AIR QUALITY EXPERT GROUP

Potential Air Quality Impacts of Shale Gas Extraction in the UK

Prepared for:
Department for Environment, Food and Rural Affairs;
Scottish Government; Welsh Government; and
Department of the Environment in Northern Ireland

AIR QUALITY EXPERT GROUP

Potential Air Quality Impacts of Shale Gas Extraction in the UK

Prepared for:

Department for Environment, Food and Rural Affairs;
Scottish Government; Welsh Government; and
Department of the Environment in Northern Ireland

This is a report from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, on potential air quality impacts of shale gas extraction in the UK. The information contained within this report represents a review of the understanding and evidence available at the time of writing (2015).

United Kingdom air quality information received from the automatic monitoring sites and forecasts may be accessed via the following media:

Freephone Air Pollution Information Service	0800556677
Internet	http://uk-air.defra.gov.uk

PB14504

Terms of reference

The Air Quality Expert Group (AQEG) is an expert committee of the Department for Environment, Food and Rural Affairs (Defra) and considers current knowledge on air pollution and provides advice on such things as the levels, sources and characteristics of air pollutants in the UK. AQEG reports to Defra's Chief Scientific Adviser, Defra Ministers, Scottish Ministers, the Welsh Government and the Department of the Environment in Northern Ireland (the Government and devolved administrations). Members of the Group are drawn from those with a proven track record in the fields of air pollution research and practice.

AQEG's functions are to:

- Provide advice to, and work collaboratively with, officials and key office holders in Defra and the devolved administrations, other delivery partners and public bodies, and EU and international technical expert groups;
- Report to Defra's Chief Scientific Adviser (CSA): Chairs of expert committees will meet annually with the CSA, and will provide an annual summary of the work of the Committee to the Science Advisory Council (SAC) for Defra's Annual Report. In exception, matters can be escalated to Ministers;
- Support the CSA as appropriate during emergencies;
- Contribute to developing the air quality evidence base by analysing, interpreting and synthesising evidence;
- Provide judgements on the quality and relevance of the evidence base;
- Suggest priority areas for future work, and advise on Defra's implementation of the air quality evidence plan (or equivalent);
- Give advice on current and future levels, trends, sources and characteristics of air pollutants in the UK;
- Provide independent advice and operate in line with the Government's Principles for Scientific Advice and the Code of Practice for Scientific Advisory Committees (CoPSAC).

Expert Committee Members are independent appointments made through open competition, in line with the Office of the Commissioner for Public Appointments (OCPA) guidelines on best practice for making public appointments. Members are expected to act in accord with the principles of public life.

Further information on AQEG can be found on the Group's website at: https://www.gov.uk/government/policy-advisory-groups/air-quality-expert-group

Membership

Chair

Professor Paul Monks
University of Leicester

Members

Dr David Carruthers
Cambridge Environmental Research Consultants (CERC)

Dr David Carslaw
King's College London (now at Ricardo Energy and Environment and University of York)

Dr Chris Dore
Aether Ltd

Professor Roy Harrison OBE
University of Birmingham

Dr Mat Heal
University of Edinburgh

Dr Mike Jenkin
Atmospheric Chemistry Services

Professor Alastair Lewis
National Centre for Atmospheric Science, University of York

John Stedman
Ricardo Energy and Environment

Professor Alison Tomlin
University of Leeds

Professor Martin Williams
King's College London

Ex officio members

Central Management and Control Unit of the automatic urban and rural networks: **Dr Richard Maggs**, Bureau Veritas

National Atmospheric Emissions Inventory: **Dr Tim Murrells**, Ricardo Energy and Environment

Non-automatic hydrocarbon monitoring networks and metals monitoring network: **Dr Paul Quincey**, National Physical Laboratory

Quality Assurance and Quality Control of the automatic urban network and the non-automatic monitoring networks: **Dr Paul Willis**, Ricardo Energy and Environment

Professor David Fowler CBE, Centre for Ecology and Hydrology

Assessors and observers

Simon Baldwin
Welsh Government

Barry McCauley
Department of the Environment in Northern Ireland

Andrew Taylor
Scottish Government

Alison Gowers
Public Health England

Secretariat

Dr Sarah Moller
Department for Environment, Food and Rural Affairs and National Centre for Atmospheric Science

Dr Ailsa Stroud
Department for Environment, Food and Rural Affairs

Previously:
Clare Dove
Department for Environment, Food and Rural Affairs

Dr Charlotte Jones
Department for Environment, Food and Rural Affairs

Acknowledgements

The Air Quality Expert Group would like to acknowledge the following individuals and organisations for their help in the preparation of this report:

Mark Broomfield (Ricardo, UK).

Foreword from the Secretariat

July 2018

At the time of preparing this report, the Department of Energy and Climate Change (DECC) was responsible for UK government's policy on shale exploration. This responsibility now lies with the Department of Business, Energy and Industrial Strategy (BEIS).

This report was compiled based upon an expert assimilation of evidence available in early 2015. Since this time, monitoring activities have been instigated and the site selection strategy for environmental monitoring in connection with shale-gas exploration has been published[1], demonstrating that some of the report recommendations have already been addressed. The wider evidence base has also progressed however, no significant exploration of shale gas with hydraulic fracturing has occurred in the UK at the time of publishing.

In such a rapidly developing area, reports will inevitably be rapidly outdated, but it is important to record and reflect the assessment of AQEG at the time and consider the actions that have been taken since.

---

[1] http://www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/YORKSHIRE.html

Contents

Executive Summary 9

Impacts at the Regional/Local Scales 10

Improving the Evidence Base Associated with UK Shale Resources and Reserves 10

Improving the Projected Emission Estimates 10

Evaluating Potential Impacts on the Local and National Scales 10

Operational Monitoring at the Regional and Local Scales 11

1 Introduction and Context 12

1.1 What is Shale Gas Extraction? 12

1.2 Projected Growth in the UK 12

2 Shale Gas Extraction in the UK 16

2.1 UK Specific Geology 16

2.2 UK Regulatory Framework 16

3 Air Quality Pollutant Emissions 20

3.1 Overview 20

3.2 Emission Estimates 24

3.3 Speciation of Emissions of Non-Methane Hydrocarbons from Shale Gas Extraction 26

4 Monitoring of Gaseous Emissions 29

4.1 Passive sampling (not real-time) point monitoring 29

4.2 Real-time point monitoring methods suitable only for higher concentrations 30

4.3 High accuracy and sensitivity real-time point measurement systems 30

4.4 Integrated-path concentration measurements 30

4.5 Remote atmospheric concentration profiling using Differential Absorption LIDAR (DIAL) 31

4.6 Wide area and regional scale assessment of emissions. 31

4.7 Meteorological measurements 36

4.8 Satellite Measurements of Methane Emissions 36

5 Potential for Ozone Formation 39

6 Conclusions and Recommendations 41

6.1 Quantifying Emissions 41

6.2 Impacts at the National Scale 41

6.3 Impacts at the Regional/Local Scales 42

7 Recommendations 43

7.1 Improving the Evidence Base Associated with UK Shale Resources and Reserves 43

7.2 Improving the Projected Emission Estimates 43

7.3 Evaluating Potential Impacts on the Local and National Scales 43

7.4 Operational Monitoring at the Regional and Local Scales 44

8 References 45

Executive Summary

Recent exploratory studies have indicated that there are significant UK on-shore shale gas reserves which have the potential to be accessed by hydraulic fracturing (commonly known as “fracking”). The objective of this report was to review the available evidence base associated with air emissions from shale gas extraction activities, and draw conclusions regarding the potential for impacts on air quality in the UK. Recommendations have then been made with the aim of supporting policy makers, and ensuring that a suitably robust and comprehensive evidence base[2] is available to support decisions.

However, the growth of shale gas operations in the UK is highly uncertain, depending on (but not exclusively) industry investment, regulation development, climate change, energy and economic policy and geological characteristics. Many of the conclusions are based on applying work from the US to the UK situation, which is very different in both in geology and proximity of extraction activities to people. As a result, recommendations below reflect the current lack of knowledge regarding on-shore shale gas extraction activities and its environmental impacts in the UK context[3].

The Environment Agency are currently undertaking a number of studies which aim to improve the current scientific understanding of emissions and resulting impacts that may arise from future shale gas extraction activities in the UK.

Conclusions

Quantifying Emissions

- Estimates of emissions of air quality pollutants including ozone precursors from activities associated with a single well are uncertain and are affected by many parameters (e.g. geology, regulation, and operating conditions).
- The emission rates of pollutants will vary in different ways across the exploration, production and abandonment life cycle of a well. For example, mobile machinery will give rise to NO_x and PM_{10} during all three phases, but fugitive emissions of CH_4 and VOCs will be primarily during the production phase only.

Impacts at the National Scale

- At the national scale, the widely differing number of wells assumed in different scenarios, and the estimates of emissions per well, impact on the extent to which future emissions can be estimated. However, estimates suggest the following indicative additional emissions expressed as a percentage of the 2012 national totals: 1-4%, 1-3%, 0.1-1% and ~0.2% for NO_X, NMVOC, PM and CH_4 respectively.

---

[2] Broadly consisting of: Projections of the number of wells, typical well lifetimes, geographical distribution, and the emissions to air associated with an individual well in the UK (which requires information on e.g. use of mobile machinery as well as gas leakage).

[3] The term “UK” is used here, but Scotland and Wales currently have a moratorium and ban respectively in place on shale gas extraction by hydraulic fracturing.

Impacts at the Regional/Local Scales

- Impacts on local and regional air quality have the potential to be substantially higher than the national level impacts, as extraction activities are likely to be highly clustered. Studies in the US have shown significant impacts on both local air quality and regional ozone formation, but similar studies have not yet been undertaken for the UK.
- There is a need to substantially improve the currently available evidence base on the potential impacts at the regional and local scales. Some improvements can be made before any on-shore shale extraction activities commence, and once activity starts it will be possible to rapidly collect evidence. Tailored air quality monitoring of O_3, CH_4, NMVOC, NO_x and PM, is required before, during and after shale gas activities to fully characterise the impacts on local air quality and contribute to the evidence base. This will also provide an indication of whether the existing legislative framework is fit for purpose. Furthermore, it can also be concluded that collecting data that supports the evaluation of impacts on regional ozone formation will be important. This evidence base will provide more detailed information on potential impacts that can be used to support planning decisions.

Recommendations

Improving the Evidence Base Associated with UK Shale Resources and Reserves

There is an increasing body of scientific information based on the limited exploratory studies undertaken in the UK. However, the scientific evidence base as a whole is still dominated by studies from the US. It is therefore recommended that studies are undertaken to continue to extend the UK evidence base, and also evaluate the representativeness and transferability of information from the US to the UK. Topics of particular interest are whether the UK geology will give rise to significantly different emissions than those observed in the US.

Improving the Projected Emission Estimates

One of the largest areas of uncertainty is the number of wells predicted to be in operation by different scenarios. Whilst it is not simple to project activity levels, differences between low and high scenarios can currently vary by more than a factor of 20. It is recommended that the impacts on air quality are reassessed as there is improved understanding and the ranges given in different scenarios converge. This will ensure that scenarios are using the most up to date information, which in turn reduce uncertainty.

Emissions per well are affected by many parameters, and it is important to better understand to what extent the UK regulatory framework will deliver effective emissions control. It is therefore recommended that research is undertaken to better characterise the emissions expected per well in the UK, and that the UK specific evidence base is improved before significant on-shore shale gas extraction activities begin.

Evaluating Potential Impacts on the Local and National Scales

Estimates have been made regarding the potential impact of shale gas extraction activities on the national UK emission estimates. However it is currently challenging to assess regional and local scale impacts. This is particularly important, because shale gas extraction activities are expected to be clustered. It is therefore recommended that more research be undertaken into evaluating the potential impact on regional ozone formation and local concentrations of air quality pollutants, and that the UK specific evidence base is improved before significant on-shore shale gas extraction activities begin. Modelling studies that use existing information will provide some understanding of the potential for regional ozone formation. However, a sufficiently improved UK evidence base is only expected to be obtained by studying the establishment and operation of the first commercial wells.

Operational Monitoring at the Regional and Local Scales

The existing legislative framework requires monitoring of CH_4 during shale gas extraction. However, in order to enable evaluation of the impact on local air quality, a full well lifecycle analysis is required for a range of pollutants relevant for a range of issues including health, and agricultural and natural ecosystems. Given the current levels of uncertainty, it is recommended that the monitoring indicated below is implemented:

A range of volatile hydrocarbons appropriate to allow risks to health to be assessed e.g. using a combined indicator and fraction approach (EA, 2005, TPHCWG, 1997);

- Ozone (at the regional scale);
- Products of combustion (e.g. PM_{10}, $PM_{2.5}$, NO_x, NO_2, PAHs).

The development of wide-area atmospheric monitoring strategies requires consideration to ensure that the development provides the most effective contribution to the monitoring of impacts at the regional scale.

