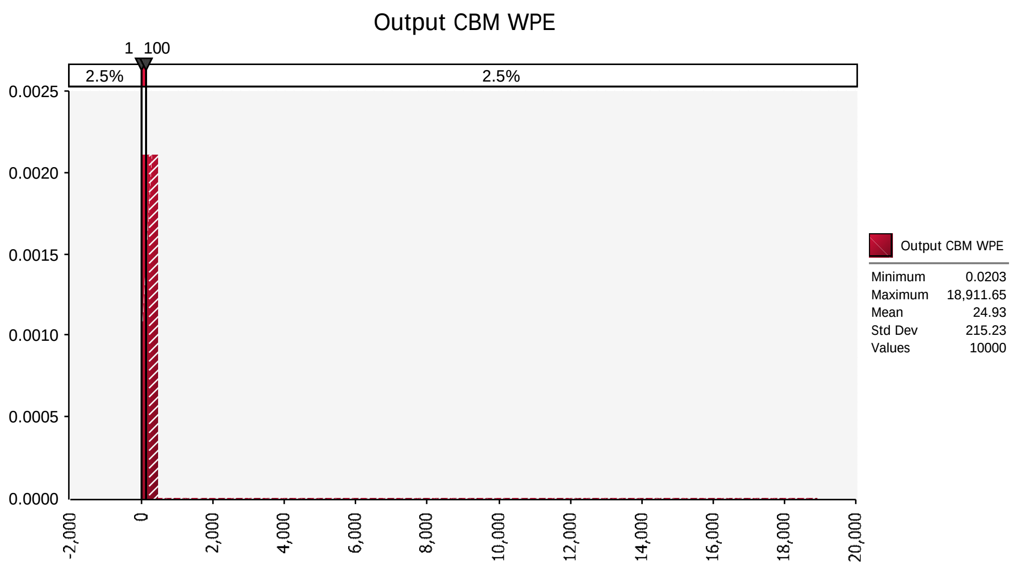
<tr><td>Coalbed methane Workover Potential Emissions ($M_{pot,work}$)</td><td>
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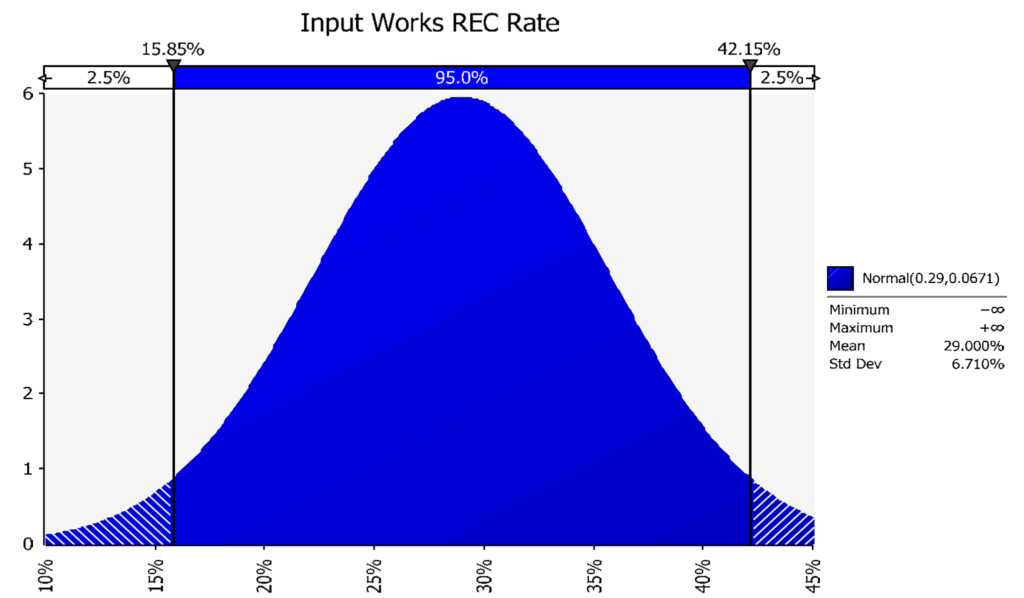
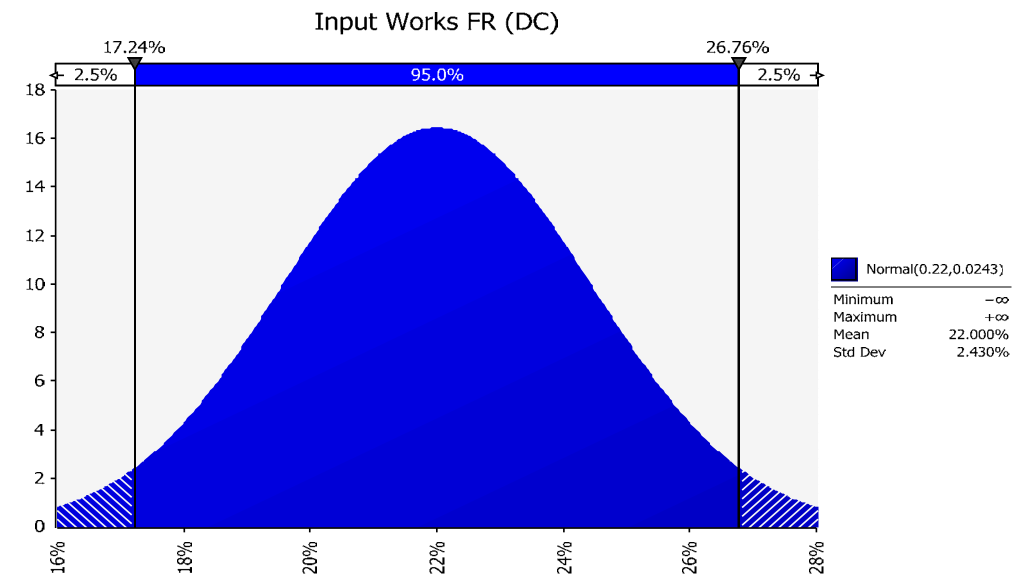
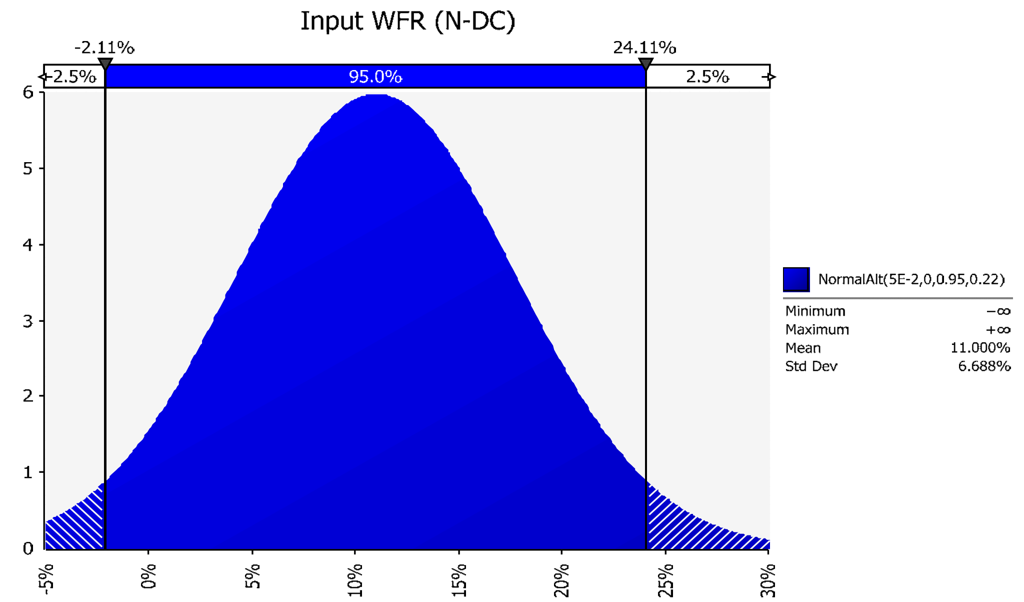
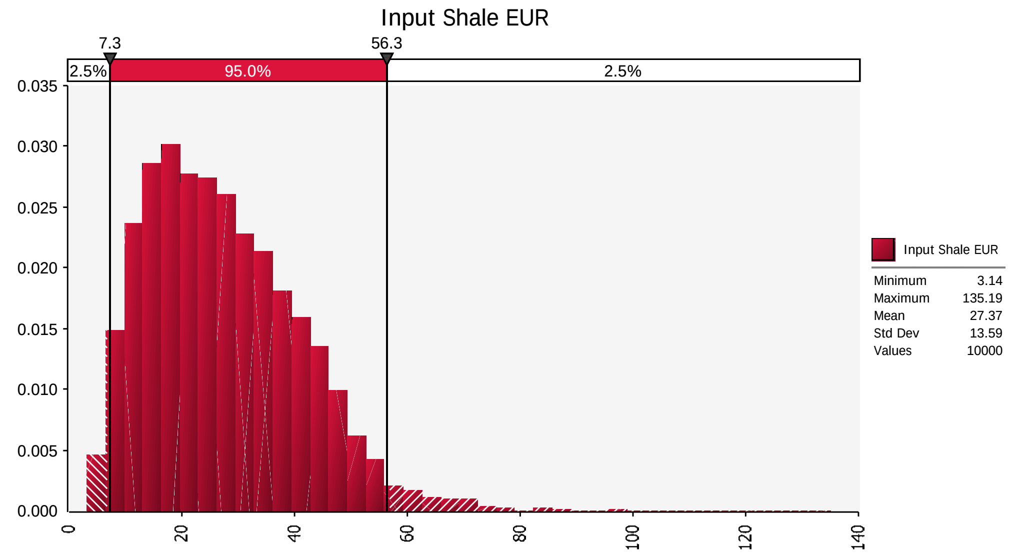
