Project Acronym and Title:

**M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas**

# FINAL REPORT ON MONITORING AND MITIGATING EMISSIONS TO AIR

**Paula Costa[1], Ana Picado[1], Justina Catarino[1], Filomena Pinto[1], Zélia Pereira[1], Elsa Ramalho[1]**

**[1]LNEG – National Laboratory for Energy and Geology**

E-mail of lead author:

**paula.costa@lneg.pt**

**D14.5**

Definitive version

**Disclaimer**

This report is part of a project that has received funding by the *European Union's Horizon 2020 research and innovation programme* under grant agreement number 640715.

The content of this report reflects only the authors' view. The *Innovation and Networks Executive Agency (INEA)* is not responsible for any use that may be made of the information it contains.

Published December 2017 by M4ShaleGas Consortium

## Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*.
The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.
The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower $CO_2$ emissions and more renewable energy. Shale gas may contribute to this transformation.
Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas ($CO_2$ and methane) and its energy efficiency compared to other energy sources
There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.
The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.


## Executive Report Summary

The European Commission in its Energy Roadmap 2050 identified gas as a critical energy source for the transformation of the energy system to a system with lower $CO_2$ emissions, but environmental impact associated with large scale shale gas development is of major concern to the public, policy makers and other stakeholders. The major knowledge on the effects and consequences of shale gas exploration and exploitation comes, mostly, from shale gas practices in the United States. It is important to address differences in geological settings and societal environment between European countries and the US and the impact of these differences for the potential future development of shale gas in Europe. It is also important to evaluate if the existing EU Directives and regulations appropriately apply to unconventional hydrocarbon extraction. The sources and types of emissions associated with the various phases of shale gas production were identified and reviewed. The relevance of atmospheric concentration baselines was also discussed. Furthermore the raw shale gas composition was investigated as shale gas components may be used to identify gas leakages. The objective of baselines is that upon implementation of shale gas activities there is clear and transparent information about the atmospheric composition before and after the activities started. There is evidence that shale gas extraction has proceeded, in most cases, without adequate environmental baseline measurements, what makes it difficult to properly identify, quantify and characterize environmental impacts associated with shale gas development. Another main concern, regarding the global climate impact of a potential European Shale gas industry, is the methane leakage. Establishing pre-fracturing baseline data as well as providing an integrated assessment of emissions from shale gas operation sites it is imperative and a low-cost sampling strategy needs to be settled. Some monitoring strategies and potential emission reduction techniques are also reported in order to minimize environmental impact of emissions to air of shale gas operations.


 

# TABLE OF CONTENTS

Page


1 INTRODUCTION ... 3
1.1 Context of M4ShaleGas ... 3
1.2 Study objectives for this report ... 3
1.3 Aims of this report ... 5
1.4 Structure of the report ... 5
2 EMISSIONS FROM SHALE GAS OPERATIONS ... 6
2.1 Air pollutants and sources ... 8
2.2 Shale gas GHG balance ... 11
3 LEGISLATION ... 13
4 KNOWLEDGE GAPS ... 15
5 POTENTIAL SOLUTIONS FOR THE KNOWLEDGE GAPS ... 17
5.1 Well integrity ... 17
5.2 Baseline measurement ... 18
5.3 Raw shale gas composition ... 19
6 MONITORING STRATEGIES FOR EMISSIONS TO AIR ... 20
7 EMISSION REDUCTION TECHNICS ... 24
8 FINAL REMARKS ... 28
9 ABBREVIATIONS AND SYMBOLS ... 31
10 REFERENCES ... 32

# 1 INTRODUCTION

## 1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower $CO_2$ emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas ($CO_2$ and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which make close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

## 1.2 Study objectives for this report

The Shale gas development plays an important role in the international energy field, especially in North America. Major shale gas reserves were, also, identified in many

[1]EIA (2015).Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

 

other countries (e.g. Algeria, Argentina, Australia, Brazil, Canada, China, Mexico, Russia, South Africa) (U.S. Department of Energy, 2013). In Europe, there are identified reserves with developments for exploitation/exploration in Poland and UK.

Environmental impact associated with large scale shale gas development is of major concern to the public, policy makers and other stakeholders. The major knowledge on the effects and consequences of shale gas exploration and exploitation comes, mostly, from shale gas practices in the United States. With the shale gas operations in Europe it became very important to address differences in geological settings and societal environment between European countries and the US and the impact of these differences for the potential future development of shale gas in Europe.

The final report synthesizes the main activities foreseen in WP14 of the M4ShaleGas project within the research on emissions to atmosphere during shale gas operations. This report is more focused in the GHG emissions once these air pollutants are of main concern, reported in many studies, and the information on the other air pollutants identified is much less available.

In the M4ShaleGas project first role was to assess the impact of gas emissions related to shale gas exploration and exploitation in North America and Europe and comparing emissions from shale gas with those of conventional fuel exploitation. The different sources and types of emissions (e.g., $CH_4$, NMVOC, NOx, SOx, PM, benzene, HPA, $O_3$) associated with the various phases of shale gas production were identified and reviewed. The evaluation of the different pollutants balance of shale gas had taken into account all air emissions related to the (1) pre-production, (2) production, transportation, distribution and end-use of shale gas, (3) end of exploration and well closure. These issues were reported in detail in Costa et al. 2015.

After a literature review, some knowledge gaps were identified. The more relevant knowledge gaps were considered to be well integrity, lack of baseline measurements and methane leakage, so, these topics were addressed in more detail in Costa et al. 2016. In this report it was discussed the relevance of atmospheric concentration baselines. Furthermore the raw shale gas composition was investigated in order to assess the shale gas components that may be used to identify gas leakages. It was concluded that concentration baselines of methane and other components in shale gas, can provide a standard of the pre shale gas development state of the environment, so, the important objective of baselines is that upon implementation of shale gas activities there is clear and transparent information about the atmospheric composition before and after the activities started. The lack of baseline data makes it difficult to properly identify, quantify and characterize environmental impacts that may be associated with shale gas development. For establishing pre-fracturing baseline data as well as providing an integrated assessment of emissions from shale gas operation sites, needs to be developed and a low-cost sampling strategy needs to be settled. Another main concern, when considering the global climate impact of a potential European Shale gas industry, is the leakage of methane. An assessment of potential leakage rates can be used to predict possible changes in methane and ethane concentrations in the atmosphere. Also the construction of a data base of raw gas composition for Europe it is very important. Other main concern is the well integrity that has been referred that remains the weak spot in the system, being the primary concern in environmental protection issues. The assessment of environmental impacts in the well integrity is hampered by a lack of information, particularly the problem of fluids escaping from incompletely sealed wells.

The emission reduction techniques are addressed as potential mitigation options to minimise the impact of shale gas exploration on the atmosphere, based on the on-going work in USA and Canada. The most prominent emission reduction techniques are Reduced Emission or Green Completions which are mainly applied to GHG.

To conclude the report scientific recommendations viewing the minimization of emissions to air associated with shale gas operations are presented.

## 1.3 Aims of this report

This report aims at integrating the reviews and research on emissions to atmosphere providing scientific based recommendations to minimise impacts and mitigate risks and footprint of shale gas emissions in Europe. The impact of gas emissions related to shale gas exploration and exploitation in Europe is assessed, presenting a review of the different sources and types of emissions associated with the different phases of shale gas production. Important issues and knowledge gaps were identified and focus was given on the importance of monitoring baselines prior shale gas development and in the raw gas composition in order to promote the construction of a data base for Europe. Furthermore, the monitoring and mitigating emissions to atmosphere are addressed in order to set the scenario of the concentration baselines and raw shale gas compositions and thereby helping the quantification of atmospheric emissions resulting from shale gas operations.

## 1.4 Structure of the report

This report is divided in nine chapters. The first one is an introductory chapter where the objectives of the M4ShaleGas and of this report are presented. The emission from shale gas operations are addressed in Chapter 2. Chapter 3 describes the existing legislation concerning GHG emissions. The knowledge gaps on shale gas existing technologies are summarised in Chapter 4. Possible ways to full fill the knowledge are presented in Chapter 5. In Chapter 6 are presented the monitoring strategies for emissions to air from shale gas. The best available techniques for reducing GHG emissions are summarized in Chapter 7. Some remarks and recommendations are presented in Chapter 8 and the References are listed in Chapter 9.