1 Introduction and Context

Recent exploratory studies have indicated that there are significant UK on-shore shale gas reserves which have the potential to be accessed by hydraulic fracturing, commonly known as “fracking”.

This objective of this report was to review the available evidence base associated with air emissions from shale gas extraction activities[4], and draw conclusions regarding the potential for adverse impacts on air quality in the UK. Recommendations have then been made with the aim of supporting policy makers, and ensuring that a suitably robust and comprehensive evidence base is available to support key decisions.

1.1 What is Shale Gas Extraction?

Shale gas is a natural gas, mostly methane (CH_4), found in impermeable shale rock. In order to extract hydrocarbons from shale rocks it is necessary to fracture the rock; this technique, called hydraulic fracturing (“fracking”), consists of drilling a well in the shale and injecting water mixed with sand (~5%) and chemical additives (~0.2%) at high pressure to fracture the rock and stimulate the release of hydrocarbons (Mair et al., 2012).

Shale gas extraction is comprised of three stages: exploration, production, and abandonment. Exploration consists of drilling a small number of vertical wells and fracturing them to ascertain the presence of shale gas. Further drilling and fracturing may then occur to determine the economic viability of the shale. The small quantities of gas produced during the exploration phase are commonly flared. The production stage involves the commercial extraction of shale gas, through horizontal wells drilled into the lateral shale reserves. When extraction of the shale gas is no longer economically viable, the well is abandoned by blocking parts of the well with cement to prevent gas leaking to the surface, and the well is then capped.

When considering underground gas resources such as shale gas, it is important to differentiate the terms ‘resources’ and ‘reserves’. Resources pertain to estimates of the amount of gas or oil thought to be contained within the source rock. Reserves refer to estimates of the amount of gas or oil that can economically and technically be expected to be produced from the rock. This requires sufficient understanding of the geology, engineering, and costs of production (DECC 2013a).

1.2 Projected Growth in the UK

The UK has some experience of hydraulic fracturing and horizontal drilling at non-shale gas wells; wells have been drilled onshore in the UK in the last 30 years, some of which have been fractured for improved extraction of resources. Drilling vertical wells onshore then drilling horizontally out to sea has sometimes been more economically viable than building offshore rigs, and has allowed operators to drill in less environmentally sensitive areas. (DECC, 2013a). Conventional gas wells in the UK have been hydraulically fractured since

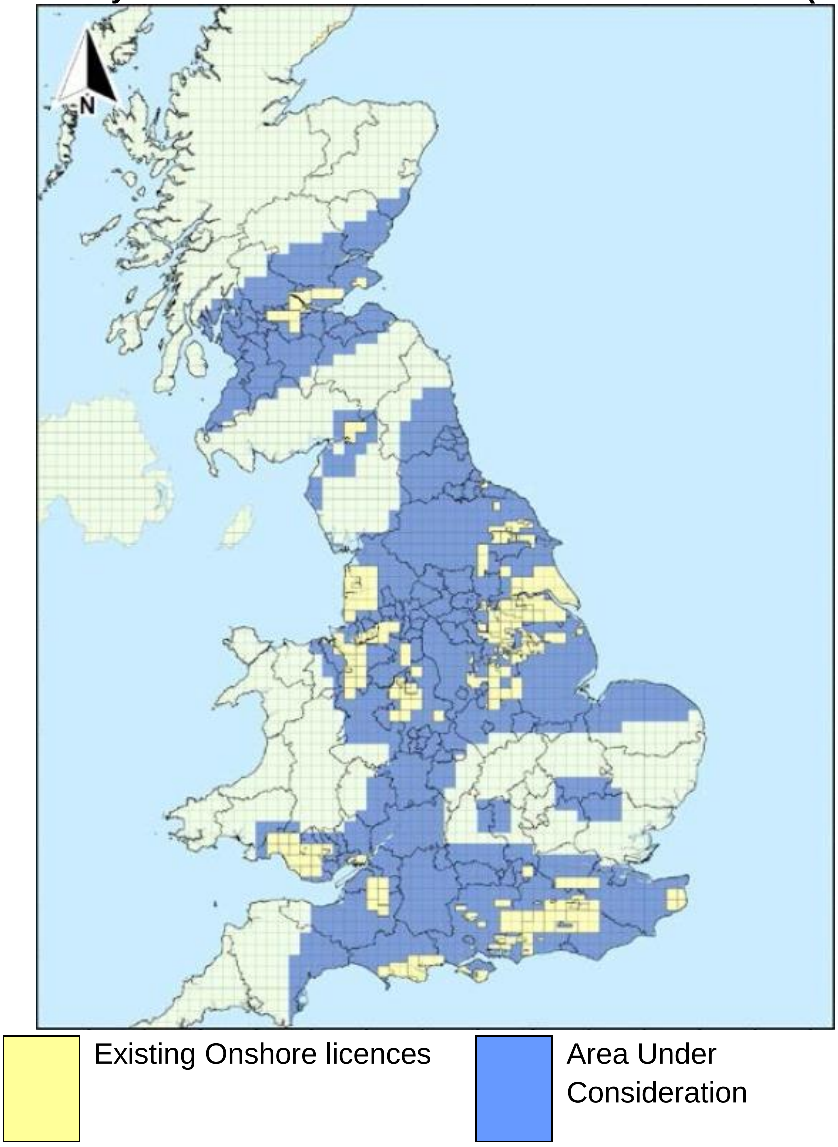
---

[4] Broadly consisting of: Projections of the number of wells, typical well lifetimes, geographical distribution, and the emissions to air associated with an individual well in the UK (which requires information on e.g. use of mobile machinery as well as gas leakage).

the late 1950s (DECC, 2013a) and it is a common method to increase flow rates by decreasing friction, and to prevent the build-up of scale on well walls or corrosion (Mair et al., 2012).

Figure 1.2a below shows the areas of the UK currently licensed and under consideration for onshore licensing (DECC 2013e). Nearly all exploratory drilling for shale gas in the UK so far has occurred in the Bowland Shales in Lancashire, by the oil and gas company Cuadrilla Resources Ltd. The first exploratory drilling took place in August 2010.

Figure 1.2a Currently Licensed Areas and Areas under Consideration (DECC 2013e)



DECC issues ‘petroleum exploration and development licenses’ (PED licences) to operators through licensing rounds. There is distinction between shale gas and conventional hydrocarbon on-shore operations.

Hydraulic fracturing for shale gas extraction is still in the exploratory phase in the UK (Mair et al., 2012), and there is still large uncertainty regarding the future scale of gas production

(DECC, 2013c, e). The British Geological Survey (BGS) studied the Bowland Shales to estimate the resource of shale gas (Andrews, 2013), and generated a central figure of 1,329 trillion cubic feet (tcf). This is a gas in-place estimate, but is high in uncertainty and does not encompass the full resource area of shale in the UK. DECC (2013e) have indicated that, under their high scenario, between 4.32 and 8.64 tcf of gas could be recovered. This total represents up to six times the annual natural gas production in the UK in 2012, which is projected to almost halve by 2030, to 0.68 tcf. Gas imports are expected to increase significantly. The government established the Office of Unconventional Gas and Oil in December 2012 to develop and oversee the UK shale gas industry (DECC, 2013b).

There are currently large uncertainties concerning the projected scale of production activities in the UK. This uncertainty is caused by several aspects, including the technological limitations of efficient shale gas extraction for UK geology, and the effects of UK Government climate change and energy policies (Mair et al., 2012). The commercial viability of shale gas reserves will be determined by geological, as well as many non-geological, factors. A detailed assessment is given in Pearson et al. (2012).

If exploration is successful, substantial contributions to the gas supply of the UK are not expected to be realised until the 2020s (DECC, 2012a).

Projections of shale gas growth in the UK have been made by Regeneris Consulting (2011) for Cuadrilla, for the Bowland Shale region between 2013 and 2028, and more recently by DECC (2013e) and Ricardo-AEA (2014). These projections are summarised in the Table 1.2a below. This illustrates the uncertainties involved in estimating future well numbers, and the evolution of estimates with time – scenarios varying by two orders of magnitude.

Table 1.2a Projected Well Numbers for Shale Gas Extraction

Source	Scenario	Well numbers	Well lifetime (years)
Regeneris Consulting (2011) [1]	Low	190	6
	Central	400	9
	High	810	16
DECC (2013) [2]	Low	180 – 360	20
	High	1440 – 2880	20
Ricardo-AEA (2014) [3]	No refracturing[4]	2970	20
	Re-fracturing of 50% of wells[4]	2592	20
	Low	580	10 - 40
	Mid	3100	10 - 40
	High	12500	10 - 40

[1] Regeneris Consulting. 2011. Economic Impact of Shale Gas Exploration & Production in Lancashire and the UK.

[2] DECC, 2013a. Onshore oil and gas exploration in the UK: regulation and best practice (England).

[3] Ricardo-AEA 2014

[4] Reported in Ricardo-AEA 2014, scenarios are “resource based” estimates from the Tyndall Centre.

However since these estimates, the Scottish and Welsh Governments have decided to stop activities associated with hydraulic fracturing for shale gas extraction:

- Scotland: A moratorium is now in place on all unconventional shale oil and gas extraction, including hydraulic fracturing, issued in 2015.
- Wales: A ban on shale gas hydraulic fracturing was issued in 2015.

2 Shale Gas Extraction in the UK

2.1 UK Specific Geology

The large increase in shale gas production in the United States has brought many economic benefits; a dramatic drop in domestic gas prices, a boost to their manufacturing industry, and an increase in energy security (Mair et al., 2012). However this growth in production occurred due to a unique set of conditions that may not be able to be replicated in the UK, and the Energy and Climate Change Committee concluded that shale gas was unlikely to be a “game changer” in the UK (ECCC, 2011).

First and foremost, the geology of the UK has some significant differences to the geology of the US. Basins of shale rock in the UK are smaller and much more fragmented than in the US, and tend to contain less gas at lower pressure (Anscombe, 2014). The clay content of UK shale is higher, making it harder to fracture (Stevens, 2012), and the depth at which shales are located and thickness of the shale tends to be greater than in the US, which could impede extraction (Andrews, 2013). The Bowland trough is located approximately 1700-3100m below the surface, and has a thickness of over 800m (Stevens, 2012); by comparison, shales in the US are typically a few 100m below the surface (although can be over 1000m), and only a few 100m thick (Kresse et al., 2011). The additional effort to extract gas from deeper shale beds may cause greater emissions from machinery in the initial exploration stages, leading to higher NO_x to non-methane volatile organic compounds (NMVOCs) air emissions ratios in the UK when compared to the US, and similarly for NO_x to CH_4 ratios.

Complex, branching fractures are desirable in the industry, to maximise the volume of gas that will flow out of the rock, and complexity is influenced through operational and natural means (Stevens, 2012). However, should discontinuities between layers exist in the Bowland Shale area, this would be likely to reduce growth of fractures, reducing the amounts of gas recoverable.

In short, the UK specific geology means that the extraction methods need to be different to those utilised in the US, and will be more technically challenging.

2.2 UK Regulatory Framework

2.2.1 Overview

The regulatory framework in the UK for shale gas is the same as for conventional gas. Ownership of hydrocarbons is conferred on the state, so operators must bid for PED licenses from the UK Government’s Oil and Gas Authority (OGA) to obtain exclusive rights to an area. This is a notable contrast from the US, where landowners have rights to the hydrocarbons beneath their land and have exploitation rights. Gaining a PED licence does not give immediate consent for drilling; operators must obtain planning permission from the Minerals Planning Authority, which may stipulate the need for an environmental impact assessment. An environmental permit also needs to be obtained from the Environment Agency (EA). The Health and Safety Executive must be notified by the operator at least 21 days before drilling commences, to allow inspection of the well design to ensure control measures are in place. Final consent is then sought from DECC, who introduced the requirement for a Hydraulic Fracturing Plan (HFP) as part of the required planning process (DECC, 2013b). A detailed overview of this process can viewed at DECC's Regulatory Roadmap (DECC, 2013a).

The Infrastructure Act (2015) introduced several regulations which relate to unconventional shale gas extraction activities in England and Wales. Notably, it cedes companies the right to use 'deep-level land' (at least 300m below the surface) without needing permission from the landowner. The Act requires an application for unconventional shale gas extraction to meet 11 criteria, among which are to publish results of monitoring of methane emissions for the period of the permit, and for local planning authorities to consider cumulative effects of other applications. In addition, the Environment Agency takes account of impacts from other sources of air pollution in a given locality when determining permit applications for individual sources.

In addition to the statutory bodies outlined above, the industry is governed by over a dozen pieces of European legislation. It has been criticised by some (Mair et al., 2012; UKOOG, 2013a) as being overly-complex and unwieldy due to the number of different organisations involved. The establishment of the Office of Unconventional Gas and Oil was part of efforts to streamline the regulatory process, but responsibilities are still assigned to several government departments (EAC, 2014).

