Project Acronym and Title:

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

INVENTORY OF QUANTIFIED SURFACE RISKS AND IMPACT OF SHALE GAS OPERATIONS

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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

The production of Shale gas by hydraulic fracturing of shale formations has modified the industrial and energy landscape in the USA, and may so in Europe. Like most industrial processes and energy production, the production and use of shale gas have environmental impacts and potential effects on public health. This report aims to summarize the existing (mainly US-based) knowledge on air quality impact and effects on public health. The focus is on GHG emissions and local toxic air pollutants, because these are the main concerns linked with shale gas operations. The studies consulted, reporting the experience in USA, present a combination of direct source emission measurements and ambient measurements, in each of these areas. While improving the level of understanding of the real impact of shale gas operations, uncertainties nevertheless remain in all of these areas. Even in USA air quality impacts/GHG emissions of shale gas is still considered an important field of research that continues to be supported.

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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 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 Aims of this report

The overall objective of this report is to give a technical-scientific basis for improving knowledge on the potential impacts on the environment and public health effects from

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

natural gas (unconventional and conventional gas development). Based on USA experience an inventory of air pollutants emissions is presented in this report. Data showed was collected from the annual USA EPA inventory that presents a combination of direct source emission measurements and ambient measurements in the areas of main concern, GHG emissions, regional and toxic air pollutants. This report also gathers information on the risks for the environment and public health posed by pollutants, linked to the production and use of shale gas.

1.3 Structure of the report

This report is divided in 5 chapters. The first one is an introductory chapter where the objectives of the M4ShaleGas and of this report are presented. The context of this report is presented in Chapter 2. In Chapter 3 air quality issues are assessed, like type of pollutants, sources and ways of release and impacts to environment and public health. This chapter also presents a case study for the USA. Some remarks and recommendations are presented in Chapter 4 and the References are listed in Chapter 5.

2 CONTEXT OF THIS REPORT

The Shale gas development is becoming very relevant in the international energy field, especially in North America. Major shale gas reserves were identified in Algeria, Argentina, Australia, Brazil, Canada, China, Mexico, Russia, South Africa, (U.S. Energy Information Administration, 2013). In Europe, there are identified reserves with developments for exploitation/exploration in Poland and the UK (https://openecho.jrc.ec.europa.eu).

Unlike conventional gas, unconventional gas is not as easy to extract. This gas is impossible to obtain using normal methods due to the low permeability of the rock, where there are poorly connected pores. So, shale gas production typically utilizes two major technologies: hydraulic fracturing and horizontal drilling (Costa et al. 2015).

The emissions to air in shale gas operation are linked to the different stages of production: (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 identified pollutants linked to shale gas operations (Costa et al. 2015), which are released to ambient air from the various stages of shale gas activities, may have significant impact on air quality. The negative impact on air quality poses risks to the environment and public health, being of major concern worldwide (McKenzie et al., 2012).

Several studies, mainly from the USA and related to air quality and shale gas, are focused on emissions inventories and air sampling, with some associated health risk characterization (Bunch et al., 2014; City of Fort Worth, 2011; Colorado Department of Public Health and Environment, 2010a; McKenzie et al., 2012; Pennsylvania Department of Environmental Protection, 2011; Omara et al., 2016, Paulik et al., 2016).

These studies were mainly based in Garfield County (Colorado) and also in Pennsylvania and Texas. Therefore, the geographic range of the information found in the literature is quite limited. This evaluation showed that air quality concerns are mostly focused in three aspects: (1) type of air pollutants, their sources and ways of release to atmosphere; (2) impact on the environment; (3) public health concerns.

3 AIR QUALITY

It is very important to understand the environmental implications of the economic and industrial transformations associated with shale gas production due to the magnitude and potential scope of these transformations. The air quality implications of the production and use of natural gas from shale formations need to be addressed. However, to estimate the pollutants emissions from shale gas operations can be challenging due to the large number of individual source locations, e.g. the Barnett Shale production region in North Central Texas has more than 10,000 individual gas wells (Allen 2014). Moreover the operational practices are relatively new and the number and types of emission sources vary among the well sites. So, specific emissions data per source is starting to be reported. Also, it is important but challenging to characterize the emissions impacts. The tools needed to characterize air pollutant impacts vary depending on the spatial and temporal scales. For instance, for the greenhouse gases emissions the impact is global and for a decade or longer, while for air toxics is local and hourly. To assess this impact tools like emission estimates, dispersion modeling, local analyses, regional photochemical modeling and inventories of emissions over spatial scales are needed.

Both ambient (top-down) and direct source (bottom-up) measurements are important to examine emissions along the natural gas supply chain. A lot of work was performed on this subject (Petron et al. 2012; Peischl et al. 2013; Karion et al. 2013). Regarding ambient measurements, suitable to assess regional emissions, large data is being collected. It is expected that in the next coming years these studies will give rise to a better understanding of the sources that contribute to the greenhouse gas footprint.

Allen (2014) reported in direct source measurements in the production stage and in other sources namely pneumatic controllers and liquids unloading. Also measurements in gathering and gas processing operations, transmission, and local distribution were performed (Cent. Altern. Fuels Engines Emiss. 2013; Engines Energy Convers. Lab. 2013; Lab. Atmos. Res. 2013).

