Project Acronym and Title:

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

INTEGRATED REVIEW OF EMISSIONS TO AIR AND CO_2 FOOTPRINT

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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

This report aims to integrate the recent delivered reports under WP3 on emissions to air and carbon footprint of shale gas operations. It focuses on the main emission causes, possible reduction options, knowledge gaps and ways to fill these gaps. The main current concern are the greenhouse gases (CH_4, CO_2) but more attention should be given to the air pollutant emissions in the future. The different sources and types of emissions (e.g., CH_4, NMVOC, NO_x, SO_x, PM, benzene, HPA, O_3) associated with the various phases of shale gas production were identified and summarized. The evaluation of the different shale gas-related emissions takes 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.
The most significant sources of emissions of GHG and other air pollutants during the pre-production phase are well completion and gas treatment, but also emissions from combustion sources (particulate matter, nitrogen oxides and hazardous air pollutants, and CO_2). The carbon foot print is a way to quantify climate impact. Different greenhouse gases were 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. With respect to emissions to air, mitigation options are available for most shale gas operations. The most prominent Reduced Emission or Green Completions option is the capture (and use) of fugitive gas, instead of venting to the atmosphere. Another option is flaring of the gas, which reduces methane emissions by combustion, releasing CO_2. The main knowledge gaps were identified and a general conclusion is that well integrity remains the weak spot in the system, being the primary concern in environmental protection issues. More attention needs to be given to this issue.

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

1.2 Study objectives for this report

In this report, different sources and types of emissions were identified and reviewed. Its main objective is to provide recommendations for reducing the emissions to air and mitigating the CO_2 footprint of shale gas operations in Europe. The pre-production and production emissions were assessed. Pre-production related emissions to air include: emissions from roads and well-pad construction and from diesel engines and compressors used during drilling. The evaluation of the greenhouse gas (GHG) balance of shale gas takes into account all GHG air emissions related to the production, transportation and end-use of shale gas. Based on the on-going work in USA and Canada, possible emission reduction techniques were discussed and knowledge gaps identified.

1.3 Aims of this report

This report aims at assessing the impact of gas emissions related to shale gas exploration and exploitation in Europe. It presents a review of the different sources and types of emissions associated with the different phases of shale gas production.

The overall objective of this report is to give an overview on the current technical-scientific knowledge base of the possible contribution of shale gas production to gaseous emissions. The available information and international experiences from both North America as well as from Europe is reviewed to establish the CO_2 footprint during different shale gas exploitation phases (mainly exploration drilling, production, transportation, end-use, end of exploration and well closure). GHG emissions resulting directly from shale gas operations are estimated for vented emissions, emissions from combustion of fossil fuels on site and fugitive emissions. This report aims to give a concise overview of the insights of these studies, but will focus on lessons and knowledge gaps for Europe.

1.4 Structure of the report

This report is divided in five chapters. The first one is an introductory chapter where the objectives of the M4ShaleGas and of this report are presented. The type of emissions and different sources of shale gas activities are addressed in Chapter 2. Chapter 3 reports the best available techniques for reducing 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.

2 TYPES OF EMISSIONS AND DIFFERENT SOURCES

The emissions to air from shale gas production has been widely studied since 2010 (e.g., Howarth et al. (2011), Skone et al. (2011), Jiang et al.(2011), Burnham et al. (2012), Zammerilli et al. (2014), Bunch et al. (2014), Robinson (2014). However, these studies present a large variation in the estimated environment impacts of shale gas, due to differences in methodology and data assumptions. Shale gas production activities can contribute to air pollution and may have a negative impact on local air quality. The greenhouse gases (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. Presently, the main concern are the GHG emissions, but more attention should be given to other types of emissions that may also be caused by shale gas production.