The UK has a risk-based proportionate approach to regulation that is designed to reduce, minimise and render harmless pollutant discharges. This means that that regulators set out the requirements which operators need to meet, and operators are then responsible for choosing the means to meet these requirements (Mair et al., 2012). The Environment Agency's regulatory regime covers several "environmental performance measures", which include compliance with standards for discharges and ambient concentrations, and reference to common control options based on Best Available Techniques" for an industry sector. As a result, the overall process has the potential to incorporate continuous improvement and innovation adopted by operators.

One of the recommendations of Mackay and Stone (2013) was that "shale gas exploration and production in the UK should be accompanied by careful monitoring and inspection of GHG emissions relating to all aspects of exploration, pre-production and production." A similar conclusion can be reached regarding air quality pollutants and ozone precursors, in that monitoring is required to evaluate emissions which have the potential to impact on human health, ecosystems or ozone formation. Given that none of the ambient monitoring stations in the current national networks are well placed for baseline monitoring of shale gas extraction activities, additional monitoring will be required (see section 4.6).

The regulatory framework in the UK is considered to be more stringent than that of the US (EAC, 2014; UKOOG, 2013a). However, as no commercial wells have yet been established in the UK, it is not yet possible to determine the effectiveness of UK regulations on mitigating emissions, or whether the development of new legislation may be appropriate.

Shale gas extraction activities are expected to be highly clustered. From the perspective of health impacts, emissions from the first well to start operating in a given location may not be significant. However, an additional well cited close to several wells that are already operating may mean that the cumulative health impacts become significant. The risk-based approach to regulation does provide the regulator with the ability to consider the impact of each new well in a given location, rather than being required to apply common environmental performance measures across the sector.

2.2.2 Fugitive Emissions

Concerns over fugitive emissions from shale gas extraction are primarily associated with CH_4 and NMVOC escaping during the fracturing process, and there have been numerous reports on such emissions from extraction activities in the US (EAC, 2014). Bond et al (2014) conclude that estimates of CH_4 emissions from fugitive sources vary greatly, and recommend that more work is undertaken to better evaluate the likely emissions from this type of source. Field et al (2014b) concluded that fugitive emissions were the largest sources of NMVOC in the Upper Green River Basin of Wyoming.

CH_4 is also released naturally from peat deposits and alluvium soils, so it is important that monitoring is carried out before, during, and after shale gas operations in order to determine the leakage that has arisen from the extraction activities (Mair et al., 2012).

2.2.3 Flaring and Venting

CH_4, NMVOCs, PM and NO_X may also be released through flaring or venting in certain circumstances. Gases may be flared for safety reasons to avoid build up, or if it is not economically viable to connect a pipeline to the national grid (UKOOG, 2013b) in cases where small volumes of shale gas are found within shale oil fields. Flaring and venting are tightly controlled by the OGA through the conditions attached to the operator’s PED licence, as well as controls enforced by the HSE under the Borehole Sites and Operations Regulations 1995 (BSOR) and Offshore Installations and Wells (Design and Construction) Regulations 1996 (DCR) (HSE, 2012). DCR applies to all wells drilled to extract petroleum (which includes shale gas) regardless of whether they are offshore or onshore. Local authorities are responsible under the Environment Act (1990) for inspecting sites for odour and noise associated with the flaring or venting of gas. Local authorities also have a statutory duty under the Air Quality Standards Regulations 2007 to monitor emissions to ensure that they do not breach local air quality standards.

2.2.4 Reduced Emissions Completions (REC)

US Environmental Protection Agency (US EPA) regulation requires reduced emissions completions for hydraulic fracturing of all shale gas wells from the start of 2015 onwards (EPA, 2012a). Hydrocarbon liquids and gases are separated from the flowback fluid and are then directed into holding condensate tanks or into pipelines (low-pressure wells have been made exempt due to technical infeasibility, but technologies are being trialled to overcome the pressure drop). The US EPA estimates that these measures will reduce NMVOCs emissions by 95% (EPA, 2012b).

Currently, there is no such requirement in the UK. The UK government did however accept the recommendation by MacKay & Stone (2013) that reduced emissions completions should be adopted at all stages following exploration (DECC, 2014b). This will be implemented through the requirement of Best Available Techniques (BAT), and the Environment Agency considers reduced emissions completions to fall under this definition. Furthermore Mackay & Stone (2013) recommended that a long-term monitoring programme be established to estimate emissions arising from shale gas extraction. The Department of Energy and Climate Change have accepted the recommendations and plan to establish a programme of CH_4 monitoring.

3 Air Quality Pollutant Emissions

3.1 Overview

Shale gas is often referred to as natural gas produced from shale, reflecting the similar chemical composition. Direct emissions associated with the combustion of shale gas, whether at the point of extraction or by a retail consumer, are therefore assumed to be similar to those from natural gas obtained from conventional sources. However differences in emissions may arise at the point of extraction, due to differences in the extraction and production processes. Emissions have been identified from the following source groups (PHE, 2013; Regeneris, 2011):

- Mobile machinery used for drilling and hydraulic fracturing operations
- Compressors used to capture and transport gas
- Venting and flaring
- Fugitive emissions
- Transport of materials to and from the site

Emissions from these sources will vary on a site by site basis. Some sources may be intermittent, and others more continuous. If best practices are adhered to and the site is well-regulated, then on-site sources are typically small compared to e.g. a large industrial installation, (PHE, 2013). However, it is possible for selected activities at some sites to give particularly high levels of emissions, and result in a so called “super emitter” site. But there is very little quantitative information that can readily be applied to the UK situation to characterise the likelihood of this arising within the UK regulatory framework.
Table 3.1a provides an overview of potential pollutants and their sources.

Table 3.1a: Air quality pollutants from shale gas operations

Pollutant	Source	Potential Consequences
Non-methane volatile organic compounds (NMVOCs)[5]	Fugitive emissions from drilling, during the extraction process, storage, venting and capped wells. Flaring and use of mobile machinery.	O_3 formation and health impacts.
Nitrogen oxides (NO_x)	Flaring, mobile machinery usage, gas processing, freight vehicles.	O_3 formation and health impacts.
Methane (CH_4)	Leakage from well exploration, extraction and abandonment activities.	O_3 formation.
Particulate matter (PM)	Suspension of bulk materials handling, flaring, mobile machinery, suspension/ resuspension from freight vehicles.	Health impacts.
Sulphur compounds	Drilling, flowback phase and flaring.	Health impacts and odour nuisance.

---

[5] The majority of natural gas leakage is CH_4, with NMVOCs accounting for a small percentage.

Organic compounds	Chemicals added to hydraulic fracturing fluids, flowback phase.	Health impacts.
Secondary PM	Oxidation of NO_x and NMVOCs from mobile machinery.	Health impacts.
Ozone	Hydrocarbons and NO_x from mobile machinery and vehicles are the precursors for ozone formation.	Ecosystem impacts and health impacts.

Several quantitative assessments of risks to public health, arising from the emission of pollutants, in areas of shale gas extraction have been reviewed by PHE (2014).

Cuadrilla's development scenarios for shale gas extraction through hydraulic fracturing in the UK are outlined in a report by Regeneris Consulting (2011), summarised in Section 1.2. The report also details the length of time each stage might be expected to last for UK test operations, which is necessary to understand the potential for air pollutant emissions. These are summarised in the following paragraphs.

3.1.1 Exploration

Test well are drilled and fractured to assess the viability of the well. There is the potential for fugitive emissions of CH_4 and NMVOCs at this stage, however the quantities of gas extracted are typically small compared to the production stage, and flaring is used to control emissions (although creating NO_x and PM emissions).

3.1.2 Production - Site Preparation

Site preparation can take between 4 and 8 weeks to complete, and this is very weather dependent. This involves the insertion of an impermeable membrane, surface drainage ponds (if allowed under UK legislation), landscaping, and preparation of the hard standing from which the drilling would occur.

Emissions from this stage are mostly NO_x and PM from large diesel-powered vehicles used during site preparation, construction, and the transport of water and sand to and from the sites. NO_x, PM and NMVOCs are emitted from diesel powered site machinery; drill rigs, generator engines, pumps, and compressors (Moore et al., 2014, Field et al 2014a).

3.1.3 Production - Drilling

Before the drilling rigs arrive on site, the top soil and gravel deposits below the ground surface are removed via water-well drilling techniques. A cement collar is then inserted. The main drilling rig is then brought to the site and assembled in a week. In the US, drilling lasts for approximately 8 weeks. However, the duration of drilling is dependent on depth and geology, and therefore this may not be representative for the UK situation. Throughout this drilling programme extensive daily deliveries and removals are necessary to provide the essential materials (such as cement for sealing the well from the freshwater zone) and to remove the debris and waste. This stage can result in emissions of NO_x and PM from freight vehicles, diesel powered mobile machinery, and CH_4, NMVOCs and sulphur compounds from the drilling activities.

3.1.4 Production – Hydraulic Fracturing

For a typical well in the US, perforation and hydraulic fracturing of the well typically begins 3-4 weeks after the well has been drilled, and can take 2-3 weeks for test wells, and longer for full commercial extraction wells. This involves the pumping of water, sand and chemical additives at extremely high pressure into the bore hole, causing the shale to fracture and enabling the gas to flow more easily from rock to well. An 8 week period of testing and monitoring typically follows, where gas levels are monitored for production and safety reasons.

CH_4, NMVOCs, sulphur compounds, and other organic compounds can be emitted during the fracturing and flowback phase, the handling of drilling fluids and waste (Field et al, 2014a).

NO_x and PM are emitted from diesel powered mobile machinery and freight vehicles transporting material to and from the site throughout the gas production phase. On-site electrical generation can emit NO_x, flaring and venting can emit NO_x, SO_2, CH_4, PM and NMVOCs.

3.1.5 Production – Gas Extraction, Processing and Separation

When production starts from the well, infrastructure is necessary to deliver the gas into the UK energy network (or in some cases operators may choose to use the gas on site, for example as a chemical feedstock). Transporting the gas can be done by constructing additional pipelines to connect the site to the UK gas network, or by generating electricity on site and connecting this to the national grid, which would lead to long-term emissions of NOx, PM and NMVOCs. Both methods require significant machinery and labour, which will increase as the number of wells in one site increases. NO_x, PM, and NMVOCs can be emitted during the construction of this infrastructure, and from mobile machinery and freight vehicles required during the operational lifetime of the well (average of 9 years (Regeneris, 2011)).

Field et al (2014b) studied VOC concentration data in the Upper Green River Basin of Wyoming. Three contributing source types were identified: combustion sources (including road vehicles), fugitive emissions from gas and fugitive emissions from condensate. Fugitive emissions from natural gas and condensate were the two principal emission source types for NMVOC. A water treatment and recycling facility was found to be a significant source of NMVOC.

Warneke et al (2014) also concluded that fugitive emissions were the main source of NMVOC, but were able to identify more specific sources. Following measurements close to different types of well pads, it was concluded that gas well pads with collection and dehydration on the well pad were clearly associated with higher emissions than other wells. The main NMVOC source categories from individual point sources were fugitive emissions from sources such as: dehydrators, condensate tank flashing (when condensate is pumped at high pressure into a tank) and pneumatic devices and pumps.

3.1.6 Abandonment

When extraction of the shale gas is no longer economically viable, the well is abandoned by sealing parts of the well with cement to prevent gas leaking to the surface, and the well is then capped. Given that the well head is capped because little gas is able to be recovered, fugitive emissions from abandoned wells are expected to be small. However, to date measurement studies in the US have focused on measuring emissions from active wells.

3.1.7 Emissions

The quantities of NO_x and VOCs emitted at each stage vary substantially in the US between different sites (see Section 3.1). Bond et al (2014) concluded that fugitive emissions of CH_4 from leaks are one of the largest sources of CH_4 from site operations, and pose a particular challenge with regards to control or mitigation. This Scotland specific study also noted that undertaking activities on peatland, such as cutting into the peat surface to lay a drilling pad, is likely to give rises to releases of CH_4 from the peat itself.

3.1.8 Resource Requirements

In the US, the activities prior to gas production (see steps 1-4 above) can take up to 6 months to complete. In the UK, in order to obtain suitable permits, additional activities may be required (such as groundwater monitoring). This could significantly extend the time needed for activities before gas production (although Cuadrilla anticipate efficiencies will emerge as the shale gas industry grows in the UK). DECC's environmental report on the strategic environmental assessment for further onshore oil and gas licensing (2013e) set out low and high development scenarios, including vehicle movements per well, the volume of water used, and the volume of flowback fluid.

Table 3.1b: Vehicle Movements per well under DECC's development scenarios (DECC 2013e)

Resource	Low	High
Total truck visits[6]	1,176	3,876
Water volume (m^3)	10,000 – 25,000	
Flowback fluid volume (m^3)	30-75% of water injected	

The volumes of water and chemical additives suggested by DECC are higher than estimates of usage in the US (Broderick et al., 2011), suggesting air pollutant emissions may be higher from the fracturing stage. In addition, more journeys are necessary for vehicles transporting material to and from the site, also resulting in higher air pollutant emissions.