The lack of published and peer-reviewed literature makes it challenging to assess, scientifically, the real impacts of shale gas operations. So, some stakeholders defend that because of this uncertainty there is no point in having additional pollution controls at this time. However, other claims that the decision to continue the pollution controls should depend of the impact of the shale gas systems on the area's ability to attain air quality standards (NAAQS).

Unconventional gas development can affect local and regional air quality. There are some evidences that in areas where drilling took place there was an increase in concentrations of hazardous air pollutants and of particulate matter and ozone plus its precursors.

Available studies, report the impacts of emissions from natural gas systems. Significant increases in VOC and/or ozone levels have been observed in several areas of the USA with heavy concentrations of drilling in Colorado (Peischl et al. 2013), in Wyoming (Karion et al. 2013) and Utah. (Cent. Altern. Fuels Engines Emiss. 2013), Northern Texas (Marrero et al. 2016). This rise on VOC emissions has been attributed to increased traffic, combustion exhaust, and the fugitive release of natural gas. However, researchers also stated that the presence of VOCs in the atmosphere is just one of the many factors that contribute to ground-level ozone formation. Another factor being the effect of stratospheric ozone intrusions well as drops in ozone values due to reductions in NO_x concentrations and changes in weather patterns (e.g., the Fort Worth (Lab. Atmos. Res. 2013) and Uinta Basins (Tex. Comm. Environ. Qual. 2013a).

3.1 Type of air pollutants, their sources and the release

The main concern, present in most of the studies, is the GHG emissions ((CH4), carbon dioxide (CO2) and nitrogen oxides (NOx)). In the literature, a group of pollutants regulated by the Environmental Protection Agency (EPA), are also referred, which are: ozone, particulate matter (PM), carbon monoxide (CO), nitric oxides (NOx), sulphur oxides (SOx), and lead. The emissions of volatile VOCs and other hazardous air pollutants (HAPs) are also reported. The VOCs and HAPs include aromatic hydrocarbons, halogenated compounds, aldehydes, alcohols, and glycols (Costa et al. 2015). The HAPs is a term used by US EPA to cover a separate group of toxic air pollutants that “cause or may cause cancer or other serious health effects, or adverse environmental and ecological effects” (ICF International, 2014).

The GHG and other gaseous emissions and their sources are presented in Table 1. (Costa et al. 2015).

Table 1. Air pollutants and their sources.

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

The proprieties of the pollutant, mainly it´s vapour pressure, determine its contribution to the air contamination when released into the environment. For instance the compounds that are gaseous at normal temperatures and pressures are more likely to be found in the ambient air, i.e. methane, ethane, and propane. Also, as the liquid substances (i.e. benzene, toluene, and m,p-xylenes) have a low boiling temperature and high vapor pressure, it can be expected that part of that liquid readily evaporates into the atmosphere (Coons and Walker 2008; Werner et al. 2015). The emissions of these aromatic compounds (mainly benzene and xylene) mostly come from the natural gas compression and processing stages, where the heavier components are released into the atmosphere. In EU the emissions of these substances are controlled by law.

The air pollutants emitted by machines used for the drilling and extraction processes such as diesel engines, are reported for USA by the US-EPA **(**Policy Department A: Economic and Scientific Policy). It is expected that these machines and the air pollutants emitted by them to be the same that will be used in Europe. In Table 2 the air pollutant emissions from stationary diesel engines used for drilling, hydraulic fracturing and well completion are shown (Horwarth et al. 2011).

Table 2. Typical specific emissions of air pollutants from stationary diesel engines used for drilling, hydraulic fracturing and completion (Policy Department A: Economic and Scientific Policy 2011).

Air Pollutant	**Emissions per engine mechanical output [g/kWh mech]**	**Emissions per engine fuel input [g/kWh diesel]**	**Emissions per natural gas throughput of well [g/kWh NG]**
SO_2	0.767	0.253	0.004
NO_x	10.568	3.487	0.059
PM	0.881	0.291	0.005
CO	2.290	0.756	0.013
NMVOC	0.033	0.011	0.000

The emission factor per engine and also their impact has to be limited, because when there are multiple drilling pads these emissions will be sum up, with a much higher potential impact. The shale operations include one or even more wells per km². So, during shale gas development the emissions from gas processing and transportation need to be monitored and restricted continuously, especially when more production lines are added up. All these issues should be taken into account in the preparation of relevant European Directives (Policy Department A: Economic and Scientific Policy, 2011).

Figure 1 shows the three exposure pathways: air, water, and soil. It is based in a general conceptual model presented for natural gas operations in Garfield County (Coons and Walker 2008). In this Figure 1 sources are identified as: devices (e.g. internal combustion engine), facilities (e.g. pond for hydrocarbon contaminated water), or processes (e.g. refueling) from which pollutants are released into the environment. The release mechanism is the way the pollutant escapes. For instance: exhaust gases are vented out of the engine; hydrocarbons either stored in ponds or present in ground water (by percolation of the soil), evaporation of the fuel into the air during refueling and spills occurrence.

Exposure medium (air, surface water, ground water, or soil) is an environmental medium which is polluted by the release and acting as an exposure via for living beings.

The exposure route is the way the pollutant enters the organism. Therefore, pollutants in air are inhaled; pollutants in drinking water are ingested; pollutants in soil can be ingested in small amounts; certain pollutants in water or soil may be absorbed through the skin. The receptor is a person which is exposed to the pollutants via exposure routes.