2.1 Emissions to air

In addition to the GHGs methane (CH_4) and carbon dioxide (CO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) can be released due to fugitive emissions from shale gas production. In the literature the emissions of six air pollutants are often discussed, whose regional ambient air concentration levels are regulated by the Environmental Protection Agency (EPA). These pollutants are: ozone, particulate matter (PM), carbon monoxide (CO), NO_x, sulphur oxides (SO_x), and lead. The emissions of VOCs (include aromatic hydrocarbons, halogenated compounds, aldehydes, alcohols, and glycols) and HAPs (term used by US EPA to cover toxic air pollutants that "cause or may cause cancer or other serious health effects, or adverse environmental and ecological effects") are also addressed (ICF International, 2014). The list of HAPs compounds include: acetaldehyde, acrolein, benzene, ethylbenzene, formaldehyde, n-hexane, hydrogen sulphide, methanol, toluene and xylene. The compounds, included in this list, that are considered relevant in shale gas emissions, are stated to be benzene, toluene, ethylbenzene, and xylenes.

The main air pollutants and their sources are discussed below:

- CO_2, SO_x and NO_x are the main emissions during fossil fuel combustion to provide energy to equipments, 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 CO_2, 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)).
- The reaction of NO_x and VOCs in the presence of sunlight can produce Ozone (O_3), which can be associated with exploration and production operations (Robinson (2014)).

- 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)).
- The main worry of vented (for example due to the release of gases during flowback) and fugitive emissions, is the CH_4, which is the principal component of natural gas. CH_4 may be released as a fugitive emission from gas processing equipment (such as pneumatic controls, valves, well heads and others) or it may escape into ground water due to fracking activities.
- 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 to the gas can reduce the presence of some of these pollutants (AEA (2012)).

Concerning GHG 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 utilisation. 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). So, the emission values presented by several authors, 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.

The potential climate impact of shale gas can only be evaluated by analysing all the emissions data associated with the life cycle of shale gas (i.e. from exploration to end-use, including end of exploration and well closure). However, this data are not always accessible and has a high degree of uncertainty. Also, the main studies assess only the GHG emissions.

The assessment of emissions should consider the complete cycle: (1) Emissions from Pre-production Stage, (2) Emissions from Production Stage, transport, distribution and storage, (3) Emissions in the end of production and closure.

The preproduction stage includes: exploration, site clearing, road construction, drilling, hydraulic fracturing, well completion and waste treatment. The GHG emissions from pre-production 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, there are two main sources of emissions, 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.

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.

2.2 Carbon footprint assessment

Greenhouse gas emissions to the atmosphere are critical to assess climate aspects of shale gas exploration and exploitation. The total of greenhouse gas emissions over a products life cycle, e.g. from well exploration to electricity generation from gas, is often referred to as carbon footprint. To sum all different gases contributing to climate change, a common scale should be used. Different types of GHGs are usually compared using a conversion factor called global-warming potential (GWP). GWP, which is calculated regularly by the Intergovernmental Panel on Climate Change (IPCC), compares the average impact of other gases and aerosols on radiative forcing (i.e., warming potential) with that of CO_2, over a defined period of time. CO_2 has a GWP of 1 by definition.

As lifetimes of different GHG in the atmosphere are different, the choice of the time horizon is important for the assessment of the relative GWP. It is most common to use a 100 year time horizon, but the IPCC also provides GWPs for 20 and 500 years. Since CH_4 has a much shorter lifetime than CO_2, its relative importance increases on the short time horizon (GWP 20) and decreases on the longer time horizons (GWP 100 and GWP 500). To make an integrated assessment of the overall climate impact, emissions of GHG (CH_4 and CO_2) released during production and shale gas use are expressed in CO_2 equivalent (CO_2-eq) emissions based on GWP 100.