The Environment Agency performed a chemical analysis of the flowback fluid from Cuadrilla's exploratory drilling at Preese Hall. They reported detection of notably high levels of arsenic, chromium, bromide, sodium, chlorine, iron, lead, magnesium, and zinc, and low

---

[6] The sum of vehicle movements per well during exploration drilling and fracturing, and during production development.

but significant levels of naturally occurring radioactive materials (Environment Agency, 2011). This is a significantly shorter list of pollutants than found in US sites, where disclosure of chemical additives and flowback composition are not required (Broderick et al., 2011). The analysis method is not disclosed in the report, but it is assumed that these species are not volatile and therefore are not released into the air.

3.2 Emission Estimates

3.2.1 Emissions Data from the US

The extensive shale gas extraction activities in the US mean that the global evidence base on the potential for air quality pollutant emissions is very much dominated by research and measurement undertaken on US shale gas operations. As there are no active wells in the UK, it is necessary to draw on the US evidence base, even if it is recognised that there may be substantial differences in the emissions characteristics.

A number of emission inventories from shale gas operations in the US have been estimated. Grant et al. (2009) made emission estimate projections for 2012 of NO_x and NMVOC from shale gas activities in the Haynesville Shale in the Texas/Louisiana region, reporting a central figure of 74 and 14.5 tonnes per day (TPD) respectively, for 830 active wells. The study also projected emissions for low, moderate and high scenarios for every year up to 2020. By 2020, they predict 9706 active wells in the moderate scenario, with corresponding emissions of 115 TPD of NO_x and 32 TPD of NMVOCs i.e. considerably lower emissions per well.

The most significant source categories for NO_x in 2012 were drill rigs (67%) and midstream compressor stations (CS) and gas processing plants (GP) (31%). The proportion of emissions from midstream CS and GP increased up to 2020, as did emissions from heaters. Drill rigs (43%), pneumatic devices (8%), midstream CS and GP (36%), and completion venting (11%) were the four most significant sources of NMVOCs in 2012, with the proportion of emissions from pneumatic devices increasing up to 2020. Midstream CS and GP includes the transportation and processing of shale gas produced from the wells.

However this study only included machinery or equipment concerned with drilling, fracturing and gas recovery activities. Freight vehicles making journeys to and from the site were not included. For a detailed methodology of these emission estimates including emission factors and operating hours, see Grant et al. (2009).

Armendariz (2009) estimated an emission inventory for the Barnett Shale region in north Texas in 2009, which comprised approximately 7,700 wells, a small proportion of which were oil wells. The results are summarised in Table 3.2a, and contrasts the results of Grant et al. (2009) by suggesting emissions of NMVOCs will be greater from shale gas operations than emissions of NO_x.

Table 3.2a: Annual average emissions from the Barnett Shale region in 2009.

Source category	NOx (TPD)	NMVOC (TPD)

Compressor engines	42	17
Condensate tanks	0	32
Production fugitives	0	24
Well drilling, fracturing, well completions	5	19
Processing fugitives	0	14
Transmission fugitives	0	25

Robinson (2012) estimated emissions for approximately 1,300 wells in 2009 in the Marcellus Shale region. 64 TPD of NO_x, 63.5 TPD of NMVOC, 1.8 TPD of PM, and 1 TPD of formaldehyde were estimated. The main sources of NO_x were emissions from freight vehicles and drilling infrastructure, whereas completion venting and condensate tanks were the main sources of NMVOCs. Compressor stations were the main source of formaldehyde, and freight vehicles, drill rigs, and fracturing pumps were the main sources of PM.

On a per well basis, Grant et al. (2009) estimate NO_x emissions to be 0.1 TPD, and NMVOC emissions to be 0.02 TPD. Armendariz (2009) estimates NO_x emissions to be 0.006 TPD, and NMVOC emissions to be 0.02 TPD. Robinson (2012) estimates NO_x and NMVOC emissions to be approximately 0.045 TPD each, and PM emissions to be 0.002 TPD. These estimates vary due to the operating conditions, local geology, and production rates.

Litovitz et al. (2013) used a variety of data sources and estimation methods to estimate total annual emissions for shale gas development and production in the US state of Pennsylvania, and the results ranged between 2,500-11,000 tonnes of NMVOCs, 17,000-28,000 tonnes of NO_x, and 460-1400 tonnes of PM, for 1741 wells. Transport-associated NMVOC emissions were estimated to have the smallest range for NMVOCs (31-54 tonnes), and compressor stations the largest (2,200-8,900 tonnes). The wide range of potential emissions was due to the different operating conditions of sites; some were operating below capacity, some had frequent shut-downs and start-ups.

The Department of Environmental Protection of Pennsylvania reported emissions from shale gas production and processing in 2011 (DEPP, 2013), covering 57 well operators, 40 midstream operators, and 150 compressor stations. They estimated 15,007 tonnes per year (TPY) of NO_x, 2,558 TPY of NMVOCs, 523 TPY of PM10, 458 TPY of PM2.5, and 111 TPY of SO_x. These levels of NMVOCs and NO_x contributed 13.8% and 8.6% respectively to emissions from stationary sources for Pennsylvania.

3.2.2 Emission Estimates for the UK

Using scenarios provided by DECC (2013e), average annual fugitive CH_4 emissions per well have been calculated as a percentage of the UK’s 2012 CH_4 emissions from natural gas distribution. The results indicate a contribution from shale gas hydraulic fracturing to the national methane emissions total[7] of 0.001% per well per year. However the wide variation in the predicted number of wells for different scenarios (see Table 1.2a) means that the resulting emission estimate from the total number of wells shows particularly wide variation – summing to a potential contribution of between approximately 0.2% and 1% of the UK 2012 CH_4 national emissions total. It is also possible to express the emissions as percentages of the CH4 emissions arising from gas distribution, to provide some context. The CH4 emissions equate to potential contributions of approximately 2% to 20% of the CH4 emissions from gas distribution.

Using available US data, average annual emissions for one well have been calculated and scaled using the number of wells in Cuadrilla's medium scenario (400 wells) for the UK. These have been converted to a percentage of the UK's 2012 total emissions per pollutant. Emissions of other air quality pollutants are also high in uncertainty. Best estimates suggest that emissions associated with shale gas extraction could contribute the following amounts to the national totals:

- NO_x : an additional 1 - 4% of the national total emission.
- NMVOC : an additional 1 - 3% of the national total emission.
- PM : an additional 0.1 - 1% of the national total emission.
- CH_4 : an additional 0.2 – 1% of the national total emission.

These should be considered as indicative estimates, as there are high uncertainties associated with the calculations, and numerous parameters that would impact on the results. The emissions from shale gas extraction are expressed here as a percentage of the 2012 UK emissions, and this does not take into account how emissions will change in future years. For example, the increased availability of gas from shale gas extraction may cause significant reduction in other emission sources associated with the energy sector.
The majority of the NO_x and a proportion of the PM emissions will come from mobile machinery and so will be regulated by European legislation. However, the emissions of NMVOC, CH_4 and a portion of PM will predominantly arise from fugitive sources, and so would not currently be regulated.

Furthermore, it is important to recognise that considering emissions as a fraction of the national total does not represent the potential local impacts on air quality. Shale gas activities are expected to be concentrated in specific regions of the UK, and would therefore be located in clusters. This would concentrate the impacts on air quality in specific locations, and it would therefore be important to monitor the impacts by implementing measurement programmes.

3.3 Speciation of Emissions of Non-Methane Hydrocarbons from Shale Gas Extraction

Non-Methane Hydrocarbons (NMHC) are a subset of NMVOC. Measurement techniques exist to provide chemical speciation of NMHCs, whereas NMVOC is more commonly measured as a total value.

---

[7] Including land use, land use change and forestry

The speciation of NMHCs emitted from hydraulic fracturing activities has a very significant impact on the air quality and health impacts of the emissions. The composition of NMHC emissions to air from shale gas extraction activities is complex to determine, since it is dependent on not only the original composition of the fossil fuel reserve, but also any selective fractionation arising from onsite processing, leakage or storage. There are also NMHC emissions from combustion activities associated with site machinery.

Ethane and propane are the two most significant NMHC emissions observed from US shale gas extraction activities to date in terms of mass emissions, with smaller contributions from higher alkanes and mono-aromatic compounds. Although benzene is the only observed NMHC emission that is directly regulated by the European Union directive on ambient air quality, a range of NMHCs are health-relevant (TPHCWG, 2007)), and high levels of secondary species such as formaldehyde are possible following oxidation. Gillman *et al*, (2013) reported a set of emission ratios relative to propane (ERpropane, reported in units of ppbv [ppbv $C_3H_8]^{-1}$) for 18 different C2- C8 NMHCs, based on near field observations made in proximity to the Wattenberg Field in Colorado. Table 3.3a reproduces those emissions ratios. Gillman *et al*, also highlighted how changes in ratio of various NMHC to acetylene (overwhelmingly released from combustion sources) can act as a marker for air masses impacted by shale gas extraction activities. From this Gillman *et al* made source contribution estimates for the Colorado region.

Warneke *et al* (2014) reported on emissions of a range of higher hydrocarbons (>C6) released from different components of the extraction processes for fields in the Uintah Basin, Utah. The instrumental technique used was targeted at benzene and higher mono-aromatic species and summed classes of higher alkane. This work reported ambient benzene mixing ratios sporadically at values up to 10 ppb, and demonstrated that both the total emission of >C6 VOCs and the speciation of that emission, varied significantly dependant on the operating conditions of the extraction and storage facility.

Table 3.3a. Emission ratios of NMHCs relative to propane for the Wattenberg Field, Colorado, adapted from Gilman *et al*, 2014, **47**, 1297-1305, *Environmental Science and Technology*

Species	**Emission ratio ERpropane (ppbv [ppbv C_3H_8]$^{-1}$)**
ethane	1.090
propane	1
i-butane	0.243
n-butane	0.563
i-pentane	0.168
n-pentane	0.190
n-hexane	0.0348
n-heptane	0.0087
methylcyclopentane	0.028
cyclohexane	0.0062
methylcyclohexane	0.0074
Benzene	0.00428
Toluene	0.0038
m- and p-xylenes	0.00099
o-xylene	0.00026
acetylene	0
ethene	0.0025
propene	0.0001

4 Monitoring of Gaseous Emissions

The 2012 Environment Agency report entitled “Monitoring and control of fugitive methane from (onshore) unconventional gas operations” provides a technical outline of the industrial processes involved in the extraction of methane gas from hydraulic fracturing, indicates the potential sources of leakage of methane and other gases to atmosphere, and gives monitoring techniques and control methods that can be employed during the different operating parts of the industrial process. These monitoring requirements will change over time and may require different approaches to be carried out. For example:

Prior to drilling it is essential to characterise the background levels of methane and possible other gaseous pollutants that may be emitted during operations;

- During drilling and production, fugitive emissions and leaks should be monitored within a leak detection and repair programme, with fence-line and other measurements;
- After closure of the well, methane monitoring should be carried out as part of the maintenance programme.

To achieve these aims, a co-ordinated approach is needed that is expected to draw on a range of different measurement techniques, each tailored to e.g. characterising background concentrations, perimeter fence monitoring, leak detection etc. These activities will require not inconsiderable resources. Some relevant measurement methods are summarised below.

4.1 Passive sampling (not real-time) point monitoring

Several passive monitoring methods are available. These include:

1. Passive diffusive samplers that are deployed in the open atmosphere upwind and downwind of the emissions, often on the fence-line. These are usually based on metal tubes filled with sorbent, from which the gases can be thermally desorbed and analysed in a laboratory. They can measure the ambient concentrations of a wide range of volatile organic compounds (VOCs), but they need to be exposed for typically one week to achieve the required sensitivity, depending on the atmospheric concentrations. The average concentrations over these exposure periods are therefore determined. Different sorbents can be used depending on the species of interest. In general each sorbent is practical for a limited range of VOC molecular size, such as C4 to C10, or C6 to C13. There are no sorbents suitable for C3 and lighter compounds.
2. VOCs, including lighter compounds such as methane, can be measured by sampling the atmosphere into stainless steel canisters, as specified by the US EPA for fugitive releases from shale gas and other applications. Tedlar bags may also be used for sampling, to provide more samples at reduced costs. These produce time-resolved snapshots of concentrations at specific locations. These are analysed in the laboratory by gas chromatography, or by gas chromatography coupled with mass spectrometry. This is a simple technique for carrying out an atmospheric survey at ground level over an industrial site and its environs.

4.2 Real-time point monitoring methods suitable only for higher concentrations

Portable flame ionisation detection units and catalytic combustion analysers, can be used to detect leaks from components, which are generally at much higher concentrations than the ambient concentrations discussed above.