 

# 2 EMISSIONS FROM SHALE GAS OPERATIONS

Shale gas is a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There is no precise chemical formula of natural shale gas. However, the main component is methane, a powerful greenhouse gas (GHG) with a global warming potential of 28 (IPCC, 2013). Quantities of methane and remaining shale gas composition may vary from area to area, depending on rocks type and formation and even wells in the same region may produce shale gas with different compositions (Bullin and Krouskop, 2009).Natural shale gas found at a well has a composition different from that received by consumers due to pre-processing of the gas. The type of well that the gas comes from also affects its composition, e.g. the gas from shale gas wells is different from that obtained from oil wells or condensate wells.

In general, it is assumed that production of shale gas is not fundamentally different from conventional gas, except for some extra activities that are required, especially for pre-production of the gas (Hauck and Denier van der Gon, 2015). Once gas is injected in high pressure transmission pipelines, no distinction can be made any more.

The potential climate impact of shale gas, and how it can be compared to other conventional fuels, can only be understood by analysing all the emissions data associated with the life cycle of shale gas (i.e. from exploration to end-use). Gaseous emissions from shale gas, specially GHG, has been the subject of a number of studies since 2010 ((Howarth et al. (2011), Skone et al. (2011), Jiang et al.(2011), Burnham et al. (2012), Zammerilli A.(2014), Bunch A. G. (2014), (Robinson A. (2014)). These studies have yielded a large variation in the estimated environmental impacts of shale gas, due to differences in methodology and data assumptions.

The GHG emissions to the atmosphere are essential to assess climate aspects of shale gas exploration and exploitation. The carbon footprint is an important way to quantify climate impact, but the available knowledge on shale gas carbon footprint arises mostly from U.S. based studies and measurements.

It is assumed that the shale gas methane leakage rates are similar of those from conventional natural gas (Council of Canadian Academies, 2014). Some studies (Petron et al., 2012; Tollefson, 2013), based on direct measurements, indicate that the natural gas emissions from exploration and production of unconventional gas may be an important fraction of total gas production. So, direct measurements at the potential source should be considered. The different conclusions reached in several publications show the complexity in estimating emissions with accuracy. It is imperative to undertake research in order to address this uncertainty. However, the high number of considerations that contribute to the various conclusions that experts have reached up to now and the technical difficulty of measuring methane leakage accurately makes it unlikely that the uncertainties will be fully resolved in the near future. More details on the GHG balance related to shale gas activities are discussed in Section 2.2.

 

Beyond to greenhouse gas emissions, there are several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in fluids used for hydraulic fracturing and drilling and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. The shale gas is impossible to obtain using normal methods due to the low permeability of the rock, where there are poorly connected pores. Shale gas exploitation phases are mainly exploration drilling, production, transportation, end-use, end of exploration and well closure; production typically utilizes two major technologies: hydraulic fracturing and horizontal drilling (Costa et al., 2015).

Presently, the main concerns are the GHG emissions, mainly methane, but more attention should be given to other types of emissions that may also be caused by shale gas production. Shale gas production activities can produce significant amounts of air pollution that could have impact on local air quality.

In addition to the GHG methane ($CH_4$) and carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), volatile organic compounds (VOCs), aldehydes (formaldehyde, acetaldehyde) and hazardous air pollutants (HAPs) can be released due to fugitive emissions from shale gas production.

The emissions of other air pollutants are often discussed: ozone, particulate matter (PM), carbon monoxide (CO), sulphur oxides ($SO_x$) and lead. As individual compounds, acrolein, benzene, ethylbenzene, formaldehyde, n-hexane, hydrogen sulphide, methanol, toluene and xylene, heptanes, pentanes, 2,2,4-trimethylpentane, styrene, halogenated compounds, aldehydes, alcohols and glycols are also referred as specific air emissions.

In general, some differences in atmospheric emissions arise from differences in geology and geography between Europe and Northern America:

- Layer position of shale gas: combustion emissions caused by drilling are expected to increase with well depth and width (Broderick et al., 2011). This may lead to higher emissions from European shales if gas fields are located deeper.
- Gas composition and pipeline gas specifications directly influence processing emissions. In Canada more $CO_2$ and $H_2S$ were removed from Horn River and Montney shale than from conventional gas (Council of Canadian Academies, 2014). No general picture can be drawn on conventional versus shale gas composition or versus gas compositions in the U.S. and Europe. These are likely shale or location dependent.
- Europe is generally more densely populated than the U.S. or Canada. Siting of extraction sites in relation to where the population lives can lead to other regulatory requirements and public perceptions.

 

- More wells per pad can lead to efficiency increases (as found for the UK compared to the U.S. (Broderick et al., 2011).

## 2.1 Air pollutants and sources

Air pollutants like $CO_2$, $SO_x$ and $NO_x$ are the main emissions during fossil fuel combustion to provide energy to equipment, such as diesel engines used for drilling, hydraulic fracturing and natural gas compression and during flaring operations. Incomplete combustion can, also, result in other emissions such as methane, VOCs and PM. Furthermore, natural gas fired engines can be a significant source of formaldehyde, which is considered a secondary pollutant (U.S. Department of Energy, 2009). For hazardous air pollutants (HAP) the main relevant compounds in shale gas emissions are proposed in the literature to be benzene, toluene, ethylbenzene and xylenes (AEA, 2012). The reaction of NOx and VOC in the presence of sunlight can produce Ozone ($O_3$) (Robinson, 2014).

The major sources of emissions of some air pollutants are:

- Primary PM are formed, mainly, during combustion, but can, also, appear from dust or soil entering the air during pad construction, due to earth movement, and traffic on access roads (US Department of Energy, 2009)).
- $CH_4$ may be released as a fugitive emission from gas processing equipment (such as pneumatic controls, valves, well heads and others) or may escape due to fracking activities (for example due to the release of gases during flowback).
- VOCs are formed during the incomplete combustion, but can also be emitted during the dehydration step of natural gas US Department of Energy (2009). It is also associated with fugitive emissions and flaring from shale gas extraction, but in small concentrations (Zammerilli et al., 2014; Bunch et al., 2014).
- The HAPs are associated with fugitive emissions, but, as they were not detected in significant amounts in the gas stream, their presence in general emissions is considered to be small. The gas treatments applied can reduce the presence of some of these pollutants (AEA, 2012).

The assessment of emissions should consider the complete cycle: emissions from preproduction stage emissions from production stage, transport, distribution and storage, emissions in the end of production and closure. Below, (fugitive) emissions sources are discussed per life cycle stage.

The preproduction stage includes: exploration, site clearing, road construction, drilling, hydraulic fracturing, well completion and waste treatment. The emissions from preproduction stage include: emissions from roads and well-pad construction; from diesel engines and compressors used during drilling. However these emissions are mainly due to combustion operations. Regarding the emission of other air pollutants, (PM, CO,

 

$SO_x$, VOCs, HAPs) their presence is associated mainly to combustion sources and fugitive emissions.

In the production phase, the main sources of emissions are from conventional equipment (e.g. dehydration equipment, pumps and compressors) and leakage from gas distribution pipes. Though, most of the emissions came from the compressors, there are also significant methane emissions from the dehydration operations (NYSDEC, 2011). Since most of the emissions in this stage arise from equipment also used for conventional gas production, there are not significant differences from shale gas and conventional gas production.

In the drilling phase, a temporary drilling rig is brought to the well pad and erected on site. The energy for the drilling operation (and for all ancillary support activities such as well pad lighting and crew housing) is provided by large diesel-fired internal combustion engines. However, alternative fuels for combustion engines can be considered. For instance, the use of gas engines or engines powered from the local electricity grid may also be possible if supplies are available at the site. This step of the process is the same for conventional and unconventional gas wells. Drilling is not a significant source of methane emissions, but the drilling rig engines are a source of combustion-related pollutants such as: nitrogen oxides, carbon monoxide, carbon dioxide and unburned hydrocarbons.

