Ambient air monitoring at shale gas sites: framework for design of adaptive monitoring regimes

Chief Scientist’s Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

This study considers the emissions to air associated with the operation of shale gas facilities in England and presents an adaptive monitoring framework capable of capturing and assessing changes in ambient air associated with the various emission sources at these sites. The framework offers a dynamic approach to the assessment of air quality which, among other aspects, takes into account background air quality, the phase of operation, and the progression of the shale gas industry from ‘early adopters’ to established operators. The study consisted of:

- a review of emissions to air from shale gas sites
- an atmospheric dispersion modelling assessment of ambient air-quality impacts during the most important phases of shale gas operations
- an identification of monitoring priorities based on the indicative results of the modelling study and on a review of monitoring options
- the development of an adaptive monitoring framework by which levels of monitoring can be increased or decreased, so that they stay proportionate to the likely ambient impacts of emissions to air from shale gas facilities.

Modelling of impacts was necessary as there are currently no fully-operational shale gas facilities in the UK where conclusions can be drawn on the effects of operations on ambient air quality.

Dispersion modelling study

This study investigated the relationship between emission sources at shale gas facilities and changes in ambient air in the surrounding area. It included the development of 6 scenarios reflecting the various phases and key emission sources at a shale gas site. The study focused on emissions that occur during the drilling, hydraulic fracturing and extraction phases; an exploration phase was also assessed to cover the potential for continuous flaring and intermittent venting of natural gas during well testing.

The potential for uncertainty around the development of shale gas facilities was addressed by including 2 development categories (‘rapid’ and ‘steady’) and by applying a range of emission factors, comprising factors from the USA and factors that reflect the likely controls to be adopted in the UK under the EU’s Non-Road Mobile Machinery (NRMM) Regulation.

Overall, the study supported the design of tailored and adaptive ambient air quality monitoring programmes at shale gas facilities. It produced the following observations:

- Pollutant concentrations may be elevated close to large plant during key operational phases, including drilling and hydraulic fracturing, but are likely to decrease quickly as the distance from a site increases.
- Emissions and impacts are likely to vary between sites owing to the nature of their activities and the influence of local meteorological conditions.
- To determine how appropriately emissions from a site are being controlled, the location(s) of monitoring stations should be selected to include the points of maximum and/or frequent impact in areas of potential exposure.
- The presence of confounding sources (that is, other local sources unrelated to shale gas emissions) may necessitate additional monitoring locations

and more detailed analysis of short-term variations, in order to differentiate the impacts of these sources from those of the shale gas site.

- Nitrogen dioxide concentrations in ambient air resulting from emissions from shale gas facilities could, under certain operational situations, cause exceedances of short-term Air Quality Objectives beyond a site boundary. Exceedances could occur within ~300m from a site's centre if emissions are controlled in line with the NRMM Regulation, but could extend to ~500m from the centre without these controls. However, these distances may not correspond to locations where people are exposed to nitrogen dioxide emissions from the site. To comply with the Objectives, emission controls would be needed in addition to those under the NRMM Regulation.

Monitoring levels

Three categories of surveillance are recommended. These are based on a review of the costs of different monitoring methods and on using expert judgement to balance cost and risk (derived from modelled impacts) for different pollutants and phases.

- **Routine surveillance** acts as the starting point, or base case, for most sites. It provides a typical monitoring requirement for specified pollutants that should be applied as a default in all cases, unless reduced and/or enhanced surveillance is indicated.
- **Reduced surveillance** is appropriate for pollutants and sites that are identified to be low risk, low concentration and low impact.
- **Enhanced surveillance** extends the routine surveillance by applying a targeted higher level or duration of monitoring for one or more pollutants, if there is a risk of elevated impacts.

Monitoring framework

The potential impact of emissions from shale gas developments warrants careful consideration of ambient air quality monitoring and the use of tailored and adaptive monitoring strategies. The monitoring framework is designed to enable the development of strategies that are cost-effective, and that include combinations of the 3 monitoring levels for different pollutants, and that address potential concerns regarding emissions from shale gas facilities. The framework uses various site characteristics to guide decisions on the development of monitoring strategies. When deciding on a strategy, users should apply the routine monitoring specifications unless the framework indicates a need for reduced or enhanced monitoring. The strategy should also be reviewed and updated before the start of each operational phase.

The study tested the flexibility and adaptability of the framework using a series of conceptual case studies. These reflected the potential variability between shale gas developments, the potential for sites and their air quality impacts to change over time, and situations where the characteristics of a site may be considered 'non-standard'.

Recommendations for further work

- Testing of the operational assumptions adopted in the study against 'real world' shale gas developments in England;
- An economic assessment of the proposed framework to determine the likely financial implications for operators of adopting these monitoring approaches;
- More detailed assessments of the potential for air quality impacts resulting from the shale gas operations on sensitive human and ecological receptors.

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1. Introduction and study context

1.1 Shale gas in the UK

The development of England's shale gas resources is at an important stage. After several years with little activity on the ground, in 2016 permission was granted for exploratory drilling and hydraulic fracturing at 2 sites, one in Lancashire and one in North Yorkshire. A licence was issued for exploratory drilling in Sussex in January 2018 and, more recently, planning approval was granted for exploratory drilling to take place in Rotherham, South Yorkshire. The government issued the 14th round of Petroleum Exploration and Development Licences – known as 'PEDL licences' – in December 2015, which potentially opens up a wider range of sites for exploration than was previously available. As a consequence, it is likely that further applications for planning permission and environmental permits for shale gas exploration will be received by the Environment Agency and other decision-making authorities in the near future.

1.1.1 Sector guidance and regulation

Sector guidance for the onshore oil and gas industry was published in August 2016 (Environment Agency 2016). This guidance highlights the activities that may be regulated by the Environment Agency. They include:

- well pad construction
- drilling exploratory wells
- flow testing and well stimulation, including hydraulic fracturing
- storing and handling crude oil
- treatment of waste gases (including flaring)
- handling, storage and disposal of flowback fluid
- managing extractive wastes
- extraction of coal mine methane

The Environment Agency is also a statutory consultee for the planning and Environmental Impact Assessment (EIA) process. Alongside these statutory obligations, a number of commitments were made in relation to baseline air quality monitoring during the passage of the Infrastructure Act in 2015. Undertakings were given that baseline monitoring would be sufficient to ensure that any significant impacts of onshore oil and gas could be detected.

These commitments are underlined by the European Commission's Recommendation on 'minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing' (2014/70/EU) (European Commission 2014). The Recommendation also places overarching obligations on Member States in relation to baseline studies. Paragraph 6.2 requires that:

> 'A baseline to be determined for:
>
> (a) quality and flow characteristics of surface and ground water;
>
> (b) water quality at drinking water abstraction points;
>
> (c) air quality;

(d) soil condition;

(e) presence of methane and other volatile organic compounds in water;

(f) seismicity;

(g) land use;

(h) biodiversity;

(i) status of infrastructure and buildings; and

(j) existing wells and abandoned structures.'

It is likely to fall to the Environment Agency to ensure that these obligations are met as the onshore oil and gas industry develops.

The Environment Agency acts as the regulator for some sources of air pollutants at a shale gas site, under the Industrial Emissions Directive, for example, flares burning >100 tonnes of waste gas per day. However, local authorities effectively control impacts from other sources (for example, off-road mobile machinery, including generators and compressors) under Local Air Quality Management and land use planning.

1.2 About this study

The study considers emission sources to air that are the responsibility of both the Environment Agency and local authorities. This is because information about their combined impacts is needed to design an appropriate ambient monitoring strategy.

The study assessed the potential for the development of an adaptive monitoring framework capable of detecting, attributing and assessing changes in ambient air due to the various emission sources at a shale gas site. Adaptive monitoring regimes are adjustable in response to 'feedback' from the data that they have collected. This means that the amount, sensitivity and cost of monitoring are increased or decreased in line with the risks shown by the data collected.

The design of an adaptive monitoring regime can be informed by a range of analysis methods including:

- emissions inventory development
- atmospheric dispersion modelling
- directional analysis of air pollution roses
- import–export analysis of air pollution levels across a site
- comparisons with operator activity schedules

Although the study used some of these methods to design a basic framework, it did not make an exhaustive review of the methods available.

It is hoped an adaptive monitoring framework will offer a dynamic approach to the assessment of changes in ambient air quality around shale gas facilities. Among other aspects, it is hoped that such a framework will take account of:

- background air quality
- the phase of operation
- operator performance

- the cost and effectiveness of monitoring methods (including new ones)
- the progression of the shale gas industry from early adopters to established sites

These variables will steer the design of monitoring strategies. They may influence:

- the number of monitoring locations
- the duration, resolution and sensitivity of the monitoring methods chosen
- the requirement for additional data analysis

1.2.1 Study objectives

An important part of the Environment Agency's regulatory role is to approve site monitoring strategies for discharges to all media (air, land, water, recycling and waste disposal) as proposed by operators. This project focuses on emissions to air.

The objective is to develop a logical and structured approach to designing ambient air quality monitoring requirements for shale gas installations – referred to as a 'framework'. By providing a structured approach to designing air quality monitoring surveys, the study will enable appropriate air monitoring programmes to be developed for all installations, which suit the circumstances of each individual site.

1.3 Structure of the report

Section 2 reviews the key phases of shale gas operations.

Section 3 describes the development of a range of scenarios that reflect the types and amounts of emissions to air from shale operations.

Section 3 presents a dispersion modelling study of the selected scenarios.

Sections 4 and 5 review the reasons for monitoring, and identify monitoring priorities by drawing on the modelling results so that monitoring is effective at identifying levels of air pollutants which might be of potential concern. Section 4 deals with general considerations and Section 5 deals with specific options.

Section 6 details the development of an adaptive monitoring framework by which levels of monitoring can be increased or decreased so they stay proportionate to the likely impacts of emissions to air from shale gas facilities.

Appendices A to D give further details of the modelling methodology.

Appendix E contains a summary of ambient air monitoring techniques and costs.

Appendix F presents 5 illustrative case studies.

2. Review of shale gas operations

2.1 Activity

A shale gas site will undergo various phases during its lifespan. Each phase involves several activities and requires the use of different equipment. Some equipment may be moved onsite for use in a specific phase and then removed before the following phase. Alternatively, some equipment may be kept onsite and used at different intensities during separate phases.

2.1.1 Periods of development

The development of shale gas resources typically takes place in 2 overall periods.

Period 1: Appraisal

Determining the economic feasibility of shale gas extraction requires key information on the geology and gas reserves. To obtain this, an operator will collect data through exploratory drilling at the prospective shale gas site. Shale gas exploration uses vertical boreholes in order to acquire information on the variability, structure and seismic properties of the rock. If deemed feasible, the next stage of exploration is to define these properties more accurately. Exploration may include:

- drilling of multiple boreholes to find the most economically viable location for commercial operations
- testing the potential shale gas resources through hydraulic fracturing trials

Period 2: Production

Once an area has been deemed viable for shale gas extraction, the next step is to carry out more extensive drilling (both vertical and horizontal) and hydraulic fracturing. This may involve:

- the drilling of several vertical wells and multiple horizontal wells at a single site
- the development of multiple sites (known as ‘clustering) across an area of geological shale resources (known as a ‘shale play’)

2.1.2 Phases of operational activity

The terms used to describe the various periods and phases of shale gas activities can differ depending on the source of information. For the purpose of this study, activity at an individual site has been separated into 5 key phases (Box 2.1).

Box 2.1: Five key phases of activity at a shale gas site

Appraisal

1. Exploration – involving the drilling of test wells, limited hydraulic fracturing trials and the flaring/venting of gas during testing.

Production

2. Drilling – drilling of vertical/horizontal wells.
3. Hydraulic fracturing – using hydraulic fracturing to open cracks in the shale to release gas.
4. Extraction – removal of the natural gas that is released.
5. Decommissioning – once the extraction of shale gas becomes uneconomical, the site is closed by sealing the extraction boreholes.

Further detail on these 5 phases and on the activities during each is given in Table 2.1. Drilling occurs during both the exploration and hydraulic fracturing phases, and so it is convenient here to consider it within both those phases. Flaring can also occur during both phases.

Table 2.1 Shale gas operational phases

Phase	Description	Key emission sources[1]
Appraisal – exploration (including drilling)	During appraisal, the site is prepared for drilling, hydraulic fracturing and gas collection. Preparation occurs both above and below the surface. Above ground, this can be the clearing of the land and the setting up the machinery (drilling rig) for other phases. Below ground, this phase includes vertical and horizontal drilling and well testing.	Key emissions during this phase include those related to surface clearing equipment and drilling. Land drilling requires the use of a large generator to create deep boreholes (Litovitz et al. 2013). During this process, pockets of gas trapped in the rock, which the drill passes through, may be flared or vented to the atmosphere.
Hydraulic fracturing (including drilling)	Hydraulic fracturing involves the use of pumps to force a combination of water, sand and hydraulic fracturing chemicals, under high pressure, into a shale formation. This creates cracks in the shale and enables shale gas to be released. Once the hydraulic fracturing process is complete, a proportion of the injected fracturing fluid flows back to the surface – this is known as 'flowback'. Flowback can last 3–10 days, but in some cases may continue throughout the life of the well (Encana 2011, Allen et al. 2013).	Drilling rigs and fracturing pumps are usually powered by large, diesel-fuelled internal combustion engines. These units are transportable, so they can be moved to the well site with relative ease; they produce considerable amounts of exhaust emissions. Sites typically have several other diesel-powered equipment including: • fracturing blenders • control units • mobile sand storage units ('sand chiefs') The exhaust generated by these units is characteristic of diesel-powered engines, and includes as pollutants: • oxides of nitrogen • carbon monoxide • particulate matter

Phase	**Description**	**Key emission sources**[1]
		- non-methane volatile organic compounds (NMVOCs) The scale of the emission differs between engines. It depends on a number of variables including: - depth of the well - nature of the shale - quantity of gas fractured Flaring of natural gas may also occur during the fracturing phase.
Extraction	Extraction is the main phase of the shale gas process and follows completion of hydraulic fracturing. Natural gas flows from the geological formation (typically shale or coal) through the borehole to the surface, where it can be collected and processed. The process of extraction can occur over several years. This phase will often require re-fracturing steps to release more shale gas.	Emission sources during this phase can include (Moore et al. 2014): - well head compressors or pumps that bring the produced gas up to the surface or up to pipeline pressure - bleeding and leaks from well pad equipment - emissions resulting from maintenance, flares and compressor stations
Decommissioning	Once the site becomes uneconomical, the process of decommissioning will begin. The boreholes are capped and production stopped. The site is then restored.	Emissions during decommissioning arise from: - the vehicles used to remove plant and machinery from the site - any land restoration activities Following the completion of the decommissioning phase, it is possible that a site will continue to experience fugitive emissions due to leaks in the well seal (Boothroyd et al. 2016).

Notes: [1] Emission sources reflect the equipment typically used at shale gas sites, based on existing and former developments. Alternative new, low emission equipment may become available in the future.

2.2 Road transport

Shale gas sites require the road transport of plant, equipment, materials, waste and personnel. The number and type of vehicle movements will vary according to:

- the scale of the operation
- the phase of the process
- the location of the site
- the availability of a local water source
- the nature of the underlying geology

Sites in England may not have access to a national gas transmission system that is dedicated for use by shale gas facilities, nor any guarantee of a local water source, which may increase their reliance on heavy goods vehicles (HGVs). Vehicle movements are typically higher during the earlier phases of a shale gas development.

A report prepared for the Scottish Government (Broomfield et al. 2016) estimated that:

- traffic movements were around 190 per week during the first 2 years for a pad with 15 wells;
- over the lifetime of a shale gas well pad (approximately 15–20 years), total vehicle movements could be as high as 93,000.

The report concluded:

> ‘Assuming that appropriate strategic policies are put in place, and appropriate mitigation is carried out, local communities would nevertheless experience an increase in traffic numbers, potentially for an extended period of a number of years. Any increase in vehicle movements could result in an increase in noise, emissions to air, road damage, or traffic accident risks, which may be identified as negligible, or may require mitigation. Provided the planning and EIA system is properly implemented, any significant impacts would be avoided through the use of appropriate mitigation measures.’

This study focused on the emissions from stationary plant, including generators and pumps. It does not factor in emissions from vehicles, which may increase background pollutant concentrations.

2.3 Timescales

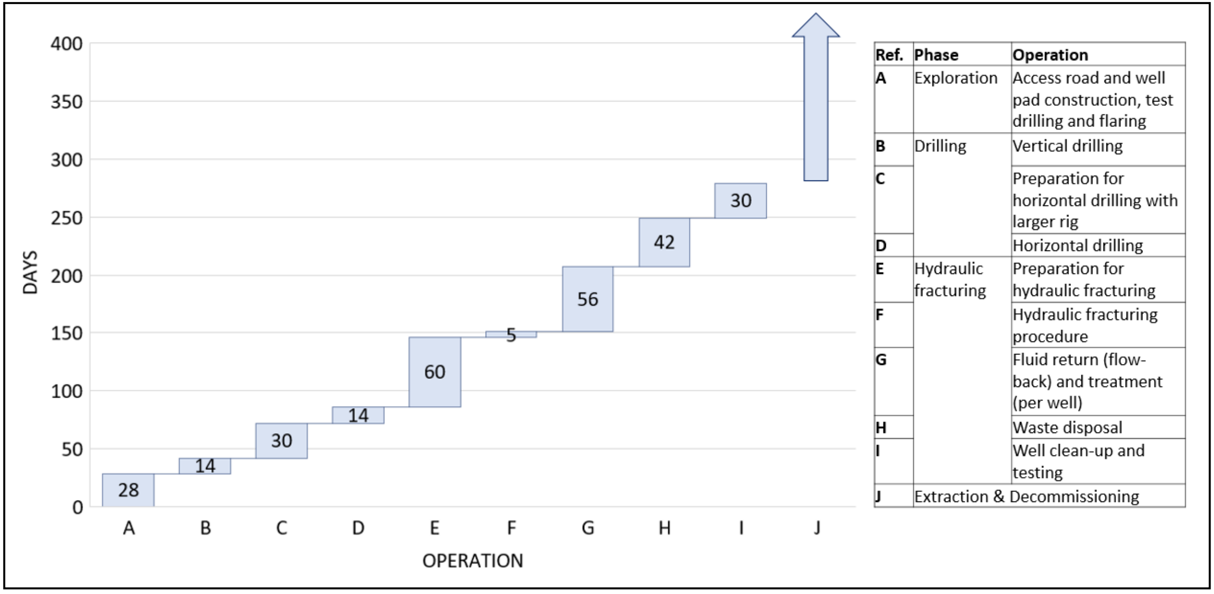
The timescales of a shale gas facility will be influenced by several factors including:

- the number of wells
- the site topography and geology
- the nature of the shale being fractured
- the level of extraction
- the rate of injection of fracturing fluid
- the intervals between phases
- the experience of the developer

These variables will directly affect the potential for impacts on air quality and releases to air.

In 2011, the Tyndall Centre for Climate Change at the University of Manchester estimated the timescales associated with a six-well multi-well pad at a shale gas site. These are shown in Figure 2.1, which reflects the durations of typical site activities prior to gas production.

Overall, the duration of activities for all operations prior to production for a six-well multi-well pad are estimated to take between 500 and 1,500 days (Broderick et al. 2011). Gas extraction may continue for several years. Onshore oil and gas facilities are also subject to significant diurnal variation in operations. These will depend on the nature of the site, any planning and/or regulatory controls, and the operator’s working methods.