Portable remote infrared imaging systems are very efficient at identifying major leaks. Such systems are becoming popular for leak detection within the gas industry, and are being used systematically to check individual valve fittings etc. They operate in real-time to detect leaks of methane and other VOCs, semi-quantitatively, and the results are displayed on a screen that allows the operator to pinpoint the leaks in a manner that is similar to a hand-held video camera. They have limitations in some weather conditions.

4.3 High accuracy and sensitivity real-time point measurement systems

There are at least two techniques suitable for in-situ point measurements in the field, with both high accuracy and high time resolution:

1. High-sensitivity cavity-ring down spectrometers for the simultaneous measurement of methane and three key greenhouse gases are commercially available. They have very high spectral resolution and hence are selective to methane or other specific gases. They can be used to obtain mobile transects of the concentrations around an industrial site, or within its boundaries. They provide the most accurate and sensitive measurements of methane currently available, and can also be used for calibrations of other monitoring systems.

2. Tuneable diode laser infrared absorption spectrometers have also been developed for a wide range of scientific and commercial applications. They have high sensitivity, rapid response speed, and are completely selective to the target gas, though they can only readily monitor one gas in each specific configuration. They can be operated unattended for extended periods.

4.4 Integrated-path concentration measurements

Integrated-path concentration measurements have some limitations for determining the total emitted fluxes from an industrial site because they have only a limited capability to monitor concentrations above the height of their optical beams, which are generally near ground level. Nevertheless, they are capable of integrating path lengths of more than 100 meters, and hence have better capabilities for intercepting fugitive emitted gases than point detection systems. The two types of integrated-path systems are:

- Open path Fourier-transform infrared spectrometry (OP-FTIR), which covers a large spectral range in the mid-infrared with an integrated path-length that may be greater than 100 metres. Atmospheric methane is readily and sensitively monitored. Its main advantage is that is has the wide spectral coverage that enables a large range of

gaseous species to be monitored simultaneously. It is not readily amenable to unattended use.
- Open-path tuneable diode-laser absorption spectroscopy (OP-TDLS). This is based on the same technology as discussed above, which can be configured in open-path mode, with path-lengths up to a few hundred metres. It has high specificity and detection sensitivity, and is more capable of unattended operation.

Both methods have the source and detection system at one end of a chosen open path and an optical retro-reflector at the other. They can be deployed downwind of the industrial site, or can also be used for radial or vertical plume mapping, where the technique can either be:

- Scanned horizontally upwind and downwind of the potential sources on the site; such data, being time resolved, this enables the quantification of the largest sources as a function of the plant operations;
- Scanned vertically to retro-reflectors at different heights on masts or towers, to give vertical concentration profiles, which, when combined with appropriate meteorological data, give the emitted fluxes from a selected area of the site.

4.5 Remote atmospheric concentration profiling using Differential Absorption LIDAR (DIAL)

This technique uses high energy pulsed tuneable lasers that operate in the infrared and ultraviolet spectral regions, where many atmospheric pollutant gases absorb. Operating LIDAR (light detection and ranging) at different wavelengths (DIAL) allows different gases to be monitored in the atmosphere from the same system, without the use of any retro-reflectors - the lasers are of sufficient energy that the atmosphere itself acts as the “mirror” at all distances. Spatially-resolved data are derived using the time of flight of the reflected pulses. Range-resolved concentration profiles of the selected gases are therefore measured in any direction that can be scanned by the laser. These can provide:

- Concentrations of the atmospheric emissions within a down-wind vertical plane, which, when combined with suitable meteorological measurements, allow the emitted fluxes of the selected gases to be determined directly, without any modelling requirements;
- Two or three dimensional concentration profiles of methane or other gases in the atmosphere, allowing the major sources and leaks to be located and quantified. These may then be investigated in detail using the other techniques listed above.

Although this is a relatively expensive technique, it is often used to investigate challenging industrial emission issues. For hydrocarbons and other species of interest at shale gas extraction sites the range of the technique is about 800 metres.

4.6 Wide area and regional scale assessment of emissions.

Earlier sections 4.1 to 4.5 show that a range of different measurement techniques exists to monitor the concentrations of CH_4 and NMVOCs from shale gas extraction at individual operating sites and other potential point sources of emissions. Whilst this type of surface ambient concentration information is very valuable for the assessment of localised air quality or health effects, such data does not easily provide a direct estimate of the rate of emissions from specific activities or emissions averaged over geographic region. Emissions from the extraction process are likely to be controlled and subject to permit, however establishing compliance will be particularly challenging, since emissions may be diffuse and released over a relatively wide geographic area, in contrast for example to a stack emission. Alternative methodologies are required that can estimate emissions over wide geographic scales.

The current national network of automatic NMVOC measurements is likely to be wholly inadequate for the assessment of wider shale gas impacts, if these expand in the UK. The number of stations is very limited, monitoring is focussed on urban locations, and there are no measurement locations capable of measuring the likely dominant alkane emissions of ethane, propane or butane close to likely shale gas extraction sites[8]. The national automatic NMVOC measurement network is complemented by non-automatic measurements at numerous sites. However these are also typically positioned in urban locations, and a small number of industrial locations.

The assessment of wider UK impacts and emissions will therefore likely to require bespoke monitoring activities that can quantify the source strength and distribution of emissions from shale gas extraction activities.

DECC is currently establishing background levels of air quality at proposed extraction sites in Blackpool and Vale of Pickering. These assessments will determine a climatology of methane, NO_2, $PM_{2.5}$, O_3 and NMHCs as well as a range of other water quality and geophysical properties.[9]

Depending on the characteristics of the gas reserve, and the details of the operation, monitoring of other pollutants might also be appropriate, for example chemicals used (or proposed for use) and H_2S.

4.6.1 Tall Tower Eddy covariance

Eddy covariance methods are now commonly used to assess the mass flux of a pollutant to/from the surface, where the geographic footprint of the measurement is determined by a combination of the height from which measurements and turbulence are determined and prevailing weather conditions. Eddy covariance methods have historically been used for the assessment of CO_2 exchanges with the surface, but there is a growing body of literature showing that the same technique can be used to determine emissions of other greenhouse gases (NMVOCs (Langford et al 2010), NO_x (Lee et al 2015) and other short-lived pollutants over areas ranging from a few 100 m^2 many km^2. Such methods produce a fast time resolved estimate of instantaneous emissions (mass emission per surface area per unit time), and would be likely to provide a means to assess the spatially averaged emissions from an extraction region and be complementary to remote sensing methods.

Over larger geographic scales measurements of atmospheric composition from very tall towers – typically telecommunications masts more around 100-300 m high - are used in

---

[8] See http://uk-air.defra.gov.uk/interactive-map?network=hc

[9] See http://www.bgs.ac.uk/news/docs/Vale_of_Pickering_press_release.pdf.

combination with model inversions that aim to optimise emissions to match observations. When averaged, typically over seasons, this can produce a regional scale assessment of emissions of a particular emission. The method relies on air mass transport over considerable distances (10s-100 km) and is hence most appropriate for chemicals that can be considered inert over several days, for example CO_2, CH_4, ethane.

Currently there are limitations in the extent to which the combination of flux measurements and modelling can identify a regional scale emission signal. Due to uncertainties, primarily in modelling air transport, the broad source location (at say a county resolution) and seasonal rate of emissions is only likely to be quantifiable if the scale of shale gas extraction in the UK followed the most rapid expansion pathways (contributing up to ~10 % of UK methane emissions). In the US, emerging techniques now use fast response eddy covariance measurements of ethane, and isotopic $13CH_4$ as more unique tracers of shale gas, and as an alternative basis to make estimates of releases.

DECC currently support a long-term observation programme of greenhouse gas monitoring including CO_2, CH_4, N_2O, SF_6 and a range of radiatively active halocarbons. This provides long-term trends in CH_4 in the UK atmosphere and with inversion modelling has been used to verify UK emissions estimates submitted to UNFCCC. Data from a network of four tall towers has provided some spatial disaggregation of emission including observation-based apportionment of emissions at a level of the Devolved Administrations.

See https://www.gov.uk/government/statistics/uk-greenhouse-gas-emissions-monitoring-and-verification

Studies using the data from the tall towers network show that it can be used to interrogate specific aspects of the current emissions inventory, and can provide regional emission estimates. However, the outputs are best suited to identifying large scale changes. Consequently, data from the tall towers network are likely to be of limited use until the shale gas extraction activities occur at the major scale, and even then can be expected to only detect broad trends (which would have to be subject to source apportionment).

4.6.2 Aircraft eddy covariance

Assessment of emissions around a fixed geographic area is possible using eddy covariance sampling towers, but these may not be economic, or visually acceptable, as a long-term solution for emissions monitoring. Application of eddy covariance numerical principles, but applied to a slow flying aircraft sampling platform, allow for the periodic assessment of emission rates over wide geographic areas, but with proportionally high spatial resolution. This approach has been used in the US in a proof of concept study for hydrocarbon extraction, and has been applied in the UK over urban areas for the assessment of NO_x and VOC releases (Vaughan et al, 2015). Similar to tower eddy covariance approaches, the technique relies upon fast response ethane, CH_4 and NO_x measurements taken in conjunction with micrometeorological assessment for turbulence and boundary layer structure. The figure below shows a recent aircraft eddy covariance assessment of NO_x emission rates over London, and a similar conceptual approach could be applied to screening for methane/ethane sources from shale extraction in the UK. The spatial resolution of the method is around 500 m.

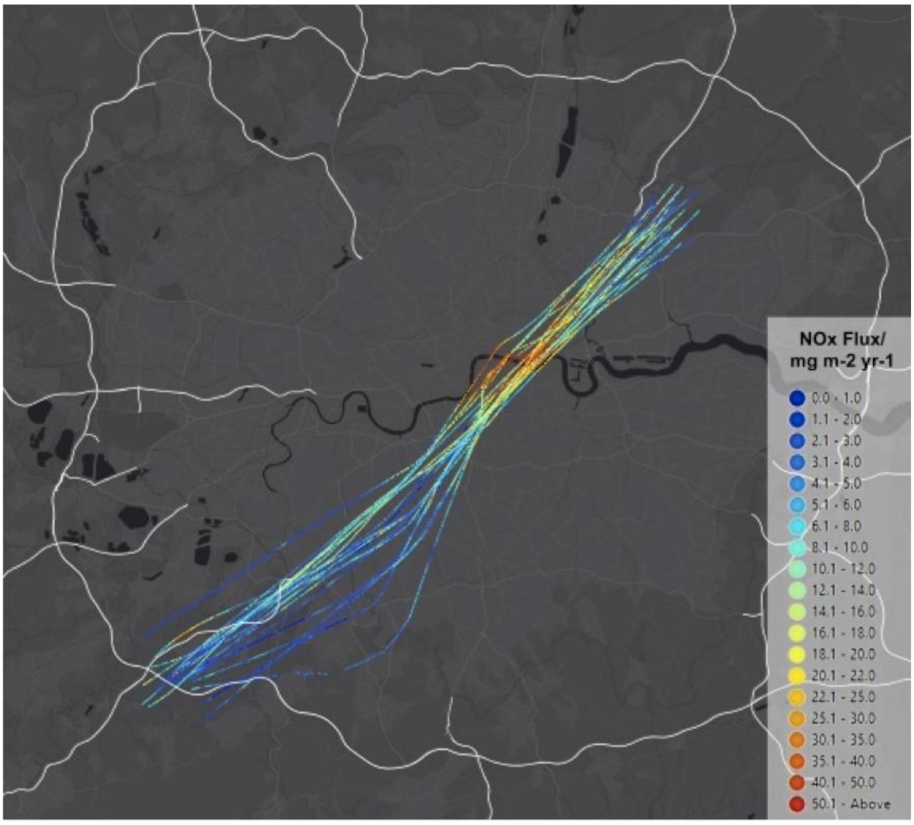


Figure 4.6a. Example aircraft eddy covariance assessment of NO over London (Vaughan et al, 2015). A similar experiment approach, but using ethane observations it is possible to identify shale gas diffusive emission rates.

4.6.3 Point source plume measurements

Releases of methane and other NMVOC from point sources in buoyant plumes can be determined also using observations from aircraft. This technique was applied most recently in the UK to establish the point source emission strength of methane and NMVOCs from the Elgin gas platform during a leak event in 2012, and is illustrated in Figures 4.6b to 4.6d below. The approach is currently being used as part of a NERC research project to establish CH_4 and NO_x emissions from North Sea gas extraction activities. (See http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FM007146%2F1). Similar experimental principles could be applied to spatially resolve emissions from shale gas regions for methane, and air quality parameters such as NO_x and NMHCs.