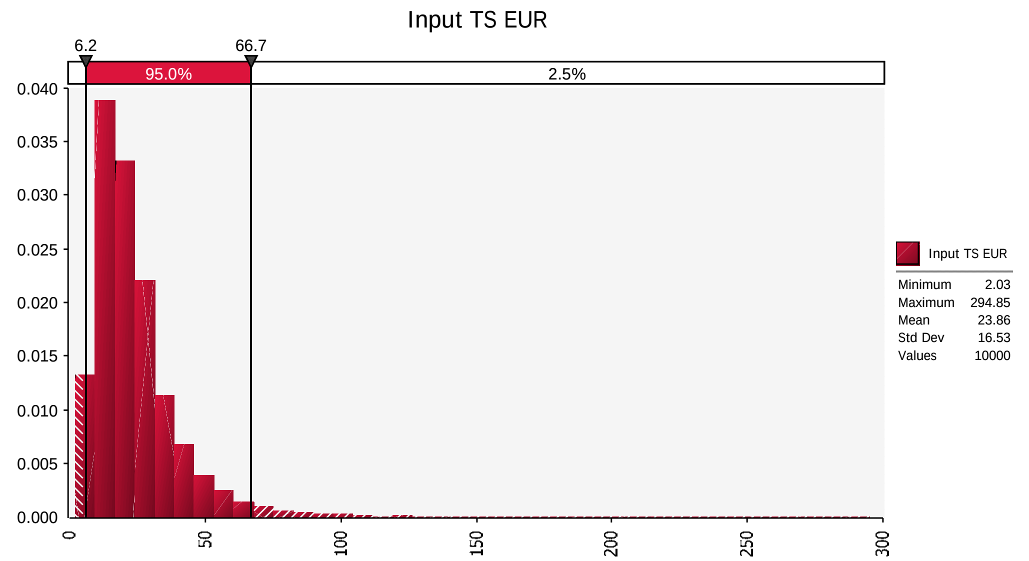
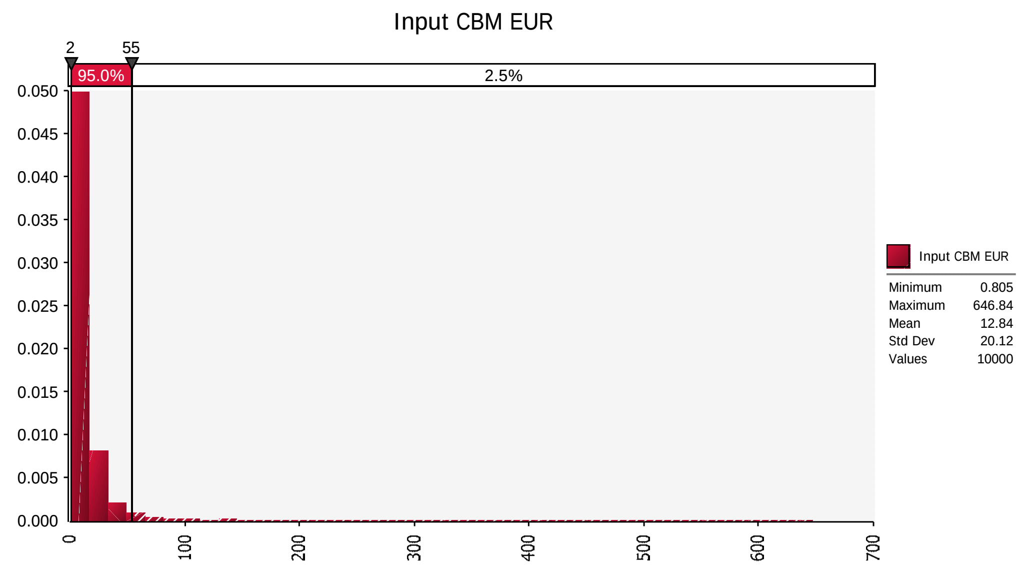
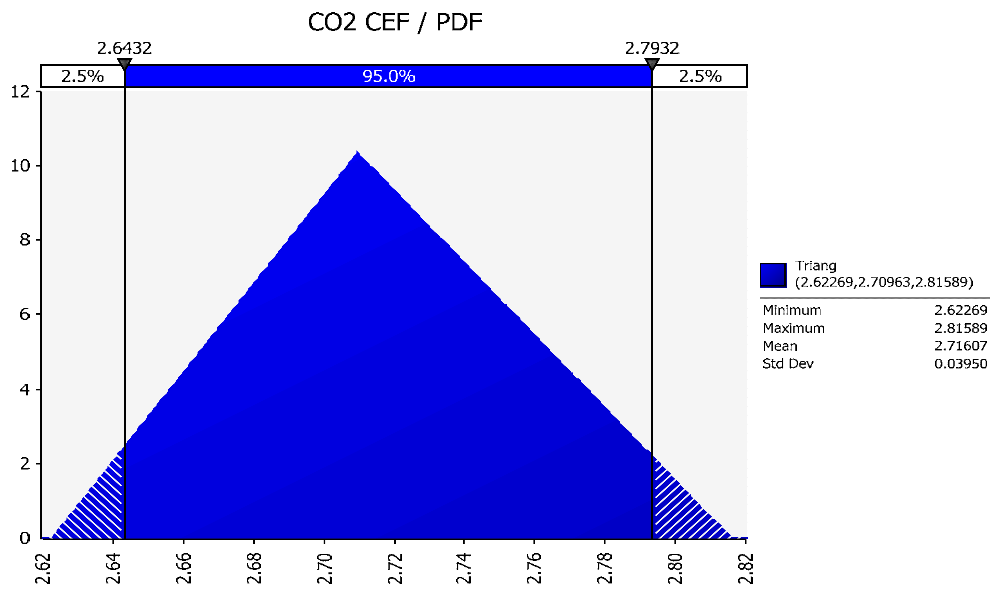
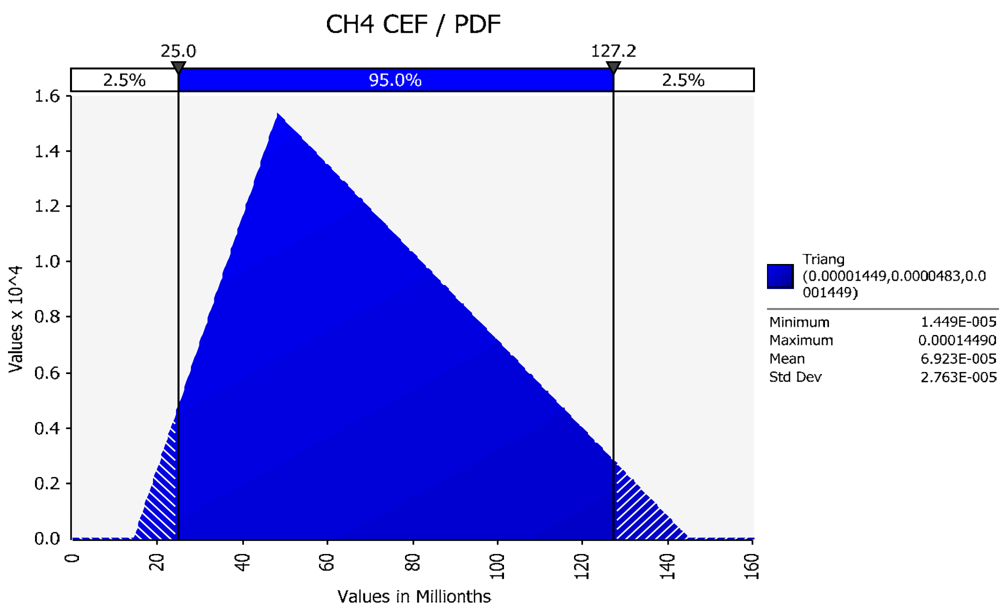
Workover REC Capture Rate (REC_{work})	
Developed Countries Workover Flaring Rate ($X_{work,flare}$)	
Non-Developed Countries Workover Flaring Rate ($X_{work,flare}$)	