During the phase of the well development process, the wellbore is fractured. Carbon dioxide emissions during the hydraulic fracturing phase are mainly a result of fuel combustion. Typically a well pad will include several wells and, after completion of the first well, gas is likely to be available at the site and the use of gas engines may be possible if gas quality is suitable. Similarly, if a well has to be re-fractured at a later stage, then use of gas engines could be an alternative to diesel-fired engines. Current industry recommended practices for hydraulic fracturing in the US can be found in API, 2009.

Upon well completion of the fracturing step, the fracturing fluid mixture, that returns to the well head, contains a mixture of a liquid (liquid hydrocarbon, produced water and waste water), a solid (sand), and gas (natural gas). In what concern completion combustions (flares), gas contained within flow back may or may not be combustible depending on the composition of inert gases, such as $CO_2$ or $N_2$. When the composition of inert gases is too high it is possible that it will not be economically favourable to recover the gas and it may be necessary to flare the gas until its composition is acceptable. Therefore, it may be necessary the use of a continuous ignition source.

The emissions from storage tanks of produced water can occur due to the volatilization of the gases present in the liquids with the changes in temperature or pressure of the tank.

The closure of unconventional wells is similar to closure of conventional wells. It consists of sealing the well, subsequently removal of the surface material and restores the production site to its previous condition. These operations are called plugging and abandonment of the well. These activities occur at the end of the productive life of a well or when the exploration has been unsuccessful. The objective of this stage is to assure that the well is sealed to prevent leakage to the surface of hydrocarbon and other fluids from the well, or their migration between different formations. The appropriate plugging is critical to avoid potential leaks. Measures to plug and abandon wells have to be frequently undertaken, mainly to make the operating site safe for further use and to prevent pollution release to water and land.

To ensure a stable quality for consumers raw shale gas needs to be processed and treated before it is injected in distribution grids. To meet pipeline, safety, environmental and quality specifications, the following compounds need to be removed: $H_2S$, $SO_2$, $CO_2$, $N_2$, heavy hydrocarbons and water. The processes used depend on the compounds to be removed and their concentrations and also on other properties of gas streams such as temperature, pressure and flow rate. However, treated gas may still present different characteristics depending upon the origin of raw natural gas.

$H_2S$ and $CO_2$ removal is usually accomplished by absorption into aqueous amine solutions. This process is suitable for treating moderate to high concentrations of the acid-gas component for high-pressure gas streams. In some cases, an alternative is the use of physical solvents like methanol, polymer DEGP, or selexol. When $CO_2$ contents are very high, as it happens in gas from $CO_2$ flooded reservoirs, membrane technology may be used initially for great $CO_2$ removals, being followed by another method to reach extremely low levels (Bullin and Krouskop, 2009).

When the gas is saturated with water, dehydration is needed to increase the gas HHV and to prevent pipeline corrosion and solid hydrates formation. A glycol is usually used and its regeneration is achieved by applying heat and reducing the pressure to the water rich glycol. Another option is the use molecular sieves, being the water removed by contact with a solid adsorbent (Bullin and Krouskop, 2009). By this process water contents can be reduced to the extremely low levels needed for cryogenic separation processes.

As a resume, table 1 shows different air pollutants, stage and type of emission source from shale gas.

 

Table 1. Air pollutants and their sources.

| AirPollutants | Stage | Type of Source |
|---|---|---|
| $CO_2$, $NO_x$, $SO_x$ | Pre-production<br>Production | Fossil fuel combustion to provide energy to equipment, such as diesel engines used for drilling, hydraulic fracturing and natural gas compression<br>Flaring operations |
| CO | Pre-production | Incomplete combustion |
| PM | Pre-production | Incomplete combustion<br>Flaring<br>Dust or soil entering the air during pad construction, due to earth movement, and traffic on access roads |
| NMVOC | Pre-production<br>Production<br>End of production and closure | Incomplete combustion<br>Dehydration step of natural gas. It is also associated with fugitive emissions from shale gas extraction, but in small concentrations.<br>Venting of condensate tanks |
| HAP (Acetaldehyde, Acrolein, Benzene, Ethylbenzene, Formaldehyde, n-Hexane, Hydrogensulphide, Methanol, Toluene and Xylene) | Pre-production<br>Production<br>End of production and closure | Fugitive emissions<br>Engine emissions (Formaldehyde) |
| $O_3$ | Pre-production<br>Production | Exploration and production operations - When sunlight reacts with NOx and VOC, it develops excessive ground-level (tropospheric) ozone as a secondary contaminant |
| $CH_4$ | Pre-production<br>Production<br>End of production and closure | Fugitive emissions |

## 2.2 Shale gas GHG balance

MacKay & Stone (2013) stated that GHG emissions from shale gas exploration and production are only a small percentage of the total carbon footprint of shale gas, as the main emissions are due to shale gas combustion for energy generation or transportation, due to the formation of $CO_2$ by oxidation reactions. Likewise, fuel combustion is the dominant source of $CO_2$ emissions for other fossil fuels.

The available knowledge on shale gas carbon footprint arises mostly from U.S. based studies and measurements. The carbon footprint is a way to quantify climate impact. Different greenhouse gases are compared by expressing the emissions of each gas in $CO_2$equivalents based on their Global Warming Potentials. Several studies indicate that the carbon footprint of generating electricity using shale gas as a fuel ranges from 420-

 

850 g $CO_2$-eq/kWh, close to the range reported for conventional gas (480-750 kg $CO_2$-eq/kWh) in the United States. In general, as combustion of gas in power plants generally contributes to about 80% of total GHG emissions, differences in power plant efficiencies are very important regarding differences in carbon footprints. The total production of a well is identified as one of the largest unknowns for the relative assessment of the carbon footprint of shale gas (Hauck and Denier van der Gon, 2015).

In the ongoing debate on greenhouse gas emissions of shale gas and climate impact, the majority of studies (Jiang et al., 2011; Stephenson et al., 2011; Cathles et al., 2012; AEA, 2012; Jenner, 2013; Zammerilli et al., 2014; Bunch et al., 2014) suggest that emissions from power generation using shale gas are lower than those when combusting coal, but higher than those due to conventional gas utilization. Some studies, however, have concluded that the lifecycle of GHG emissions from shale gas may be larger than those from conventional natural gas, oil, or coal viewed over the time scale of 20 years, mostly because of high leakage rates of $CH_4$ during shale gas production (Howarth et al., 2011). It has to be stressed that $CH_4$ is emitted only from gas (not coal or oil), has a higher GWP than $CO_2$ and that depends on the time horizon.

The AEA (Foster and Perks, 2012) conducted a hypothetical life cycle assessment (LCA) for electricity generation from shale gas for Europe. No site-specific data were included due to the early stage of the assessment. Local differences were taken into account via sensitivity analysis. On a life cycle basis, they found carbon footprints of 409-472 g $CO_2$-eq/kWh. A LCA by Stamford and Azapagic (2014) mainly builds on company data from explorative wells in the UK report a median CFP of 460-470 g $CO_2$-eq/kWh, with a total range from 402-1102 g$CO_2$-eq/kWh. These ranges mainly derive from gaps in knowledge.

When not taking the combustion phase in consideration, GHG emissions range between 7g and 27 g $CO_2$-eq per MJ of gas delivered. Most of these emissions arise from losses of gas during production (gas winning from wells) and preproduction (the preparation of the wells). At the same time, these emissions are most uncertain over the gas life cycle because measurements show a wide range. In addition, emission estimates derived bottom-up (from equipment emission factors) or top-down differ and indicate large uncertainties. Top-down assessments are made by measuring around and/or over a large production area and establishing in integrated overall source strength. For comparison with other fossil sources, the fraction of shale gas from a producing well that is lost to the atmosphere is important. A trade-off point is often suggested to be around 3% of well production (Heath et al., 2014).

 

# 3 LEGISLATION

In the United States have been several debates on the issue and "shale gas governance remains a patchwork of rules" (Konschnik, 2014) with regulators facing a changing industry operating tens of thousands of wells across 30 states and EPA requiring GHG emissions reporting from oil and gas wells and green completions of natural gas wells to cut NMVOC and methane. In EU it is important to evaluate whether or not the existing EU Directives /regulations apply to unconventional hydrocarbon extraction.

There are a number of directives designed to prevent or to reduce emissions into the air, water and land and to prevent the generation of waste. These directives are applied in European member states through transposition into national law, the extent of which depends on each member state.