Pollutants roadmap can be generated linking sources to receptors through, release mechanism, exposure medium and exposure route. Exposure only happens when there is a link between source and receptor creation a pathway. Often this pathway is not completed so only a potential exposure pathway takes place. Potential pathways must be assessed carefully to evaluate if there is a significant risk of exposure. The release mechanisms, exposure media, and exposure routes are highly dependent on the properties of each pollutant. For instance a pollutant with low vapour pressure has less probability to appear as a gas in air.

The concentration of pollutants is higher in the centerline of the plume and decreases with increasing distance from the release location (cone of the plume). The pollutants concentration is also dependent on the meteorological conditions being significantly affected by temporal variability. As an example, variability in wind direction results in dispersal of the pollutant over a greater volume of air.

Also higher wind speed spread the pollutants over a larger volume of air causing a decrease in pollutant concentrations compared with what would be expected for lower wind speeds. Besides the atmospheric conditions, it is important to take into account the land topography and soil occupation, since it influences both the horizontal and vertical movement of air and air pollutants.

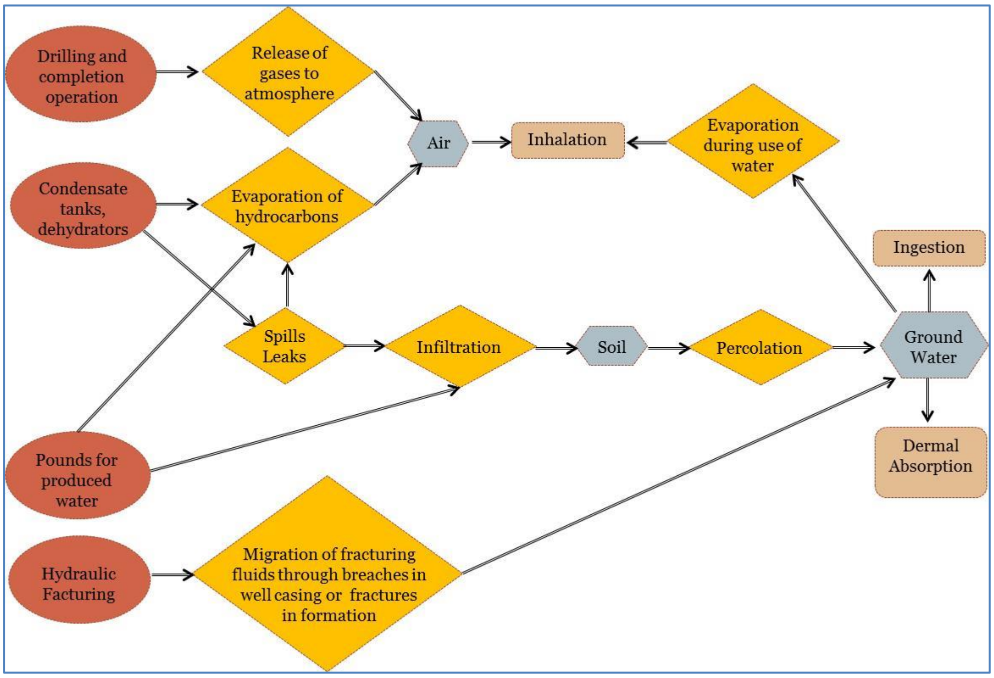

Figure 1. Possible model for air transport of contaminants in Shale gas operations (adapted from Coons and Walker 2008).

3.1.1 Air emissions estimation along the Natural Gas Supply Chain

The US Environmental Protection Agency publishesInventories of U.S. Greenhouse Gas Emissions and Sinks with data since 1990 (US EPA 2010 - 2016), by economic sector. In the energy sector, the emissions from the natural gas system do not specify the difference between conventional and unconventional. So, it is not possible, from the EPA inventories, to distinguish the contribution of shale gas activity to this data.

<u>USA</u> - <u>Emissions inventory</u>

In the United States, the Environmental Protection Agency (US EPA 2010 - 2016) estimates the greenhouse gas emissions, including those from the natural gas supply chain, annually. In contrast with the emissions of carbon dioxide from combustion of natural gas that can be estimated with a reasonable degree of accuracy from fuel consumption data, the methane emissions have a much higher degree of uncertainty. This can be concluded by looking at the US EPA inventories of methane emissions from 2007 to 2014 (US EPA 2010 - 2016). In these inventories the emissions are grouped into production, processing, transmission/storage, and distribution.

In 2014, in the US, natural gas sector was the largest source of CH_4 emissions. The U.S. natural gas system includes hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. So, this system emitted 176.1 MMT CO_2 Eq. of CH_4 in 2014, which account for a decrease of 15% (30.6 MMT CO_2 Eq.) compared to 1990 emissions (206.8 MMT CO_2 Eq.) and a rise of less than 1% compared to 2013 emissions (175.6 MMT CO_2 Eq.) (Figure 2).