Shale gas Estimated Ultimate Recovery (EUR)	
Tight sands gas Estimated Ultimate Recovery (EUR)	
Coalbed methane Estimated Ultimate Recovery (EUR)	

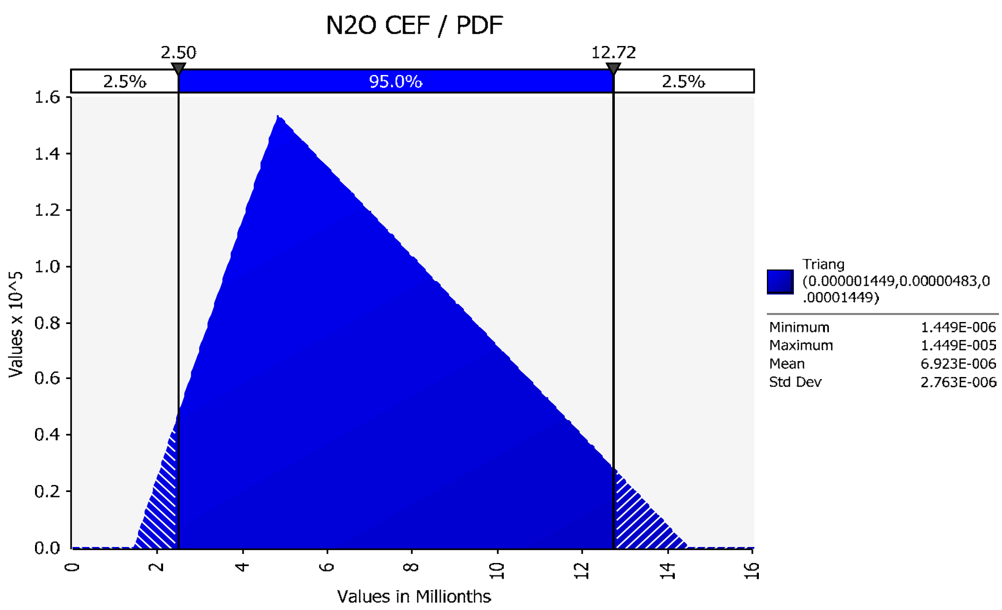
Combustion Emission Factor for Carbon Dioxide (CEF_{CO2})