The overview analysis of the EU legal acts identified as relevant to shale gas has shown that there are very few requirements applicable specifically to GHG emissions from shale gas projects.

The EIA Directive (*85/337/EEC on the assessment of the effects of certain public and private projects on the environment codified by 2011/92/EU and amended by the Directive 2014/52/EU)*,the most relevant, sets requirements as to the consideration of climate change effects and air emissions. It requires Member States to ensure that developers supply information, such as a description of estimated air emissions and significant environmental impacts resulting from the project. Furthermore, the Directive provides for competent authorities to give an opinion on the information supplied which, as a minimum, should include a description of the measures envisaged in order to avoid, reduce and if possible, remedy significant adverse side effects.

Despite these requirements, uncertainties remain as to whether Member States would require an EIA for shale gas operations and if so how Member States should implement the EIA, e.g. implementation of the methodology to be used to quantify GHG emission baseline scenarios.

The EIA Directive requires that public and private projects likely to have significant effects on the environment should be subject to an EIA. The main requirement of an EIA is to identify, describe and assess the direct and indirect effects of the project on different factors of the environment. This includes air and climate, and its interactions (Article 3).

The European Commission stresses the need for the precautionary principle to be applied in deciding that an EIA is needed, if the project could not be excluded due to expected significant environmental effects. In case of doubts as to the absence of knowledge on significant effects, an EIA must be carried out according to the precautionary principle.

 

Operations on shale gas are in its beginning in Europe and the scenario at the level of legislation can be rather complex among member states application of the rules.

 

# 4 KNOWLEDGE GAPS

There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly if shale gas shall play a role in Europe's energy mix in the coming decennia.

A debate is still ongoing on the greenhouse gas emissions of shale gas ($CO_2$ and methane) and its energy return on investment compared to other energy sources. Several issues about the specific environmental footprint of shale gas in Europe as a whole as well as in individual member states need to be taken into account. During the M4ShaleGas project main knowledge gaps were identified in order to look for potential solution.

The most important identified knowledge gaps are report below.

- The leakage of methane (rate and volume) is also a question of global climate impact of a potential European shale gas industry. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Leakage during production and in particular (for shale gas) during flowback after hydraulic fracturing is often cited as an important source of uncertainty. This uncertainty is related to the leakage rate and the number of (re-) fracturing events during a well life-time.

- The total production of a well is currently largest unknown, making life cycle emission comparisons with coal and other fossil fuels difficult. At the same time, these emissions are most uncertain over the gas life cycle because measurements show a wide range.

- Emission values require an extensive study to understand the energy and carbon emission of different sources, including sub-surface manipulation, product clean-up and separation and other activities. A careful analysis is required as the emission values will depend on the specific extraction and processing systems devised.

- Well integrity is one of the weak spot in the system, being an important concern in environmental protection issues. Even with the use of best practices, lacks in the methods for the evaluation of the degree of well integrity remain. The results of gas leakage measurements (e.g., surface casing vent flows, noise logs to detect behind-the-casing flow) lead to an extensive gap on the nature of the leakage pathways and gas leakage rates. There is currently no implemented method that adequately provides the needed data (Council of Canadian Academies, 2014).

- There is a lack of robust studies on direct health outcomes caused by the activities of unconventional natural gas development. The literature suggests knowledge gaps and public concern on environmental health issues (Werner et al., 2015).

 

Other issues were also identified as gaps (AEA, 2012; Council of Canadian Academies, 2014):

- Depth and width of specific well in Europe ;
- Number of wells per pad;
- Ranges of production per well by shale formation in Europe;
- Re-fracturing (workover) events on average or for a specific well and effects of the re-fractures on overall production;
- Water needed for fracking, transportation to the well site source and its treatment;
- Information about wells in Europe (do they have sufficient gas pressure to allow application of green completion?);
- Information on chemicals for fracking fluid and amounts;
- Wellbore cementation;
- Processing infrastructure for captured gas on well completion;
- Availability and experience in equipment/technology to capture the gas released on well completion and re-fracturing activity;
- Gas composition at various European plays;
- Lack of transparency of emissions of methane from specific fugitive or vented sources, or from specific activities on the site;
- Environmental and health studies - cumulative effects of development on communities and land and risks of human exposure to chemical substances;
- Absence of important baseline information about environmental conditions in shale gas regions;
- Evaluation of transportation distance of water, materials and gas which influence emissions.

 

# 5 POTENTIAL SOLUTIONS FOR THE KNOWLEDGE GAPS

Shale gas development has had an enormous development in the past two decades and many improvements have been made to reduce the potential of environmental impacts (Costa et al., 2016). However, there has been no extensive investment in research and no real concern in monitoring the environmental and health impacts for the application of best current practices or for the implementation of safety procedures in the case of accidental releases that cannot be reduced to zero. Many of the relevant questions, stated in several reports are hard to answer objectively and scientifically, either for lack of data or due to divergent interpretations of existing data (Council of Canadian Academies, 2014).

The more relevant knowledge gaps are considered to be well integrity, lack of baseline measurements and methane leakage (connected to raw gas compositions), so, these topics will be addressed in more detail.

## 5.1 Well integrity

Well integrity remains the weak spot in the system, being the primary concern in environmental protection issues due to the lack of information, particularly the problem of fluids escaping from incompletely sealed wells. A reliable monitoring program is needed and results should be reported concerning well integrity issues in order to implement mitigation measures.

Well integrity is an issue of national and international importance, but the problem is that implementing characterization and monitoring for each of the shale gas fields has to be a local activity. The extent of the approaches and technologies, to conduct such characterization and monitoring, needs to be locally established. However, the types of characterization and monitoring to be used should be common and established by legislation, national or by the European Commission.

The natural gas leakage due to improperly formed, damaged, or deteriorated cement seals is an extensively recognized, but no yet resolved problem, that continues to challenge engineers. The leaking wells due to improperly placed cement seals, damage from repeated fracturing treatments, or cement deterioration over time, present the potential to create pathways to increase GHG emissions. The well integrity issue is common to all well types, including water and conventional gas or oil wells. So, the oil and gas industry experience has a relevant role in understanding these issues. The long-term impact related to leakage is more relevant for shale gas development than for conventional oil and gas, due to a larger number of wells needed for shale gas extraction and the possible need of repeating the fracturing process and the diverse chemicals used in hydraulic fracturing operations that may contaminate groundwater resources.

 

## 5.2 Baseline measurement

The objective of baselines is that upon implementation of shale gas activities there is clear and transparent information about the atmospheric composition before and after the activities started.

A baseline can be considered as the level or quantity of emissions in a specific scenario where there is a projection of possible activities to be implemented in future. Thus the baseline and the baseline scenario are hypothetical in nature and depend on a number of factors, such as demand for services, availability of various resources to implement the activity, environmental and other policies relevant to the activity to be implemented (Shrestha et al. 2005). There was not found relevant data on the literature about baseline measurements established before the shale gas exploration starts, although the baseline monitoring of water, air and soil should be established at the moment that a potential site is identified. In fact baseline observations of air quality are missing in several regions, where shale gas exploration has taken place or where there is a strong possibility of future shale gas exploration. Up to now, shale gas extraction has proceeded in most cases without sufficient environmental baseline data being collected (e.g., nearby groundwater quality, critical wildlife habitat). This makes it difficult to properly identify, quantify and characterize environmental impacts that may be associated with shale gas development. Different sources may influence air quality such as, cars, trucks, aircraft, biomass boilers and incinerators. Total emissions from the different sources and the distance to the receptor influences air pollution concentrations and air quality impacts.

The implementation of a baseline air monitoring program is imperative to be able to assess the total emissions related with shale gas operations. In fact, any monitoring programme should be designed to provide indicative information on background levels.

A baseline air monitoring program should identify and characterize targeted air pollutants, ($CH_4$, $CO_2$, PM, $NO_x$ most frequently described from monitoring and emission measurements, as well as those expected from hydraulic fracturing activities, and establish ambient air conditions prior to start-up of potential emission sources from shale gas operations. The baseline monitoring should take place before and during well development, production and gas treatment. This allows a "before-during-after" comparison essential to characterize air quality impacts. This program has to be planned for at least one year accounting for ambient variations and the baseline sites have to be located at a spatial scale defined as "urban" or "regional" (NCDENR, 2013).