Available knowledge on shale gas carbon footprint employed life cycle assessment (LCA) to estimate the carbon footprint of electricity generation using shale gas in the United States. In LCA, carbon footprints are calculated per unit of final product (MJ gas delivered or kWh electricity generated). Most studies distinguish the following life cycle stages:

production/extraction, processing, transmission and combustion in power plants. The contribution of gas combustion in power plants is, in general, about 80% of total GHG emissions. Thus, differences in power plant efficiencies (combined cycle vs. single cycle) are very important regarding differences in carbon footprints. A study by Foster and Perks (2012) compared results from different studies, showing that carbon footprints are generally around 60 - 70 g CO_2-eq/MJ and are mostly generated by combustion. For combined cycle power plants the total carbon footprints for electricity generation are lower. When the combustion phase is not considered, GHG emissions are about 27 g CO_2-eq/MJ of gas delivered. Most of these emissions are due to losses of gas during production and preproduction. These emissions are most uncertain over the gas life cycle, because measurements show a wide range of values.

EUR (expected ultimate recovery) is an estimation of the expected ultimate recovery of oil or gas from a producing well. Several methods are used to estimate an EUR, but are dependent on the purpose of the study (Cook (2005)).The EUR (or production rate and well lifetime), is an indicator of the total production of a gas well, and reliably identified as influential for total carbon footprint per MJ gas delivered. The total production influences the amount of GHG attributed to each output (the higher the production, the lower the GHG emission per unit output), once all emissions, occurring over the life cycle (regularly or incidentally), are attributed to the final product. Additionally, the EUR is generally estimated with uncertainty.

At the moment, only two attempts to make a CFP assessment for Europe are published. In 2012, Foster and Perks, presented a study, largely based on US data, where a hypothetical life cycle assessment, including sensitivity assessment (to account for the uncertainties when extrapolating between continents) is presented. A LCA performed by Stamford & Azapagic, in 2014, used mainly company data from explorative wells in UK. Both studies report an average CFP of 460/470 g CO_2-eq/ kWh, with a total range of 402-1102 g CO_2-eq/kWh. This broad range is, probably, due to existing gaps in knowledge.

3 EMISSION REDUCTION TECHNIQUES

AEA (Foster and Perks, 2012) summarizes best available techniques for GHG emission reductions. The most significant difference in GHG emissions from shale gas production compared to conventional gas production arises in the pre-production phase. Mitigation options are available for most shale gas operations although they are not always implemented due to economic constraints.

The most prominent are the Reduced Emission Completions (REC), also known as green completions, where 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 conversion to CO_2 through combustion. 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 in the leakage rates in recent years (2014-2015) when compared to earlier shale gas exploration. Nevertheless, the variation between different plays remains large (0.2 – 4%) and is still not well understood.

3.1 By process phase

3.1.1 Site preparation

For site-selection the main mitigation options include efficient use of resources and transport minimization. Appropriate site selection and preparation may reduce GHG emissions, and in particular CO_2, from combustion emissions by reducing fuel consumption. Preparation of the well pad requires resources, for example to level the site, prepare well cellars and install impermeable membranes. Use of existing roads, water resources and other infrastructure can minimise such work and the associated emissions from their construction. Provision of on-site storage of water and hydraulic fracturing fluids is often achieved through use of mobile tanks but some sites install reservoirs or lagoons for water and drilling/hydraulic fracturing fluids, but these have to be removed and land restored on completion. Use of transportable tanks will generally require less site preparation, but this will depend on the site and availability of water, quantity of generated materials and treatment facilities. Consideration of drilling and well completion requirements during site selection will avoid or minimise situations where combustion or recovery of flow back gas (or accidental releases) might be constrained by proximity to buildings or other amenity space.

The following measures could be included to reduce these emissions: drilling as many wells as possible using one rig move; optimising the well spacing for efficient recovery of natural gas; planning for efficient rig and fracturing equipment moves from one pad to another; ensuring that personnel and equipment can be sourced locally; 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 and using efficient transport engines.

3.1.2 Drilling

During 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. Three-way catalytic oxidizers may be used on drilling rig engines to reduce non-CO_2 emissions. Appropriate well design and supervision, including choice and depth of casings, seals and monitoring are essential to assure safety, avoid gas/fluid migration and maintain well integrity during the drilling phase.

3.1.3 Hydraulic Fracturing

During the phase of the well development process, the wellbore is fractured. Carbon dioxide emissions during the 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).