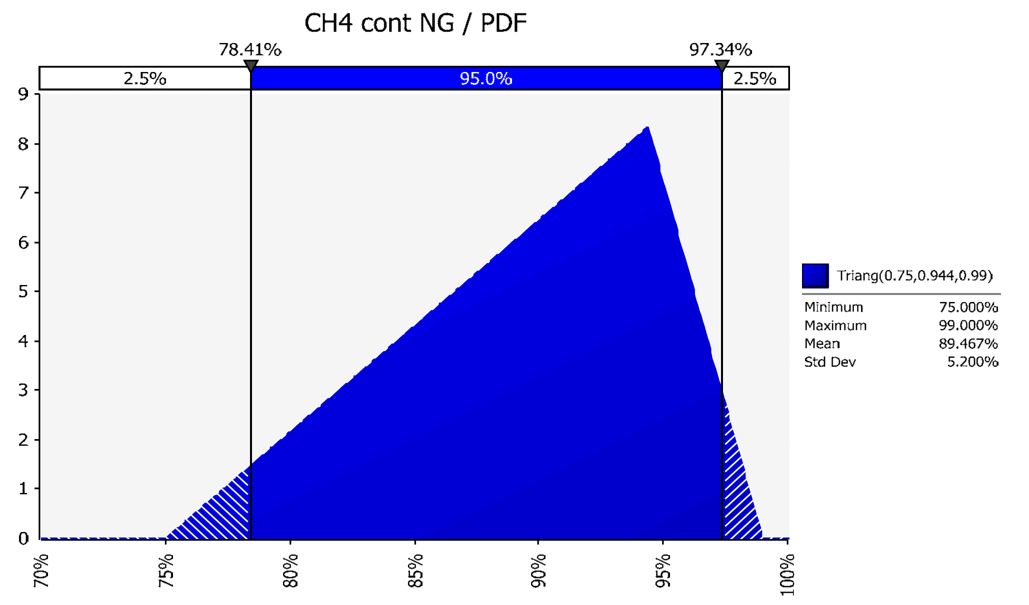
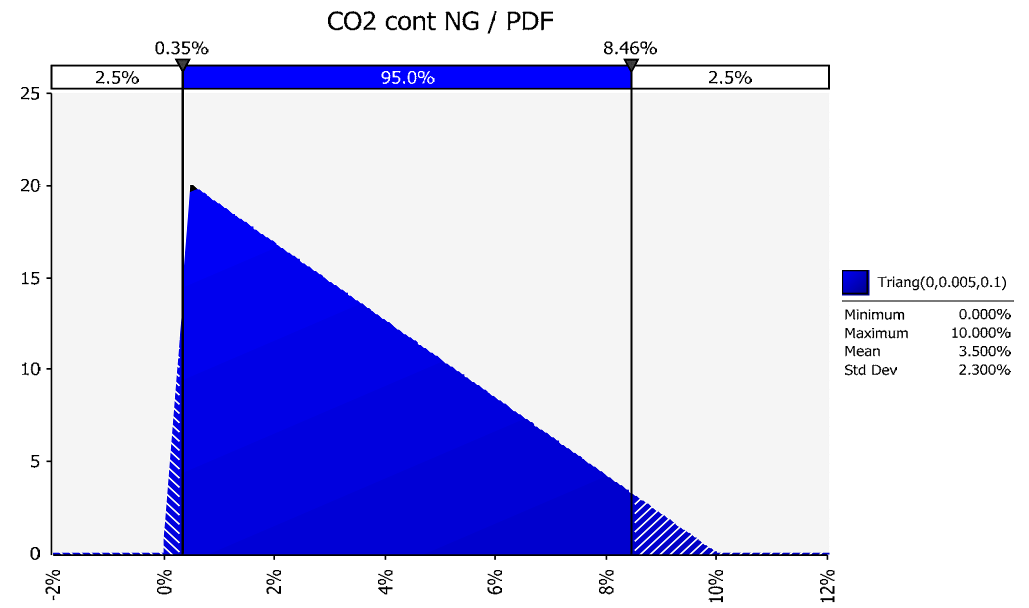
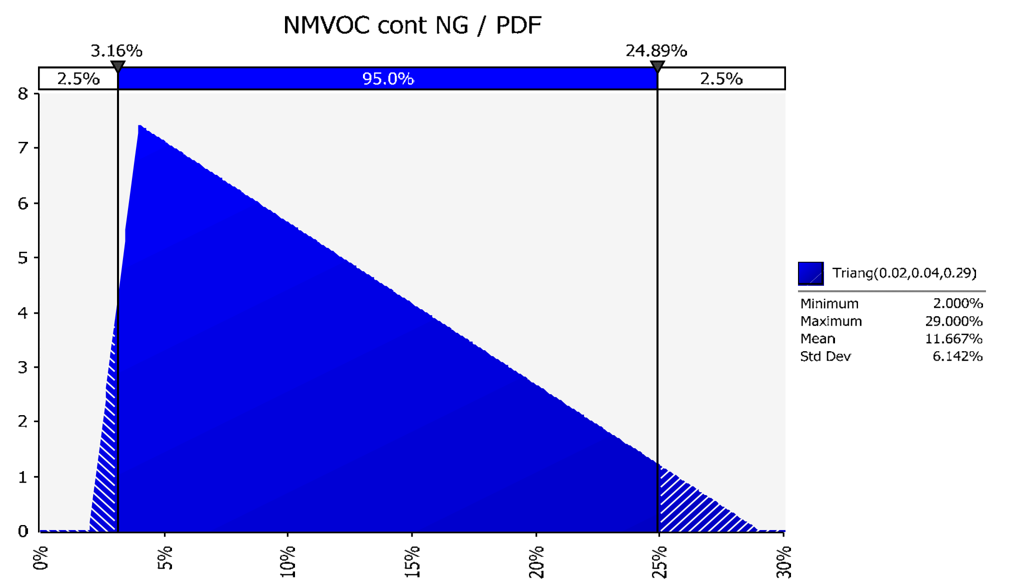