Baseline data have to be analysed and the results including any change of baseline due to oil and gas development should be used to inform policy makers, improve regulations, and ensure compliance with existing or adjusted legislation. Such study shall cover a timescale permitting both approval and implementation of the baseline monitoring module of the programme prior to the start of drilling operations (Broomfield et al., 2014).

 

## 5.3 Raw shale gas composition

The main concern on the global climate impact of a potential European Shale gas industry in this topic is the leakage of methane, being this compound the main component present in raw shale gas composition. The identification of methane leakage from Shale gas activities is complex due to the existence of several other $CH_4$ sources (e.g. cattle, landfills, wetlands. However, a unique feature of natural gas and shale gas is the presence of other hydrocarbons in the raw gas that are not emitted by other potential $CH_4$ sources. If measured at the same time as $CH_4$ concentrations, the information on the accompanying hydrocarbons can potentially be used as a tracer to distinguish the fossil fuel gas sources from the other $CH_4$ sources. So, the construction of a raw shale gas composition data base could be an instrument to identify leakage during the shale gas operations.

 

# 6 MONITORING STRATEGIES FOR EMISSIONS TO AIR

Emissions that can affect the regional air quality need to be addressed in a monitoring program. It is recommended that the monitoring should not only provide a snapshot of the emissions and concentrations but should consider the changes over time (Jacobs 2014).

The understanding of emissions of toxic air pollutants associated with natural gas production is limited (Allen, 2014). The toxic air pollutants assessment can be performed using the same tools applied to greenhouse gases and air pollutants, including bottom-up and top-down emission inventory assessments, dispersion and photochemical modeling, and life-cycle analyses. Measurements of specific species like formaldehyde, chloroform, carbon tetrachloride, and other halogenated organics (Olaguer, 2012; Rich et al., 2013) were reported. Formaldehyde can be linked to engine emissions (Olaguer, 2012) but the presence of chlorinated organic compounds is not yet understood as these compounds are not expected to be present in oil and natural gas or in their combustion products (Rich et al., 2013). One possibility is that these compounds are part of the fracturing fluid or a reaction product that can be formed during the interaction between the fracturing fluids and the reservoir fluids and surfaces at high temperatures and pressures. Their detection in air samples can be explained by the venting during processes such as flow backs (Allen, 2014).

As previously stated, to assess the impact of shale gas exploration on the atmosphere it is imperative to monitor ambient air quality prior to and during operations. The development of a low cost sampling strategy, suitable for establishing pre-operations baseline data as well as an integrated monitoring program to assess the emissions from shale gas operation sites strategy needs to be settled.

Methane is the main concern because it is a powerful greenhouse gas. For shale gas there are some complications in identifying leakage from its activities is the large amount of other $CH_4$ sources, like cattle, landfills, and wetlands. However, a unique feature of natural gas and shale gas is the presence of other hydrocarbons in the raw gas. An integrated monitoring study of methane emissions may be a suitable mean of distinguishing the contribution of different sources of methane to ambient levels. This subject is linked with the potential presence of other methane source and may also be important in the case of high levels of methane that are of potential concern in the local area. Any future large scale European shale gas production in Europe will occur in a complex landscape with many different sources of methane present such as e.g. animal husbandry, wetlands and landfills. This complicates the monitoring and timely recognition of potential high methane leakage rates during shale gas production. This problem can be solved by using unique tracers such as isotopes or co-emitted (hydrocarbon) species (see e.g. Petron et al., 2012). A good example of applying the isotope ratio technique in Europe to distinguish methane sources was recently published by Röckmann et al. (2016). Isotopic analysis is however expensive and complicated. Based on a review, concerning shale gas, ethane has been identified as a useful tracer for gas leakage as it is nearly always present in natural gas, comprising a significant part of the gas' content of higher hydrocarbons ($C^{2+}$).

Ethane with a photochemical lifetime of several weeks is essentially inert with respect to photochemical loss on time scales of transport from the sources to the location of monitors (1-2 days). In addition it is still reactive enough not to have a large background concentration (like e.g. methane). This makes ethane a suitable tracer. Examples of using ethane for natural gas plume detection are found in e.g. Petron et al., 2012 and Roscioli et al., 2015.

Nevertheless, ethane concentrations across Europe have a seasonal cycle, with the lowest concentrations (around 1000 ppt or lower) in summer and the highest (3000-4000 ppt monthly average) in winter. Concentrations of ethane fluctuate quickly. This may be due to the fluctuation of source strength or changing wind direction. These fluctuations are the most important cause of differences between years; the seasonal pattern is roughly the same for each year. To smooth out the sharp fluctuations a little, weekly averages can be used. This is a compromise between high temporal resolution to be able to identify unexpected elevations quickly and reducing the spikiness of the data. The elevation of ethane concentrations would have to persist for a longer period (e.g. a few months) to be able to say that an elevation is due to a leakage.
All data analysis needs to be carefully interpreted taking, also, into account the meteorological conditions of the site. This may require the implementation of a more intensive monitoring programme (Broomfield et al., 2014).

For new shale gas exploration the baseline measurements of methane needs to be required via permitting process. However if adequate methane baseline have already been carried out no further action is needed. The existence of this data would be useful for all stakeholders because it provides the baseline that sets the context for assessing any future measured data (Broomfield et al., 2014).

In what concerns carbon footprint estimation of shale gas produced in Europe for consumption within Europe, there are at least one useful tool, GHGenius, that is already able to estimate carbon footprints for conventional gas and oil delivered to four European regions (North, Central, Southwest, Southeast). GHGenius is extended with 8 European shale gas plays as production regions and extra emission sources during production such as fugitives from hydraulic fracturing or combustion emissions from horizontal drilling. Results are expressed as $CO_2$-eq. per MJ delivered, but can also be calculated for a kWh of electricity generated.

As to minimize some uncertainty in monitoring programs, the UK Environment Agency provides a series of indications of the possible sources of uncertainty in the Technical Guidance Notes:

- The leakage in the sample handling line and losses to the walls of the sampling system must be quantified;

 

- The typical sources of uncertainty for instrumental methods include lack of linearity, zero drift, span drift, sensitivity to sample volume flow, to atmospheric pressure, to ambient temperature, to electrical voltage. Also, interferences from other gaseous components present in the flue gas, repeatability standard deviation in laboratory at span level, and calibration gas should be considered (Broomfield et al., 2014);
- The temperature and pressure measurements of sample gas volume at the gas meter have associated uncertainty. So, the uncertainty of the water vapour and oxygen concentrations must be included before reporting the result obtained at reference conditions;
- The portable emission monitoring systems can be used to make measurements in a wide variety of applications, such as fugitive emissions. For stack emission monitoring they may be used for indicative purposes. These systems have to comply with the Monitoring Certification Scheme for instruments, monitoring and analytical services;
- The continuous monitoring of emissions to air is desirable where the levels of emissions are environmentally significant and provides improved process control and public assurance. Relevant EC Directives (2000/76/EC, 2001/80/EC) require continuous monitoring, manual sampling and analysis methods;
- Monitoring standards should follow, in order of priority, as given in the IPPC Reference Document on the General Principles of Monitoring, (European Commission, 2003):

    - Comité Européen de Normalisation (CEN);
    - International Organization for Standardization (ISO);
    - National standards;

- Long term sampling programs should be implemented once short term sampling programmes are unlikely to give data representative of general conditions, e.g. meteorological conditions and source variations, which have significant effects on pollutant concentrations that are significantly affected by temporal variability;
- Open-path monitoring methods are the most suitable for fugitive emissions because they are usually emitted relatively close to the ground level, and are often monitored adjacent to the site boundary. However, in some occasions monitoring appreciably above ground level should be performed, e.g. when there is the need to remove the dominance of ground-level emissions in order to assess the impact of elevated releases;
- Methane is classified as a GHG and is also a VOC but not included in the definition of NMVOC (Non-Methane Volatile Organic Compounds) as used in air quality reporting. There are two published CEN standards for measuring methane:

 

- o Manual method - EN ISO 25139:2011 – based on samples collection in an inert bag or canister, followed by analysis using gas chromatography in a laboratory;
- o Automated method - EN ISO 25140:2010 – uses an FID (Flame Ionization Detector) fitted with a catalytic converter which removes all organic compounds in the sample gas, except methane. Portable FID are also available for applications in fugitive emissions monitoring. However this simpler, unheated and portable FID have not the same accuracy and precision as the more complex and heated FID.