Further, MacKay & Stone (2013) mainly recommend REC and early warning monitoring during production and end-of-life for low emission shale gas in the UK. GAO (2010) states that available measures like capture emissions from completions, liquid unloading or venting from pneumatic devices and optimization of plunger lifts could reduce vented and flared emission of natural gas in general in the US by about 40%.

3.1.4 Well completion and flow back

Upon 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). Methane emissions from the flow back/well completion step may be controlled through the use of reduced emission completions (REC), or green completions (AEA (2012)). The most known REC is the capture of fugitive gas and its use, instead of venting to the atmosphere. However, to facilitate the recovery of the gas, the separation of the three phases of the flow back has to be performed. If this gas is not captured or used, the methane within the natural gas will be released into the atmosphere. When this procedure is 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 US, RECs can capture up to 90% of the initial gas flows, reducing the need for flaring (EPA, 2009).

A reduced emission completion involves the temporary installation of equipment designed to handle the high initial flow of water, sand, and gas. A sand trap is used to remove the solids, and is followed by a three phase separator, which separates the water from the condensate (liquid hydrocarbons) and gas. The gas is then sent to a sales pipeline (or to other processing facilities where needed). When the pipeline infrastructure is not yet in place to receive saleable gas, the gas stream may be routed to suitable storage before treatment and transfer offsite or to a temporary flare.

Limitations include availability of pipelines to transport the gas for sale or utilisation of equipment for other forms of natural gas (e.g. small scale power production); during the exploratory phase the sales pipelines may not have been constructed and the pressure of the produced gas may be not high enough for transportation.

If pressure is too low then it may be difficult to displace the hydraulic fracturing fluid - compressed natural gas or inert gas may need to be pumped down the well to help displace the hydraulic fracturing fluid. Low pressure may limit effectiveness of any treatment stages (it may not be possible to produce sales or pipeline quality gas) and will limit the amount of gas that can be recovered into a storage vessel (without additional compression).

3.1.5 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. To try to mitigate the economic issues, ICF International (2014) and Foster and Perks (2012) suggest a monetary incentive to extra sellable methane that could exceed the costs of REC. 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.

3.1.6 Production, transport, distribution and storage

In the production phase, there are two main sources of emissions, conventional equipment (e.g. dehydration equipment, pumps and compressors) and leakage from gas distribution pipes. Though, most of the emissions come from the compressors, there are also significant methane emissions from the dehydration operations (NYSDEC (2011)). The first emissions can be reduced with the improvement of the technologies applied to the conventional equipment. 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). The use of desiccant (not glycol) dehydrators for dehydration may reduce drying emissions. Regarding compressors, better reciprocating compressors (with replacement of rod packaging system) can be chosen instead of centrifugal compressors (with dry seals). The reduction of emissions due to leakage from gas distribution pipes will involve improvements in the gas supply infrastructure off-site. Leak reduction via leak detection and reduction programs can have efficiencies of 45-96%.

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. These emissions can be reduced by, approximately, 95% using vapour recovery units.

In Europe, gas pressure might be less a problem, because no shallow sources such as coal bed methane are expected. However, processing facilities and equipment for green completions might not be yet available locally.

GAO (2010) states that available measures, which capture emissions from completions, liquid unloading or venting from pneumatic devices and optimization of plunger lifts could reduce vented and flared emission of shale gas in general by about 40% in the US.

3.2 Management techniques

- Technology provides part of a best available techniques approach for management of methane emissions from unconventional gas exploration and production. However, best available techniques in other areas of industrial activity include 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.
- The management of the risks caused by shale gas development is imperative. 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.

4 KNOWLEDGE GAPS

One of the M4ShaleGas project aims is to identify gaps in knowledge for environmentally sound shale gas exploration and use in Europe. A review of the different sources, types of emissions and carbon footprint associated with all phases of shale gas production was done. Further research will focus on identifying the relative importance of these uncertainties for a European shale gas footprint.