Combustion Emission Factor for Methane (CEF_{CH4})



Combustion Emission Factor for Nitrous Oxide (CEF_{N2O})



Volume Fraction for Methane (y_{CH4})	
Volume Fraction for Carbon Dioxide (y_{CO2})	
Volume Fraction for Non-Methane Volatile Organic Compound (y_{NMVOC})	

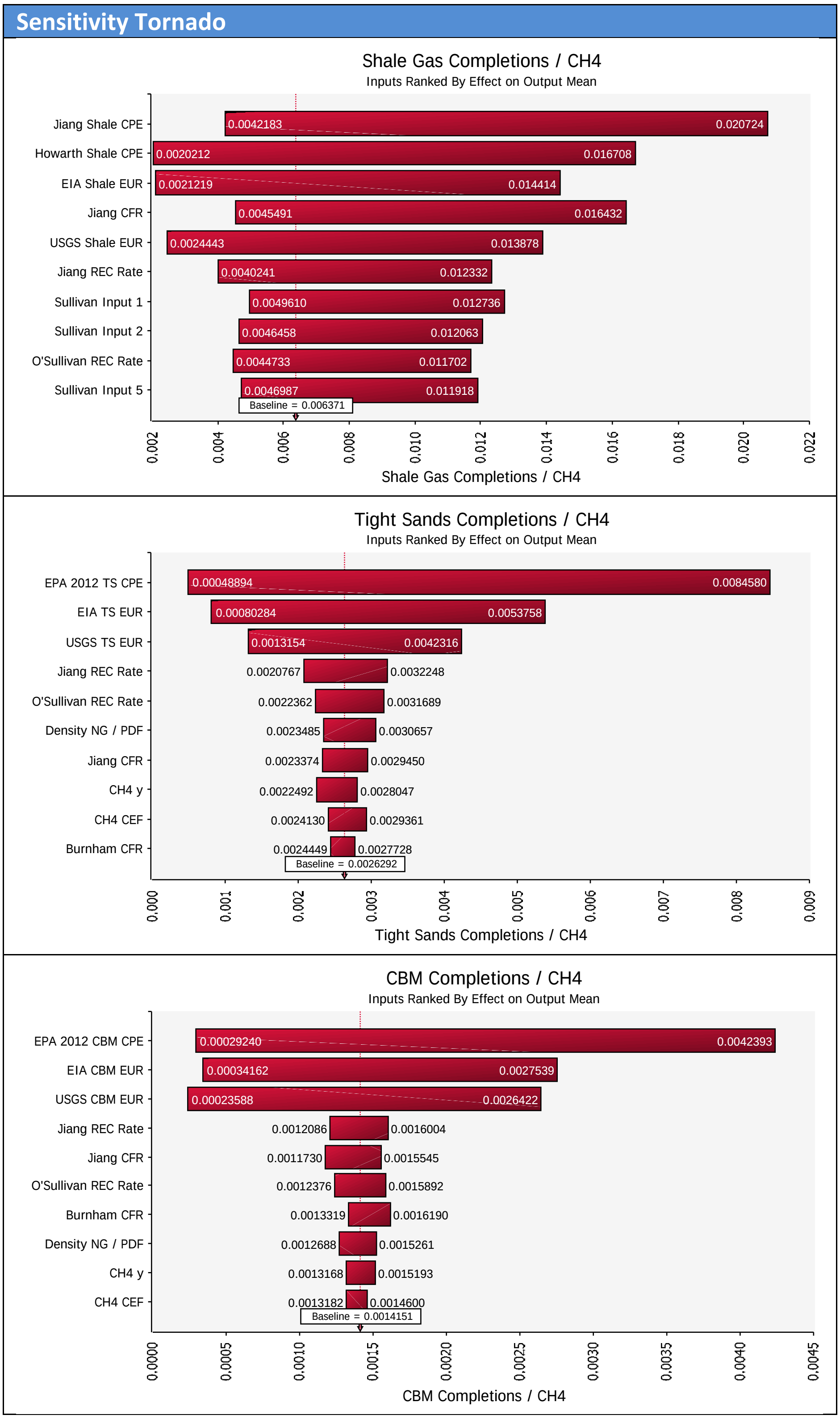
Appendix 4

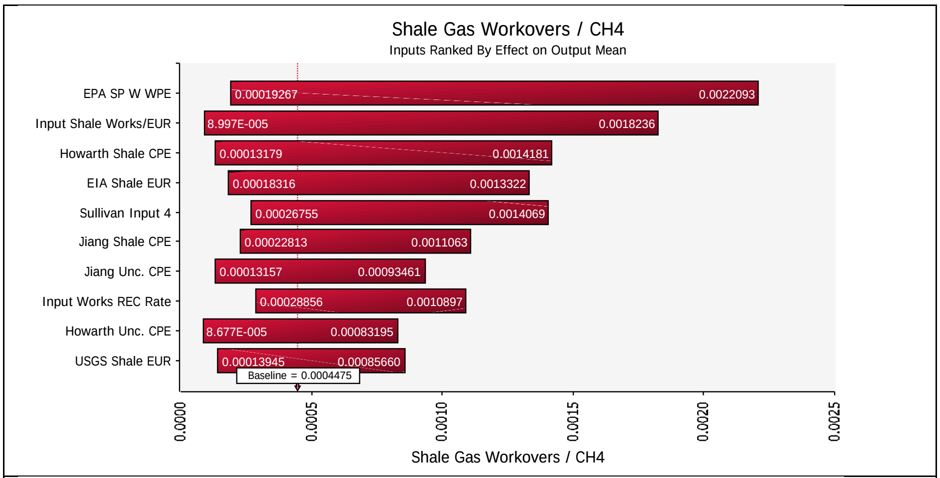
Dealing with Different Causes of Uncertainty