As a synthesis, some recommendations about monitoring can be made:

- Long-term air monitoring, increase the frequency of sampling, and develop a complete list of contaminants associated with oil and gas development;
- Conduct short-term (acute) air monitoring by collecting 1-hour air samples in order to evaluate health risks posed by intermittent peak exposures;
- Assess source distribution including sources other than the oil and gas operations, such as stationary industrial sources and mobile traffic sources;
- Management of the risk posed by potential exposures to air toxics as a result of increase in oil and gas development activities (e.g. additional monitoring, sample analysis, and action as appropriate);
- Operators should monitor potential leakages of methane or other emissions to the atmosphere before, during and after shale gas operations;
- Data collected by operators should be submitted to the appropriate regulator. These data could inform wider assessments, such as the carbon footprint of shale gas extraction;
- An Environmental Risk Assessment should be mandatory for all shale gas operations, involving the participation of local communities at the earliest possible opportunity and assess risks across the entire lifecycle of shale gas extraction (including the disposal of wastes and well abandonment).

# 7 EMISSION REDUCTION TECHNICS

Minimising the impact of shale gas exploration on the atmosphere requires the prevention and minimization of greenhouse gases and toxic chemicals emissions and monitoring of ambient air quality prior to and during operations, by systematically identifying emission sources of all sizes. A low-cost sampling strategy, suitable for establishing pre-fracturing baseline data as well as providing an integrated assessment of emissions from shale gas operation sites, should be developed.

Mitigation options are available for most shale gas operations although they are not always implemented (yet) due to cost constraints. The most prominent are Reduced Emission or Green Completions (REC) which are mainly applied to GHG's. In REC, the fugitive gas is captured and used instead of vented to the atmosphere. A second option is flaring of the gas, which reduces methane emissions by combustion to $CO_2$.

As can be seen from the American experiences, introduction of REC and, in general, more legislation or "good practices", such as avoiding operating of pneumatic valves on shale gas, has resulted in a decrease (0.2 – 4%) in the leakage rates in recent years (2014-2015) when compared to earlier shale gas exploration.

For the Netherlands, a report by TNO for Dutch ministry of Economic Affairs (Heege, et al., 2014) concludes that technologies for emission reductions, such as flaring or capture and reuse are available, but not always cost-effective. If no norms apply, implementation of such techniques becomes a cost consideration. The report did not investigate specific individual techniques, but the authors state that no life cycle stages were identified where large leakages are unavoidable. Large leakages still do exist, because the spread in emissions as observed in the U.S. is very large with many low emitting wells and few wells with very high emissions. Preventing of venting during production is identified as important contributor to emissions reductions. AEA (Foster and Perks, 2012) summarizes best available techniques for GHG emission reductions. For site-selection these mainly include efficient use of resources and transport minimization.

For well drilling, next to efficiency and safety, alternative fuels (gas or electricity) for combustion engines could be considered. This is also true for (in particular re-) fracturing when gas is available as fuel. Green or reduced emissions completions (REC) entails the separation of the solid (sand), fluid (water) and gas (natural gas) phases of the flow back to be able to process and sell the otherwise vented gas. If not possible (due to low pressure or high concentrations of inert gasses) or not compulsory, gas could be flared instead of vented. EPA assumes that for the U.S. 90% of the currently emitted gas could be recovered this way. Emissions from storage tanks for produced water (from volatilization of the gas in the liquids with temperature or pressure changes) during production can be reduced using vapour recovery units (about 95% reduction), the alternative again is combustion.

Mitigation options can be summarized by process phase (Table 2).

 

Table 2. Mitigation options by process phase.

| Phase | Mitigation option |
|---|---|
| **Site preparation** | Drilling as many wells as possible using one rig move;<br>Optimising the well spacing for efficient recovery of natural gas;<br>Planning for efficient rig and fracturing equipment moves from one pad to another;<br>Ensuring that personnel and equipment can be sourced locally;<br>Identifying sources or materials locally (including water and sand used in the hydraulic fracturing process);<br>Identifying local facilities to recycle and dispose of waste products;<br>Planning to reduce the number of vehicle journeys and using efficient transport engines. |
| **Drilling phase** | Three-way catalytic oxidizers may be used on drilling rig engines (reduce non-$CO_2$ emissions);<br>Appropriate well design and supervision, including choice and depth of casings, seals and monitoring. |
| **Hydraulic fracturing** | REC and early warning monitoring during production and end-of-life (MacKay and Stone, 2013).<br>Capture emissions from completions; liquid unloading or venting from pneumatic devices and optimization of plunger lifts (GAO, 2010). |
| **Well completion and flow back** | REC or green completions (AEA, 2012):<br>Capture of fugitive gas and its use, instead of venting to the atmosphere;<br>Separation of the three phases of the flow back;<br>Temporary installation of equipment designed to handle the high initial flow of water, sand, and gas. |
| **Completion combustions (flares)** | It may be necessary the use of a continuous ignition source. Completion combustion devices are, already, used to control VOC in many industrial applications. They can be as simple as a pipe with a basic ignition source. These devices (pit flares) are not controlled and it is not possible to test or monitor its efficiency (O'Sullivan and Paltsev, 2012). The self-sustained flaring may not be possible due to variable conditions during flow back, so a continuous supply of gas may not be possible. Furthermore the exposed flame may expose a fire hazard or other impacts in some situations, for example dry windy conditions and proximity to nearby occupied buildings. However such issues may be mitigated by appropriate management techniques including location of the well pad and design and location of the flare. |
| **Production, transport, distribution and storage** | Most of the emissions come from the compressors where reductions with the improvement of the technologies applied the conventional equipment can be useful.<br>For pneumatic devices such as controllers in separators, storage tanks and dehydrators, high bleeding can be replaced by low bleeding and better maintenance, with an effectiveness of about 90% (but not everywhere possible).<br>The use of desiccant (not glycol) dehydrators for dehydration may reduce drying emissions.<br>Better reciprocating compressors (with replacement of rod packaging system) instead of centrifugal compressors (with dry seals).<br>The reduction of emissions due to leakage from gas distribution pipes will involve improvements in the gas supply infrastructure off-site.<br>Leak reduction via leak detection and reduction programs can have efficiencies of 45-96%.<br>The emissions from storage tanks of produced water can be reduced by, approximately, 95% using vapour recovery units. |

 

The best available techniques approach for management of methane emissions from unconventional gas exploration and production should include both technological solutions and management techniques.

In natural gas refining, best available techniques include a range of measures which can help an operator to avoid and mitigate emissions. These include (AEA, 2012):

- Environmental Management System: this can provide a focus for monitoring performance, benchmarking, continuous improvement plans, energy management, emissions assessment and reporting to stakeholders. An externally accredited system provides credibility and assurance that the processes and plans are being applied;
- Application of good practice for maintenance and cleaning;
- Development of environmental awareness;
- Implementation of monitoring systems, including Leak Detection and Repair.

An efficient framework for managing the risks should include five different elements (Council of Canadian Academies, 2014):

- Technologies to develop and produce shale gas - Equipment and products must be adequately designed, installed according with specifications, tested and maintained for reliability;
- Management systems to control the risks to the environment and public health - The safety management of equipment and processes associated with the development and operation of shale gas sites must be comprehensive and precise;
- Effective regulatory system - Rules to run the development of shale gas must be based on appropriate scientific recommendations, regulations with strong performance monitoring, independent inspection, and enforcement;
- Regional planning – Local and regional environmental conditions, including existing land uses and environmental risks, have to be taken into account in the drilling and development plans, for cumulative impacts to be assessed;
- Involvement of local citizens and stakeholders - Public involvement is needed, not only to inform the local residents of development achieved, but also to receive their contribution on what values should be protected, to reflect their concerns, and to earn their trust. The environmental data should be available to all stakeholders and provided by a trustable source.