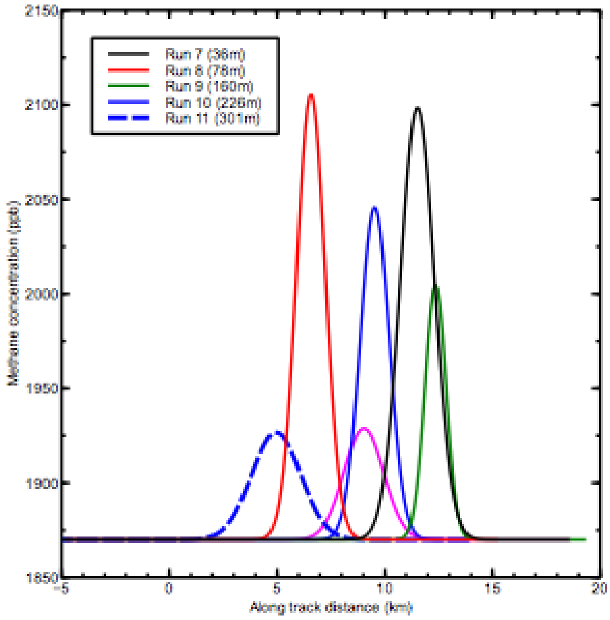


Figure 4.6b (Left): Left Plume measurements of methane made at various heights and distances downwind of the Elgin gas platform, used to then estimate the mass emission strength.

Figure 4.6c (Right): Typical aircraft flight plans used to assess methane and NMVOC emissions from North Sea platforms.

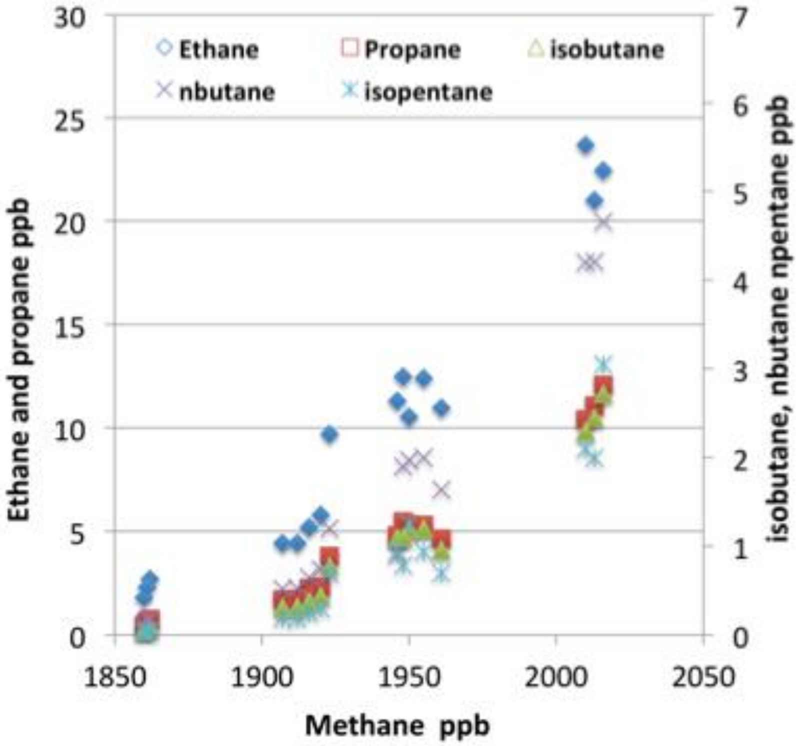


Figure 4.6d: Relationships between methane and other NMVOC in Elgin North Sea gas platform plumes.

4.7 Meteorological measurements

Most of the monitoring techniques outlined in the sections above provide more valuable information when combined with suitable meteorological measurements. At a minimum, wind speed and direction that are representative of the site are required, preferably together with information covering their variation with height. These can be obtained if there are already local sources of information (e.g. airports) or from erectable masts that can be deployed as required.

4.8 Satellite Measurements of Methane Emissions

Space-based observations of CH_4 can be used to identify regions of anomalously large CH_4 emissions, quantitatively inform emission rates (Alexe et al., 2015) and guide ground-based follow-up studies.

A pair of satellite studies of studies over the USA have shown significant methane leakage beyond official estimates (Schneising et al., 2014; Kort et al., 2014) (see Figures 4.8a and 4.8b). The data in the Figure 4.8a shows enhanced concentrations of methane from the mole fraction anomalies taken from averages for the period 2009–2011 relative to the period 2006–2008. The average wind directions are plotted showing asymmetry on the observe methane distributions in line with the observed wind vectors. The data demonstrate the ability of this method to detect wide area anomalies in methane. The advantage of satellite techniques are that it is possible to perform measurements on decadal timescale across any hydraulic fracturing development and exploitation cycle using a method not susceptible to bias by short time limited area sampling.

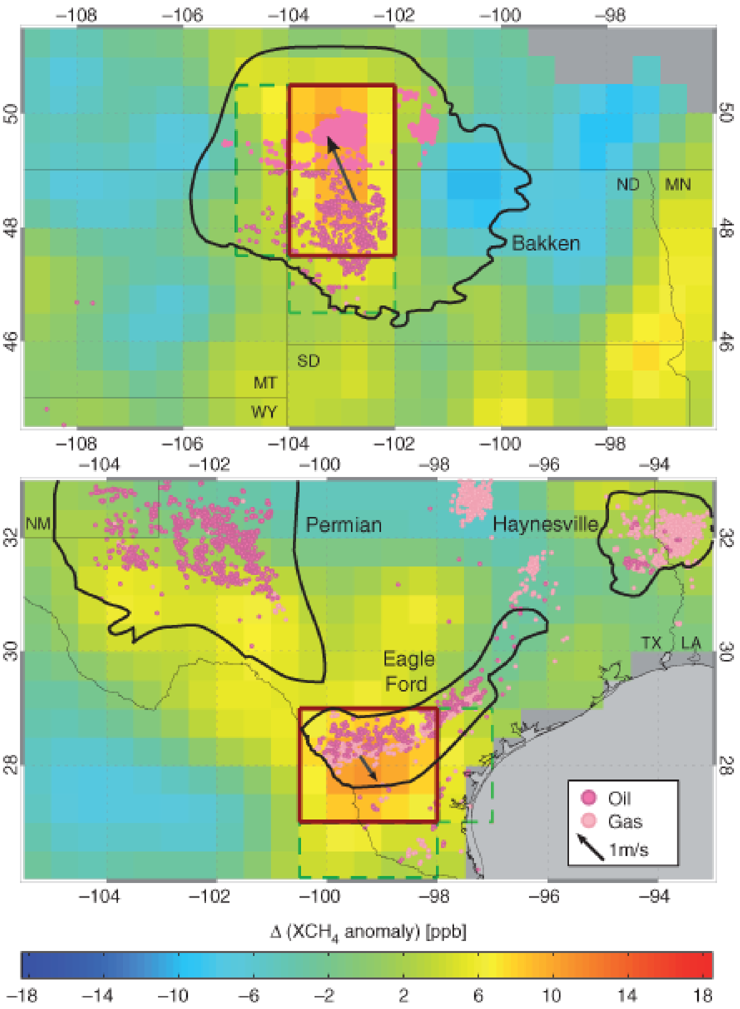


Figure 4.8a - The difference between the mole fraction anomalies of methane, for the period 2009–2011 relative to the period 2006–2008 (Schneising et al., 2014). The locations of the oil and gas wells are shown in pink. The perimeters used for the box model estimates are shown in red. The corresponding regions used to determine the background values are framed by the green dashed lines. Averaged vectorial boundary layer wind differences between the periods are illustrated by dark grey arrows.

Figure 4.8b shows inverted estimates in absolute and relative terms for the emissions of methane. A range of satellite and ground-based data suggest that the relative leakage rate in a range of U.S. shale-gas fields are larger than EPA inventory estimates.

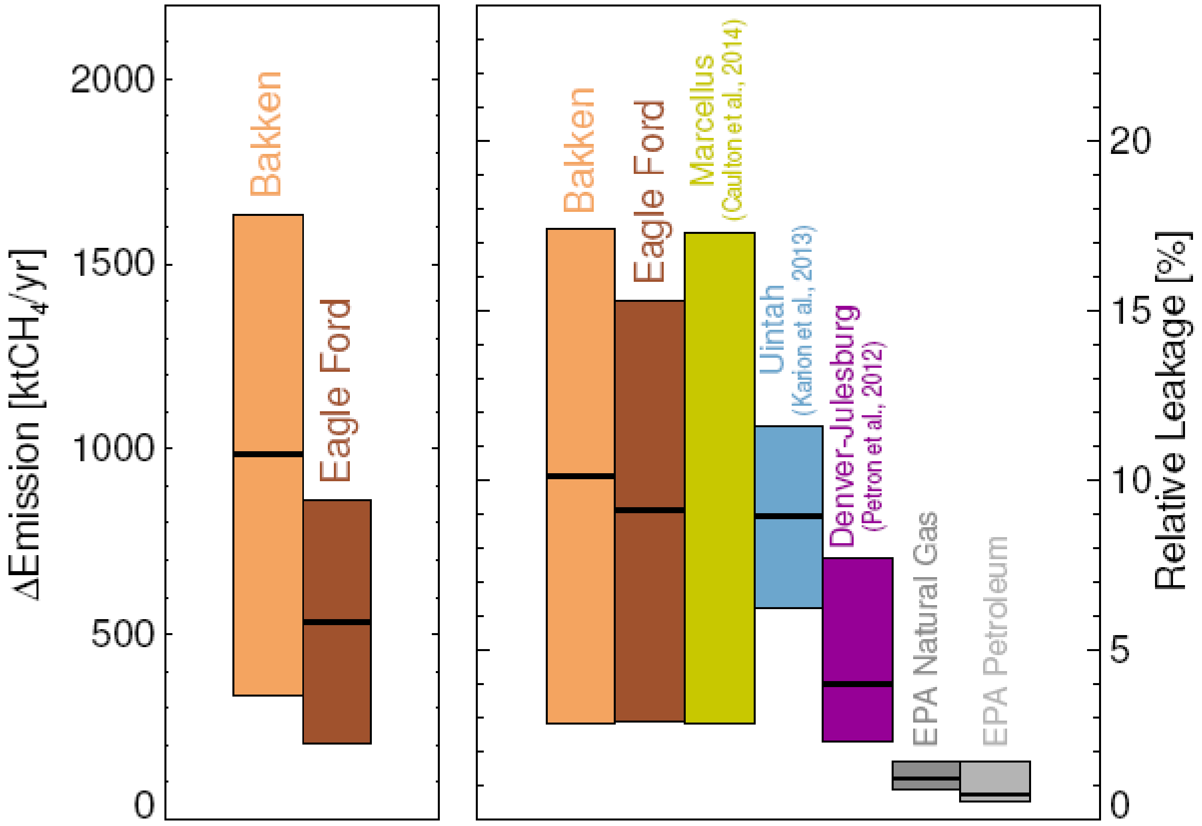


Figure 4.8b - Estimated methane emissions are shown for the targeted regions Bakken in light brown, and Eagle Ford in dark brown from satellite remote sensing measurements (Schneising et al., 2014). These two sites produce a mixture of oil and gas.

Shown are absolute emission increase (2009–2011 relative to 2006–2008) in the left panel, and the leakage rate relative to production in the right panel, with the 1σ uncertainty ranges. For comparison, leakage estimates from previous studies in Marcellus (2012) (Caulton et al., 2014), Uintah (2012) (Karion et al., 2013), Denver-Julesburg (2008) (Pétron et al., 2012) . EPA bottom-up inventory estimates for natural gas and petroleum systems (2011) are shown for comparison (EPA, 2014).

5 Potential for Ozone Formation

Both short- and long-term exposure to ozone can adversely affect health, including effects on the cardiovascular and respiratory systems (WHO, 2013). Minimising ozone formation is an important health consideration for shale gas operations. In addition, elevated levels of ozone can have significant impacts on ecosystems, reducing the levels of photosynthesis in plants and making them more susceptible to certain diseases, insects, harsh weather and other pollutants.

The potential for the emissions arising from the exploration, production and abandonment stages to collectively impact regional ozone levels varies according to local conditions. NO_x and NMVOC emissions from shale gas activities at Marcellus Shale, Pennsylvania, have been projected to contribute 12% each to regional ozone formation in 2020 (Roy et al., 2014), which could result in a breach of local air quality standards. Olaguer (2012) estimated that under typical midday meteorological conditions in June, emissions associated with compressor stations could increase ozone in the Barnett Shale region, Texas, by at least 3 ppb more than 2 km downwind, and flares can briefly increase peak ozone by 10 ppb up to approximately 16 km downwind. Rodriquez et al. (2009) pointed out that shale gas operations may result in ozone formation in rural areas where the necessary mix of precursors did not previously occur. For example, NO_x emissions from a diesel generator may react with terpenes emitted from pine forests, resulting in ozone levels in national parks that are near to breaching acceptable limits. They modelled ozone concentrations in Western US and found ozone increased from between 1-7 ppb for the 8 hour average. Kemball-Cook et al. (2010) modelled increases of up to 5 ppb of ozone in the Texas and Louisiana regions as a result of hydraulic fracturing at the Haynesville Shale area, largely due to the industrial activities of drill rigs and compressor stations.