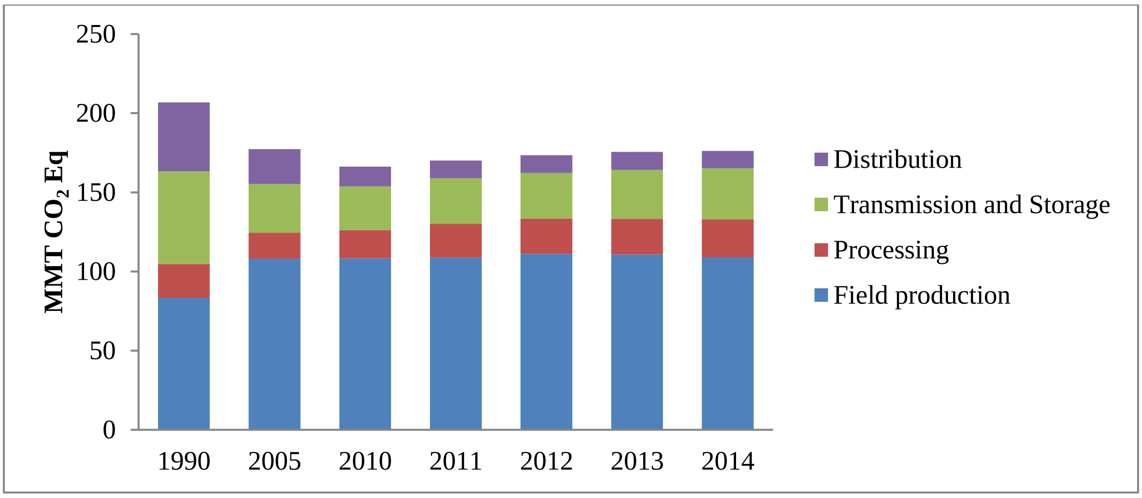

Figure 2. CH_4 emissions from Natural Gas System (MMT CO_2 Eq.)

The assessment in this period of time shows an inconsistency across sectors. Data reported showed that emissions from production operations seem to be the largest contributor to methane emissions (109.0 MMT CO_2 Eq.). In general, from 1990 to 2014 the CH_4 emissions decreased due mainly to the reduction in the transmission/storage (due to reduced compressor station emissions) and distribution segments emissions (increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating stations). On the other hand the methane emissions from production and processing segments increased about 31 and 13%, respectively. However, in production, the main increase was observed between 1990 and 2005, afterwards the variations were very small.

Natural gas systems also emitted 42.4 MMT CO_2 Eq. of non-combustion CO_2 in 2014, corresponding to 12% increase compared to 1990 emissions and a 10% increase from 2013 emissions (Figure 3). Both these increases in CO_2 are due mostly to flaring sincethe volume of gas flared increased 93% from 1990 and 12% from 2013 (US EPA 2016). Flaring of the gas, reduces methane emissions by combustion, releasing CO_2, so reduces de methane concentration but increases the CO_2.

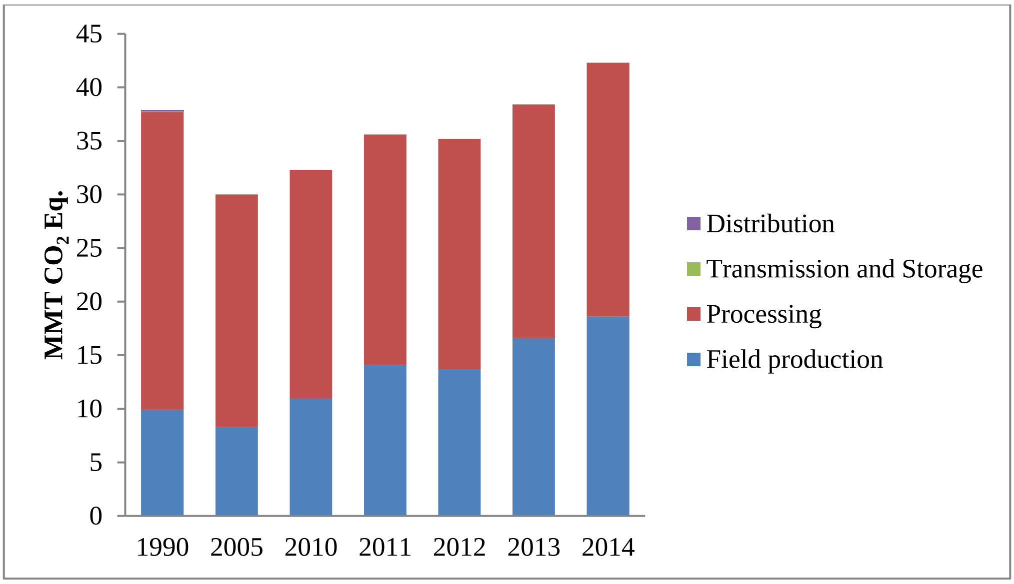

Figure 3. Non combustion CO_2 emissions from Natural Gas System (MMT CO_2 Eq.)

The CH_4 and non-combustion CO_2 emissions from natural gas systems comprise those resulting from normal operations, routine maintenance, and system upsets. In the emissions from normal operations are included: natural gas engine and turbine uncombusted exhaust, bleed and discharge emissions from pneumatic controllers, and fugitive emissions from system components. The routine maintenance refers to emissions from pipelines, equipment, and wells during repair and maintenance activities. The system upset emissions can occur due to pressure surge relief systems and accidents. In Table 3 is presented more details on the major sources of methane emissions. This values presented are based on EPA values. EPA first estimates the potential emissions for source categories then reduces the potential emissions by estimated voluntary reductions and reductions required by regulations. Potential emissions, emission reductions, and net emissions are presented in Table 3 (Allen 2014). The characterization of the four major stages of the natural gas system can be consulted in US EPA 2016.