Ref.	Phase	Operation
A	Exploration	Access road and well pad construction, test drilling and flaring
B	Drilling	Vertical drilling
C		Preparation for horizontal drilling with larger rig
D		Horizontal drilling
E	Hydraulic fracturing	Preparation for hydraulic fracturing
F		Hydraulic fracturing procedure
G		Fluid return (flow-back) and treatment (per well)
H		Waste disposal
I		Well clean-up and testing
J	Extraction & Decommissioning	

Figure 2.1 Estimated development timescales of shale gas sites per well prior to production

Notes: [1] These timescales are estimates for a single well at a well pad. In practice, a well pad is likely to be the start point for several wells that are drilled into a shale bed horizontally in different directions. The timescales for each well are likely to be staggered, so that at any given time and well pad, there may be different wells in different phases of operation.

[2] The phases shown in this diagram broadly reflect those considered in this study, except that extraction and decommissioning have been combined.

[3] The figure is based on Table 2.5 of Broderick et al. (2011, p. 28).

The variability in the timescales of shale gas facilities means that an adaptive monitoring approach is necessary to ensure that:

- changes in emissions and resulting ambient air quality impacts during different operational periods are adequately monitored;
- monitoring effort is kept proportionate to risk and cost.

2.4 Key pollutants at shale gas sites

Shale gas operations result in emissions to air from several sources. These can occur during normal operations, maintenance, leaks or abnormal site activities. Emissions from shale gas facilities include:

- air pollutants, which may pose a risk to human health and/or sensitive habitat sites
- greenhouse gases (GHGs), which are associated with climate change effects

Although this study focused on pollutants that have toxicity standards relating to human health and ecosystems, it also includes methane which is a powerful greenhouse gas but does not have toxicity standards. Shale sites may also be a source of ‘nuisance’ pollutants that affect amenity (for example, odour, grit and dust, visible plumes), but these are not the focus of the study.

The primary pollutants of concern are associated with fugitive, vented and combustion emissions. Table 2.2 provides a summary of the key sources of these pollutants at a shale gas site and the most important risks to human health and ecosystems.

Table 2.2 Summary of key pollutants emitted at shale gas sites

Pollutant		**Description**
Methane (CH_4)	**Sources**	Methane is the most important product of shale gas operations. Releases to air may be caused by venting or as a result of fugitive emissions. Fugitive releases are related to leaks in the system such at the gas escapes to the atmosphere. Considering the large quantities of methane that are associated with shale gas and the pressure that the gas is under, even short releases or small gaps in gas seals can account for large volumes of methane. The estimation of fugitive emissions associated with leaks in equipment, and during particular site activities, can pose challenges. There is potential for methane to be released during well completion, which involves the installation of equipment to ensure an efficient flow of natural gas. This can occur before a strong enough stream of natural gas can be established to either flare or commercially tap off. The introduction of ‘green completion’ technologies, where the gas is dissolved in water to separate it from the fracturing liquid, enables more methane to be collected. A report for the US Environmental Protection Agency (USEPA) estimated that using green completion technology can reduce emissions by ~90% (USEPA 2011). With this technology, a large percentage of methane is collected, reducing both vented emissions during completion and fugitive emissions from condensate. During commercial production, vented gas and/or fugitive emissions are likely to decrease over time as gas production rates fall. Unlike other pollutants associated with shale facilities, there is potential for methane emissions to be released after the site has been decommissioned (for example, due to potential leakages from the wellhead).
	Risks	Methane is a greenhouse gas contributing to the effects of climate change. It can also contribute to the formation of photochemical ozone, which is harmful to health.
Non-methane volatile organic compounds (NMVOCs)	**Sources**	Within shale gas are other organic compounds known as NMVOCs; examples are propane and ethane. Volatile organic compounds (VOCs) are a selection of organic compounds with different carbon chain formations but which behave similarly (this is why they are often grouped together). NMVOCs will be emitted at any point where methane emissions occur. NMVOCs are also emitted by combustion sources (for example, mobile machinery).
	Risks	There are numerous species of VOCs, each having different effects on human health and the environment. Some species are carcinogenic, such as benzene. NMVOCs are also a precursor to ozone formation and can react in the atmosphere to form secondary particulate matter.
Polycyclic aromatic hydrocarbons (PAHs)	**Sources**	PAHs are emitted during extraction and from internal combustion engines.
	Risks	Health concerns associated with exposure to PAHs include cancer risk and respiratory distress.
Oxides of nitrogen (NOx)	**Sources**	NOx emissions at shale gas facilities relate to the operation of internal combustion engines and flaring. NOx is the term usually used to refer to the combination of nitrogen dioxide (NO_2) and nitric oxide (NO), which are by-products of the fuel combustion. The UK has an ongoing issue

Pollutant		Description
		with annual ambient concentrations of NO_2, which exceed standards in some areas.
	Risks	NOx can cause respiratory problems, particularly in sensitive individuals (for example, asthmatics), and can also result in damage to plant life and the formation of acid rain. Nitrogen dioxide is a 'no threshold' pollutant, meaning even slight increases in concentrations can result in adverse health effects (that is, there is evidence that some adverse effects occur at all levels of nitrogen dioxide, though they decrease for lower concentrations). Nitrogen dioxide is also a key precursor for the formation of photochemical pollution (for example, ozone).
Particulate matter	**Sources**	Particulate matter is formed or emitted from shale gas operations due to: • combustion (especially in diesel engines) • non-exhaust traffic sources (tyre and brake wear) • other site activities including site preparation, construction and stockpiles Particulate matter (PM) covers a wide range of solid and liquid particles, suspended in the air, which fall within set size fractions: PM_{10} (≤10μm), $PM_{2.5}$ (≤2.5μm).
	Risks	Particulate matter exacerbates respiratory and cardiovascular conditions. Smaller particulates are termed $PM_{2.5}$, or 'fine particulates', and pose the greatest threat as they are carried deeper into the lungs. Particulate matter can also cause damage to plants, materials and buildings. $PM_{2.5}$ is a 'no threshold' pollutant, meaning that some adverse effects occur at all levels, although they decrease for lower concentrations. Some particulates are 'primary pollutants' emitted at source, but others are formed later in the atmosphere and are known as 'secondary pollutants'.
Carbon monoxide (CO)	**Sources**	Carbon monoxide emissions are related to incomplete combustion. At shale gas sites, these emissions relate to flaring and the use of internal combustion engines.
	Risks	The inhalation of carbon monoxide at high concentrations can be fatal. Long-term exposure at low concentrations can cause neurological damage and harm unborn infants. Carbon monoxide reacts with other pollutants to form ground level ozone.
Sulphur dioxide (SO_2)	**Sources**	Emissions of sulphur dioxide arise due to the combustion of sulphur-bearing fuels. Fuels with high levels of sulphur are processed to remove sulphur from the fuel, resulting in generally low sulphur dioxide concentrations. At shale gas sites there may be some low percentage of sulphur in the diesel burned, resulting in minor emissions of sulphur dioxide.
	Risks	At high levels, sulphur dioxide is an irritant that causes difficulty breathing, with effects occurring within a short space of time. Sulphur dioxide can also damage plant life and contribute to the formation of acid rain.
Ozone (O_3)	**Sources**	Ozone is a pollutant that is not released to the atmosphere through any of the activities related to shale gas, but is produced by photochemical reactions that occur in the atmosphere involving sunlight and precursors (NOx, CO, VOCs and CH_4), some of which are released by shale gas activities. These reactions culminate in the formation of ozone in the lower atmosphere.

Pollutant		**Description**
	Risks	Ozone is an irritant to the lungs and can exacerbate the symptoms of those suffering from lung diseases (for example, asthma). It can also affect plant growth, including crop yields.

Notes: With the exception of ozone, this table draws on the Pollutant Fact Sheets available on the website of the Scottish Environment Protection Agency (SEPA) (http://apps.sepa.org.uk/spripa/Pages/SubstanceSearch.aspx).

2.4.1 Conceptual model of key sources and emissions

Figure 2.2 shows an example of a conceptual model for the most important sources and emissions of air pollutants arising from a shale gas facility, during exploration (which includes drilling), hydraulic fracturing and extraction. The model covers NMVOCs, particulate matter, methane, NOx, hydrogen sulphide (H_2S) and carbon dioxide (CO_2). These pollutants generally correspond to those in Table 2.2, although there are some differences e.g. PAHs, carbon monoxide and ozone are in Table 2.2 2.1 only, but carbon dioxide and hydrogen sulphide are in Figure 2.2 only.

The emission sources in Figure 2.2 were identified on the basis of shale gas facilities in North America. Some of the activities at these sites may not be permitted for shale facilities in the UK; for example, operators would be expected to store waste drilling mud in a skip or sealed container rather than in a pit.

Exclusions from the model

Ozone is excluded as it is a secondary pollutant formed by photochemical reactions between emissions from the site (for example, NOx, NMVOCs) and potentially other sources.

It is assumed all fuels will be low sulphur to comply with the Sulphur Content of Liquid Fuels (England and Wales) Regulations 2007 (amended in 2014) and the Gas Safety (Management) Regulations 1996, and so sulphur dioxide has also been excluded.

Emissions from site vehicles, including those transporting equipment and materials onto and away from the site, have also been omitted, because the focus of this assessment is on site plant and equipment. However, it should be noted that site vehicles would be expected to contribute to background air pollutant concentrations.

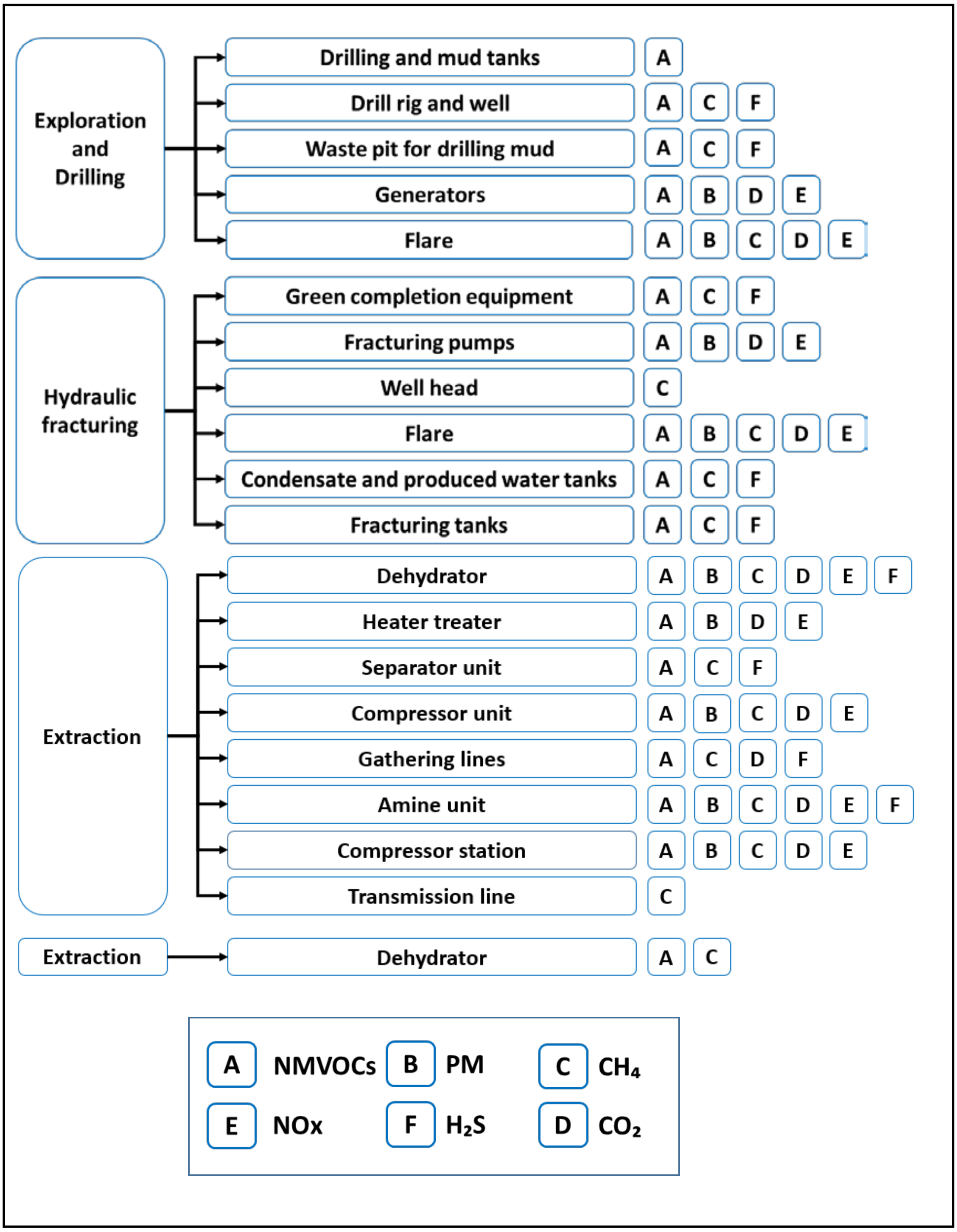


Figure 2.2 **Conceptual site model of emissions from a shale gas facility**

3. Assessment of emissions and impacts from a shale gas facility

This section presents the results of a dispersion modelling study carried out to assess the air pollutant emissions and ambient impacts from a conceptual shale gas site.

3.1 About the scenarios

The study included the development of 6 scenarios which were designed to reflect the emissions associated with various phases of site development. The scenarios were also designed to reflect the most important emission sources at a site, and to cover higher and lower estimates of those emissions.

Emissions data were collected through a review of published literature. The majority of the literature available reflects emissions associated with plant used in the USA. So to reflect the tighter emission controls that are currently, or are planned to be, in place in the UK, a scenario (Scenario 6) was included to reflect the controls under the EU's Non-Road Mobile Machinery Regulation – referred to hereafter in the report as the NRMM Regulation (European Parliament and the Council of the European Union 2016).

Scenarios 1 and 2 model the exploration phase only; they focus on the impact of the flares and venting assumed to occur prior to a site becoming fully operational. Scenarios 3–6 focus on impacts from the next phases after exploration (that is, drilling, hydraulic fracturing and extraction).

The rate of development of a site during these phases is an important consideration that may vary between sites and geological conditions, but which directly affects the scale and rate of emissions and the scale of impacts. To account for this variability, Scenarios 3 and 4 assume 'rapid' development with 10 wells becoming operational within 2 years, while Scenarios 5 and 6 assume 'steady' development with 4 wells becoming operational within 2 years. The geological conditions may mean that 'steady' development is more likely to occur in the UK than 'rapid' development.

To account for the variability in emissions data available for shale gas sources, a range of emissions data were collected, and high and low emission factors selected (see Appendix A and Table A.1).

- Scenarios 1, 3 and 5 use the low range of emission factors from the literature review – emission factor set A (EFA).
- Scenarios 2 and 4 use the high range of emission factors from the literature review – emission factor set B (EFB).
- Scenario 6 uses emission factors that reflect the controls under the NRMM Regulation – emission factor set C (EFC) – for applicable plant machinery (including the fracturing pumps and the drilling rig) and the low range of emission factors from the literature review for all other sources. EFC is expected to be a more likely representation of the emission characteristics for shale gas plant in the UK.

Full details of the methodology applied in the dispersion modelling assessment are provided in Appendix A.

3.2 Assumptions and uncertainty

This study primarily considers emissions that occur during the drilling, hydraulic fracturing and extraction phases. An exploration phase was assessed, which focuses on the potential for continuous flaring and intermittent venting of natural gas while well testing is being conducted. The inclusion of venting is a conservative assumption, as sites in the UK are unlikely to be permitted to vent to the atmosphere.

The study sought to address the potential for uncertainty surrounding emissions to air from shale gas facilities by:

- including 2 development categories (‘rapid’ and ‘steady’);
- applying a range of emission factors from the USA and those which reflect the likely controls to be adopted in the UK under the NRMM Regulation.

The various operational assumptions applied in the study are described in detail in Appendix A. Note that:

- these operational assumptions do not reflect the impacts of any specific shale gas site on its surrounding environment;
- the determination of air quality impacts associated with individual facilities will require targeted air quality impact assessments that reflect the characteristics of the site and the surrounding environment.

The primary goal of the dispersion modelling exercise was to investigate the relationship between emission sources at shale gas facilities and changes in ambient air quality in the surrounding area in order to make the development of an adaptive monitoring framework easier.

3.3 Results

The results of the dispersion modelling assessment are presented below. The discussion considers the impact of the conceptual shale gas facility on the long-term and short-term concentrations of selected pollutants. The scale of the process contributions provides an indication of the changes due to shale operations that may be expected to occur in ambient air around a facility of this type.

3.3.1 Long-term concentrations

A summary of long-term concentrations at the receptor points predicted to receive the highest concentrations is given for nitrogen dioxide and PM10 in Table 3.1 and for NMVOCs and methane in Table 3.2. The tables also confirm the distance and bearing of the applicable receptor from the centre of the site, and the process contribution from the site as a percentage of the applicable Air Quality Objective (AQO) for the protection of human health. Although not considered by this dispersion study, it is likely an operator would be required to consider the impact of emissions from proposed shale gas facilities on sensitive ecological receptors, as well as on human health.

Table 3.1 Highest long-term concentrations at modelled receptors for nitrogen dioxide and PM$_{10}$

Scenario		Emission factor set	Nitrogen dioxide annual mean[1]			PM$_{10}$ annual mean		
			µg per m^3	% of AQO[2]	Receptor	µg per m^3	% of AQO[2]	Receptor
1	Exploration (3 months flaring and venting)	EFA	4.08	10%	100m N	1.07	3%	100m north
2		EFB	9.05	23%	100m north-east	2.37	6%	100m north-east
3	10 well site: all sources (2 years)	EFA	76.1	190%		3.73	9%	
4		EFB	126.9	317%		6.07	15%	
5	4 well site: all sources (2 years)	EFA	38.0	95%		1.97	5%	
6		EFC	16.9	42%		1.26	3%	

Notes: [1] Assumes 70% of modelled NOx is NO$_2$.
[2] 40µg per m^3 (annual mean)

Table 3.2 Highest long-term concentrations at modelled receptors for NMVOCs and methane

Scenario		Emission factor set	NMVOCs annual mean			Methane annual mean		
			µg per m^3	% of AQO[1]	Receptor	µg per m^3	% of AQO	Receptor
1	Exploration (3 months flaring and venting)	EFA	0.0205	0.41%	100m north	0.155	n/a	100m north
2		EFB	0.0341	0.68%		0.258	n/a	
3	10 well site: all sources (2 years)	EFA	9.42	188%	100m north-east	4.61	n/a	100m north-east
4		EFB	14.1	283%		25.5	n/a	
5	4 well site: all sources (2 years)	EFA	6.14	123%		4.87	n/a	
6		EFC	5.84	117%		4.87	n/a	

Notes: [1] 5µg per m^{-3} (annual mean; assumes 100% of modelled NMVOC is benzene)
n/a = not applicable

3.3.2 Short-term concentrations

A summary of the short-term concentrations at the receptor points found to show the highest value are given for nitrogen dioxide and PM$_{10}$ in Table 3.3 and for NMVOCs and methane in Table 3.4. The tables also confirm the distance and bearing of the applicable receptor from the centre of the site, and the process contribution as a percentage of the applicable AQO for the protection of human health.