In addition, studies in the US have shown that ozone formation occurs during winter months, for example in the Upper Green River Basin of Wyoming (Field et al, 2014b). Edwards et al (2014) found ozone mixing ratios commonly in excess of 100 ppb occurred in the wintertime background atmosphere in regions with high levels of extraction activity. The chemical conditions for the formation of such high ozone were noted to be low NO_x and high VOC, and a dominant radical source from carbonyl photolysis at longer wavelengths, rather than ozone photolysis (JO1D) which controlled ozone formation in summertime. The build-up of ozone at the surface was exacerbated by a very shallow wintertime planetary boundary layer occurring over a predominantly snow covered surface.

There are, however, several reasons why the results modelled in the US may not be directly applicable to the UK:

- Shale gas fields in the UK are typically deeper underground than in the US (Andrews, 2013, and see Section 2.1), and as such will require more energy to extract the gas. Consequently, it may be expected that surface emissions are greater than in the US. However, conversely, investment in drilling technology could reduce drilling times and associated emissions (Kemball-Cook et al., 2010).

- Both the density and the number of sites in the UK is likely to be smaller than in the US due to both the fragmented nature of UK shale gas fields (Stevens, 2012) and the greater population density in the UK (Mair et al., 2012). This could reduce the aggregate impact of shale gas operations on ozone levels compared to the US.

- Operating conditions in the UK are likely to be substantially different, driven by the need to comply with a very different regulatory framework. Flaring and venting are more tightly regulated in the UK regime compared to historic US operations (HSE, 2012). The Environment Agency have said that no open flaring will occur, only enclosed flaring – although the main impact of this is to reduce noise pollution and the localised impacts of excessive heat rather than emissions of air pollutants. There is no direct requirement in the UK for reduced emissions completions, which can reduce VOC emissions by 95% (EPA, 2012b), but the Environment Agency does consider reduced emissions completions to be included in Best Available Technology (DECC, 2014), which is a requirement.

- Differences in the composition of the gas held within different shale fields may result in differences in the type and range of NMVOCs emitted from shale gas operations; some fields are rich in NMVOCs, whilst others contain relatively low amounts (PHE, 2013). Since the majority of NMVOC in hydrocarbon reservoirs, in reactivity terms, are saturated hydrocarbons, it is likely that the total amount emitted, rather than internal speciation of those emissions would be the controlling factor in ozone formation potential.

- Regions identified for shale gas extraction in the UK may well currently experience higher ambient concentrations of NO_x than some US equivalents (UK locations having considerably higher average density of population than the US, and hence sources associated with NO_x emissions). Shale gas NMVOC emissions released into an atmosphere with already elevated NO_x, may have a higher ozone forming potential than the US.

The evidence base for the formation of elevated ozone in the US from extraction activities is clear and the chemistry of these processes is reasonably well understood. However, it is difficult to translate these US case studies meaningfully to the UK since the regulatory environment may be more demanding, resulting in lower emissions. There is a clear potential however for shale gas extraction to contribute to elevated ozone in the UK, the scale of impact being dependant on intensity of activity and the extent to which emissions are controlled.

6 Conclusions and Recommendations

The growth of shale gas operations in the UK is highly uncertain, depending on (but not exclusively) industry investment, regulation development, climate change, energy and economic policy and geological characteristics. Many of the conclusions are based on applying work from the US to the UK situation, which is very different in both in geology and proximity of extraction activities to people. As a result, recommendations below reflect the current lack of knowledge regarding on-shore shale gas extraction activities and its environmental impacts in the UK context[10].

The Environment Agency are currently undertaking a number of studies which aim to improve the current scientific understanding of emissions and resulting impacts that may arise from future shale gas extraction activities in the UK.

6.1 Quantifying Emissions

- Estimates of emissions of air quality pollutants including ozone precursors from activities associated with a single well are uncertain and are affected by many parameters (e.g. geology, regulation, and operating conditions).
- The emission rates of pollutants will vary in different ways across the exploration, production and abandonment life cycle of a well. For example, mobile machinery will give rise to NO_x and PM_{10} during all three phases, but fugitive emissions of CH_4 and VOC will be primarily during the production phase.

6.2 Impacts at the National Scale

- At the national scale, the widely differing number of wells assumed in different scenarios, and the estimates of emissions per well, impact on the extent to which future emissions can be estimated. However, estimates suggest the following indicative impacts:
    - NO_x : an additional 1 - 4% of the 2012 national total emission.
    - NMVOC : an additional 1 - 3% of the 2012 national total emission (which equates to up to an additional 40% of gas mains leakage).
    - PM : an additional 0.1 - 1% of the 2012 national total emission.
    - CH_4 : an additional 0.2 - 1% of the 2012 national total emission[11].
- The majority of the NO_x and a proportion of the PM emissions will come from mobile machinery and so will be regulated by European legislation. However, the emissions of NMVOC, CH_4 and a portion of PM will predominantly arise from fugitive sources, and so would not currently be regulated.

---

[10] The term “UK” is used here, but Scotland and Wales currently have a moratorium and ban respectively in place on shale gas extraction by hydraulic fracturing.

[11] Including land use, land use change and forestry

6.3 Impacts at the Regional/Local Scales

- Impacts on local and regional air quality have the potential to be substantially higher than the national level impacts. This is because extraction activities are likely to be highly clustered. Studies in the US have shown significant impacts on both local air quality and regional ozone formation, but similar local and regional studies have not yet been undertaken for the UK.
- There is a need to substantially improve the currently available evidence base on the potential impacts at the regional and local scales. Some improvements can be made before any on-shore shale extraction activities commence, and once activity starts it will be possible to rapidly collect evidence. Tailored air quality monitoring of O_3, CH_4, NMVOC, NO_x and PM, is required before, during and after shale gas activities to fully characterise the impacts on local air quality and contribute to the evidence base. This will also provide an indication of whether the existing legislative framework is fit for purpose. Furthermore, it can also be concluded that collecting data that supports the evaluation of impacts on regional ozone formation will be important. This evidence base will provide more detailed information on potential impacts that can be used to support planning decisions. The Environment Agency is currently undertaking a study to review the potential for regional air quality impacts.

7 Recommendations

7.1 Improving the Evidence Base Associated with UK Shale Resources and Reserves

- There is an increasing body of scientific information based on the limited exploratory studies undertaken in the UK. However, the scientific evidence base as a whole is dominated by studies from the US. It is therefore recommended that studies are undertaken to evaluate the representativeness and transferability of information from the US to the UK. Topics of particular interest are whether the UK geology will give rise to significantly different emissions than those observed in the US.

7.2 Improving the Projected Emission Estimates

- One of the largest areas of uncertainty is the number of wells predicted to be in operation by different scenarios. Whilst it is not simple to project activity levels, differences between low and high scenarios can currently vary by more than a factor of 20. It is recommended that the impacts on air quality are reassessed as there is improved understanding and the ranges given in different scenarios converge. This will ensure that scenarios are using the most up to date information, which in turn reduce uncertainty.
- Emissions per well are affected by many parameters, and it is important to better understand to what extent the UK regulatory framework will deliver effective emissions control. It is therefore recommended that research is undertaken to better characterise the emissions expected per well in the UK, and that the UK specific evidence base is improved before significant on-shore shale gas extraction activities begin. It is likely that this can only be achieved by studying sites as the first commercial wells are established and operated.

7.3 Evaluating Potential Impacts on the Local and National Scales

- Estimates have been made regarding the potential impact of shale gas extraction activities on the national UK emission estimates. However it is currently challenging to assess regional and local scale impacts. This is particularly important, because shale gas extraction activities are expected to be clustered. It is therefore recommended that more research be undertaken into evaluating the potential impact on regional ozone formation and local concentrations of air quality pollutants, and that the UK specific evidence base is improved before significant on-shore shale gas extraction activities begin. Modelling studies that use existing information will provide some understanding of the potential for regional ozone formation. However, a sufficiently improved UK evidence base is only expected to be obtained by studying the establishment and operation of the first commercial wells.

7.4 Operational Monitoring at the Regional and Local Scales

- The existing legislative framework requires monitoring of CH_4 during shale gas extraction. However, in order to enable evaluation of the impact on local air quality, a full well lifecycle analysis[12] is required for a range of pollutants relevant for a range of issues including health, and agricultural and natural ecosystems. Given the current levels of uncertainty, it is recommended that the monitoring indicated below is implemented. The monitoring is listed in a suggested order of priority related to the pollutants novelty and specificity to shale gas exploitation, compared with emissions from urban sources or other industrial installations. Depending on the characteristics of the gas reserve, and the details of the operation, monitoring of other pollutants might also be appropriate:
    - A range of volatile hydrocarbons appropriate to allow risks to health to be assessed e.g. using a combined indicator and fraction approach (EA, 2005, TPHCWG, 1997);
    - Ozone (at the regional scale);
    - Products of combustion (e.g. PM_{10}, $PM_{2.5}$, NO_x, NO_2, PAHs).
- The development of wide-area atmospheric monitoring strategies requires consideration to ensure that the development provides the most effective contribution to the monitoring of impacts at the regional scale.

---

[12] A full well life cycle analysis would comprise of monitoring: before shale gas extraction activities commence, throughout operations, and after extraction activities are finished. Monitoring would need to be located at a site (or sites) relevant to assessing population exposure and evaluating the risks to public health.

8 References

Alexe, M., Bergamaschi, P., Segers, A., Detmers, R., Butz, A., Hasekamp, O., Guerlet, S., Parker, R., Boesch, H., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Sweeney, C., Wofsy, S. C., and Kort, 2015, E. A.: Inverse modelling of CH4 emissions for 2010-2011 using different satellite retrieval products from GOSAT and SCIAMACHY, Atmospheric Chemistry and Physics, 15, 113-133, 10.5194/acp-15-113-2015.

Allen, D. T.; Torres, V. M.; Thomas, J.; Sullivan, D. W.; Harrison, M.; Hendler, A.; Herndon, S. C.; Kolb, C. E.; Fraser, M. P.;Hill, A. D.; Lamb, B. K.; Miskimins, J.; Sawyer, R. F.; Seinfeld, J. H., 2013, Measurements of methane emissions at natural gas production sites in the United States. Proc. Natl. Acad. Sci., DOI: 10.1073/pnas.1304880110.
Andrews, I.J., 2013, The Carboniferous Bowland Shale gas study: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226874/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf

Andrews, I.J., 2014, The Jurassic shales of the Weald Basin: geology and shale oil and shale gas resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/313701/BGS_DECC_JurassicWealdShale_study_2014_MAIN_REPORT.pdf

Anscombe, N., 2014, Fracking for shale gas: geologists demand more data for UK. Engineering and Technology, vol. 9 issue 6.
http://eandt.theiet.org/magazine/2014/06/getting-to-grips-with-shale-gas.cfm

Armendariz, A., 2009, Emissions from Natural Gas Production in the Barnett Shale Area and Opportunities for Cost-Effective Improvements.
http://www.edf.org/sites/default/files/9235_Barnett_Shale_Report.pdf

Bamberger & Oswald, 2012, Impacts of Gas drilling on human and animal health. NEW SOLUTIONS, Vol. 22(1) 51-77, 2012,
http://baywood.metapress.com/media/272ktmqxlm3317hp9g7t/contributions/6/6/1/4/661442p346j5387t.pdf

Bond C.E., Roberts J., Hastings A., Shipton Z.K., João E.M., Tabyldy Kyzy J., Stephenson M, 2014, Life-cycle Assessment of Greenhouse Gas Emissions from Unconventional Gas in Scotland.

Broderick, J., Anderson, K., Wood, R., Gilbert, P., Sharmina, M., Footitt, A., Glynn, S., Nicholls, F., 2011, Shale gas: an updated assessment of environmental and climate change impacts (Tyndall Centre Report). Commissions by the Co-operative and undertaken by researchers at the Tyndall Centre, University of Manchester.

Broomfield, M., 2012, Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe.
Broomfield, M. and B. Donovan, 2012, Monitoring and control of fugitive methane from unconventional gas operations. Environment Agency: Bristol.

Cathles et al., 2012, A commentary on “The greenhouse gas footprint of natural gas in shale formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea”, Climate Change, 113(2), 525-535. http://link.springer.com/article/10.1007/s10584-011-0333-0#

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A., and Miller, B. R., 2014, Toward a better understanding and quantification of methane emissions from shale gas development, Proc. Natl. Acad. Sci. U. S. A., 111, 6237-6242, 10.1073/pnas.1316546111, U.S. Environmental Protection Agency (2014), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf and http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHGInventory-2014-Annexes.pdf

Colborn T, Kwiatkowski C, et al, 2011, Natural gas operations from a public health perspective. *Human and Ecological Risk Assessment: An International Journal* **17**(5): 1039–56.