It is fundamental to supply credible, science based information to develop and apply regulations. So these elements would need to be supported by environmental monitoring programs.

 

Other management areas relevant to GHG emissions from unconventional gas include:

- Consider transport distances, access roadway provision and compression / processing emission options for sitting of well pads;
- Availability of gas for drilling technology;
- Avoiding constraints on deploying on flare or capture technology for well-completion;
- Transport of recovered gas from completion activities to processing facilities.

As a resume, table 3 shows mitigation measures per emission source from ICF International (2014).

Table 3. Mitigation measures form ICF International and GAO.

| Rank | Emission Source | Mitigation technology | Specific to Unconventional Gas Wells? |
|---|---|---|---|
| **1** | Gas well venting/flaring during well completions with hydraulic fracturing.<br>Gas well venting during well workovers with hydraulic fracturing. | Reduced Emission Completions (REC) | Yes |
| **2** | Equipment leaks from valves, connectors, open ended lines, pressure relief valves, pumps, flanges, and other equipment leak sources (such as instruments, loading arms, stuffing boxes, compressor seals, dump lever arms, and breather caps). | Conducting Directed Inspection and Maintenance | No |
| **3** | Natural gas driven pneumatic pump venting | Convert Natural Gas-Driven Chemical Pumps to Instrument Air Driven or to Electrical Pumps | No |
| **4** | Well venting for liquids unloading | Installing Plunger Lifts Systems in Gas Wells | No |
| **5** | Dehydrator vents | Optimise Glycol Circulation and Install Flash Tank Separators in Glycol Dehydrators | No |

 

# 8 FINAL REMARKS

ICF International (2014) highlights the importance of legislation as different approaches in different U.S. states lead to different emissions. Details of U.S. legislation and up-stream gas cycle emissions are discussed by Bradbury et al. (2013).

Additionally, they highlight the importance of reporting for policy development, but also the openness of reporting (of venting and flaring ratios) to enable peer and public pressure. In detail, they derive the following recommendations for a European shale gas policy:

- Communication and sound research for perception and risk mitigation;
- Continuous monitoring over all stages;
- Results openly disclosed;
- Development of requirements for proper equipment usage;
- Clearly define where flaring/venting is allowed in extraordinary cases;
- Play-based regulations and attention for cumulative risks;
- Flexible enough for play difference (e.g. low pressure);
- Coordination throughout regulatory layers.

They derive preferred EU policy measures:

- Voluntary approach to reduced on-site fugitive emissions;
- Shale gas included in Industrial Emissions Directive (IED);
- Shale gas included in Environmental Impact Assessment (EIA) directive;
- Specific framework for shale gas.

The review done in the framework of M4ShaleGas project suggests the existence of knowledge gaps and public concern on environmental health issues related to unconventional gas development activities. Also, it is pointed out the lack of evidence on the direct health outcomes caused by these activities. Anyway the absence of evidence does not mean evidence of absence. The research on this field should be intensified to improve the understanding of potential health impacts, including baseline monitoring and studies to identify, and predict the environmental health impacts. Also, direct and clear public health assessments should be included in the Environmental Impact Assessment previous to the approval of a gas development project.

The following scientific recommendations tend to minimize emissions to air associated with shale gas operations.

Table 4 presents some recommendations and corresponding advantages to minimize the emissions to air and to monitor the emissions to air associated with shale gas operations. These points were addressed in detail in previous M4ShaleGas project reports (Costa et al. 2015, Costa and Picado, 2016, Costa et al. 2016, Hauck and Denier van der Gon, 2015).

 

Table 4. Recommendations and advantages to minimize the emissions to air.

| Topic | Recommendations | Advantages |
|---|---|---|
| Pre-production | Ensuring that personnel and equipment can be sourced locally | Reduction of GHG emissions from pre-production stage<br>- Combustion sources: bull dozers, graders, loaders, trucks used to deliver equipment and materials (e.g. water, sand) to the site and clearing equipment, powered by diesel engines;<br>- Non-combustion sources: fugitive dust/particulate. |
| | Identifying sources or materials locally (including water and sand used in the hydraulic fracturing process) | |
| | Identifying local facilities to recycle, and dispose of waste products | |
| | Planning to reduce the number of vehicle journeys | |
| | Using efficient transport engines | |
| | Using alternative fuels for combustion engines (gas engines or electric engines) | |
| | Recycling of flow back water, using more tanks (rather than ponds) to store waste water and improve pond designs | |
| | Assess the quantity of water that will be needed for fracking and how will it be transported to the well site and from which source | |
| | Use of gas engines or local electric grid in the hydraulic fracturing and re-fractured (if needed) operations | Reduce GHG combustion emissions. |
| | Placing more wells per pad and drilling longer laterals resulting in less pads and roads | |
| | Assess the realistic ranges of production per well by shale formation in Europe | Reduce GHG combustion emissions. |
| | Assess the depth and width of specific well in Europe | |
| | Use of reduced emission completions (REC), or green completions to control methane emissions from the flow back / well completion step | Reduction of the release of the methane, within the natural gas, into the atmosphere. |
| Production | Use of vapour recovery units (VRU) and flares | Significant reduction of emissions from storage tanks. |
| | Replacing glycol dehydrators with desiccant dehydrators | Reduction of methane and BTEX (benzene, toluene, ethylbenzene, and xylene) emissions. |
| | Replacing high-bleed pneumatics devices by low-bleed pneumatics devices | Effectiveness reduction of methane emission. |
| | Implementation of a Leak Detection and Repair (LDAR) programme (Include: identifying component; Leak definition; Monitoring components; Repairing components; Record keeping) | Reduction in the frequency of leaks and promptness in the leaks repair. |
| Monitoring | Implement a monitoring baseline program prior to shale gas development (to promote the set-up of a data base for Europe) | Establish ambient air conditions prior to start-up of potential emission sources from operations |
| | Monitor gas compositions at different European scenarios | Identify gas leakages based on the shale gas components. |
| | Assess the potential leakage rates and model methane and ethane concentrations, determining the elevations | Allow to predict possible changes in methane and ethane concentrations in the atmosphere |
| | Operators should be made mandatory to monitor potential leakages of methane or other emissions to the atmosphere before, during and after shale gas operations | These data could inform wider assessments, such as a location specific the carbon footprint of |

 

| | | |
|---|---|---|
| | Data collected by operators should be submitted to the appropriate regulator | shale gas extraction. |
| | Assess source distribution including sources other than the oil and gas operations, such as stationary industrial sources and mobile traffic sources | Distinguish the shale gas methane from other sources. |
| | Use tracers for shale gas methane detection (ethane, possibly in combination with propane) | |
| | Long-term air monitoring, increasing the frequency of sampling | Elaborate a complete list of contaminants associated with oil and gas development. |
| | Conduct short-term (acute) air monitoring by collecting 1-hour air samples | Allows the better evaluation of health risks posed by intermittent peak exposures. |

 

# 9 ABBREVIATIONS AND SYMBOLS

**Abbreviations**

$CH_4$ - Methane
$CO_2$ – Carbon Dioxide
EIA - Environmental Impact Assessment
EPA Environmental Protection Agency
HAP- Hazardous air pollutants
$N_2$ – Nitrogen
NAAQS - Air quality standards
NG – Natural Gas
$NO_x$- Nitrogen oxides
NMVOC – Non-Methane Volatile organic compounds
PM - Particulate matter
$SO_x$ – Sulphur oxides
TCEQ - Texas Commission on Environmental Quality
UK – United Kindom
USA – United States of America
VOC - Volatile organic compounds

**Symbols**

$CO_2Eq$ - carbon dioxide equivalent
Gg - gigagram
g/kWh - grams per kilowatt-hour
MMT - millions of metric tons

# 10 REFERENCES

ACOLA (Australian Council of Learned Academies), 2013.Engineering Energy: Unconventional Gas Production. Melbourne, Australia: ACOLA.

AEA, 2012. Climate impact of potential shale gas production in the EU – Final Report. AEA/ED57412/Issue 2 34.

Allen DT, 2014. Atmospheric Emissions and Air Quality Impacts from Natural Gas Production and Use. Annu. Rev. Chem. Biomol. Eng. 5:55-75.