Table 3. National emission inventory estimates by source category (Allen 2014).

<table>
<tr><th>EPA source activity</th><th>Potential emissions (Gg)</th><th>Emission reductions (Gg)</th><th>Net emissions (Gg)</th></tr>
<tr><td>Completions with hydraulic fracturing</td><td>1221</td><td>567</td><td>654</td></tr>
<tr><td>Refractures (workovers with hydraulic fracturing)</td><td>266</td><td>124</td><td>143</td></tr>
<tr><td>Pneumatic device vents</td><td>1134</td><td>779</td><td>355</td></tr>
<tr><td>Chemical injection pumps</td><td>64</td><td>30</td><td>34</td></tr>
<tr><td>Equipment leaks: gas wells</td><td>52</td><td>24</td><td rowspan="5">172</td></tr>
<tr><td>Equipment leaks: separators</td><td>107</td><td>50</td></tr>
<tr><td>Equipment leaks: metters/piping</td><td>102</td><td>48</td></tr>
<tr><td>Equipment leaks: heaters</td><td>33</td><td>15</td></tr>
<tr><td>Equipment leaks: dehydrators</td><td>31</td><td>15</td></tr>
<tr><td>Workovers without hydralic fracturing</td><td>0.6</td><td>0.3</td><td>0.3</td></tr>
<tr><td>liquids unloading</td><td>257</td><td>0</td><td>257</td></tr>
<tr><td>Kimray pumps</td><td>365</td><td>180</td><td rowspan="11">930</td></tr>
<tr><td>Condensate tanks</td><td>313</td><td>167</td></tr>
<tr><td>Gas engines</td><td>276</td><td>49</td></tr>
<tr><td>Dehydrators vents</td><td>114</td><td>73</td></tr>
<tr><td>Reciprocating compressores</td><td>84</td><td>35</td></tr>
<tr><td>Pipeline leaks</td><td>170</td><td>80</td></tr>
<tr><td>Well drilling</td><td>0.8</td><td>0.4</td></tr>
<tr><td>Blowdowns</td><td>6.7</td><td>2.3</td></tr>
<tr><td>Compressor starts</td><td>6</td><td>3</td></tr>
<tr><td>Pressure relief valves</td><td>0.7</td><td>0.3</td></tr>
<tr><td>Mishaps</td><td>2</td><td>1</td></tr>
<tr><td>Total</td><td>4605.8</td><td>2243.3</td><td>2545.3</td></tr>
</table>

Regional air quality assessment

The emission that can affect the regional air quality needs also to be addressed in a monitoring program; top-down and bottom-up measurements can also be used to assess these emissions. The VOCs emissions are one of the main concerns. In the inventory published in US-EPA, 19,914 point sources were reported, with a total of 19,833 tons per year of VOC emissions (Allen 2014). In Figure 4 is showed the VOC emissions by source type from the Texas Commission Environmental Quality (TCEQ) inventory.

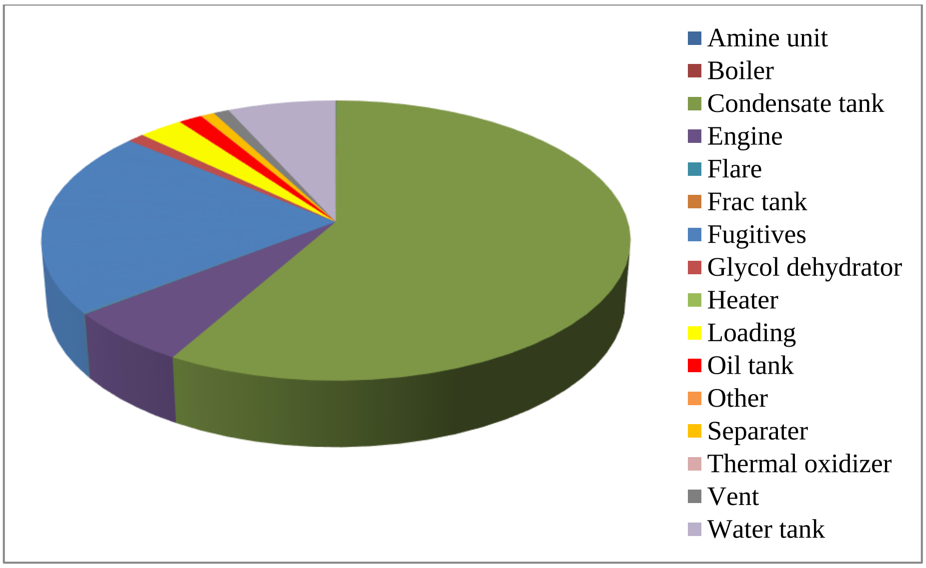

Figure 4. VOC emissions by source type (% total) (Allen 2014).