Table 3.3 Highest short-term concentrations at modelled receptors for NO_2 and PM_{10}

Scenario		Emission factor set	Nitrogen dioxide (99.79th percentile of hourly means)[1]			PM_{10} (90.4th percentile of 24-hour means)		
			µg per m^3	% of AQO[2]	Receptor	µg per m^3	% of AQO[3]	Receptor
1	Exploration (3 months flaring and venting)	EFA	182	91%	100m north	12.6	25.2%	100m north-east
2		EFB	364	182%		95.2	47.6%	
3	10 well site: all sources (2 years)	EFA	1,268	649%	100m east	9.63	19.3%	
4		EFB	2,329	1,165%		15.8	31.6%	
5	4 well site: all sources (2 years)	EFA	1,278	639%		6.52	13.0%	
6		EFC	777	389%		2.90	5.8%	

Notes:
[1] Assumes 35% of modelled NOx is NO_2.
[2] 200µg per m^3 (not to be exceeded more than 18 times a year)
[3] 50µg per m^3 (not to be exceeded more than 35 times a year)

Table 3.4 Highest short-term concentrations at modelled receptors for NMVOCs and methane

Scenario		Emission factor set	NMVOCs (maximum hourly means)			Methane (maximum hourly means)		
			µg per m^3	% of AQO	Receptor	µg per m^3	% of AQO	Receptor
1	Exploration (3 months flaring and venting)	EFA	29.5	n/a	200m west	220	n/a	200m west
2		EFB	49.2	n/a		366	n/a	
3	10 well site: all sources (2 years)	EFA	3,844	n/a	100m north-west	238	n/a	100m north-east
4		EFB	6,407	n/a		1,437	n/a	
5	4 well site: all sources (2 years)	EFA	2,264	n/a	100m north-east	238	n/a	
6		EFC	2,259	n/a		238	n/a	

3.3.3 Dispersion plots

The dispersion plots shown in Figures 3.1 to 3.4 reflect the long-term process contributions from the modelled shale gas site under Scenario 6; they include the locations of the receptor points. Dispersion plots of the long-term process contributions under Scenarios 3–6 are provided in Appendix D.

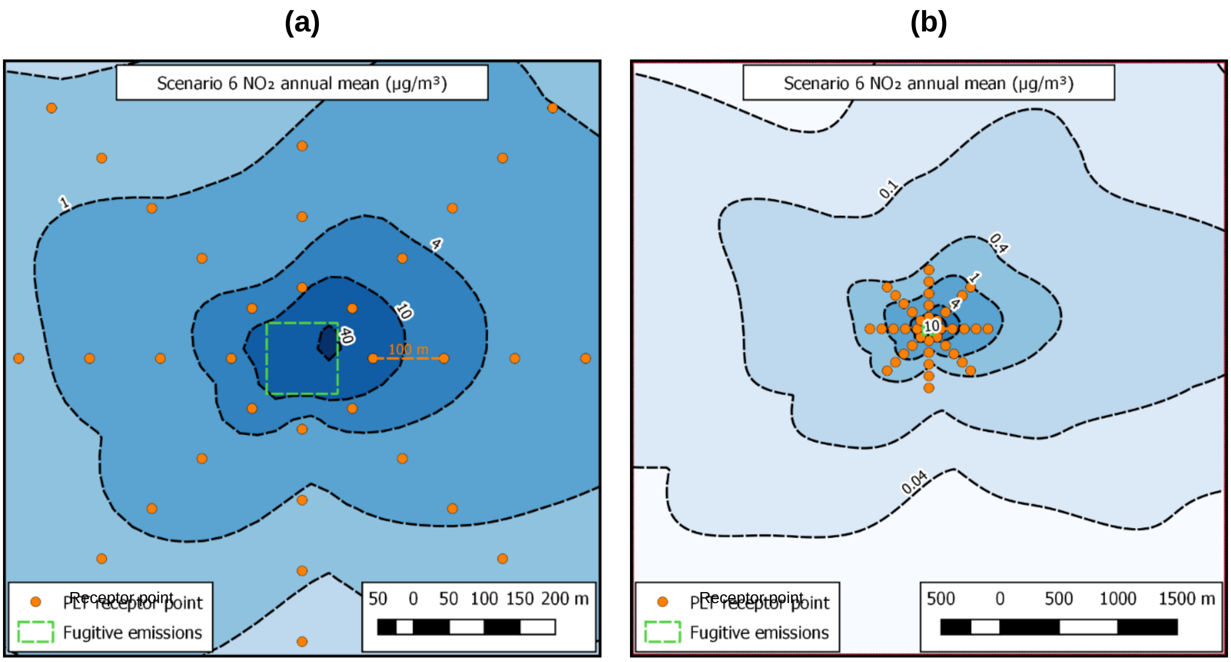


Figure 3.1 Annual mean nitrogen dioxide concentrations under Scenario 6: (a) near field and (b) wide

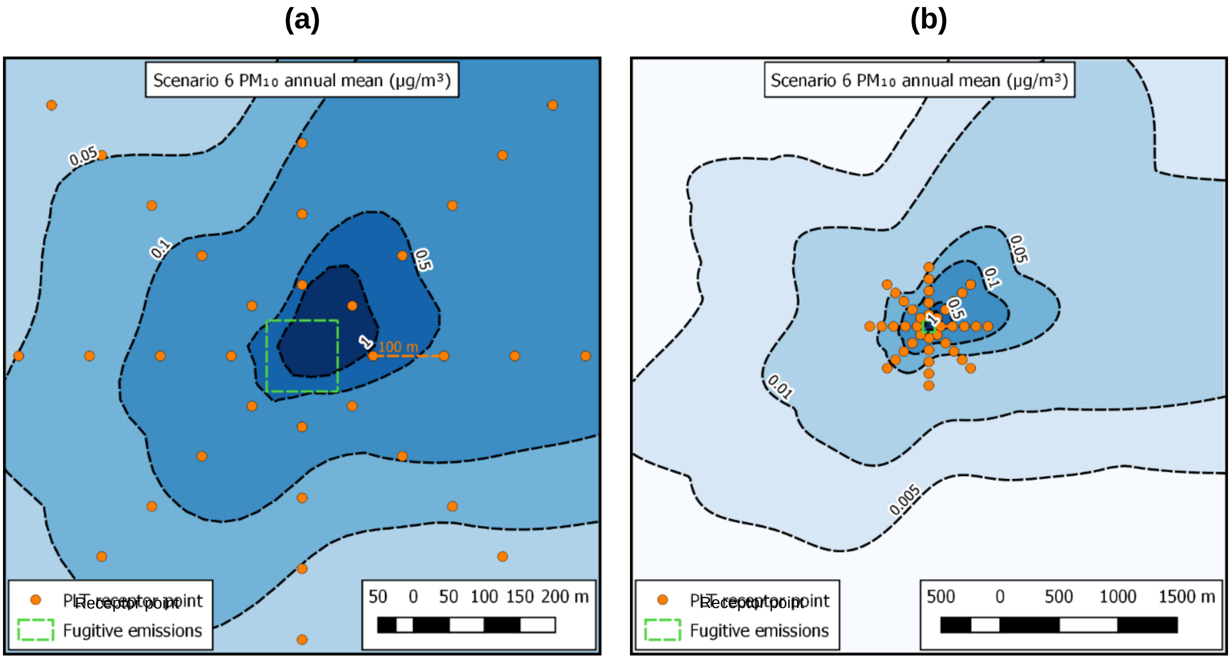


Figure 3.2 Annual mean PM_{10} concentrations under Scenario 6: (a) near field and (b) wide

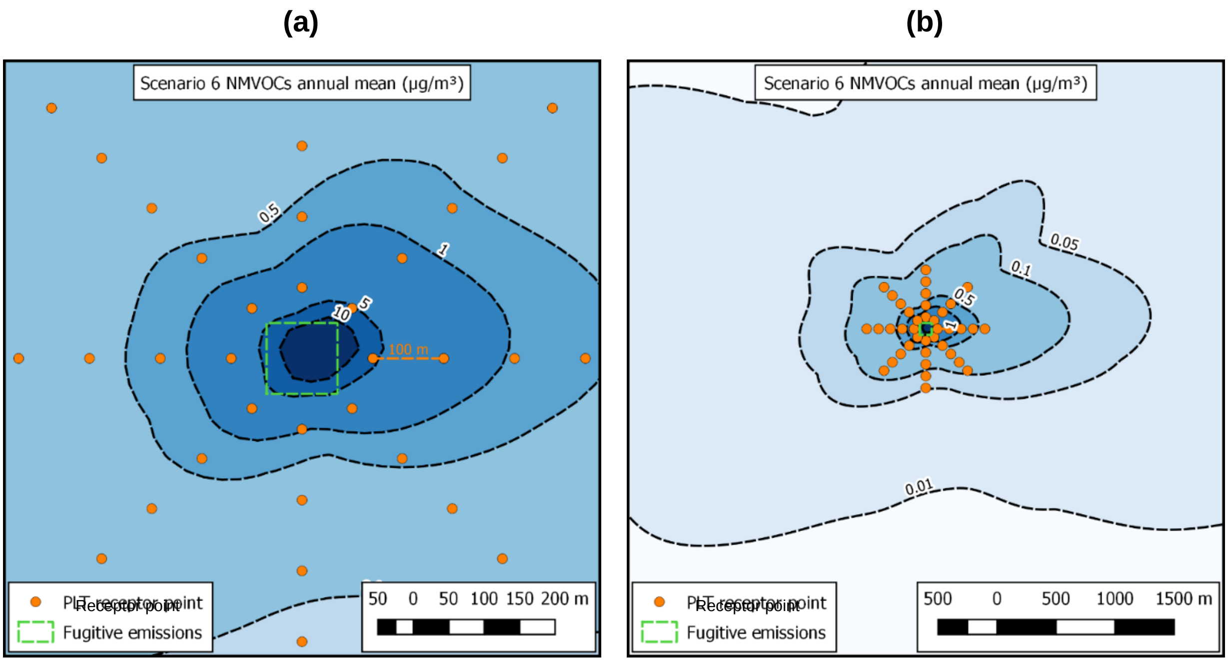


Figure 3.3 Annual mean NMVOC concentrations under Scenario 6: (a) near field and (b) wide

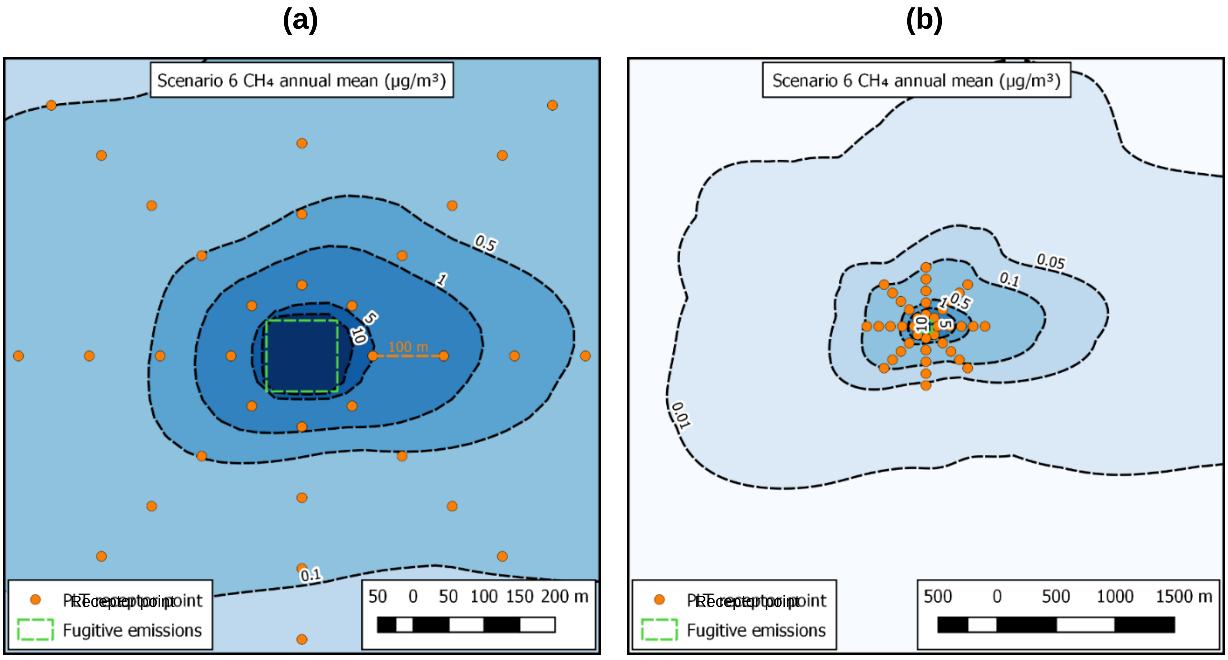
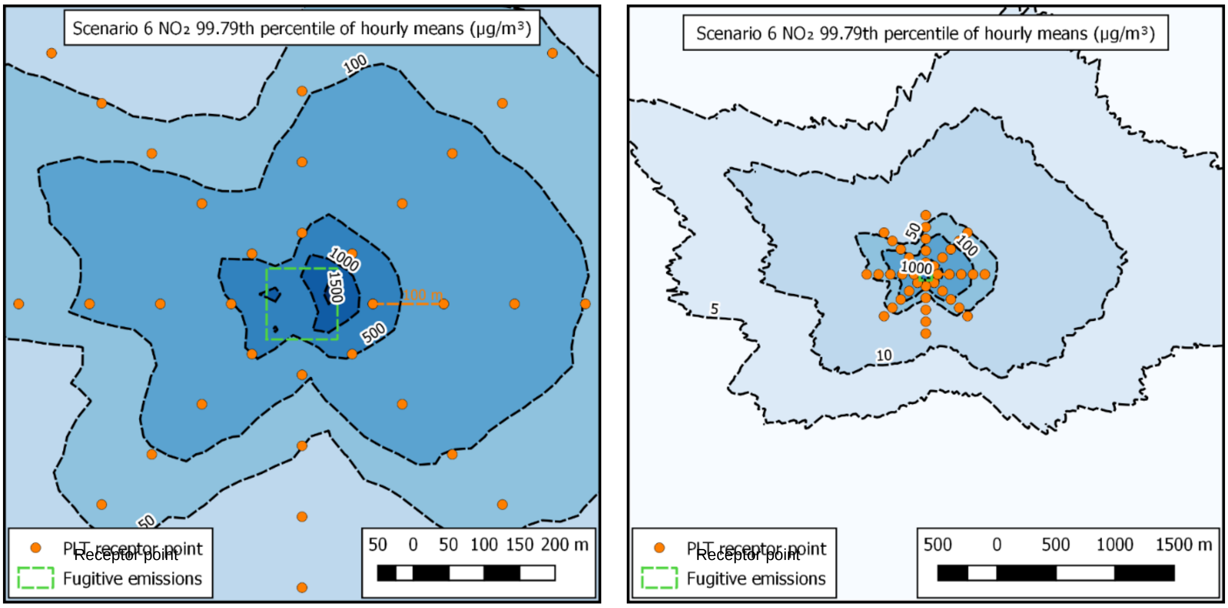


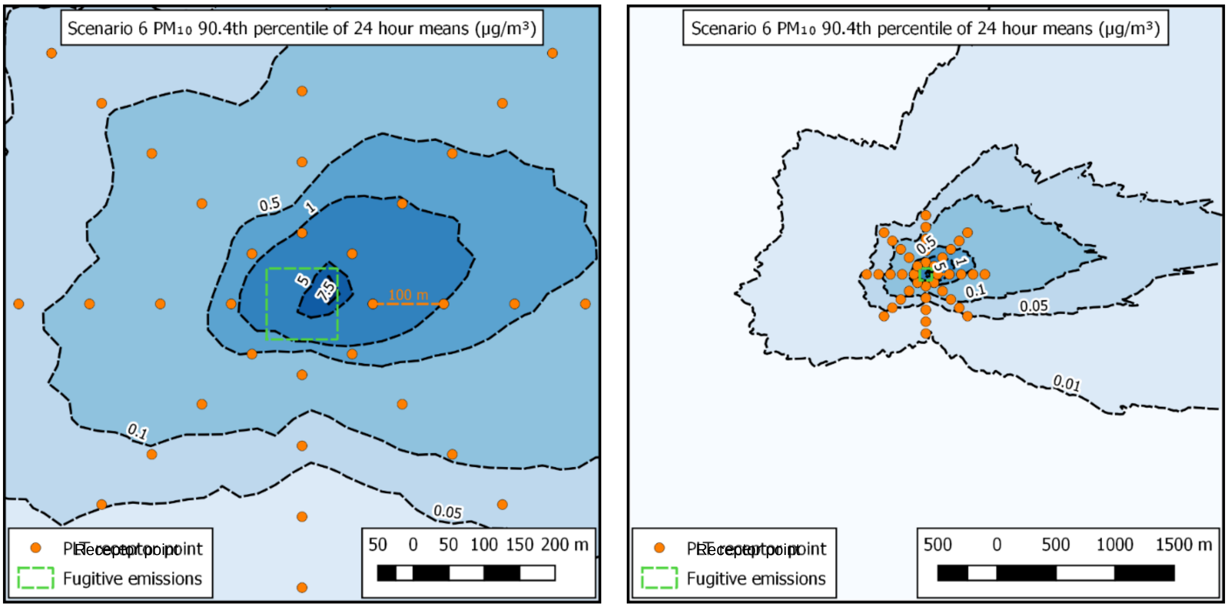
Figure 3.4 Annual mean methane concentrations under Scenario 6: (a) near field and (b) wide

Nitrogen dioxide and PM_{10} are also subject to short-term AQOs. Figures 3.5 and 3.6 set out the short-term dispersion plots for nitrogen dioxide and PM_{10} respectively.



(a) (b)

Figure 3.5 **Short-term mean nitrogen dioxide concentrations under Scenario 6: (a) near field and (b) wide**



(a) (b)

Figure 3.6 **Short-term mean PM_{10} concentrations under Scenario 6: (a) near field and (b) wide**

3.3.4 Confounding sources

The modelling study considered the behaviour of emissions from static plant at a conceptual shale gas site in order to understand how these activities could add impacts to the local baseline (that is, pre-existing) air quality, so that the extra impacts could be identified through ambient monitoring. In practice, however, shale gas activities may occur in complex environments – involving continuously changing baseline air quality that is affected by other local and regional emission sources. Although it is difficult to reflect this type of environment in a modelling study, an additional model run was carried out to demonstrate how a confounding source might influence pollutant concentrations at monitoring locations around a shale gas site.

This additional run involved modelling 2 busy A roads, which were assumed to be located 250m west and east of the centre of the shale gas site, running linearly from north to south. Traffic emissions of NOx and nitrogen dioxide were calculated from vehicle speed and traffic flow data using the Emission Factor Toolkit version 8.0.1 developed by Defra and the devolved administrations.[1] Traffic flows were taken from counts published by the Department for Transport (DfT) for a rural A road. Diurnal traffic variations were modelled by applying national average diurnal traffic profiles published by DfT for 2016. The contributions of the roads to long-term ambient nitrogen dioxide concentrations were then combined with the Scenario 6 results, as illustrated in the dispersion plots shown in Figure 3.7.