API (American Petroleum Institute), 2009. Hydraulic Fracturing Operation – Well Construction and Integrity Guidelines. Washington (DC): API.

Bradbury, J., Obeiter, M., Draucker, L., Wang, W., Stevens, A., 2013.Clearing the air: reducing upstream greenhouse gas emissions from U.S. natural gas systems.Working paper, 58.

Broderick, J., Anderson, K., Wood, R., Gilbert, P., Sharmina, M., 2011. Shale gas: an updated assessment of environmental and climate change impacts. A report commissioned by The Co-operative and undertaken by researchers at the Tyndall Center, University of Manchester.

Broomfield M., Donovan B., Leonard A., Considerations for quantifying fugitive methane releases from shale gas operations, Environmental agency (EA), 2014.

Bullin K., Krouskop P., Composition Variety Complicates Processing Plans for US. Shale Gas, Oil and Gas Journal, 107, 50-55, 2009.

Bunch AG, Perry CS, Abraham L, Wikoff DS, Tachovsky JA, Hixon JG, et al., 2014.Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. Sci Total Environ.468–469: 832–42.

Cathles III L. M., Brown L., Taam M., Hunter A., 2012.A commentary on “The greenhouse-gas footprint of natural gas in shale formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea.Climatic Change 113:525–535.

Costa P, Pinto F, Picado A, Catarino J, Pereira Z, Ramalho E. 2015. Deliverable 14.1. Review of gas emissions to air related to shale gas operations. M4ShaleGas project.

Costa P. and Picado, A. 2016. Deliverable 16.2 - Integrated review of emissions to air and $CO_2$ footprint. M4ShaleGas project.

Costa, P. Pinto, F., Picado, A., Catarino, J., Denier van der Gon, H., Visschedijk, A., Segers, A. 2016. Deliverable 14.2. Report on methodologies for establishing concentration base-lines and raw gas compositions in Europe. M4ShaleGas project.

EIA 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. US Energy Information Agency EIA, U.S. Department of Energy, Washington DC, United States.

EN ISO 25139:2011 - Stationary source emissions -- Manual method for the determination of the methane concentration using gas chromatography

EN ISO 25140:2010 - Stationary source emissions - Automatic method for the determination of the methane concentration using flame ionisation detection (FID)

 

European Commission, Integrated Pollution Prevention and Control (IPPC) Reference Document on the General Principles of Monitoring July 2003.

Foster, D., Perks, J., 2012. Climate Impact of potential shale gas production in the EU.Final Report for the European Commission DG CLIMA.AEA/R/ED57412, 158.

GAO (2010) Federal oil and gas leases. Opportunities exist to capture vented and flared natural gas, which would increase Royal Payments and reduce greenhouse gases. Report to Congressional Requesters. United States Government Accountability Office. GAO 11-34, 57.

Hauck, M., Denier van der Gon, H., 2015. Deliverable 15.2. Review report on carbon footprint from shale gas exploitation with identified gaps in knowledge. M4ShaleGas - Measuring, monitoring, mitigating managing the environmental impact of shale gas.

Heath, G.A., O'Donoughue, P., Arent, D.J., Bazilian, M., 2014.Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation.Proc. Natl. Acad. Sci. U. S. A. 111, E3167-E3176.

Horwarth, RW, Santoro, R, Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim. Change. 106, 679-690.

Howarth R., Ingraffea A., Engelder T., 2011. Natural gas: should fracking stop? Nature 477 271–5.

ICF International, 2014. Mitigation of climate impacts of possible future shale gas extraction in the EU: available technologies, best practices and options for policy makers, Final report.

IPCC, 2011. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, p1075.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K.Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge Uni-versity Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jacobs, Air Quality: Baseline, Prepared for the Airports Commission November 2014.

Jenner S., Lamadrid A. J., 2013.Shale gas vs. coal: Policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States, Energy Policy (53), 442-453.

Jiang M., Griffin W. M., Hendrickson C., et al., 2011. Life cycle greenhouse gas emissions of Marcellus shale gas. Environ. Res. Lett. 6.

Konschnik, K., Boling, M., 2014 Shale Gas Development: A Smart Regulation Framework. Environ. Sci. Technol., 2014, 48 (15), pp 8404–8416 DOI: 10.1021/es405377u.

MacKay, D., Stone, T., 2013. Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use. URN 13D/230.

NCDENR, 2013. Project Plan for Baseline Ambient Air Monitoring near Potential Shale Gas Development Zonesin Lee County, NC, Department of Environment and Natural Resources Division of Air Quality.

 

NEB (National Energy Board), 2013. Filing Requirements for Onshore Drilling Operations Involving Hydraulic Fracturing. Calgary (AB): NEB.

NYSDEC, 2011.Supplemental generic environmental impact statement on the oil, gas and solution mining regulatory programme: Well permit issuance for horizontal drilling and high-volume fracturing to develop the Marcellus shale and other low-permeability gas reservoirs, New York State Department of Environmental Conservation.

O'Sullivan, F., Paltsev, S., 2012. Shale gas production: Potential versus actual green-house gas emissions. Environmental Research Letters. 7.

Olaguer EP. 2012. The potential near-source ozone impacts of upstream oil and gas industry emissions. J. Air Waste Manag. Assoc. 62:966–77 71.

Petron G., Frost G., Miller B. T., Hirsch A. I., Montzka S. A., Karion A., Hall B., 2012. Hydrocarbon emissions characterization in the Colorado Front Range – a pilot study. Journal of Geophysical Research: Atmospheres 117 (D4) D04304, doi:10.1029/2011JD016360, 2012.

Rich A, Grover JP, Sattler ML, 2013. An exploratory study of air emissions associated with shale gas development and production in the Barnett Shale. J. Air Waste Manag. Assoc. 64:61–72.

Robinson A., 2014. Health impact assessment of shale gas extraction, National Institutes of Health, NCBI Bookself, National Institutes of Health.

Röckmann et al., 2016. In situ observations of the isotopic composition of methane at the Cabauw tall tower site, Atmos. Chem. Phys., 16, 10469–1048.

Roscioli, J. R., Yacovitch, T. I., Floerchinger, C., Mitchell, A. L., Tkacik, D. S., Subramanian, R., Martinez, D. M., Vaughn, T. L., Williams, L., Zimmerle, D., Robinson, A. L., Herndon, S. C., and Marchese, A. J. 2015. Measurements of methane emissions from natural gas gathering facilities and processing plants: measurement methods, Atmos. Meas. Tech., 8, 2017-2035, doi:10.5194/amt-8-2017-2015

SEAB (Secretary of Energy Advisory Board), 2011. Shale Gas Production Subcommittee Second Ninety Day Report. Washington (DC): U.S. Department of Energy.

Shrestha R. M., Sharma, S., Timilsina, G. R., Kumar S. 2005. Baseline Methodologies For Clean Development Mechanism Projects, A guidebook UNEP Risø Center, Denmark Editor Myung-Kyoon Lee, Keimyung University, Korea.

Stamford, L., Azapagic, A., 2014. Life cycle environmental impacts of UK shale gas. Appl. Energy. 134, 506-518.

Stephenson T., Valle. J. E., Riera-Palon X., 2011.Modelling the relative GHG emissions of conventional and shale gas production. Environ. Sci. Tech. 45: 10757–10764.

Tollefson J., 2013. Nature News: Methane leaks erode green credentials of natural gas. Nature, 493 (7430), 12.

U.S. Department of Energy - Energy information administration office of integrated analysis and forecasting (2013) Annual Energy Outlook 2013 with Projections to 2040.

U.S. Department of Energy - Office of Fossil Energy and National Energy Technology Laboratory, 2009. Modern Shale Gas Development in the United States: A Primer.

 

Werner A K, Vink S, Watt K, Jagals P., 2015. Environmental health impacts of unconventional natural gas development: A review of the current strength of evidence (Review), Science of the Total Environment 505:1127–1141.

Zammerilli A., Murray R., David T., Littlefield J., 2014. Environmental impacts of unconventional natural gas development and production, prepared by Energy Sector Planning and Analysis (ESPA) for the United States Department of Energy (DOE), National Energy Technology Laboratory (NETL).

 