As showed in Figure 4, condensate tanks are the highest source of VOC emissions, followed by fugitives, engines, and water tanks. These values were obtained by TCEQ that has installed automated gas chromatographs which recorded hourly averaged atmospheric concentrations of hydrocarbons in the Barnett Shale production region and neighbouring areas since 2010 (TCEQ 2013). The dominate species detected were ethane, propane, and butane accounting for approximately 70% of the identified hydrocarbon concentrations. These results are in agreement with the expected composition of emissions from natural gas production operations (Allen 2014). This analysis performed for Barnett Shale, seems to indicate that VOC emissions associated with shale gas production are reasonably well accounted for using the emission inventory methods (Zavala-Araiza et al. 2012).

Regarding the estimation of NO_x emissions of using the top-down and bottom-up methods, these did not seem to be as precise as for VOCs. NO_x is mainly emitted as by-product of combustion of the engines associated with vehicles and compressors used in the natural gas supply chain. NO_x is not as stable as ethane, propane, and butane, since it can react relatively quickly in the atmosphere. Top-down estimations of emission rates has to have these transformations into account, so, it is difficult to perform a quantitative top-down assessment of NO_x inventories in natural gas production (Allen 2014).

Toxic air pollutants from Shale gas production

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).

3.2 Impact on health

It has been discussed earlier that local and regional air quality can be affected by unconventional gas activity. Drilling operations are responsible for the increase in concentrations of hazardous air pollutants as well as particulate matter and ozone plus its precursors which have harmful effects on health and the environment (California Environmental Protection Agency Air Resources Board. 2012). Exposure to high levels of air pollutants potentiate adverse health effects (EPA 2013) being the risks higher for populations in the vicinity of those activities (Bamberger and Oswald 2012; Colborn et al. 2011; Colorado Department of Public Health and Environment 2010b; Ferrar et al. 2013; McDermott-Levy et al. 2013; McKenzie et al. 2012; Queensland Government 2013, Werner et al. 2015).

It has to be noted that epidemiological studies are in general difficult, rare, and expensive to conduct, requiring robust data that are typically absent or inadequate for assessment. This is also the case for precise and accurate estimates of emissions, fate and transport, exposure levels as well as impact data on relatively large populations of exposed individuals over extended durations of time. So, it is challenging to scientifically assess the impacts of natural gas operations. The relevant question for determining if pollution controls are needed seems to be, whether or not, the natural gas systems have impact on an area's ability to attain National Ambient Air Quality standards (NAAQs) set by EPA (Lattanzio 2016).

Health effects reported to be in some way associated to environmental impacts, include symptoms of upper respiratory tract ailments, burning eyes, headaches, vomiting, diarrhea, rashes, and nosebleeds (Bamberger and Oswald 2012; Colorado Department of Public Health and Environment 2010b; McDermott-Levy et al. 2013; Queensland Government 2013; Saberi 2013; Subra 2009, 2010).

The review by Werner et al. (2015), aims to present a strength-of-evidence analysis of scientific reports on the environmental health impacts of unconventional natural gas development. It addresses the environmental hazard, exposure, and health related to public main concerns.

As a conclusion this review shows a lack of robust studies on direct health outcomes caused by the activities of unconventional natural gas development. The literature reviewed in this paper continues to suggest knowledge gaps and public concern on environmental health issues (Werner et al. 2015).

3.2.1 Air-born pollutants – hazards

The identified pollutants with relevant effects on public health are summarized in Table 4.

Broni-Bediako and Amorin (2010) concluded that exposure to drilling fluids is mainly through the inhalation, dermal, and oral routes and that circulation of drilling fluids can result in vapours, aerosol and/or dust, which can be inhaled. Searl and Galea (2011) undertook a toxicological review of drilling fluids and noted that the main health risks associated with inhalation of aerosol and vapour from oil-based drilling fluid are irritation of mucous membranes and neurotoxicity. Long-term exposure to drilling fluids is associated with increased risk of developing chronic respiratory illness, as well as impaired cognition, neurological impairment, and possibly dementia (Searl and Galea 2011).

Despite the increase in studies, toxicological data is still limited, with only a few reported inhalation-related toxicity values (Colorado Department of Public Health and Environment, 2010b). Furthermore, while studies on ambient air monitoring and risk characterisation evaluated human exposure and potential risks to human health, the information available to be used for these assessments does not necessarily provide information on what is taken up in an individual's body base (Bunch et al. 2014), suggesting the requirement for parallel biomonitoring studies. Only few studies explored potential health risks and shale gas activities using biomonitoring (Adgate et al. 2014).

Table 4. Summary of air pollutants and effect on public health.

Pollutant	Effect	Reference
Nitrogen oxides, PM, CO	Irritation of the respiratory system and particulate matter can aggravate existing respiratory and cardiovascular problems, cause respiratory health effects, and damage lung tissue.	Colorado Department of Public Health and Environment, 2009, Lattanzio 2016
HAPs , VOCs	Acute exposure: cause drowsiness, headaches, and eye, skin, and respiratory tract infections and chronic expo-sure can cause blood disorders, including aplastic anaemia, as well as reproductive effects. Human carcinogen.	Colorado Department of Public Health and Environment, 2009, Lattanzio 2016
Tropospheric ozone	Pulmonary irritant that can affect respiratory mucous membranes, as well as respiratory function vascular markers of inflammation and changes in heart rate and fibrinolysis markers	Ebi and McGregor, 2008 Devlin et al., 2012

Ground-level (tropospheric) ozone is a secondary contaminant produced in the reaction of sunlight with NOx and VOCs (Walther 2011; Witter et al. 2008).