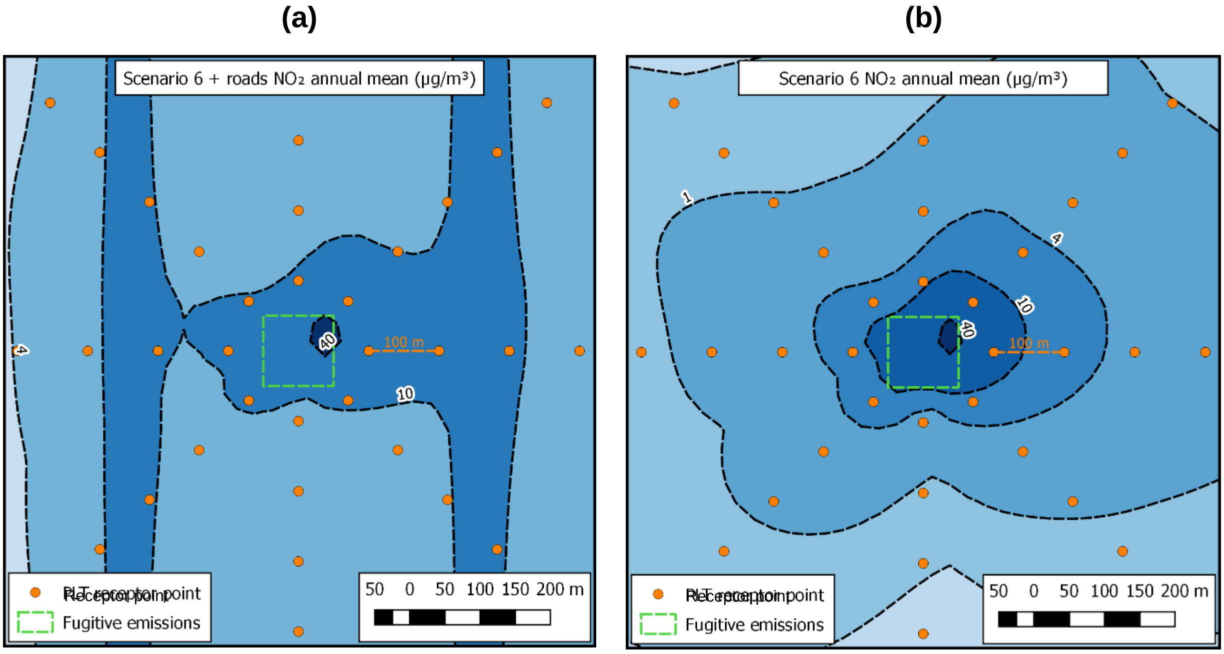


Figure 3.7 Predicted nitrogen dioxide impacts from: (a) shale gas site + roads and (b) shale gas site only

Figure 3.7 illustrates how concentrations at specific monitoring locations will be influenced by confounding emission sources. Figure 3.8 shows the long-term NO_2 process contributions from shale and roads sources as separate percentages of the total predicted environmental concentration at a selection of receptor locations. These receptors are located to the north, east, south and west of the centre of the site at distances of 100m, 300m and 500m. In practice, the predicted environmental concentration would include contributions from other background pollutant sources.

Figures 3.7 and 3.8 demonstrate that, where there are confounding sources, it may be difficult to differentiate between the confounding source and emissions from the shale gas facility at a single monitoring location.

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[1] https://laqm.defra.gov.uk/review-and-assessment/tools/emissions-factors-toolkit.html

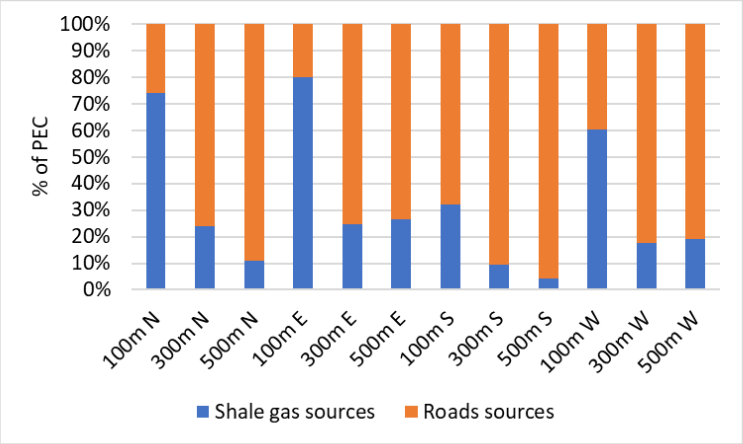

Figure 3.8 **Long-term nitrogen dioxide process contributions from shale and roads sources at receptor locations as percentages of the predicted environmental concentration**

Figure 3.8 also demonstrates how the relative signal strength from shale gas sources will vary depending on the position of the monitoring in relation to the site (for example, shale gas sources make up approximately 5–80% of the combined (site + road) impact). These variations mean that the selection of monitoring locations needs to:

- take account of the relative signal strengths from shale-related emissions and other sources
- avoid shale gas signals being obscured by signals from confounding sources such as nearby roads

The application of a more detailed analysis of short-term variations in the pollutant concentrations detected through ambient monitoring – in conjunction with local meteorological data – will allow better discrimination of the contributions made by shale activities to total pollutant concentrations (for example, wind sector analysis).

3.3.5 Short-term pollutant fluctuations

Figure 3.9 illustrates how the expected short-term variations in nitrogen dioxide concentrations correlate with the key phases during production, under Scenario 6, over the two-year period. The plot highlights the large peaks in concentration experienced during the periods when the hydraulic fracturing pumps are in operation. Equivalent plots for PM_{10}, NMVOCs and methane are provided in Appendix D.

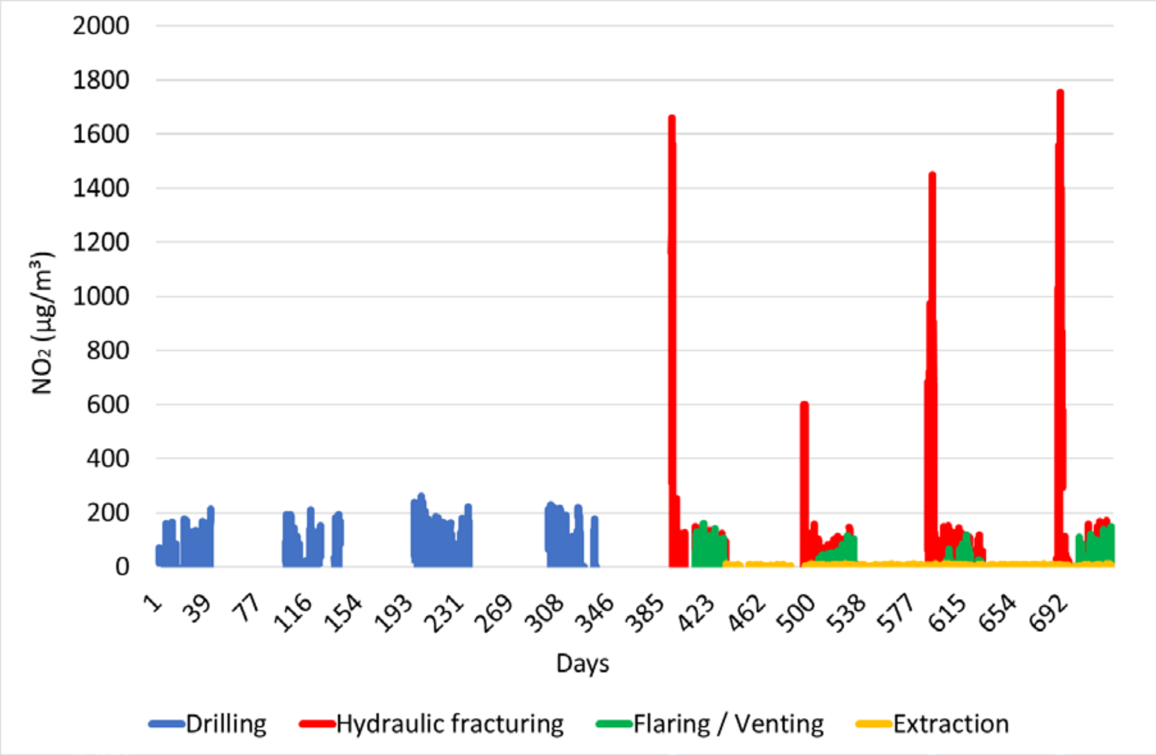

Figure 3.9 Short-term variations in hourly average nitrogen dioxide concentrations at the worst case receptor location showing the contributions of different shale production activities for Scenario 6

Notes: Based on 2016 to 2017 meteorological data.
Worse case receptor location is 100m north-east.

3.3.6 Summary of results

The dispersion modelling allows a number of observations to be made about the relationship between the operation of a shale gas facility and potential changes in ambient air quality surrounding the site that may require monitoring.

Long-term model

The long-term model results for the drilling, hydraulic fracturing and extraction phases indicate the following.

Nitrogen dioxide

Drilling, hydraulic fracturing and extraction at shale gas sites have the potential to result in elevated contributions of nitrogen dioxide.

Where the higher emission factors (EFB) identified from the literature review were applied and ‘rapid’ development was assumed, the highest nitrogen dioxide contribution was found to be 126.9µg per m^3 (Table 3.1, Scenario 4) at 100m from the centre of the site, representing an exceedance of the long-term AQO of 40µg per m^3.

Where the lower set of factors identified from the literature review (EFA) were applied and ‘rapid’ development was assumed, the highest contribution was 76.1µg per m^3 (Table 3.1, Scenario 3), which still represents an exceedance of the AQO.

But where ‘steady’ development was assumed with EFA, the highest process contribution falls below the AQO, that is, 38.0µg per m^3 (Table 3.1, Scenario 5).

Also, where ‘steady’ development was assumed with EFC (that is, emission factors which reflect the emission controls likely to be applied in England under the NRMM Regulation), the highest process contribution was found to be well below the AQO at 16.9µg per m^3 (Table 3.1, Scenario 6).

Although concentrations above the long-term AQO were predicted for ‘rapid development using emission factors EFB and EFA, this does not mean exceedances would be permitted in practice. This is because further emission controls would be required in order to lower concentrations so they complied with the AQO.

Particulate matter

Process contributions of particulate matter (PM_{10}) from the drilling hydraulic fracturing and extraction phases were found to be below the long-term AQO in all scenarios. Where EFC was applied and ‘steady’ development was assumed, the contribution was found to represent 3% (Table 3.1, Scenario 6) of the AQO (40µg per m^3). Note, however, that particulate emissions which would be expected to occur as a result of other activities at a shale gas site (for example, stockpiling, vehicle movements) were not considered in the assessment.

NMVOCs

Process contributions of NMVOCs from the drilling, hydraulic fracturing and extraction phases were found to exceed the long-term AQO in all scenarios with the exception of the exploration phase. Where EFC was applied and ‘steady’ development was assumed, the contribution was found to represent 117% of the AQO for benzene (Table 3.2, Scenario 6), which has an annual average objective of 5µg per m^3.

Although concentrations above the long-term AQO were predicted, this does not mean exceedances would be permitted in practice, because further emission controls would be required to lower concentrations so they complied with the AQO. Also, it is unlikely that benzene concentrations as high as those predicted would occur in practice. This is because NMVOCs are a category of pollutants which includes a large variety of chemical compounds, and the assumption that all NMVOCs are emitted as benzene can be considered conservative (although this assumption is typical for an industrial air quality impact assessment). A more detailed study of NMVOC sources and emissions at shale gas facilities would be required to determine the likelihood of an exceedance. Furthermore, the standards have been developed to be applied at locations of long-term human exposure and this is highly unlikely to occur within 100m of the centre of a shale gas site.

Methane

Process contributions of methane were found to range from 4.61µg per m^3 to 25.5µg per m^3 under ‘steady’ development (Table 3.2, Scenarios 3 and 4) and were 4.87µg per m^3 under ‘rapid’ development (Table 3.2, Scenarios 5 and 6).

There is no applicable AQO for methane, but it is useful to compare the modelled process contributions with typical ambient concentrations. The Mace Head Atmospheric Research Station on the west coast of Ireland in County Galway typically provides readings for methane of ~1,300 µg per m^3 at a remote location. The long-term-average incremental impact of shale fugitive emissions would therefore be <5% of the background and so difficult to detect with monitoring.

Short-term model

The short-term model results for the drilling, hydraulic fracturing and extraction phases indicate the following.

Nitrogen dioxide

Short-term concentrations of nitrogen dioxide are predicted to exceed the relevant AQO during all the scenarios for shale development over 2 years; they were predicted to be up to 389–1,165% of the AQO (Table 3.3, Scenarios 3–6). They are also predicted to exceed or approach the AQO during both scenarios for shale exploration, when they were predicted to be up to 91–182% of the AQO (Table 3.3, Scenarios 1 and 2).

The highest short-term concentrations anticipated for nitrogen dioxide are associated with the hydraulic fracturing phase; this corresponds specifically to when the 15 fracturing pumps are active along with all other fracturing phase sources.

The highest nitrogen dioxide concentrations associated with the drilling phase occur when the air drilling compressor package and the main drilling rig are both active. Air drilling, if used in the UK, would likely occur for only the first week of drilling each well.

NB Most of the sources considered in this study were modelled using emission factors for NOx, followed by estimating nitrogen dioxide concentrations from predicted NOx impacts. However, the flare source in the exploration phase and the heater source in the extraction phase were modelled – due to limitations in the available literature data – using emission factors for nitrogen dioxide itself (see Appendix A).

Although concentrations above the short-term AQO were predicted, this does not mean exceedances would be permitted in practice, because further emission controls would be required to lower concentrations so they complied with the AQO

Particulate matter

Short-term concentrations of PM_{10} are not predicted to exceed the relevant AQO for any scenario (Table 3.3). The highest short-term PM_{10} concentrations are associated with the flare source in the exploration phase, followed by contributions from the hydraulic fracturing phase, the drilling phase and extraction phase in that order.

NMVOCs

The highest short-term concentrations anticipated for NMVOCs are associated with the drilling phase. Although not illustrated in Figure 2.2, the mud–gas separator is a predominant contributor to NMVOC concentrations. Although the mud–gas separator can contribute to elevated hourly mean concentrations, it only operates in response to unplanned gas kick events. To ensure a conservative approach to this study, the mud–gas separator was modelled as being operational once every 2 weeks during drilling phases. It is anticipated that, on an actual shale gas site, the mud–gas separator would be operational less frequently than that.

There is no relevant AQO for short-term NMVOC concentrations and so the column in Table 3.4 for comparing predictions with an AQO is marked as ‘not applicable’.

The extraction phase has been shown to contribute significantly to hourly mean NMVOC concentrations, resulting from both fugitive emissions and emissions from equipment that was modelled as point sources. Unlike the mud–gas separator, which operates very infrequently, emissions from the extraction phase sources are more likely to be continuous.

Overall, the mean hourly and annual concentrations for NMVOCs are likely to be dominated by extraction sources for most of the operation of the site, with occasional spikes in hourly mean concentration during drilling activities.

Methane

The highest short-term hourly methane concentrations are associated with fugitive emissions during the extraction phase. As discussed in Appendix A, extraction sources are expected to be essentially continuous once extraction begins at the site.

Overall, the mean hourly and annual concentrations for methane are likely to be determined by emissions from the extraction phase and by fugitive emissions in particular. During the exploration phase, high hourly concentrations of methane were shown to occur during venting activities.

There is no relevant AQO for short-term methane concentrations and so the column in Table 3.4 for comparing predictions with an AQO is marked ‘not applicable’.

3.3.7 Discussion

The dispersion modelling study relies on emissions data collected from a review of published literature. The predicted impacts on air quality should therefore be considered indicative for shale gas sites in the UK rather than definitive. Scenario 6, which is based on emission factors that reflect the controls under the NRMM Regulation (EFC) and assumes a ‘steady’ rate of development, is considered to be most representative for future shale gas operations in the UK. However, the impacts on air quality associated with a shale gas facility will depend largely on the scale of the operation and on the effectiveness of the measures to control and mitigate emissions. Shale gas operators could be expected to conduct dispersion modelling assessments for each facility, reflecting the individual specifications and local conditions at the site, so that the modelling results can be used to plan appropriate ambient air quality monitoring that takes account of risk and cost.

Although concentrations above Air Quality Objectives are predicted for some emission scenarios and pollutants, this does not mean that exceedances would be permitted in practice, because further emission controls would be required to lower concentrations so they comply with the AQO.

The following conclusions can be drawn from the results of the dispersion modelling study.

- The ordering of higher and lower impacts for different scenarios was broadly in line with the ordering of emissions (that is, the predicted levels for the drilling, hydraulic fracturing and extraction phases were generally higher than for the exploration phase). Similarly, Scenario 6 had the lowest impacts during drilling, hydraulic fracturing and extraction in line with its lowest emissions during these phases. This applies to both the long-term and short-term predicted impacts.
- The operation of shale gas facilities may result in relatively high ambient concentrations of nitrogen dioxide and NMVOCs in close proximity to the point of emission. The highest annual mean concentrations of nitrogen dioxide and NMVOCs under Scenario 6 (4 wells and EFC emissions) at the indicative receptor locations in the study were 16.9µg per m^3 and 5.84µg per m^3 respectively. These concentrations were found to occur at a distance of 100m from the centre of the site. This is not uncommon for facilities which rely on the operation of diesel-powered plant and such impacts have prompted the emission controls under the NRMM Regulation. It is also important to note that the study did not include specific locations of relevant exposure (for example, houses, schools). It is highly unlikely that these receptors would be situated within 100m of a shale gas facility, though ecological sites could be in close proximity.

- The results indicate the emissions from a shale gas facility for Scenario 6 could result in an exceedance of the short-term AQO for nitrogen dioxide at distances of up to about 300m from the centre of the site (Figure 3.5a). This objective corresponds to 200µg per m^3 as the 99.79th percentile of hourly average concentrations in a year. This exceedance result indicates a need for further work to understand the short-term impacts of shale gas facilities on ambient air quality.

- The different phases of a shale gas development can be seen to result in varying contributions to levels of pollutants in ambient air. The drilling and hydraulic fracturing phases were found to have the greatest impact.

- Where a confounding source was factored into the assessment, the results indicate the baseline (pre-existing) concentrations may be higher and thus the relative signal strength of pollutants arising from the shale gas facility would be altered. The roads considered as confounding sources in the study were representative of a busy A road (traffic data taken from the A34 in Oxfordshire); however, further studies may be considered for roads with different traffic profiles and/or located at varying distances from shale gas sites.

- All modelled long-term concentrations can be seen to reduce with increasing distance from the site. The long-term AQO for nitrogen dioxide is 40µg per m^3 as an annual average. Long-term nitrogen dioxide concentrations were found to represent ~1% of the AQO at distances beyond ~1km from the centre of the site (see 0.4µg per m^3 contour in Figure 3.1b) when 'steady' development is assumed and when emission factors that represent the restrictions under the NRMM Regulation (EFC) are applied (that is, Scenario 6 emission factors). However, data on background concentrations would be required to confirm that ambient impacts on sensitive human receptors will not exceed AQOs for the protection of human health at locations of relevant exposure.

- The results indicate careful selection of monitoring sites may be needed to detect shale contributions clearly and with sufficient frequency. A pair of upwind and downwind monitoring locations will provide an improved insight into the long-term and short-term variations in pollutant concentrations, particularly in the presence of confounding sources. Careful mapping of signal-to-noise ratios and impact frequencies (based on dispersion modelling) will provide the best opportunity of monitoring at the optimum locations.

- It is expected that shale gas operators will need to consider conducting air quality impact assessments of individual facilities, involving atmospheric dispersion modelling, similar to that described in this report. Such a study would be required to consider the relative significance of air quality impacts. The Institute of Air Quality Management (IAQM) provides a method for describing the impact of changes in long-term-average air quality at locations of relevant exposure (for example, homes, hospitals and schools) (IAQM 2017). The IAQM method requires consideration of background air quality concentrations; note that background air quality was not factored into this modelling study. If a location of relevant exposure is assumed to be located at the receptor 300m to the east of the site in this study and background nitrogen dioxide concentrations are ≤75% of the AQO, the impact of emissions from the facility under Scenario 6 on long-term nitrogen dioxide concentrations could be described as 'slight' under the IAQM's impact descriptors (IAQM 2017, Table 6.3).

- The Environment Agency uses a threshold criterion of 10% of the short-term AQO as a screening criterion for the maximum short-term impact. Under Scenario 6, the short-term nitrogen dioxide concentrations were found to be >10% of the AQO at the maximum receptor. If the results of an assessment of a specific shale gas facility were found to show similar impacts, short-term impacts on air quality could not be screened out as insignificant.