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)).

Other issues were also identified as gaps (e.g., 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;
- Wells in Europe have sufficient gas pressure to allow application of green completion;
- Information on chemicals for fracking fluid and amounts;
- Improve 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 compositions at various European plays;
- Variability in fugitive methane emissions - rate and volume;
- 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 KNOWLEDGE GAPS – POTENTIAL SOLUTIONS

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, such as:

- Placing more wells per pad;
- Drilling longer laterals resulting in less pads and roads;
- Using lesser and different chemicals (more benign);
- Recycling of flowback water, using more tanks (rather than ponds) to store waste water;
- Improvements in pond designs;
- Using alternative fuels for combustion engines (gas engines or electric engines).

During this time, 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, so, these topics will be addressed in more detail.

5.1 Well integrity

It has been referred that well integrity 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. For well integrity issues to be understood and mitigation measures to be considered reliable, rigorous monitoring in the field is needed and results should be transparently reported in peer-reviewed journals.

Well integrity is obviously 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. For instance, in Canada, the sustained funding needed for rigorous well-integrity research is likely much higher than the resources that any individual province could compel (Council of Canadian Academies (2014)). The extent of the approaches and technologies, to conduct such characterization and monitoring, need to be established locally. However, the types of characterization and monitoring to be used should be common and established by national legislation or by the European Commission. It will be a challenge to find opportunities for research, using industry funds, but assuring that the results produced are highly credible for both the scientific and public community.

Three important reports, Australian report (ACOLA (2013), US report (SEAB (2011)) and UK report, (The Royal Society and Royal Academy of Engineering (2012)) advocate well integrity monitoring over the life of the well.

Also, in Canada, the National Energy Board (NEB) assessed the well integrity issues as part of its responsibilities associated with granting permits under the *Canada Oil & Gas Operations Act* on federal lands. In its filing requirements for hydraulic fracturing, the NEB specifies that the purpose of these requirements is to ensure that the operator demonstrates that (NEB (2013)):

- Two or more independent and tested physical well seals are in place during all phases of well operations;
- Well seals ensure well integrity during the entire well life cycle, and under all load conditions, hydraulic fracturing and completion;
- Repairs are made or other action taken without delay if the well control is lost or if safety environmental protection or conservation of resources are threatened;
- The safety of the workers and population is maintained and hydraulic fracturing will not cause waste or pollution;
- All equipment is tested to the maximum pressure to which it is likely to be subjected.

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; the possible need of repeating the fracturing process and the the diverse chemicals used in hydraulic fracturing operations that may contaminate groundwater resources.

5.2 Baseline measurement

Baseline observations can provide a standard of the pre-shale gas development state of the environment. Such 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. Baseline data, once obtained 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.

Minimising the impact of shale gas exploration on the atmosphere requires (1) the monitoring of ambient air quality prior to and during operations, and (2) the prevention and minimization of greenhouse gases and toxic chemicals emissions by systematically identifying emission sources of all sizes and implementing operational practices to reduce emissions. 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.

5.3 Methane emissions during production and processing

The studies regarding methane emissions during production and processing are related to conventional natural gas development, but it is assumed that the shale gas methane leakage rates are similar of those from conventional natural gas (Council of Canadian Academies (2014)). Some of these 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 in the potential source should be considered.

The debate of the environmental impact of shale gas with respect to GHG emissions and climate change continues. 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 satisfactorily in the near future.

6 ABBREVIATIONS

GHG – Greenhouse gas
CH_4 - Methane
CO_2 – Carbon Dioxide
EIA - Environmental Impact Assessment
EPA - Environmental Protection Agency
EUR – Expected ultimate recovery
GWP - Global-warming potential.
HAP - Hazardous air pollutants
LCA - life cycle assessment
N_2 - Nitrogen
NO_x- Nitrogen oxides
PM - Particulate matter
REC - Reduced Emission Completions
SO_x – Sulphur oxides
VOC - Volatile organic compounds

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