Witter et al. (2013), in Colorado, found that residents could potentially experience health effects from exposure to pollutants air emissions, including headaches and other neurologic symptoms, as well as airway and mucous membrane irritation. Long-term health effects e.g. cancer and birth defects, as well as potentiating of chronic diseases were perceived as possible (Witter et al. 2013).

Unconventional natural gas development presents multiple stressors that might affect pregnancy and the foetus. Short-term impacts on infant health were reviewed by Hill (2012) and McKenzie et al. (2014) and outcomes include preterm birth, low birth weight, congenital malformations, respiratory distress syndrome, and sepsis. Long-term outcomes include cerebral palsy, chronic pulmonary disease, and learning disabilities (Misra et al. 2003). Hill (2012) suggested that exposure to shale gas operations within a distance of 2.5 km from a gas well is harmful to foetal development. McKenzie et al. (2014) study reported an association with maternal residential proximity to tight gas well sites and the occurrence of congenital heart defects and neural tube defects.

There is limited information on setback (distance) restrictions in terms of air emissions from shale gas development and health. Colborn et al. (2014) alerts that new gas wells are being drilled closer to densely populate urban regions, raising the issue on whether the current requirements are sufficient to protect public health (City of Fort Worth 2011; Fry 2013). As each well pad is unique it is frequently difficult to determine one setback distance for all residences (Witter et al. 2013).

4 REMARKS AND RECOMMENDATIONS

The review presented in this report continues to suggest 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. Also, it is mentioned some monitoring strategies. The carbon footprint and potential impact on global climate forcing are also discussed. The carbon footprint was defined as the life cycle emissions of the greenhouse gases carbon dioxide and methane, expressed in CO_2-equivalents. GWPs were used to transfer greenhouse gases on a comparable unit. As GWPs are the cumulative radiative forcing of each greenhouse gas related to that of CO_2, effects on carbon footprint and on global climate forcing are considered equal in these recommendations. As many measures taken to reduce emissions to air (particularly methane and other VOCs) also reduce emissions of greenhouse gasses (mainly methane and CO_2), both types of emissions are discussed jointly. Finally, also recommendations for further research to improve the knowledge base for quantifying emissions to air and carbon footprints related to shale gas operations are also presented.

The presented recommendations are organized by process stages.

Pre-production Stage

The pre-production stage includes exploration, site clearing, and road construction to drilling, hydraulic fracturing, well completion and waste treatment. The GHG emissions from pre-production stage comprise: emissions from roads and well-pad construction; diesel engines and compressors used during drilling. These emissions are mainly due to combustion operations. Other pollutants are also present; especially the ones associated with flow back and combustion sources (Costa et al. 2015).

This stage of operations includes the identification of a suitable site for locating a well pad as well as steps taken to prepare a site for drilling (e.g. vegetation removal, building of access roads and the well pad, drilling rig mobilization and demobilization). The site preparation involves cleaning, levelling, and digging at a well site to install the well pad, freshwater pits, and associated access roads (Costa et al. 2015).

Forster and Perks (2012) stated that the most significant source of GHG emissions, in this stage, are the well completion and gas treatment, which account for 39% and 27% of pre-combustion emissions respectively. However, these authors indicate that if flaring of flow back gases or green completion take place, the importance of the well completion stage decreases significantly, only accounting for between 7% and 14% of pre-combustion emissions (Costa et al. 2015).

The flow back takes place after the injection phase is completed in the well completion phase. Part of the injected fracturing fluid (dependent on the geology) flows back to the surface, with large volumes of gas. For the quantification of the possible emissions produced during this stage, it is important to assess both, the duration of the flow back stage, and the rate of gas production (AEA 2012). The gas can go directly to the atmosphere (vented), flared (with the emission of pollutants), or captured (to reduce the emissions) (MacKay and Stone 2013).

The emission estimation of the pre-production stage is very difficult because it depends on the characteristics and dimension of the site. The studies found in the literature present very different values for this kind of emissions. This difference can be justified by different calculation methodology (Costa et al. 2015).

The estimates found in the literature are from de USA and are, probably, applicable to the EU as similar practices will be required for the development of shale gas wells in Europe. Europe has higher population densities so, it is expected that shale gas developments would have a smaller overall land-footprint compared to USA. Moreover, developments may be closer to existing infrastructure and the operators in Europe may be under more pressure to reduce the impact of well developments on the landscape (AEA 2012). For instance in the USA it is assumed an initial single-well pad size of 1.3 ha which increases by approximately 0.16 ha per well (i.e. a six well pad would have a footprint of 2.1 ha (Clancy et al. in press). For UK, Broderick et al (2011) refer to plans by Cuadrilla for exploration and production from the Bowlands Shale, quoting a well pad size of 0.7 ha, which will contain 10 wells, while, Taylor et al. (in Clancy et al. in press) mentions future scenarios with shale gas pads of 2 ha. In order to minimise the surface footprint it is advisable to makes maximum use of horizontal drilling technology in spacing multi-well pads in dense clusters (Clancy et al. in press), when possible accounting for geology and existing infrastructure (Broderick et al. 2011). Though it is important to assess additional footprint required for well site access roads, this discussion has been difficult due to different criteria used in the reviewed studies (general infrastructure area vs area specifically required for roads).