The modelling has shown that there are potentially significant incremental impacts on local air quality near a shale gas site – especially impacts of nitrogen dioxide, which is a 'no threshold pollutant' (Table 2.2).

- For annual average concentrations, the incremental impact of nitrogen dioxide may amount to ~40% of the AQO with abated emissions (Scenario 6) and may approach the AQO (Scenario 5) or exceed it AQO (Scenarios 3 and 4) with unabated emissions (Table 3.1).
- For short-term average concentrations, the incremental impact of nitrogen dioxide may approach or exceed the AQO for all scenarios (Table 3.3).

These impacts mean that:

- monitoring the impacts is more justifiable than if there were no significant incremental impacts
- modelling the impacts is warranted in order to infer appropriate positions, frequencies, sensitivities and methods for monitoring

Moreover, the modelling did not include all the impacts from shale-related activities; for example, it did not include NOx emissions from HGV transport passing to or from the site. If these additional impacts were added to the modelled impacts from shale activities, then the case may be strengthened for ambient monitoring and also for modelling to inform the design of that monitoring.

Overall, the results of the modelling exercise support the development and application of a tailored and adaptive ambient monitoring strategy at shale gas facilities. In particular the modelling indicates that:

- all emission scenarios would approach or exceed short-term AQOs for nitrogen dioxide in the near field;
- emissions from shale gas facilities could account for ~40% of the annual average AQO for nitrogen dioxide in close proximity to the sites if emissions from NRMM are abated, and could exceed it if they are unabated;
- it may not be possible to screen out short-term impacts on nitrogen dioxide concentrations as insignificant as per the Environment Agency's screening criterion;
- exceedances of the short-term AQO for nitrogen dioxide may occur.

4. Monitoring: general considerations

4.1 Reasons for monitoring

Monitoring is important for many industrial processes to both demonstrate and provide reassurance that emissions are not causing a pollution event, or not increasing ambient concentrations, or not resulting in an exceedance of an AQO.

A monitoring campaign will have cost and resource implications, so a carefully designed monitoring regime will provide the most benefit while avoiding excessive costs. The reasons for monitoring will dictate: the monitoring approach, the monitoring period, and the level of complexity (for example the scope and number of measurements).

Some of the characteristics of shale gas installations that need to be taken into account can be summarised as follows.

- A high proportion of releases take place via diffuse pathways (e.g. via leaks or multiple small discharges), which mean that in-source or at-source measurements are less effective or, in many cases, not possible. This means that operators, regulators and other stakeholders have to rely on ambient environmental monitoring to verify the expected environmental performance of a facility.
- Installations may be located in densely-populated areas and may be close to sensitive locations including schools, health and social care facilities, and residential properties.
- The activities giving rise to environmental releases are intermittent in nature.
- Shale gas installations are the subject of substantial public interest.
- The UK has little experience of shale gas exploration and extraction activities using high-volume hydraulic fracturing techniques.
- Shale gas operations involve extracting variable resources directly from local geology, rather than operating with more consistent and prepared resources such as a conventional industrial feedstocks. Hence the quantities and constituents of emissions may be relatively variable and/or uncertain.
- There may be confounding source(s) nearby, so monitoring needs to consider:
  - the cumulative impacts from these and the sources related to the shale gas facility
  - how it may resolve the contributions of the various individual sources

A monitoring system adopted at a shale gas installation will need to:

- reflect these characteristics and considerations
- balance the requirements and expectations of key stakeholders including shale gas operators, local communities and scientific/regulatory bodies

The many reasons for undertaking a monitoring campaign can be split into the 4 broad categories as outlined in Sections 4.1.1-4. Table 4.1 summarises some of the reasons for undertaking air quality monitoring at shale gas sites, and indicates where they correspond broadly to the 4 categories.

4.1.1 Baseline conditions

A key aspect of any monitoring regime is the establishment of a baseline. Baseline monitoring allows the regulator and the operator to determine the conditions prior to any activity. In doing so, any adverse change that may arise following the start of activities can be identified by comparison with the known original conditions.

The monitoring of baselines should be designed so that any subsequent changes after shale activities start can be detected and attributed to different sources.

4.1.2 Operator compliance

Compliance monitoring is adopted to demonstrate that compliance with an environmental permit is being achieved, including compliance with ambient air quality standards and the minimisation of releases using Best Available Techniques (BAT).

4.1.3 Process understanding

Monitoring can provide valuable insight into the variations in ambient air quality that occur due to changes in the processes at a site. Incremental monitoring (that is, where monitoring is designed to resolve the contributions of emissions associated with particular processes) can be applied to gain a better understanding of changes in ambient concentrations during different phases of a process.

Incremental monitoring can provide reassurance about additional exposure, including exposure to ‘no threshold’ pollutants for which all additional exposures may have adverse effects such as nitrogen dioxide and $PM_{2.5}$ (see Table 2.2).

Incremental monitoring can also be used to investigate small changes in concentrations. However, this brings additional challenges relating to distinguishing process signals from noise due to other sources, as well as understanding the reasons for any changes in measured concentrations and identifying any potentially contributing source(s).

4.1.4 Investigative/research

As data on shale gas operations are limited, especially in the UK, there is a clear need for monitoring to increase the understanding of the impact on air quality of these processes. Understanding the activities involved in shale gas operations will facilitate significant improvements in monitoring, regulation and emission factor estimates. All additional data that can be compiled from shale gas monitoring will help in the determination of more robust emission factors. As the knowledge base improves with a greater availability of data, the need for monitoring in certain environments and conditions may subside if they are determined to be insignificant areas of emissions.

Table 4.1 Reasons for monitoring ambient air quality

Reason	**Baseline conditions**	**Operator compliance**	**Process understanding**	**Investigative / research**
Establish a baseline	✓			
Detect changes in ambient concentrations during site operation	✓	✓	✓	
Determine exceedances of AQOs and/or guidelines	✓	✓		
Assess the site's performance against set criteria	✓	✓	✓	
For public information and to improve confidence in site operations	✓			
Assess the accuracy of predicted impacts on air quality	✓			
Source apportionment to support regulatory controls		✓	✓	
Support complaint analysis	✓	✓	✓	
Support onsite emissions testing			✓	✓
Contribute towards industry emissions data			✓	✓
Provide a comparison between different monitoring approaches				✓

It is important that ambient air quality data are accompanied by other information so that they can be interpreted for regulatory and process management purposes, including for the design of adaptive monitoring regimes. Specifically, the data need to be accompanied by information on:

- the phase of site operations – including details of the types and timings of site activities during a particular monitoring period, which may include information from onsite monitoring
- concurrent meteorological conditions – which determine the dispersion situation, including data on wind direction which determines if the air being monitored has come from the site or from other sources of air pollutants
- site layout – including the positions of potential onsite sources of air pollution relative to potential ambient monitoring locations

Layout information is particularly useful if an ambient monitor is near a site because it can be used with wind direction data to attribute monitored air pollution signals to specific onsite sources.

There is a general need to:

- plan the recording and reporting of additional information ('metadata') so that it is readily available and compatible with concurrent data from ambient air quality monitoring

- take account of monitoring results when considering if a monitoring regime needs to be modified (that is, a general need for feedback between monitoring results and monitoring adaptations so that regimes stay proportionate to risk and cost).

4.2 Monitoring techniques

Numerous techniques can be used to monitor pollutant concentrations in ambient air. These vary in complexity and cost, and range from simple diffusion tubes and handheld monitors, to complex analysis of absorption spectra. Table 4.2 summarises the main approaches – and the most important considerations – for choosing monitors of pollutant concentrations in ambient air that are likely to be applicable to shale gas operations.

Table 4.2 Ambient air monitoring approaches

Approach	Description
Continuous sampling, or short period cumulative sampling	The level of variability in the concentrations of a pollutant will determine the need to adopt a sampling approach that is either continuous or that takes cumulative samples regularly over short periods. Sporadic 'grab samples' should generally be avoided as they are likely to be less representative and harder to interpret than continuous or regular short period cumulative monitoring. Continuous sampling may involve the use of real-time analysers and subsequent laboratory analysis. The averaging period against which measurements are to be reported will determine the duration of short period cumulative samples, which should be taken regularly and consecutively, and at locations that are consistent between periods.
Omnidirectional sampling, or directional sampling	Methods of sampling in ambient air can either be omnidirectional or directional: • Omnidirectional – sampling of air from all directions under all wind directions. The approach requires interpretation using continuous meteorological data. • Directional – sampling of air when the wind is blowing from a specific direction and may also be above a certain speed. More commonly applied where background concentrations are low and there is a specific source being assessed. A single sampler can be located downwind of a target source to provide an indication of the pollution levels arising from it. However, the concentrations detected by the monitor will depend on variations in the direction and speed of the wind at the site. To gain a more detailed insight into emissions arising from a facility, a directional sampler with 2 wind vane operated receptors can be used. These samplers may have a foreground sampling arc of 40° centred on the target source, and a background arc of 320° that excludes the target source. If there are confounding sources within the foreground arc, the contribution from the target source may be overestimated. To counteract this, more than one sampler can be set up around the target source, enabling the separate contributions from the target, confounding and background sources to be resolved.
Fixed path or open path	Concentrations are determined by either: • Fixed point – consists of a network of sites at fixed locations, with each providing either time-averaged concentrations or spot concentration values from a fixed point in space. As a result, the

Approach	Description
	results for fixed point sampling depend largely on the selection process for the locations of the sites. • Open path – measurements are made directly in the atmosphere without obtaining samples. Rather than concentrations being measured at a specific point, the average concentration of a pollutant is calculated over an extended measurement path, with certain methods allowing the concentration to be spatially resolved. Open path sampling allows the determination of pollutant concentrations across site boundaries and along roadways, for example. However, difficulties can arise in the interpretation of integrated path data.
Active or passive monitoring	Monitoring can either be active or passive. Active monitoring involves the operation of automatic sampling, where air is drawn into the monitor using a pump. Active monitoring can offer greater levels of accuracy, but it is typically more expensive and the choice of monitoring locations may be restricted by the availability of power supplies. Passive monitors are more approximate, but have the advantage of being cheap and easy to deploy (as they are compact). Also they do not require a power supply. Passive monitoring can be omnidirectional (for example, diffusion tubes) or directional (for example, directional passive air samplers which can be deployed in upwind or downwind pairs to resolve site contributions).

4.2.1 Timescales and averaging periods

Three aspects of monitoring timescales need to be considered when designing a monitoring campaign.

- **Temporal resolution** – the interval between consecutive individual measurements. This is generally dictated by the type of measurement device (instrument or sampler). An automatic sampler might make successive measurements every few seconds, whereas diffusion tube samplers might make consecutive cumulative measurements every few weeks. Some monitoring approaches do not make measurements consecutively or at regular intervals (for example, occasional grab samples); this can make it difficult to infer trends and source performance.

- **Averaging time** – the period over which consecutive measurements are averaged for reporting purposes. Averaging periods will be determined by the aims and objectives of the study (for example, assessment against Limit Values in EU directives) and will reflect the likely emission patterns, pollutant chemistry, associated health impacts and the time over which that impact will occur. Table 4.3 lists the recommended averaging times for selected applications.

- **Duration** – the overall length of a monitoring campaign when a record of period-averaged concentrations is collected. This is generally dictated by the need to collect a representative sample of emission and dispersion conditions.

The timescales of the monitoring campaign will affect the measurement techniques selected, as some methods are only able to sample within a limited range of averaging times (Table 4.3).

Table 4.3 Recommended minimum averaging times for ambient air quality monitoring

Minimum averaging period	Type of survey
10 seconds	• Odour assessment • Mobile sensors • Acute respiratory effects • Studies of puffs
3 minutes	• Useful for studying odours and acute health effects if faster response not available
1 hour	• Time-averaged concentrations • Dispersion studies • Diurnal changes • Discrete source studies • Short-term exposure events • Health effects
24 hours	• Longer term exposure patterns and prolonged/chronic health effects • Area source studies • Effects of weather systems • Effects occurring on different days of the week
1 month	• Seasonal and annual variations • Long-term and long-range effects from regional or global sources

Source: Environment Agency (2011, Table 7.2)

4.2.2 Location of monitoring

The location of monitoring equipment is an important consideration as it will affect the likelihood of capturing and resolving emissions from the site. The determination of the monitoring location(s) will be necessary to establish a baseline and then to assess changes against this baseline once operations commence.

The location of a sampling point could be:

- **Site boundary** – where net emission fluxes from site can be estimated through the use of measured concentration transects at the permit boundary of the site in support of relevant regulation or reporting
- **Sensitive receptors** – providing localised measurements at high sensitivity receptors
- **Background** – to help determine ambient conditions in the absence of contributions from the target source (that is, the shale gas site)
- **Maximum offsite concentrations** – this location is dependent on meteorological and release data, and may be determined by atmospheric dispersion modelling
- **Optimum discrimination** – the location where the incremental ‘signal’ of impacts from the target source is strongest relatively to confounding ‘noise’

due to the impacts of other local sources, so the target source performance is as clear and easily tracked as possible

The main aim of a monitoring campaign is to check and report on how well a site performs at controlling its impacts on air quality. Monitoring should therefore collect data from places where site-derived contributions are frequent and are relatively prominent compared with other sources, because this will allow site performance to be checked more often and with greater confidence. It is expected that the monitoring campaign will require at least one down-prevailing-wind monitoring station.

The selection of a monitoring location with the greatest potential for identifying the maximum change in concentrations will require an assessment of dispersion from the plant. Key factors when considering this are:

- wind speed
- wind direction
- height of emission releases
- atmospheric mixing
- type of pollutant
- topography

When these factors are appropriately considered, the location of the maximum concentration can be identified. This would often be done through an atmospheric dispersion modelling assessment.

It may be advantageous to establish more than one monitoring station, as the additional data and the inference from this can enable the contributions of individual sources on a site to be more readily resolved. This may be required where there are nearby sensitive receptors, existing air quality problems or confounding sources (for example, clusters of shale gas sites, nearby roads, nearby agricultural facilities).

Monitors may also be placed up-prevailing-wind and down-prevailing-wind of a target source to help determine changes in ambient concentrations due to the source (for example, as the wind passes over the site from its upwind to its downwind side).

The choice of monitoring location should follow the guidelines set out by the Environment Agency guidance on ambient air monitoring (Environment Agency 2011).

The recommended monitoring options and the framework for establishing a monitoring strategy for a shale gas site that is adaptable for changes are set out in Sections 5 and 6, respectively.

4.3 Selecting a monitoring technique

Various methods are available for the monitoring of pollutants in ambient air. These will differ considerably in cost, duration and applicability for certain operational phases. The method and type of monitoring should be selected to match the study objectives in terms of:

- the ranges of substances to be assessed
- the limits of detection for those substances
- the sampling and survey duration

Appendix E provides an overview of the methods available, including detail on the frequency, duration and approximate costs of different approaches to ambient air quality monitoring.

The findings of the dispersion modelling assessment and literature review have drawn on these methods to set out recommendations for monitoring options that reflect the likely levels and changes in ambient air pollutant concentrations around a shale gas facility. Expert judgement has been applied to recommend monitoring options which balance cost and risk for different pollutants and phases.

5. Monitoring: specific options

This section sets out the monitoring priorities and options for the key phases of a shale gas site. These options have been developed to reflect the risks posed by the pollutant emissions identified from the literature review and the dispersion modelling study. An adaptive monitoring framework for selecting the most appropriate suite of monitoring activities for an individual shale gas facility and phase is proposed in Section 6.

5.1 Factors to consider

5.1.1 Strategic considerations

The monitoring of pollutants should take account of the risk posed by onsite emissions during each phase of shale gas operations. Target pollutants and methods of monitoring should be determined based on the following strategic considerations:

- emissions review (types and amounts)
- air quality standards (available for most pollutants)
- baseline levels (including proximity to standards)
- public interest and 'societal licence to operate' factors
- experience from monitoring comparable sites (if/when available in the UK)
- modelling (especially when/where comparable monitoring experience is limited)
- overall risk and cost

5.1.2 Local and practical factors

Monitoring will also need to take account of local and practical factors such as:

- local topography and meteorology
- presence, proximity and types of sensitive receptors
- availability of secure and accessible sites for deploying monitoring equipment
- presence of confounding sources that could obscure impacts due to the shale gas site
- availability of power supplies

5.1.3 Achieving best practice

Monitoring methods and techniques should be suitable and appropriate for the determinand they are assessing to ensure best practice. That is, European (CEN) and national (ISO) standards that meet the Environment Agency's Monitoring Certification Scheme (MCERTS) performance requirements should be used if available and appropriate (for example, if regulatory regimes are similar).

5.2 Selecting the level of surveillance

The review of shale gas operations and the dispersion modelling study enabled the following conclusions to be drawn on the potential changes in ambient pollution concentrations around a shale gas facility.

- During the different phases of a shale gas site, some pollutants will be present in higher concentrations, and so monitoring requirements will vary accordingly. For example, certain pollutant concentrations will be present in higher concentrations during the drilling and hydraulic fracturing phases than in the extraction phase.
- Pollutant concentrations are likely to reduce quickly with distance from the site, but will be highly variable due to the nature of the activities on the site and the influence of local meteorological conditions.
- It will therefore be essential for monitoring locations to be selected in order to reflect the point of maximum impact in the areas of potential exposure, while also considering locations where the overall frequency and scale of impacts are high and where these impacts are readily distinguished from those of other sources.
- If there are confounding sources, which may affect the ability to identify the signals associated with the shale gas site, additional monitoring locations and more detailed analysis of short-term variations will be required. Confounding sources may also be associated with higher background concentrations and less leeway with respect to achieving ambient AQOs; risks may thus be higher and monitoring plans may need to be adapted accordingly.

This study recommends the 3 categories of surveillance levels to reflect these conclusions. These levels are designed to elaborate the monitoring requirements for different pollutants at each phase of a typical shale gas development. The levels are considered to be appropriate for the expected emission levels during each phase of shale gas operations, as illustrated by the literature review and dispersion modelling exercise, and thus reflect the potential impact on the air quality.

The recommendations factor in the monitoring costs set out in Appendix E, with expert judgement applied to develop monitoring strategies that balance risk and cost.

- A central cost basis is envisaged for routine surveillance in mid-risk situations.
- A lower cost basis is envisaged for more indicative measurements under reduced surveillance.
- A higher cost basis is envisaged for more intensive monitoring at an enhanced surveillance level, where the risks are greater.

A full cost–benefit analysis of monitoring was outside the scope of the study.

Section 6 outlines a framework that can be used by operators and regulators to identify the most appropriate suite of monitoring approaches reflecting the characteristics of an individual shale gas site. Application of this monitoring framework would allow the most appropriate level of surveillance to be selected. This will:

- ensure the monitoring strategy reflects the specific characteristics of the shale gas site

- enable the strategy to adapt to any changes in the nature of the development as a site moves from one shale gas phase to the next

5.2.1 Routine surveillance

Routine surveillance would be a consistent and convenient starting point (or default case) for planning of monitoring at most sites. It meets a typical monitoring requirement that would generally be expected for each specified pollutant unless there were site-specific reasons to indicate that reduced or enhanced surveillance is more appropriate.

Routine surveillance involves quantitative monitoring at one or more locations which reflect the maximum potential impact of emissions of certain shale-related pollutants beyond the boundary of the site. It may also include additional offsite measurements to coincide with traffic related contributions to ambient air quality, resulting from site vehicles.

Under ‘routine’ surveillance there would generally be a single continuous (automatic) monitoring station for key pollutants at a down-prevailing wind location near the site boundary, as the main monitor. Additional monitoring locations may be established if deemed necessary such as when the situation is complicated by other local sources so that additional monitor(s) are needed to distinguish between impacts from shale activities and these other sources.