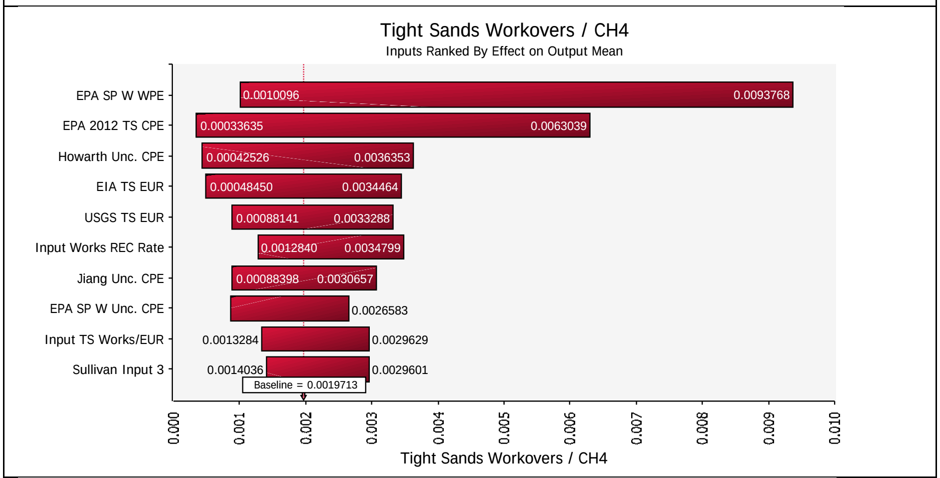
Causes of Uncertainty	Action
Lack of completeness	• All key components of the system have been considered • Errors in the data collected through literature review are non-quantifiable but have for the most part been verified through peer-review
Model (bias and random errors)	• The model is complete as far as available data permits • Uncertainty ranges in the model predictions are rigorously derived through Monte Carlo analysis • The model is considered accurate as available data permits • Model predictions and uncertainty ranges fall within ranges resulting from other peer-reviewed studies • The level of precision is not confirmable based on the level of disagreement between studies to date • Model predictions lie within the ranges of expert judgement
Lack of data	• Where data was lacking, values provided by expert judgement have been used • Where only small sample data populations were available this was taken into account in the statistical analysis and subsequent uncertainty ranges
Lack of representativeness of data	• The data used is taken from the most recent and reliable sources available • Serious doubts have arisen on the accuracy of this data based on recent research but at this time the data used still represents the most representative
Statistical random sampling error	• Monte Carlo analysis was used in the derivation of model predictions and associated uncertainty ranges to account for statistical random sampling errors
Measurement error	• Measurement error has not been accounted for in this study • The majority of data used has been through peer review which is the only extent to which measurements can be verified
Missing data	• Monte Carlo analysis was applied to ensure missing data was accounted for with the uncertainty ranges developed