Colborn et al, 2012, An Exploratory Study of Air Quality near Natural Gas Operations. http://www.fraw.org.uk/files/extreme/colborn_2014.pdf

DECC, 2012a, Gas Generation Strategy. http://www.decc.gov.uk/en/content/cms/meeting_energy/oil_gas/gasgenstrat/gasgenstrat.aspx

DECC, 2012b, The Unconventional Hydrocarbon Resources of Britain’s Onshore Basins - Shale Gas. https://www.og.decc.gov.uk/UKpromote/onshore_paper/UK_onshore_shalegas.pdf

DECC, 2013a, Onshore oil and gas exploration in the UK: regulation and best practice (England). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/265988/Onshore_UK_oil_and_gas_exploration_England_Dec13_contents.pdf

DECC 2013b, About shale gas and hydraulic fracturing (fracking). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/268017/About_shale_gas_and_hydraulic_fracturing_Dec_2013.pdf
DECC 2013c, Developing onshore shale gas and oil – facts about fracking. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/270980/Developing_Onshore_Shale_Gas_and_Oil__Facts_about_Fracking_140113.pdf

DECC 2013d, Production and demand projections – Oil and gas: field data. https://www.gov.uk/oil-and-gas-uk-field-data

DECC 2013e, Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing.

DECC, 2014a, Oil and gas: licensing rounds. https://www.gov.uk/oil-and-gas-licensing-rounds

DECC, 2014b, The Government’s response to the MacKay-Stone report: Potential greenhouse gas emissions associated with shale gas extraction and use. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/305811/140424_MacKay_Stone_Response_.pdf

DEPP, 2013, Air Emissions Inventory for the Natural Gas Industry. http://files.dep.state.pa.us/Air/AirQuality/AQPortalFiles/Natural_Gas_Inventory_Fact_Sheet_02-11-13.pdf

EAC, 2014, The Economic impact on UK Energy Policy of Shale Gas and Oil.
http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/17202.htm

Edwards et al, 2014, High winter ozone pollution from carbonyl photolysis in an oil and gas basin. Nature 514, 351–354.
http://www.nature.com/nature/journal/v514/n7522/full/nature13767.html

Energy and Climate Change Committee (ECCC), 2011. Shale Gas. Fifth Report of Session 2010-12, Volume 1. HC 975.
http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/795/795.pdf

Environment Agency, 2005, The UK Approach for Evaluating Human Health Risks from Petroleum Hydrocarbons in Soils, Science Report P5-080/TR3, 2005.

Environment Agency, 2011, Shale Gas, North West Monitoring of Flow Back Water, Results.
http://www.fraw.org.uk/files/extreme/envage_flowback_2011.pdf

EPA, 2012a, Summary of key changes to the new source performance standards.
http://www.epa.gov/airquality/oilandgas/pdfs/20120417changes.pdf

EPA, 2012b, Summary of requirements for processes and equipment at natural gas well sites.
http://www.epa.gov/airquality/oilandgas/pdfs/20120417summarywellsites.pdf

EPRI, 2012, Air Quality Impacts from Natural Gas Extraction and Combustion.
http://www.epri.com/Our-Work/Documents/Natural_Gas_Air_Quality_Brief_1026597.pdf

Field et al., 2014a,. Air quality concerns of unconventional oil and natural gas production. Environmental Science Processes & Impacts. 16, 954. DOI: 10.1039/c4em00081a

Field R.A. 2014b, Soltis J., McCarthy M. C., Murphy S., Montague M. C., Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter. Atmos. Chem. Phys. Discuss., 14, 24943–24984, 2014. www.atmos-chem-phys-discuss.net/14/24943/2014/.

Jessica B. Gilman, Brian M. Lerner, William C. Kuster, and Joost de Gouw, 2013, Source signature of volatile organic compounds (VOCs) from oil and natural gas operations in northeastern Colorado
Environ. Sci. Technol., DOI: 10.1021/es304119a

J.B Gilman, B.M Lerner, W.C Kuster and J.A de Gouw, 2014, Source Signature Of Volatile Organic Compounds From Oil And Natural Gas Operations In Northeastern Colorado *Environmental Science and Technology,* 47, 1297-1305.

Grant et al., 2009, Development of emissions inventories for natural gas exploration and production activity in the Haynesville shale. ENVIRON International Corporation. Prepared for The East Texas Council of Governments.
http://www.netac.org/UserFiles/File/NETAC/9_29_09/Enclosure_2b.pdf

Health Effects Institute, 2013, Understanding the Health Effects of Ambient Ultrafine Particles. HEI Review Panel on Ultrafine Particles.
http://pubs.healtheffects.org/getfile.php?u=893

HM Treasury, 2013a, Budget 2013. HC 1033.

HM Treasury, 2013b, A fiscal regime for shale gas. https://www.gov.uk/government/consultations/harnessing-the-potential-of-the-uks-natural-resources-a-fiscal-regime-for-shale-gas

Howarth, R., Santoro, R. & Ingraffea, A., 2011, Methane and the greenhouse gas footprint of natural gas from shale formations. Climate Change, Volume 106, Issue 4, pp 679-690. http://link.springer.com/article/10.1007%2Fs10584-011-0061-5

HSE, 2012, Shale gas regulations. http://www.hse.gov.uk/shale-gas/assets/docs/shale-gas.pdf

Infrastructure Act, 2015. Available at http://www.legislation.gov.uk/ukpga/2015/7/contents/enacted (Accessed 30.06.2015)

Inglethorpe, S., 2013. Seismicity: a case of the shakes. UK Shale gas and the environment, ENDS.

Kampa, M., Castanas, E,. 2008, Human health effects of air pollution. Environmental Pollution. Vol 151, Issue 2, pp 362-367

Karion, A., Sweeney, C., Petron, G., Frost, G., Hardesty, R. M., Kofler, J., Miller, B. R., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S. A., Schnell, R., Tans, P., Trainer, M., Zamora, R., and Conley, S., 2013, Methane emissions estimate from airborne measurements over a western United States natural gas field, Geophysical Research Letters, 40, 4393-4397, 10.1002/grl.50811.

Kemball-Cook, S., et al., 2010, Ozone Impacts of Natural Gas Development in the Haynesville Shale. Environmental Science & Technology, 2010. 44(24): p. 9357-9363. http://www.epa.gov/ttnchie1/conference/ei19/session2/kemball_cook.pdf

Kort, E. A., Frankenberg, C., Costigan, K. R., Lindenmaier, R., Dubey, M. K., and Wunch, D., 2014, Four corners: The largest US methane anomaly viewed from space, Geophysical Research Letters, 41, 2014GL061503, 10.1002/2014gl061503, 2014.

Kresse, T.M., Warner, N.R., Hays, P.D., Down, A., Vengosh, A., and Jackson, R.B., 2012, Shallow groundwater quality and geochemistry in the Fayetteville Shale gas-production area, north-central Arkansas, 2011: U.S. Geological Survey Scientific Investigations Report 2012–5273, 31 p.

Litovitz et al., 2013, Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania. Environmental Research Letters, volume 8. doi:10.1088/1748-9326/8/1/014017 http://www.fraw.org.uk/files/extreme/litovitz_2013.pdf

MacKay & Stone, 2013, Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction And Use. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237330/MacKay_Stone_shale_study_report_09092013.pdf

Mair, R., M. Bickle, D. Goodman, B. Koppelman, J. Roberts, R. Selley, Z. Shipton et al. 2012, Shale gas extraction in the UK: a review of hydraulic fracturing, http://eprints.gla.ac.uk/69554/1/PY-Shale-gas-2012-06-28-.pdf

Moore, V., Beresford, A., & Gove, B., 2014, Hydraulic fracturing for shale gas in the UK: Examining the evidence for potential environmental impacts. Sandy, Bedfordshire, UK: RSPB.

Moore, C. et al., 2014,. Air Impacts of Increased Natural Gas Acquisition, Processing, and Use: A Critical Review. Environmental Science and Technology. dx.doi.org/10.1021/es4053472

Olaguer, E.P., 2012, The potential near-source ozone impacts of upstream oil and gas industry emissions. Journal of the Air & Waste Management Association, 62, 966-977

Pearson, P. Zeniewski, F. Gracceva, P. Zastera, C. McGlade, S. Sorrell, J. Speirs, G. Thonhauser, C. Alecu, A. Eriksson, P. To and M. Schuetz, 2012, Unconventional Gas: Potential Energy Market Impacts in the European Union, JRC 70481, EUR 25305 EN, ISBN 978-92-79-19908-0, ISSN 1831- 9424, European Commission Joint Research Centre, Report.

Pétron, G., Frost, G., Miller, B. R., Hirsch, A. I., Montzka, S. A., Karion, A., Trainer, M., Sweeney, C., Andrews, A. E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E. J., Patrick, L., Moore, C. T., Ryerson, T. B., Siso, C., Kolodzey, W., Lang, P. M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., and Tans, P., 2012, Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study, Journal of Geophysical Research: Atmospheres, 117, D04304, 10.1029/2011jd016360.

Public Health England, 2014, Review of the potential Public health impacts of exposures to chemical and radioactive pollutants as a result of the shale gas extraction process. https://www.gov.uk/government/publications/shale-gas-extraction-review-of-the-potential-public-health-impacts-of-exposures-to-chemical-and-radioactive-pollutants

Regeneris Consulting, 2011, Economic Impact of Shale Gas Exploration & Production in Lancashire and the UK. http://www.cuadrillaresources.nl/wp-content/uploads/2012/02/Full_Report_Economic_Impact_of_Shale_Gas_14_Sept.pdf

Ricardo-AEA, 2012, Unconventional Gas in England: Description of infrastructure and future scenarios. Report for Environment Agency.

Ricardo-AEA, 2014, Unconventional Gas in England: Description of infrastructure and future scenarios. Report for Environment Agency. Ricardo-AEA/R/ED58661, RMP6225. http://ee.ricardo.com/cms/assets/Uploads/Misc-uploads/ED58661-scenarios030214v14.pdf

Robinson, A., 2012, Air pollutant emissions from shale gas development and production. http://www.iom.edu/~/media/Files/Activity%20Files/Environment/EnvironmentalHealthRT/2012-04-30/Robinson.pdf

Rodriquez, M., Barna, M. & Moore, T., 2009, Regional Impacts of Oil and Gas Development on Ozone Formation in the Western United States. Air and Waste management Association. 59:1111–1118, DOI:10.3155/1047-3289.59.9.1111

Roy, A., Adams, PJ. & Robinson, AL., 2014, Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. J Air Waste Manag Assoc. Jan;64(1):19-37.

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H., 2014 Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earth's Future, 2014EF000265, 10.1002/2014ef000265.

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H., 2014, Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earth's Future, 2, 548-558, 10.1002/2014EF000265.

Stevens, P., 2012, The 'Shale Gas revolution': Developments and Changes. Energy, Environment and Resources. EERG BP 2012/04

TPHCWG., 1997, Total Petroleum Hydrocarbon Criteria Working Group Series Volume 4: Development of Fraction Specific Reference Doses (RfDs) and Reference Concentrations (RfCs) for Total Petroleum Hydrocarbons (TPH). ISBN 1-884-940-13-7

UKOOG, 2013a, Onshore Oil and Gas Regulation. Issue 1. http://www.ukoog.org.uk/images/ukoog/pdfs/fact%20sheets/regulation.pdf

UKOOG, 2013b, Fact Sheet: Emissions. Issue 1 http://www.ukoog.org.uk/images/ukoog/pdfs/fact%20sheets/emissions.pdf

Vaughan, A., Lee, J.D., Misztal, P., Metzger, S., Shaw, M.D., Lewis, A.C., Purvis, R., Carslaw, C., Goldstein, A., Hewitt, C.N., Davison, B., Beevers S.D., and Karl, T., 2015, Spatially resolved flux measurements of NO_x from London suggest significantly higher emissions than predicted by inventories. Faraday Discuss., DOI: 10.1039/C5FD00170F

Warneke C., F. Geiger, P. M. Edwards, W. Dube, G. Pétron, J. Kofler, A. Zahn[3], S. S. Brown, M. Graus, J. B. Gilman, B. M. Lerner, J. Peischl, T. B. Ryerson, J. A. de Gouw, and J. M. Roberts, 2014, Volatile organic compound emissions from the oil and natural gas industry in the Uintah Basin, Utah: oil and gas well pad emissions compared to ambient air composition. *Atmos. Chem. Phys*., 14, 10977-10988. http://www.atmos-chem-phys.net/14/10977/2014/acp-14-10977-2014.html

WHO, 2013a, *Review of Evidence on Health Aspects of Air Pollution - REVIHAAP Project: Technical Report*. World Health Organization Regional Office for Europe, Copenhagen. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report

Wolf, 2009, Town of Dish, Texas, Ambient Air Monitoring Analysis, Final Report, Prepared by Wolf Eagle Environmental. http://www.townofdish.com/objects/DISH_emergency_res_report_pdf.pdf