5.2.2 Reduced surveillance

Reduced surveillance methods would be appropriate for sites and pollutants that are deemed to be low risk, low concentration, low impact and which may also align with limited permitting requirements and/or use of standard permitting. This would allow a lower level of monitoring/surveillance than may be required in other circumstances. Examples of situations where reduced surveillance would be appropriate are:

- intermittent surveys targeted on particular pollutants or phases (for example, at commissioning)
- occasional campaigns with mobile monitoring equipment
- simplified/indicative monitoring (for example, with passive directional samplers)
- reliance on regular onsite monitoring to confirm close control of all releases
- use of results interpolated from existing ambient monitoring networks in comparable and/or nearby situations

5.2.3 Enhanced surveillance

The monitoring requirements for enhanced surveillance would essentially extend the routine surveillance by applying a higher accuracy, frequency or duration of monitoring for one or more pollutants where there is an objective reason for doing so. Such an approach may be indicated, for example:

- where there is little headroom for additional air pollutants in or near an Air Quality Management Area (AQMA)
- for sites where verified complaints have been received
- where an operator has a history of non-compliance

A higher frequency, or time resolution, of monitoring may be needed to resolve short periods of emissions and impacts from intermittent shale-related activities. Where a higher resolution, frequency or duration of measurement is justified, this may be provided using continuous ambient monitors, higher sensitivity quantitative instruments or bespoke monitoring programmes.

In some cases, the type and/or duration of monitoring recommended may be the same across different surveillance levels. However, a site may undertake different levels of surveillance for different pollutants because of differences in risk. The level of monitoring at a site should be adapted to take account of changes in operating phase and performance (for example, as shown by recent monitoring results), so that monitoring effort is always proportionate to risk and cost.

It will be necessary to select a monitoring surveillance level for each pollutant during the following 5 phases:

- baseline
- drilling
- hydraulic fracturing
- extraction
- decommissioning

Note that the ‘baseline’ here is for a specific air pollutant, and may not be the same as the general baseline described in Section 1.1.1 (under Commission Recommendation 2014/70/EU). The one here is designed to establish the pollutant-specific conditions at the site prior to activities taking place.

Note also that, although the exploration phase will occur prior to a site becoming fully operational, the monitoring options for drilling are considered to be appropriate for this phase.

5.3 Recommendations from dispersion modelling study

The results of the dispersion modelling assessment indicate a continuous monitoring approach will be required during certain phases of an operational shale gas facility for key pollutants released from combustion, flaring and venting, and fugitive sources. This will be necessary to reflect the variable nature of the emission sources and the relatively high concentrations that may occur in close proximity to the site.

The technique selected must have an appropriate limit of detection for the expected signal strength for the pollutant in question. The indication of the expected signal strengths during the different phases provided by the modelled study forms the basis of the following monitoring techniques that are recommended during routine level surveillance.

- For **nitrogen dioxide**, this is likely to include continuous monitoring – using chemiluminescence instruments – during the exploration, drilling, hydraulic fracturing and extraction phases.
- For **NMVOCs**, this is likely to include continuous monitoring using gas chromatography (GC) or gas chromatography–mass spectroscopy (GC-MS) during the exploration, drilling, hydraulic fracturing and extraction phases.

- For **PM_{10},** this is likely to include continuous monitoring using a tapered element oscillation microbalance (TEOM), a beta attenuation monitor (BAM) or optical light scattering during the exploration, drilling and hydraulic fracturing phases.
- For **methane**, this is likely to include continuous monitoring using a flame ionisation detector (FID) or a Fourier transform infrared (FTIR) instrument during the exploration, drilling, hydraulic fracturing and extraction phases.

Most other pollutants can be monitored using similar techniques. In certain circumstances, however, it may be appropriate to adopt non-continuous methods such as short period cumulative sampling. The process for selecting the most appropriate method is discussed in Section 4.

Note that, due to the limited availability of data, it was not possible in this study to model all types of pollutant emissions from shale gas facilities. It was therefore necessary to apply professional judgement to determine the monitoring requirements for pollutants not included in the modelling exercise.

5.4 Outline monitoring surveillance strategies

Outline surveillance levels applicable to the different development phases are provided below for each relevant air pollutant in turn. Tables 5.1 to 5.5 reflect the potential risks posed by each pollutant to ambient air quality throughout the key phases of a shale gas site and the likely costs of implementation (see Appendix E). Note that this report does not provide a comprehensive account of every phase of a shale gas site, but an outline that focuses on the most significant phases in terms of emissions to air.

Recommendations are provided for:

- **Proposed approach** – this may include fence line monitoring, automatic downwind monitoring , simplified/indicative monitoring
- **Monitoring duration** – this may be required for the length of the relevant phase (for example, 1 year, 6 months, 3 months) or there may be no requirement
- **Monitoring frequency** – this may include continuous monitoring, short period cumulative sampling, or no monitoring required
- **Monitoring method** – this will depend on the applicable monitoring approach, reflecting the likely concentrations in ambient air and potentially the characteristics of relevant AQOs

The recommendations for monitoring design should be treated as a guide. For example, the regulator may stipulate monitoring requirements outside of these parameters such as specifying the monitoring duration to be the full length of the development phase at a specific site.

The monitoring should be adjusted as more information on site performance or conditions emerges; that is, results should be reviewed as they become available so the findings can be ‘fed back’ as appropriate to revise or refine the ongoing monitoring work. On this basis, the periods recommended for monitoring (that is, 3, 6, 12 months) are durations over which data should be initially collected and analysed in order to inform a review of the air quality situation and monitoring requirement at the end of that period. Depending on the findings of the review, the monitoring of a pollutant may be continued, modified or stopped. Hence the periods are recommended as the minimum durations for collecting enough data to inform a review of the monitoring, so that the strategy can be adapted in line with risk and cost.

For the majority of air pollutants, continuous monitoring techniques are preferable in order to provide high frequency, real-time data of pollutant concentrations on and around a shale gas site. Performance requirements for continuous monitoring will be determined by:

- air quality standards and guidelines set for the protection of human health and the natural environment
- the likely increases and variations in ambient concentrations that can be expected to arise due to the operation of shale gas installations
- current industry practices and standards

For some pollutants, cumulative monitoring techniques (for example, using passive diffusion tubes or high/low volume samplers) would be acceptable. However, the use of cumulative monitoring techniques is only recommended for circumstances where the risk is identified as being low or to supplement continuous monitoring methods. The general performance requirements for all diffusive samplers used for the determination of the concentration of gases and vapours in ambient air, irrespective of the nature of the sorption process and the analytical determination, are covered by BS EN 13528:2002 ‘Ambient air quality. Diffusive samplers for the determination of concentrations of gases and vapours. Requirements and test methods’.

Environment Agency Technical Guidance Note M8 has more information on all the different methods specified for monitoring pollutants to ambient air (Environment Agency 2011). Where ‘roadside’ monitoring is proposed, this indicates a recommendation for an assessment of pollutant concentrations along site access roads at points of relevant exposure (for example, homes, schools). Roadside monitoring may need to be combined with traffic count data to determine the impact of additional site vehicles on nearby roads. More information on the monitoring methods specified, and associated costs, can be found in Appendix E.

The recommended monitoring surveillance strategies for shale gas facilities are set out below for:

- the baseline period before any activity is carried out on the site facility (Section 5.4.1)
- drilling – which includes site preparation and exploration (Section 5.4.2)
- hydraulic fracturing (Section 5.4.3)
- extraction (also commonly termed production) (Section 5.4.4)
- decommissioning (Section 5.4.5)

As discussed, the monitoring surveillance strategies for drilling are also applicable to the exploration phase.

Note that the different surveillance strategies relate to the duration of monitoring employed, as well as the sampling method with the associated surveillance strategy, and not specifically to the number of monitoring sites around a shale gas site.

5.4.1 Baseline

A baseline survey is unlikely to be done at a reduced level of surveillance because reduced monitoring would increase the potential for uncertainty in determining changes from the baseline once the site becomes operational. If a reduced level of monitoring is used to establish a baseline, this should be supported by objective reasons. Recommendations for additional baseline monitoring locations are included in the monitoring framework presented in Section 6.

Recommendations for the baseline period are given in Table 5.1.

If an enhanced surveillance strategy is required under the monitoring framework, the baseline monitoring requirements for several of the relevant pollutants should be conducted over the course of a year. For these higher risk sites, enhanced surveillance would allow comparisons with annual AQOs or limits for those pollutants, and having data for a full annual cycle would help to highlight any underlying issues of air quality in and around the vicinity of the site. Identifying any particular air quality issues during the baseline monitoring could also help to determine future monitoring surveillance requirements, with the potential for some pollutants to be monitored using an enhanced surveillance strategy should it be deemed necessary.

For other pollutants, 3–6 months of monitoring is considered to be broadly suitable for baseline requirements if routine surveillance is required under the monitoring framework. Several ambient air pollutants were identified as not requiring any baseline monitoring, as background levels of these pollutants in the UK are normally low. In these cases, data from the UK's Automatic Urban and Rural Network (AURN)[2] and other non-automatic networks would be sufficient to determine a baseline.

Table 5.1 Recommended monitoring methods for emissions from shale gas facilities during the baseline period

Substance	**Monitoring surveillance required**	**Proposed approach**	**Monitoring duration**	**Monitoring frequency**	**Monitoring method**
NOx/nitrogen dioxide	Reduced	Ambient monitoring	6 months	Cumulative – short period	Passive samplers
	Routine	Ambient monitoring	6 months	Continuous – hourly	Chemiluminescence
	Enhanced	Ambient and roadside monitoring	1 year ambient 6 months roadside	Continuous – hourly	Chemiluminescence
Sulphur dioxide	Reduced	No monitoring required; data from AURN network sufficient for baseline			
	Routine	No monitoring required; data from AURN network sufficient for baseline			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	Ultraviolet (UV) fluorescence, FTIR or electrochemical
Carbon monoxide	Reduced	No monitoring required; data from AURN network sufficient for baseline			
	Routine	No monitoring required; data from AURN network sufficient for baseline			

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[2] https://uk-air.defra.gov.uk/networks/network-info?view=aurn

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	Non-dispersive infrared (NDIR), electrochemical or open path laser diode
Ozone	Reduced	No monitoring required; data from AURN network sufficient for baseline			
	Routine	No monitoring required; data from AURN network sufficient for baseline			
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} and $PM_{2.5}$)	Reduced	No monitoring required; data from AURN network sufficient for baseline			
	Routine	Ambient monitoring	6 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Enhanced	Ambient and roadside monitoring	1 year ambient 6 month roadside	Continuous – hourly	TEOM, BAM or optical light scattering
Benzene and NMVOCs	Reduced	No monitoring required; data from Hydrocarbon network sufficient for baseline			
	Routine	Ambient monitoring	6 months	Cumulative – short period	Passive samplers
	Enhanced	Ambient monitoring	1 year	Continuous – hourly	GC or GC-MS
PAHs, assessed as benzo(a)pyrene (BaP)	Reduced	No monitoring required; data from PAH network sufficient for baseline			
	Routine	Ambient monitoring	6 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
	Enhanced	Ambient monitoring	1 year	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
Methane	Reduced	Ambient monitoring	Three months	Continuous – hourly	FID or FTIR
	Routine	Ambient monitoring	6 months	Continuous – hourly	FID or FTIR
	Enhanced	Ambient monitoring	1 year	Continuous – hourly	FID or FTIR

5.4.2 Drilling (including site preparation and exploration)

Recommendations for the drilling phase are given in Table 5.2.

Monitoring during drilling (including site preparation and exploration) for several of the relevant pollutants should be conducted over the course of 3–6 months under a routine surveillance strategy. Routine surveillance (using continuous sampling techniques) would enable short-term trends and peaks to be identified, even though this phase of a shale gas facility would tend to be lower risk than other operational phases (that is, fracturing). It would also enable comparison with hourly AQOs or limits for certain pollutants where appropriate.

An enhanced surveillance strategy, should it be deemed necessary, would focus on monitoring for a generally longer duration (6 months or throughout the drilling phase for the majority of pollutants) to enable characterisation of some longer term trends. For certain key pollutants, it would also mean additional ambient monitoring locations to resolve offsite sources (for example, traffic, local processes) as well as any onsite process contributions.

Reduced surveillance would, in some cases, imply no monitoring is required during this particular phase of a shale gas facility. For other pollutants, it would mean a lower resolution of monitoring (for example, cumulative short-term sampling with passive samplers rather than continuous sampling) or a shorter monitoring duration.

Table 5.2 Recommended monitoring methods for emissions from shale gas facilities during drilling (including site preparation and exploration)

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
NOx/nitrogen dioxide	Reduced	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
	Routine	Ambient and roadside monitoring	6 months	Continuous – hourly	Chemiluminescence
	Enhanced	Ambient and roadside monitoring	Duration of drilling phase	Continuous – hourly	Chemiluminescence
Sulphur dioxide	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
Carbon monoxide	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	NDIR, electrochemical or open path laser diode
Ozone	Reduced	No monitoring required			
	Routine	No monitoring required			

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} and $PM_{2.5}$)	Reduced	Ambient monitoring	3 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Routine	Ambient monitoring	6 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Enhanced	Ambient and roadside monitoring	Duration of drilling phase	Continuous – hourly	TEOM, BAM or optical light scattering
Benzene and NMVOCs	Reduced	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
	Routine	Ambient monitoring	6 months	Continuous – hourly	GC or GC-MS
	Enhanced	Ambient monitoring	Duration of drilling phase	Continuous – hourly	GC or GC-MS
PAHs, assessed as BaP	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
	Enhanced	Ambient monitoring	6 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
Methane	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	FID or FTIR
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	FID or FTIR

5.4.3 Hydraulic fracturing

Recommendations for the hydraulic fracturing phase are given in Table 5.3.

During the hydraulic fracturing phase, pollutants under routine surveillance would all be monitored for a minimum of 3–6 months, usually by continuous sampling methods where available. The hydraulic fracturing phase is potentially higher risk (site-dependant) in terms of ambient pollutant emissions and so it is important that real-time data are produced to help identify changes, trends and altered peak concentrations. Continuous monitoring is also important for checking ongoing regulatory compliance for specific pollutants, such as those produced by temporary combustion processes, generators and flaring.

For sites that may require enhanced monitoring during this phase, the monitoring duration will in most cases be increased to a minimum of 6 months and potentially extended to the duration of the hydraulic fracturing phase, with continuous monitoring recommended for all pollutants where possible. For a reduced monitoring surveillance strategy, no monitoring would be required for certain pollutants that would be expected to be present or produced in lower concentrations during this phase – and thus regarded as lower risk.

Table 5.3 Recommended monitoring methods for ambient air emissions from shale gas facilities during hydraulic fracturing phase

Substance	**Monitoring surveillance required**	**Proposed approach**	**Monitoring duration**	**Monitoring frequency**	**Monitoring method**
NOx/nitrogen dioxide	Reduced	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
	Routine	Ambient and roadside monitoring	6 months	Continuous – hourly	Chemiluminescence
	Enhanced	Ambient and roadside monitoring	Duration of hydraulic fracturing phase	Continuous – hourly	Chemiluminescence
Sulphur dioxide	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
Carbon monoxide	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	NDIR, electrochemical, or open path laser diode
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
Ozone	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} and $PM_{2.5}$)	Reduced	Ambient monitoring	3 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Routine	Ambient monitoring	6 months	Continuous – hourly	TEOM, BAM or optical light scattering

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
	Enhanced	Ambient and roadside monitoring	Duration of hydraulic fracturing phase	Continuous – Hourly	TEOM, BAM or optical light scattering
Benzene and NMVOCs	Reduced	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
	Routine	Ambient monitoring	6 months	Continuous – hourly	GC or GC-MS
	Enhanced	Ambient monitoring	Duration of hydraulic fracturing phase	Continuous – hourly	GC or GC-MS
PAHs, assessed as BaP	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
	Enhanced	Ambient monitoring	6 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
Methane	Reduced	No monitoring required			
	Routine	Ambient monitoring	6 months	Continuous – hourly	FID or FTIR
	Enhanced	Ambient monitoring	Duration of hydraulic fracturing phase	Continuous – hourly	FID or FTIR

5.4.4 Extraction

Recommendations for the extraction phase are given in Table 5.4.

The different monitoring surveillance strategies for the pollutants during the extraction phase are in essence similar to those during the hydraulic fracturing phase. This is due to operational similarities, with this phase periodically requiring re-fracturing to maintain gas production. As such, routine surveillance for the majority of parameters would involve continuous monitoring (where applicable), usually for a period of 6 months, in order to produce real-time data during onsite operations and to help identify trends and/or spikes during certain processes. Real-time continuous data would also enable approximate comparison to be made with UK hourly AQOs or limits (where applicable for certain pollutants) for ongoing regulatory compliance.

Enhanced monitoring would involve the same continuous monitoring techniques for the pollutants in question, but usually for a longer duration (1 year) and, in some cases, additional monitoring locations to those onsite (for example, for NOx).

Reduced surveillance would range from no monitoring required to 3 months' monitoring (using either passive or continuous sampling techniques depending on the pollutant in question).

Table 5.4 Recommended monitoring methods for ambient air emissions from shale gas facilities during the extraction phase

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
NOx/nitrogen dioxide	Reduced	Ambient monitoring	6 months	Cumulative – short period	Passive samplers
	Routine	Ambient and roadside monitoring	6 months	Continuous – hourly	Chemiluminescence
	Enhanced	Ambient and roadside monitoring	1 year	Continuous – hourly	Chemiluminescence
Sulphur dioxide	Reduced	No monitoring required			
	Routine	Ambient monitoring	6 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
	Enhanced	Ambient monitoring	1 year	Continuous – hourly	UV fluorescence, FTIR or electrochemical
Carbon monoxide	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	NDIR, electrochemical, or open path laser diode
Ozone	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} and $PM_{2.5}$)	Reduced	Ambient monitoring	3 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Routine	Ambient monitoring	6 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Enhanced	Ambient and roadside monitoring	1 year	Continuous – hourly	TEOM, BAM or optical light scattering
	Reduced	No monitoring required			

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
Benzene and NMVOCs	Routine	Ambient monitoring	6 months	Cumulative – short period	Passive samplers
	Enhanced	Ambient monitoring	1 year	Continuous – hourly	GC or GC-MS
PAHs, assessed as BaP	Reduced	No monitoring required			
	Routine	Ambient monitoring	6 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
	Enhanced	Ambient monitoring	1 year	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
Methane	Reduced	No monitoring required			
	Routine	Ambient monitoring	6 months	Continuous – hourly	FID or FTIR
	Enhanced	Ambient monitoring	1 year	Continuous – hourly	FID or FTIR

5.4.5 Decommissioning

Recommendations for the decommissioning phase are given in Table 5.5.

For the pollutants deemed the highest risk or present in highest concentrations, the monitoring requirements during the decommissioning phase for routine surveillance would usually be for 3–6 months’ sampling after the site operations have ceased. For other pollutants, which would not be expected to be present in high concentrations during this phase, no monitoring would be required.

In the case of enhanced surveillance, monitoring would be of the same duration (3–6 months) for those pollutants that required sampling under routine surveillance, but may involve a more precise monitoring method for certain pollutants or involve additional monitoring locations. During the decommissioning phase, a reduced surveillance strategy would not require monitoring to be carried out for those sites where this is deemed appropriate (that is, low risk).