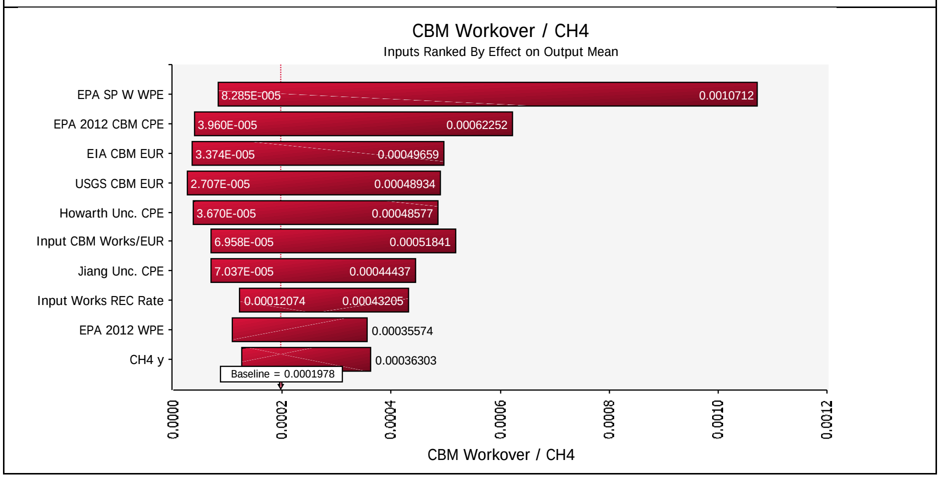
Appendix 5

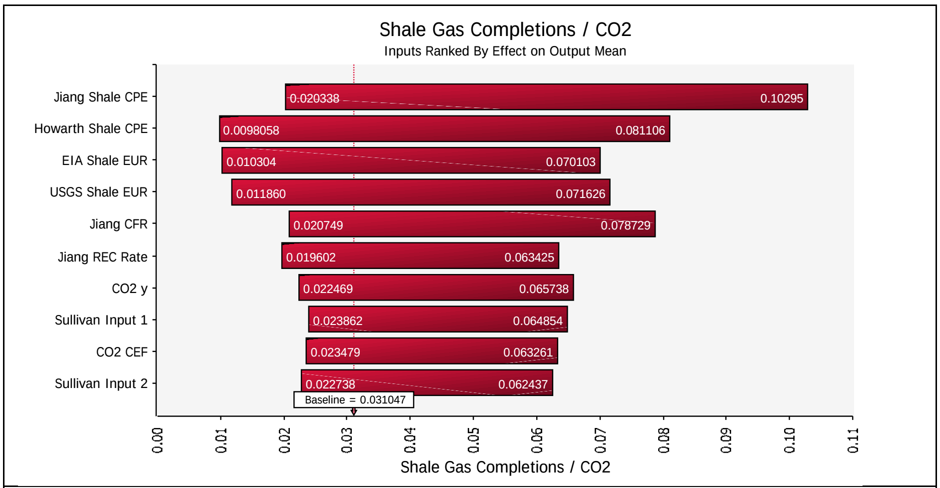
Sensitivity Analyses

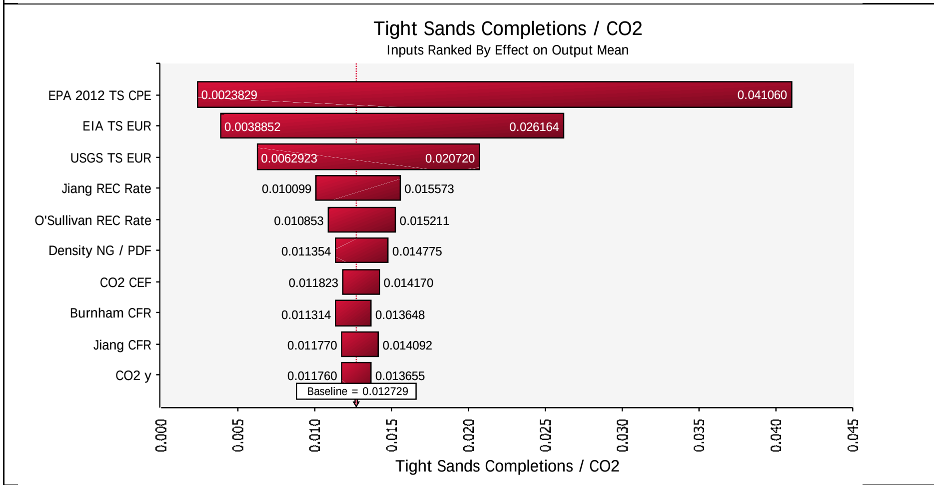


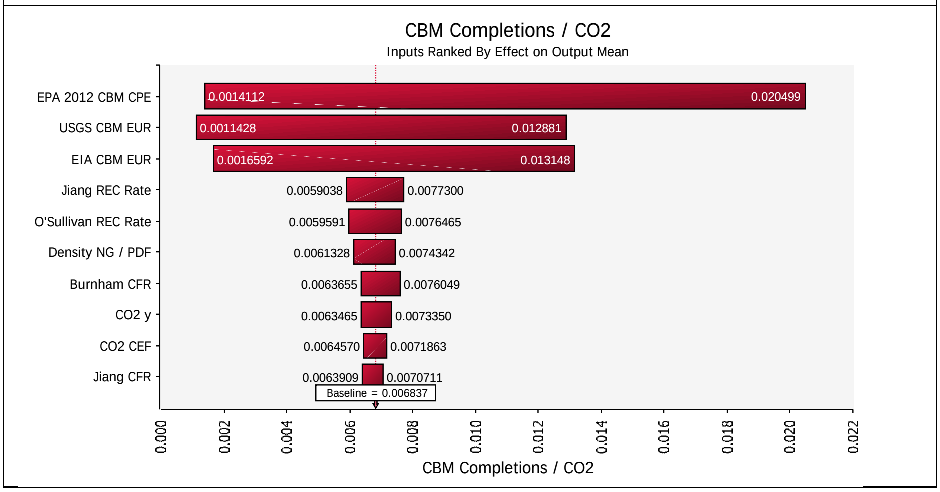

Shale Gas Workovers / CH4
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
Input Shale Works/EUR
Howarth Shale CPE
EIA Shale EUR
Sullivan Input 4
Jiang Shale CPE
Jiang Unc. CPE
Input Works REC Rate
Howarth Unc. CPE
USGS Shale EUR
0.00019267
0.0022093
8.997E-005
0.0018236
0.00013179
0.0014181
0.00018316
0.0013322
0.00026755
0.0014069
0.00022813
0.0011063
0.00013157
0.00093461
0.00028856
0.0010897
8.677E-005
0.00083195
0.00013945
0.00085660
Baseline = 0.0004475
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
Shale Gas Workovers / CH4

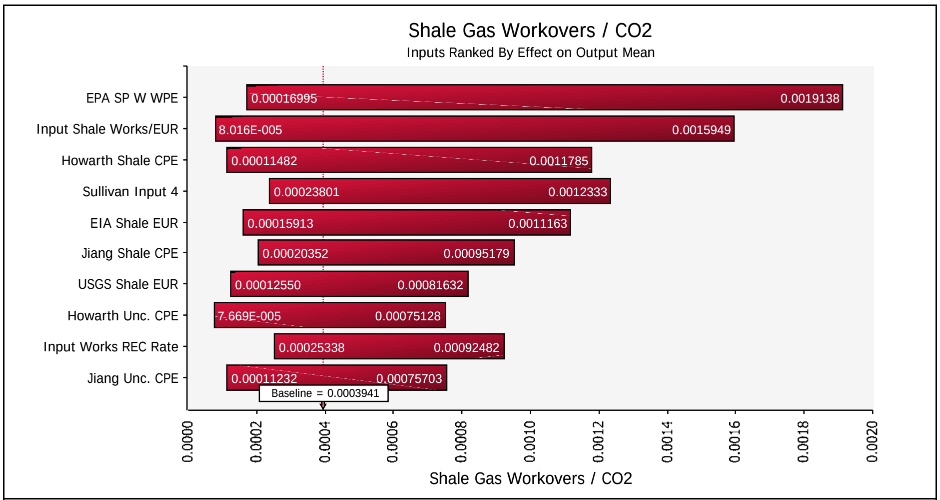

Tight Sands Workovers / CH4
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
EPA 2012 TS CPE
Howarth Unc. CPE
EIA TS EUR
USGS TS EUR
Input Works REC Rate
Jiang Unc. CPE
EPA SP W Unc. CPE
Input TS Works/EUR
Sullivan Input 3
0.0010096
0.0093768
0.00033635
0.0063039
0.00042526
0.0036353
0.00048450
0.0034464
0.00088141
0.0033288
0.0012840
0.0034799
0.00088398
0.0030657
0.0026583
0.0013284
0.0029629
0.0014036
0.0029601
Baseline = 0.0019713
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
Tight Sands Workovers / CH4

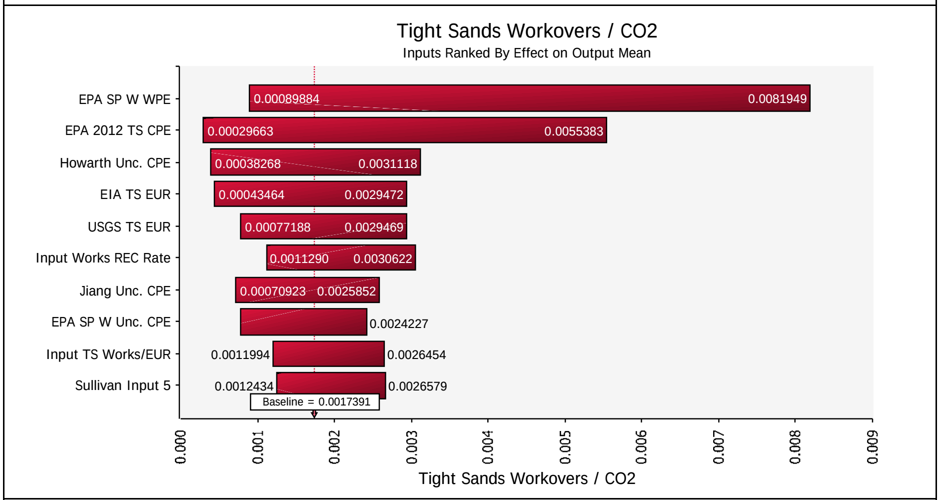

CBM Workover / CH4
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
EPA 2012 CBM CPE
EIA CBM EUR
USGS CBM EUR
Howarth Unc. CPE
Input CBM Works/EUR
Jiang Unc. CPE
Input Works REC Rate
EPA 2012 WPE
CH4 y
8.285E-005
0.0010712
3.960E-005
0.00062252
3.374E-005
0.00049659
2.707E-005
0.00048934
3.670E-005
0.00048577
6.958E-005
0.00051841
7.037E-005
0.00044437
0.00012074
0.00043205
0.00035574
0.00036303
Baseline = 0.0001978
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
CBM Workover / CH4