Recently, a UK study was performed aiming to determine the expected physical footprint of well pads in case of shale gas developments in Europe in order to understand the carrying capacity of new infrastructure developments and their impact on existing infrastructure and the environment. In this study is evaluated the potential impact of the development of a shale gas industry within the UK. The authors report that there is a 33% probability that a shale gas well pad would directly impact existing infrastructure, increasing, potentially, to 91% when a setback of 609 m is used (Clancy et al. in press). In the same study the issue of the carrying capacity of the land surface (number of wells and setback) and the limitation in the recovery of the resource are discussed.

In the M4ShaleGas report D15.2 (Hauck et al. 2017) on the development of a tool to estimate carbon footprint of shale gas produced in Europe, for consumption within Europe, It was assumed that one well pad covers 25km^2 (5 x 5 km square) and that 25-30 wells are drilled in one pad. Under these assumptions and the area per play, the required number of wells per play could be deduced (Hauck et al. 2017).

In Table 5 are presented some recommendations and corresponding advantages to minimize the emissions to air in the pre-production stage. These points were addressed in detail in previews M4ShaleGas project reports (D14.1, D14.2, D15.1, D15.2, and D16.1).

Production, storage and distribution stages

During the production stage emissions can occur from a number of sources including: Gas treatment (sweetening); Storage Tanks; Dehydration; Pneumatic Devices; Compressors; leakage from gas distribution pipes.

The Gas treatment (sweetening) typically requires reduction in moisture (dehydration), inert gases (CO_2, N_2) and might require separation of natural gas liquids and non-methane hydrocarbons, recovery of helium, reduction of hydrogen sulphide and mercury (AEA 2012).

Emissions from storage tanks of the produced water can occur from working losses, breathing losses (due to temperature changes) and flashing losses. Glycol dehydrators accounts for methane emissions and are also a source of BTEX (benzene, toluene, ethylbenzene, and xylene). The pneumatic devices emit small quantities of natural gas on a continual basis (continuous bleed) or in short bursts (intermittent bleed). Regarding compressors two types can be used, centrifugal compressors and reciprocating compressors. These compressors are typically powered by natural gas-fired engines or turbines, which emit combustion by-products, but these combustion-related emissions can be eliminated using the local electrical grid. The reciprocating compressors emit significantly less methane than for centrifugal compressors (AEA 2012).

Leaks can be a significant source of emissions occurring from several potential sources: including pipework and equipment (compressors and pneumatic devices), open ended lines and sampling connections may leak. Due to the large number of components proper maintenance is imperative to prevent leakage welded connections and flanges and valves (AEA 2012).

In Table 6 are presented some recommendations and corresponding advantages to minimize the emissions to air in the production stage. These points were addressed in detail in previews M4ShaleGas project reports (D14.1, D14.2, D15.1, D15.2, and D16.1).

Table 5. Recommendations and advantages to minimize the emissions to air in the pre-production stage.

Recommendations	Advantages
Ensuring that personnel and equipment can be sourced locally	Reduction of GHG emissions from pre-production stage - 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; - 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 (the quantity of fuel consumed, and the associated emissions, depend on the specific characteristics of the site (e.g. depth and lateral length of the well and number of wells)
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 (The most known REC is the capture of fugitive gas and its use, instead of venting to the atmosphere - EPA assumes that for the US, RECs can capture up to 90% of the initial gas flows, reducing the need for flaring (EPA, 2009)

Table 6. Recommendations and advantages to minimize the emissions to air in the production stage.

Recommendations	Advantages
Use of vapour recovery units (VRU's) 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

Well Plugging and Abandonment stage

The objective of this stage is to assure that the well is sealed and 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. Well integrity remains the weak spot in the system (i.e. problem of fluids escaping from incompletely sealed wells) being the primary concern in environmental protection issues (Costa et al. 2015). 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. The abandonment procedures for onshore gas wells should be defined and regulated (in USA these procedures are defined in Federal and State regulations), including the technical requirements and observation of the plugging procedure by local inspectors. 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.

Monitoring Strategies

Minimising the environmental impacts that may be associated with shale gas development on the atmosphere requires the monitoring of ambient air quality prior to and during operations, and the prevention and minimization of greenhouse gases and toxic chemicals emissions. The research on sampling strategy for monitoring atmospheric composition will provide guidelines to monitor air quality. This issue will be address in a further derivable (D14.3, D16.3).

Methane is the main component of shale gas but identifying methane leakage from shale gas activities is difficult due to the large amount of other CH_4 sources (e.g. cattle, landfills, wetlands). However, the presence of other hydrocarbons in the raw gas is unique and if measured at the same time as CH_4 concentrations, the information on the accompanying hydrocarbons can potentially be used as a tracer to identify the fossil fuel gas sources from the other CH_4 sources (Costa et al. 2016).

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).

In Table 7 are presented some recommendations and corresponding advantages to monitor the emissions to air associated with shale gas operations. These points were addressed in detail in previews M4ShaleGas project reports (D14.2, D16.1).

Table 7. Recommendations and advantages to monitor the emissions to air.

Recommendations	**Advantages**
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 shale gas 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 shale gas extraction
Data collected by operators should be submitted to the appropriate regulator	
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

5 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_2 Eq - carbon dioxide equivalent
Gg - gigagram
g/kWh - grams per kilowatt-hour
MMT - millions of metric tons

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