Table 5.5 Recommended monitoring methods for ambient air emissions from shale gas facilities during decommissioning phase

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
NOx/nitrogen dioxide	Reduced	No monitoring required			
	Routine	Ambient and roadside monitoring	3 months	Cumulative – short period	Passive samplers

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
	Enhanced	Ambient and roadside monitoring	6 months	Cumulative – short period	Passive samplers
Sulphur dioxide	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	UV fluorescence, FTIR or electrochemical
Carbon monoxide	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	NDIR, electrochemical, or open path laser diode
Ozone	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} and $PM_{2.5}$)	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	TEOM, BAM or optical light scattering
	Enhanced	Ambient and roadside monitoring	6 months	Continuous – hourly	TEOM, BAM or optical light scattering
Benzene and NMVOCs	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Cumulative – short period	Passive samplers
PAHs, assessed as BaP	Reduced	No monitoring required			
	Routine	No monitoring required			
	Enhanced	Ambient monitoring	3 months	Cumulative – short period	High/low volume samplers (minimum 2 samples per month)
Methane	Reduced	No monitoring required			
	Routine	Ambient monitoring	3 months	Continuous – hourly	FID or FTIR

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	FID or FTIR

5.5 Summary of monitoring options and priorities

The monitoring surveillance recommendations developed during this study reflect the likely pollutant contributions to ambient air throughout the different phases of a shale gas site, as demonstrated by the dispersion modelling exercise. The calculation of annual statistics, based on monitoring during the different phases at a shale gas facility, will ensure data can be compared with relevant standards for the protection of human health and sensitive ecological sites.

For each phase, the surveillance option chosen should be appropriate to the different site-specific location and/or scenario. Furthermore, if site activities are forecast to change during operation (for example, extraction from an increasing number of wells), then the monitoring scope and timeframes may need to be extended.

Monitored data should be reviewed on a regular basis so that the strategy can be adjusted to reflect the prevailing level of risk at each site.

Section 6 outlines a framework that can be used by operators and regulators to identify the most appropriate suite of monitoring approaches, reflecting the characteristics of an individual shale gas site. The framework can be used to select appropriate monitoring components from the options for different phases summarised in Sections 5.4.1 to 5.4.5.

6. Monitoring: adaptive framework

This section sets out a methodology for establishing a systematic and proportionate monitoring programme for individual shale gas sites.

6.1 Variables to consider

The establishment of a monitoring strategy at a shale gas facility requires the consideration of several variables. Examples of the most important variables are given in Table 6.1; cost is also an important consideration, but this is considered in Section 6.2 and Appendix E rather than included in Table 6.1. The entries in Table 6.1 should be used as a generic checklist to ensure a monitoring strategy takes account of the most relevant variables.

This generic checklist should be combined with more detailed information on the emissions and impacts associated with a particular proposed development (for example, through the completion of a dispersion modelling assessment).

The potential effect of local confounding sources should also be considered in order to understand how the local conditions around a site will influence combined impacts from shale and other sources, and thus support the effective siting of monitoring stations.

Table 6.1 Ambient air monitoring considerations for shale gas sites

Variable	**Considerations for a shale gas site**
Scope of risk	Whether the site is 'normal' (that is, a typical site, an operator with a good track record and so on) or abnormal (that is, an 'early adopter' facility, a large multi-well pad development, an operator with a poor track record and so on).
Reasons for monitoring	These can be considered in 4 broad categories: baseline, operator compliance, process understanding and investigative/research (see Section 4.1).
Phase	The 3 core phases of a shale gas operation are drilling, hydraulic fracturing and extraction. Site appraisal will also take place prior to the facility becoming fully operational, involving site preparation and exploration. For the purposes of this study, however, the requirements for monitoring during exploration are covered by the drilling phase.
Regulatory context	This is split into sources regulated by the Environment Agency (for example, flaring) and sources regulated by bodies other than the Environment Agency (for example, offsite traffic).
Background	Representing variations in background ambient pollutant concentrations, including rural sites (likely good air quality), near-urban sites (likely poorer air quality), sites near major roads (likely traffic impacts) and sites near other shale gas operations (likely combined impacts due to clustering of sites).
Source category	Including the different emission source categories found at a shale gas site (that is, combustion, venting and fugitive).
Release geometry	Including point (stack), area (diffuse), and line (for example, road) geometries.

Variable	Considerations for a shale gas site
Substance	Representing the key pollutant and GHG emissions associated with shale gas sites (NOx, PM_{10}, $PM_{2.5}$, VOCs, GHGs) and nuisance pollutants like odour and dust.
Time resolution	Representing the nature of the emission – whether it be continuous, intermittent or occasional.
Range	Representing the likely geographical range of impacts from the facility (that is, point of maximum impact), that is, whether the process contributions occur adjacent to site, in the near field or across wider/regional areas.
Receptors	Representing the sensitive receptors likely to be affected by emissions, including human (health and nuisance) and protected habitats and/or species.
Duration	Representing the periods over which that emission will be assessed, ranging from instantaneous to long term, and reflecting the averaging periods as specified by air quality standards and objectives.

6.2 Proposed monitoring framework

The monitoring framework is designed to provide an objective basis for working through the considerations set out above, with the aim of arriving at a proportionate monitoring programme. The programme should take account of risk and cost, and include a combination of the reduced, routine and enhanced monitoring options as appropriate to different phases and pollutants as explained in Section 5.4. The monitoring programme resulting from applying the framework is intended to be:

- sufficient to address the key questions raised by the reasons for monitoring
- cost-effective in avoiding excessive monitoring requirements

Based on the primary considerations identified for shale gas sites (see Table 6.1), an operator should provide the following information on the characteristics of the site as part of the information needed to determine an appropriate risk-based monitoring programme:

- Is the facility an ‘early adopter’ development?
- What size is the facility?
- Is there is a high degree of interest and/or concern from local residents?
- Will the facility be situated in close proximity to sensitive human receptors?
- Is the facility located in close proximity to a confounding source?
- Does local ambient air quality data indicate existing air quality issues?
- Is the facility located within close proximity to protected ecological sites?

The framework uses these site characteristics to inform the decision-making process for the development of a monitoring strategy.

When deciding on a monitoring strategy, operators and/or regulators should apply the routine monitoring specifications (see Tables 5.1 to 5.5) unless the framework indicates a requirement for reduced or enhanced monitoring approaches. If one characteristic indicates a reduced monitoring approach is required for a phase and pollutant, while another characteristic indicates an enhanced monitoring approach is required for the same phase and pollutant, then the concluding recommendation would be the enhanced approach.

The monitoring strategy should be reviewed and updated before each phase starts. Where phases overlap, the more stringent monitoring approaches should be applied. Similarly, if a phase is repeated (for example, refracturing), then the strategy should be reviewed and the operator should revert to the applicable phase.

The routine monitoring specifications require the installation of a single, downwind automatic monitoring station.

Under the enhanced monitoring specifications, operators may be required to install additional monitoring locations. The requirement to monitor at more than one location in and around a shale gas site will:

- allow triangulation and apportionment of sources (point and diffuse)
- help to determine the rate of decline of pollutant concentrations away from the site

The ability to triangulate the source of pollutant contributions in an area with several sources may be particularly appropriate for situations where several shale gas sites are likely to become operational in close proximity.

‘Recommendations’ are not definitive regulatory requirements. Instead, the advice given here is an example of a relevant and available monitoring option that the authors of this report consider to be broadly in line with the risk/cost.

The monitoring framework is set out in Table 6.2. Figure 6.1 summarises the most important considerations in a flow diagram and Figure 6.2 provides a decision tree to be followed when developing a monitoring strategy. In Table 6.2 and Figure 6.1, the comment “no change” means that the associated site characteristic does not indicate that the level of monitoring needs altering, so the level of monitoring can stay the same when proceeding to consider the next characteristic in the sequence.

Table 6.2 Ambient air monitoring framework for shale gas sites

Site characteristic	Detail	Response	Monitoring criteria	Phase	Pollutants	Additional recommendations
?	→	→	→	→	→	i
Is the facility an 'early adopter'?	One of the first 20 facilities to become operational in the UK	Yes	Enhanced	All	All	Minimum of 2 site boundary monitoring locations
		No	No change			
What size is the facility?	Total number of vertical wells planned for development	<10 wells	No change			
		10–20 wells	Enhanced	Drilling Hydraulic fracturing	NOx	Minimum of 2 site boundary monitoring locations
		>20 wells	Enhanced	Drilling Hydraulic fracturing Extraction	NOx NMVOCs PM_{10}/$PM_{2.5}$	Minimum of 4 site boundary monitoring locations
Is there a high degree of interest and/or concern from local residents?	Residents have expressed a particularly high degree of concern about the possibility of adverse air quality impacts and are seeking a commensurate level of monitoring.	Yes	Enhanced	Drilling Hydraulic fracturing Extraction	NMVOCs	Minimum of 2 site boundary monitoring locations Include measurement of odours or potentially odorous chemicals
		No	No change			
Do the results of a dispersion modelling study show an insignificant impact at human receptor sites?	Human receptors – process contribution: <1% long-term AQO/ standard and <10% short-term AQO/ standard	Yes	Reduced	Baseline Extraction Decommissioning	All	
		No	No change			Minimum of 2 site boundary monitoring locations Add 2 monitoring locations (non-automatic) within local communities

Site characteristic	Detail	Response	Monitoring criteria	Phase	Pollutants	Additional recommendations
?	→	→	→	→	→	i
Is the facility located in close proximity to a confounding source?	Existing emission sources that pose the potential for cumulative impacts	A. <350m of a major roadway	Enhanced	Baseline	NOx PM$_{10}$/PM$_{2.5}$	Undertake directional analysis to identify monitoring location with greatest signal strength If available, review existing background air quality data collected by permitted industrial facility, to support development of baseline
		B. <10km of another shale gas facility	Enhanced	Baseline	NOx NMVOCs PM$_{10}$/PM$_{2.5}$	
		C. <2km of Part A permitted industrial facility	Enhanced	Baseline	NOx NMVOCs PM$_{10}$/PM$_{2.5}$	
Does local ambient air quality data indicate existing air quality issues?	<5km of an AQMA	Yes	Enhanced	All	NOx and/or PM$_{10}$/PM$_{2.5}$	Minimum of 2 site boundary monitoring locations Substances for enhanced monitoring dependant on designation of AQMA Add at least 2 monitoring locations (non-automatic) within local communities
		No	No change			
Do the results of a dispersion modelling study show an insignificant impact at ecological receptor sites?	Process contribution <1% long-term critical level or load, and <10% short-term critical level, at designated habitat sites	No	Enhanced	Drilling Hydraulic fracturing	NOx	Consider extending the monitoring strategy to designated habitat sites, focusing on substances identified as posing a risk to ecological sites under the Habitats Directive
		Yes	No change			

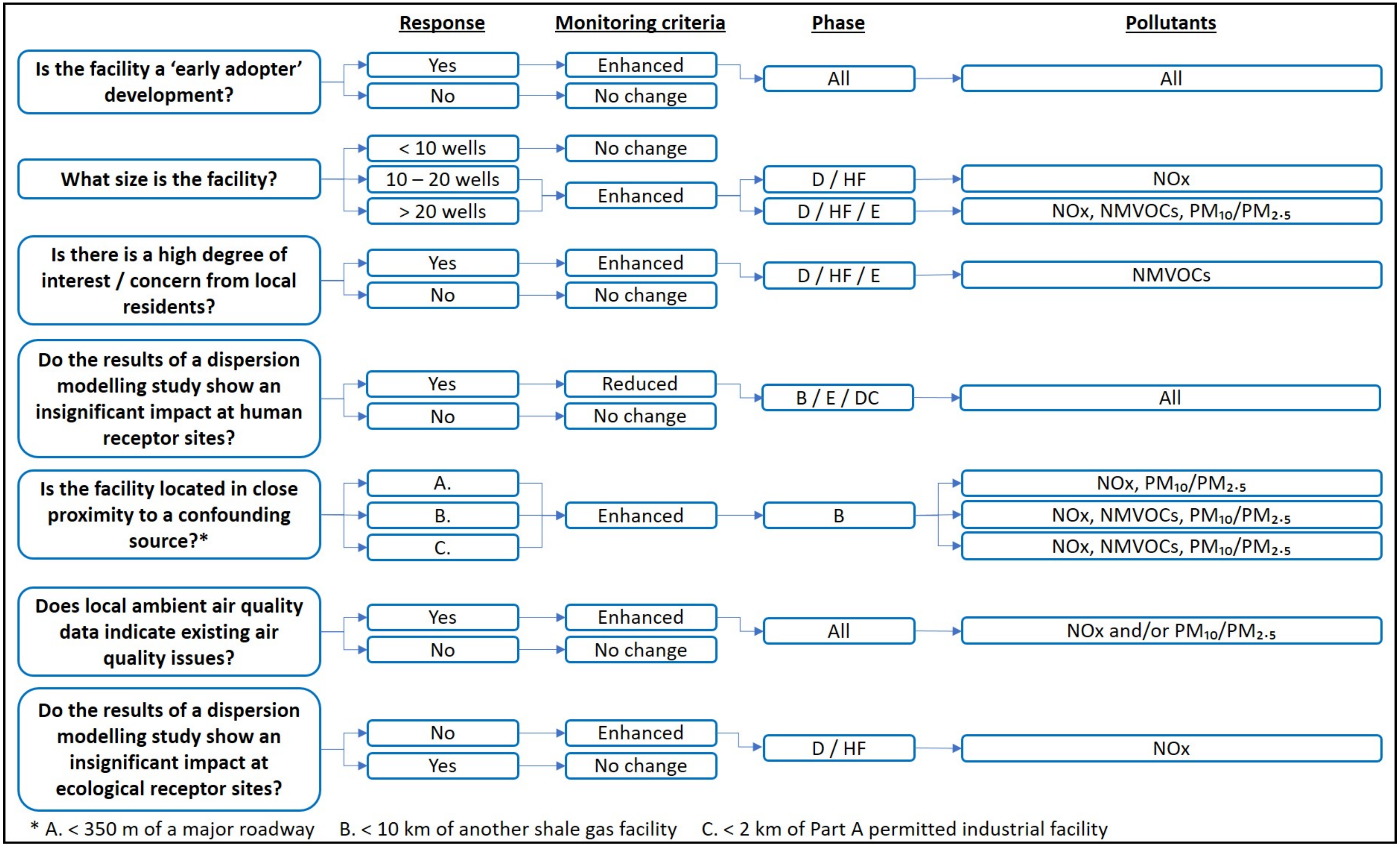

Figure 6.1 Methodology for the development of a monitoring strategy

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Notes: B = baseline; D = drilling; HF = hydraulic fracturing; E = extraction; DC = decommissioning

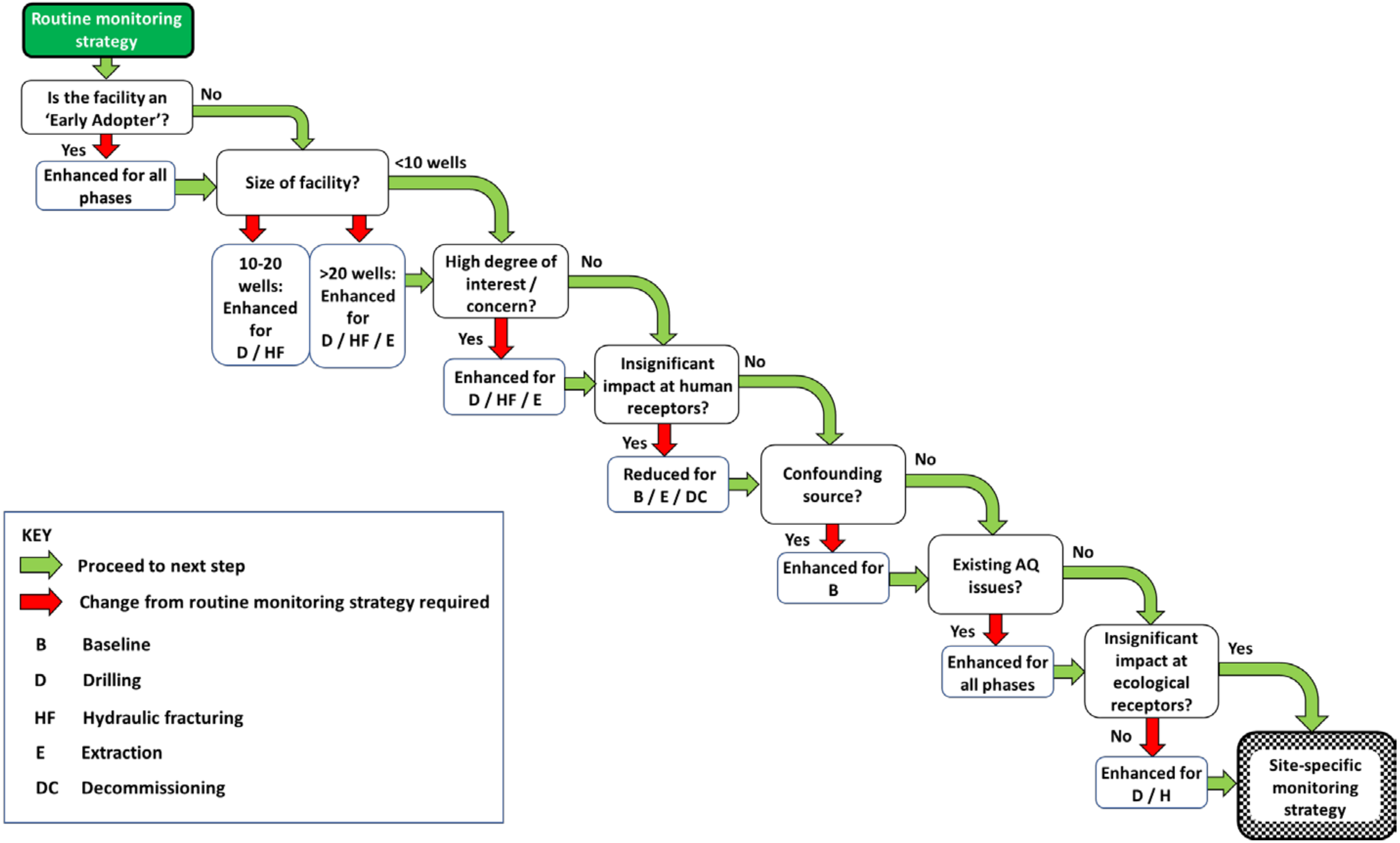

Figure 6.2 Monitoring strategy decision tree

7. Case studies

To test the flexibility and adaptability of the monitoring framework, the process was applied to a series of case studies for hypothetical shale gas facilities in the UK. These were developed to reflect:

- the variability among shale gas developments
- the potential for sites to change over time
- circumstances where the characteristics of the site may be considered ‘non-standard’

Details of the case studies are provided in Appendix F.

In summary, the case studies illustrate the following.

Case study 1 illustrates how the framework will require the monitoring strategy to be updated to reflect any changes to background levels of air quality as indicated by the declaration of a new AQMA, specifically where this indicates an exceedance of an AQO. The change in background air quality results in adopting a more stringent monitoring strategy after the drilling phase has ended. In addition, the case study demonstrates the need to consider a more detailed baseline study in cases where another permitted industrial facility is nearby.

Case study 2 illustrates how the framework will require a monitoring strategy to be updated to reflect any changes to the size of the facility, specifically where an increase in the number of wells is proposed. In the case study, an increase in well numbers results in a more stringent monitoring strategy being adopted after the baseline period.

Case study 3 illustrates how the framework requires additional controls where the site is an early adopter and is located in close proximity to a European designated habitat site. The case study is also an example of where the characteristics of a site may indicate the requirement for both reduced and enhanced monitoring approaches for a given pollutant. In this situation, the enhanced monitoring approach should be prioritised.