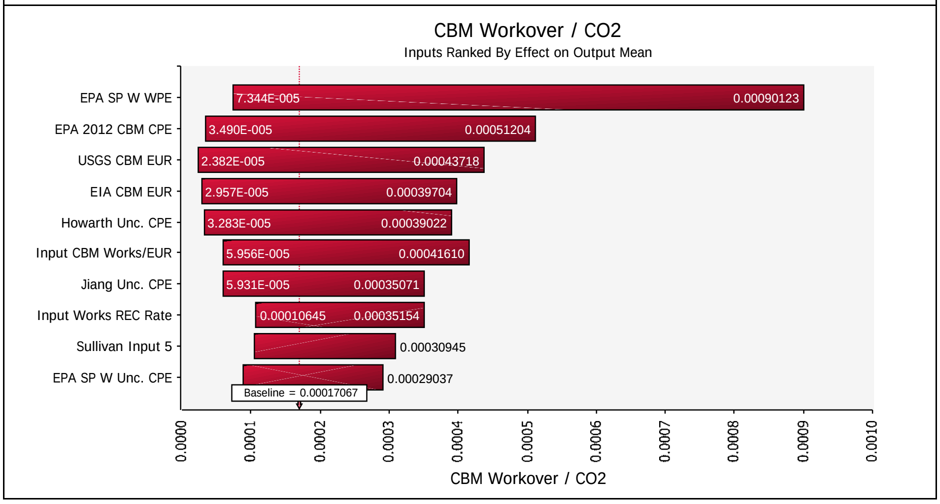

Shale Gas Completions / CO2
Inputs Ranked By Effect on Output Mean
Jiang Shale CPE
Howarth Shale CPE
EIA Shale EUR
USGS Shale EUR
Jiang CFR
Jiang REC Rate
CO2 y
Sullivan Input 1
CO2 CEF
Sullivan Input 2
0.020338
0.10295
0.0098058
0.081106
0.010304
0.070103
0.011860
0.071626
0.020749
0.078729
0.019602
0.063425
0.022469
0.065738
0.023862
0.064854
0.023479
0.063261
0.022738
0.062437
Baseline = 0.031047
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
Shale Gas Completions / CO2


Tight Sands Completions / CO2
Inputs Ranked By Effect on Output Mean
EPA 2012 TS CPE
EIA TS EUR
USGS TS EUR
Jiang REC Rate
O'Sullivan REC Rate
Density NG / PDF
CO2 CEF
Burnham CFR
Jiang CFR
CO2 y
0.0023829
0.041060
0.0038852
0.026164
0.0062923
0.020720
0.010099
0.015573
0.010853
0.015211
0.011354
0.014775
0.011823
0.014170
0.011314
0.013648
0.011770
0.014092
0.011760
0.013655
Baseline = 0.012729
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
Tight Sands Completions / CO2


CBM Completions / CO2
Inputs Ranked By Effect on Output Mean
EPA 2012 CBM CPE
USGS CBM EUR
EIA CBM EUR
Jiang REC Rate
O'Sullivan REC Rate
Density NG / PDF
Burnham CFR
CO2 y
CO2 CEF
Jiang CFR
0.0014112
0.020499
0.0011428
0.012881
0.0016592
0.013148
0.0059038
0.0077300
0.0059591
0.0076465
0.0061328
0.0074342
0.0063655
0.0076049
0.0063465
0.0073350
0.0064570
0.0071863
0.0063909
0.0070711
Baseline = 0.006837
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.022
CBM Completions / CO2


Shale Gas Workovers / CO2
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
Input Shale Works/EUR
Howarth Shale CPE
Sullivan Input 4
EIA Shale EUR
Jiang Shale CPE
USGS Shale EUR
Howarth Unc. CPE
Input Works REC Rate
Jiang Unc. CPE
0.00016995
0.0019138
8.016E-005
0.0015949
0.00011482
0.0011785
0.00023801
0.0012333
0.00015913
0.0011163
0.00020352
0.00095179
0.00012550
0.00081632
7.669E-005
0.00075128
0.00025338
0.00092482
0.00011232
0.00075703
Baseline = 0.0003941
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
0.0014
0.0016
0.0018
0.0020
Shale Gas Workovers / CO2


Tight Sands Workovers / CO2
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
EPA 2012 TS CPE
Howarth Unc. CPE
EIA TS EUR
USGS TS EUR
Input Works REC Rate
Jiang Unc. CPE
EPA SP W Unc. CPE
Input TS Works/EUR
Sullivan Input 5
0.00089884
0.0081949
0.00029663
0.0055383
0.00038268
0.0031118
0.00043464
0.0029472
0.00077188
0.0029469
0.0011290
0.0030622
0.00070923
0.0025852
0.0024227
0.0011994
0.0026454
0.0012434
0.0026579
Baseline = 0.0017391
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
Tight Sands Workovers / CO2


CBM Workover / CO2
Inputs Ranked By Effect on Output Mean
EPA SP W WPE
EPA 2012 CBM CPE
USGS CBM EUR
EIA CBM EUR
Howarth Unc. CPE
Input CBM Works/EUR
Jiang Unc. CPE
Input Works REC Rate
Sullivan Input 5
EPA SP W Unc. CPE
7.344E-005
0.00090123
3.490E-005
0.00051204
2.382E-005
0.00043718
2.957E-005
0.00039704
3.283E-005
0.00039022
5.956E-005
0.00041610
5.931E-005
0.00035071
0.00010645
0.00035154
0.00030945
0.00029037
Baseline = 0.00017067
0.0000
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
0.0007
0.0008
0.0009
0.0010
CBM Workover / CO2

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