Case study 4 illustrates how the framework may require additional controls where a site is attracting significant opposition from a local community in order to provide reassurance that the facility does not pose a risk to local air quality. Under such circumstances, the application of enhanced monitoring would be indicated for certain phases and recommendations made for further monitoring of nuisance pollutants.

Case study 5 illustrates how the framework would require a monitoring strategy to be extended to reflect a decision to refracture existing wells. Furthermore, it demonstrates how the framework would require more detailed analysis where a confounding source is close to the site.

8. Conclusions

This aim of this study was to provide an ambient air quality monitoring framework that will enable the development of air quality monitoring surveys that appropriately reflect the impacts of shale gas facilities in the UK. In support of this study, the potential impacts of shale gas facilities on air quality have been characterised through:

- a literature review of shale gas site activities and emissions
- an atmospheric dispersion modelling assessment of a conceptual shale gas site

The findings of the literature review and modelling assessment confirmed the following.

- Shale gas developments have the potential to result in increases in pollutant concentrations near to shale gas sites. The results of the dispersion modelling indicate the potential for exceedances of long-term and short-term AQOs, unless further emission controls are applied. However. the exercise was not site-specific; for example, it did not consider locations where relevant exposure could occur near a particular site such as houses or a school, or the details of particular operations and controls at individual sites. These would need to be considered for each site.
- During the different phases of a shale gas site, some pollutants will be present in higher or lower concentrations. Hence, the monitoring strategy will need to be varied and adapted accordingly.
- Pollutant concentrations are likely to decrease quickly with distance from the site, but will be highly variable due to both the nature of the activities and the influence of local meteorological conditions. It is therefore recommended that monitoring locations are selected which reflect the point of maximum impact in areas of potential exposure.
- If there are confounding sources that affect the ability to identify the signals associated with the shale gas sites, additional monitoring locations and more detailed analysis of short-term variations should be adopted to resolve the various signals.
- The scale of the potential impacts from shale development implies that some ambient air quality monitoring may be advisable. However, the level of monitoring needs to be aligned with risk and cost.

The findings of the literature review and dispersion modelling study were used to:

- develop a database of monitoring options
- provide options for reduced, routine and enhanced monitoring strategies for the key phases of shale gas development

A framework was then developed that allows operators to create a bespoke monitoring package, which reflects the individual and evolving characteristics and risks of each shale gas site. Although the broad feasibility of the scheme has been demonstrated, it is important to note that the study incorporates various assumptions, approximations and uncertainties that should be addressed by further work. The framework is therefore not a definitive regulatory procedure, but an indicative methodology with recommendations for refinement and further testing.

9. Recommendations

Although the extraction of shale gas in the UK is at an early stage of development, the sector has the potential to develop quickly, as demonstrated by its rapid expansion in the USA. It is therefore important that regulators in the UK have a thorough understanding of the potential environmental impacts of shale gas sites, including those on air quality. This study has aimed to provide greater insight into these impacts and has used this to develop a practicable and effective framework for monitoring of ambient air quality. However, there may be further opportunities to improve understanding in this area.

The following are recommendations for further work to supplement the findings of this study.

- The monitoring framework has been developed to reflect the potential risks associated with emissions from shale gas facilities, while using expert judgement to factor in the likely costs of implementing the monitoring approaches. It is recommended that an economic assessment of this framework should be made to determine the likely financial implications for operators in carrying out these monitoring approaches. This assessment should consider the costs associated with equipment purchase, deployment, operation and maintenance, data analysis and reporting.

- The study has relied on emissions data from reference literature and has incorporated several assumptions on the operation of shale gas facilities in the UK. These assumptions should be tested against operational facilities in the UK as data continue to emerge from UK experience.

- The monitoring framework should be applied to the site-specific characteristics of shale facilities in the UK (for example, Kirby Misperton, Preston New Road) in order to test and refine the suggested monitoring approaches. This should be combined with an assessment of detailed operational data and directional analysis to determine how ambient pollution concentrations are affected by different phases or operations, and by differences in the number of wells at a site and the number of sites in a neighbourhood.

- Consideration should be given to the how monitoring data can be used throughout the lifespan of shale gas facility (including analysis, comparison and reporting) to ensure this information is used to inform adaptive monitoring decisions. This includes considering how monitoring data can be used to give timely feedback to operators of shale gas sites on their air quality performance during individual phases.

- The recommended monitoring durations (for example, 3, 6, 12 months) should be tested at live sites in the UK to ensure they appropriately reflect the variability and risk of pollutant concentrations during the different phases of a shale gas facility.

The following are areas in which it may be beneficial to conduct additional research on the air quality impacts of shale gas sites.

- Undertake a detailed speciation of NMVOCs at a shale gas site to support the identification of an appropriate benchmark for ambient monitoring.

- Revisit and update the dispersion modelling study as UK-specific data become more available from current and future exploratory operations. It may also be prudent to factor in emissions from shale-related vehicle impacts and small-scale generators.

- Review the techniques available for regularly analysing and summarising monitoring data. This includes considering the timescales for regular analysis and reporting (for example, quarterly, monthly, weekly) and the methods available for discriminating between the contributions of different sources.
- Review what information is needed on site activities to inform the interpretation of air quality monitoring data, and how this information can be made available concurrently with air quality monitoring data.
- Conduct an assessment of best practice measures for shale gas facilities to develop specific operator guidance, which encourages the mitigation and/or avoidance of short-term air quality episodes.
- Review the potential for updating existing planning and/or permitting guidance to reflect recent findings on the potential impact of shale gas facilities on local air quality.
- Consider the potential for the application of emerging monitoring techniques (for example, low-cost sensors) to supplement the established monitoring approaches recommended in this study.
- The nomenclature used to define shale activities and phases differs depending on the source reference. A consistent nomenclature for shale gas operations should be agreed for developments in the UK.

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List of abbreviations

AQMA	Air Quality Management Area
AQO	Air Quality Objective
AURN	Automatic Urban and Rural Network [UK]
BAM	beta attenuation monitor
BaP	benzo(a)pyrene
DfT	Department of Transport
EFA	emission factor set A
EFB	emission factor set B
EFC	emission factor set C
EIA	Environmental Impact Assessment
FID	flame ionisation detector
FTIR	Fourier transform infrared
GC	gas chromatography
GHG	greenhouse gas
GC-MS	gas chromatography–mass spectrometry
HGVs	heavy goods vehicles
IAQM	Institute of Air Quality Management
IGES	Institute for Global Environmental Strategies
MCERTS	Monitoring Certification Scheme [Environment Agency]
n/a	not applicable
NDIR	non-dispersive infrared
NMVOCs	non-methane volatile organic compounds
NOx	oxides of nitrogen
NRMM	non-road mobile machinery
PAHs	polycyclic aromatic hydrocarbons
PM	particulate matter
TEOM	tapered element oscillation microbalance
TexN	Texas NONROAD [model]
USEPA	US Environmental Protection Agency
UV	ultraviolet
VOCs	volatile organic compounds

Appendix A: Dispersion modelling methodology

This appendix describes the methodology developed and applied for atmospheric dispersion modelling.

A.1 Site layout and size

The area of land required to hold a multi-well site (that is, well pad) and associated infrastructure can range between approximately 1 and 2.5 hectares (ICF International 2009). This assessment used a conceptual site model that covers 1 hectare.

The emission sources in this assessment are largely point sources, with the only exception being the treatment of fugitive emissions, which have been assessed as an area source measuring 100m × 100m, spread evenly across the site. Traffic emissions and emissions from smaller generators (that is, those used to power lighting) were not assessed in the study. However, they would contribute to background levels of pollutants arising from fuel combustion and vehicle movements, and could have different source geometries (for example, line sources for vehicle traffic).

Figure A1.1 illustrates schematically the layout of the sources included in the modelling assessment, which were modelled in different combinations depending on the development phase (as illustrated in the key to Figure A1.1). The area marked with diagonal lines illustrates the extent of the fugitive emission source.

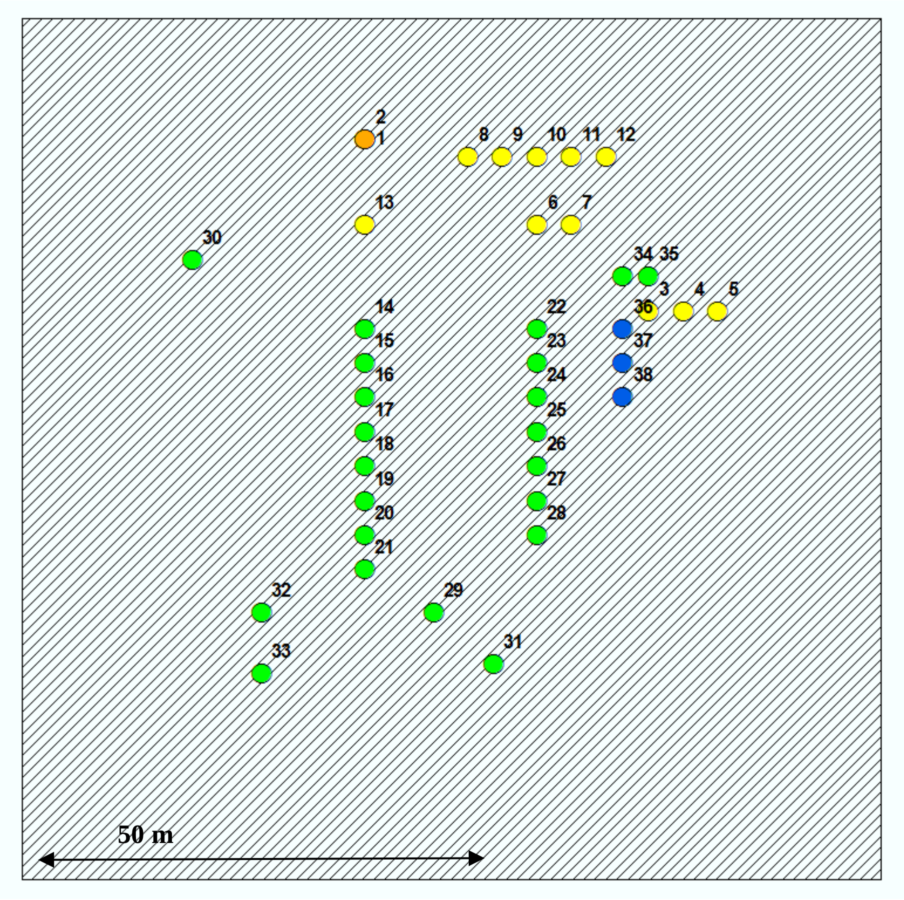


Figure A.1 Shale gas emission sources included in the modelling assessment

Key of modelled emission sources

Reference	Phase	Source
1	Exploration	Flare
2		Vent
3–5	Drilling	Drilling rig generators
6		Drilling mud pump engine
7		Drilling rig engine
8–12		Drilling rig compressor package
13		Mud–gas separator
14–28	Hydraulic fracturing	Fracturing pumps (15 units)
29		Fracturing blender
30		Fracturing control van
31		Hydration unit
32–33		Sand chiefs (2 units)
34–35		Water transfer pumps (2 units)
36	Extraction	Heaters
37		Dehydrator vents
38		Extraction control van

A.2 Timescales

The timescales for each phase of a shale gas development at a multi-well site will vary depending on a number of factors including:

- the geology of the site
- the number of wells
- the experience of the developer

Furthermore, the overall duration of operations at the site will depend on:

- the nature of the shale being fractured
- the level of extraction
- the rate at which the fracturing fluid is injected
- the intervals between phases

Timescales were assumed using estimates provided by ICF International (2009) and professional judgement.

The timescales adopted in the assessment were split into 2 categories:

- **Rapid development** – involving the consecutive drilling, fracturing and extraction of 10 wells over 2 years. This category is considered to reflect a relatively accelerated rate of development of shale gas sites in the UK, so that relatively more pollutants would be emitted in a given time – leading to higher concentrations (that is, conservative estimates of air quality impacts). This applies to Scenarios 3 and 4.
- **Steady development** – involving the consecutive drilling, fracturing and extraction of 4 wells over 2 years. This category is considered to reflect a more likely rate of development for shale gas sites in the UK. This applies to Scenarios 5 and 6.

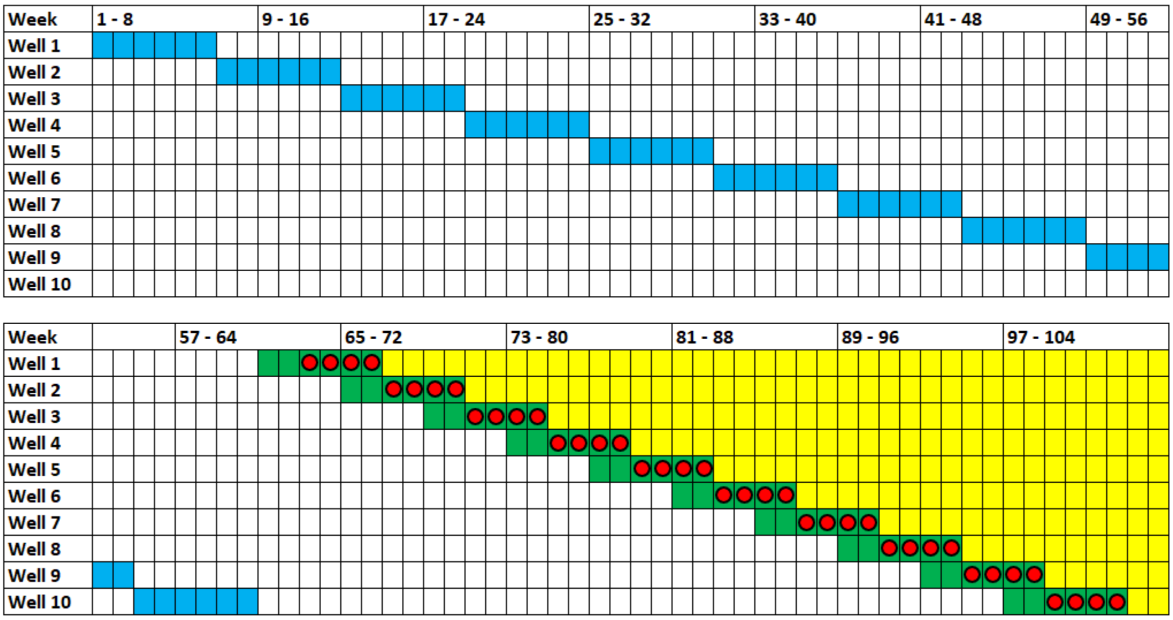
Both categories have been developed to inform the design of the monitoring framework. They should not be interpreted in any other context.

The timescales for both categories are presented in Figure A.1.2 and include:

- drilling for 6 weeks per well
- hydraulic fracturing for 6 weeks per well
- flaring and venting for 4 weeks per well (corresponding with the last 4 weeks of the hydraulic fracturing phase)
- continuous extraction following the completion of the hydraulic fracturing, flaring and venting (up to 2 years)

The exploration phase would occur during the appraisal prior to production, and was assumed to include 3 months of continuous flaring (and venting for 5% of this time), prior to the main drilling phase of the site. Exploration would also include other activities, including drilling, but the impacts of these sources have been assessed in the drilling and hydraulic fracturing phases of this study. The exploration phase is not illustrated in Figure A.2 because this phase is unlikely to occur immediately before a site enters full-scale operation.

Rapid development category



Steady development category

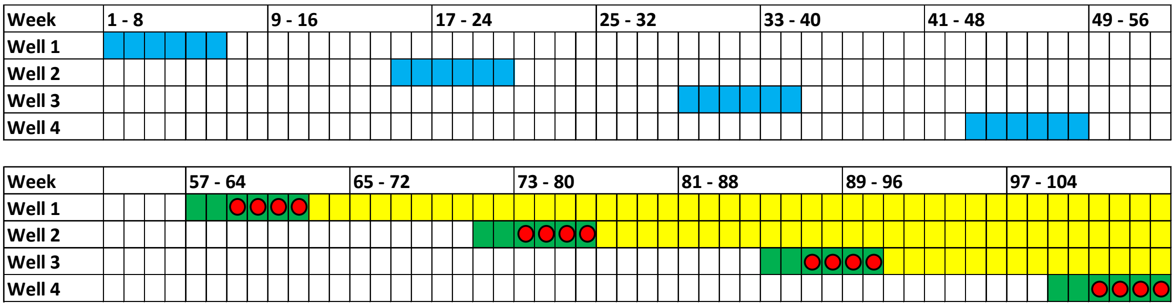


Figure A.2 Assumed two-year schedule of post-exploration activities for modelling Scenarios 3–6, showing ‘rapid’ category with 10 wells (top) and ‘steady’ category with 4 wells (bottom)

Key to Figure A.2

Drilling	🟦
Hydraulic fracturing	🟩
Flaring / Venting	●
Extraction	🟨

A.3 Assumptions

The following assumptions were factored in to the modelling assessment for Scenarios 3–6. These assumptions were made solely in order to provide a basis for developing the monitoring framework.

A.3.1 Drilling phase

During the drilling phase, equipment included in the drilling rig (3 generators, 1 mud pump engine and 1 additional engine) will be operational for 12 hours per day (7am to 7pm) throughout the entire six-week period.

Air drilling, where gases are used to cool the drill bit, may or may not be used in the development of a shale gas site; however a conservative approach was adopted and it was assumed that air drilling would occur for the first week of drilling each well, with the air compressor package operating for 12 hours per day (7am to 7pm) during the first 7 days of the six-week period.

The mud–gas separator source is only operational during a gas ‘kick’ event, which occurs when a gaseous zone is encountered during drilling and some gas is returned with the drilling fluid. Gas kicks are unplanned events, where the pressure found within the drilled rock is higher than expected and forces fluids into the wellbore. In order to adopt a conservative approach, it was assumed that the mud–gas separator would become active in response to a gas kick event for 1 hour every 2 weeks during the drilling phase.

A.3.2 Hydraulic fracturing phase

During the hydraulic fracturing phase, the pumps will be operational for 5 days at the beginning of each six-week period, and will run for 12 hours per day (7am to 7pm). All other equipment will run throughout the six-week period, for 12 hours per day (7am to 7pm).

Flaring and venting are assumed to occur during the final 4 weeks of hydraulic fracturing at each well for 96% and 4% of the time, respectively. The pattern of flaring and venting is based on dividing each four-week period into three-day sub-periods, and by assuming that venting occurs in the first 3 hours of each sub-period and that flaring occurs for the remaining 69 hours. Venting and flaring do not occur simultaneously.

A.3.3 Extraction phase

During the extraction phase, all equipment will operate continuously, 24 hours per day, and emissions will be ongoing. Emissions are assumed not to increase as a result of the operation of each new well so that, for example in the rapid category, the emissions associated with the extraction phase in week 67 are equal to emissions in week 104. This is because it is assumed that the same equipment will be used for all wells, by successively redeploying at each new well during the extraction phase.

It is assumed that fugitive emissions will occur uniformly and continuously across an area of 100m × 100m during the extraction phase. This is to account for the uncertainty about where and when fugitive emissions will occur, and it can be considered a conservative assumption. Fugitive emissions from the multi-well site are assumed not to increase as a result of the operation of each new well, but to continue across the site at a constant rate during extraction.

A.4 Modelling parameters

The atmospheric dispersion model ADMS5.2 was used to model emissions from the conceptual shale gas site. ADMS5.2 is widely used in the UK as a current industry standard model for dispersion from point and area sources, and as such was deemed appropriate for the modelling of emission sources applicable to a shale gas site.

As a starting point, the model takes information on emissions from each source including:

- release rate of the substances under consideration (g per second for point sources and g per m^2 per second for area sources)
- release temperature (°C)
- release velocity or volumetric flow (m per second or m^3 per second)
- release point location (x,y coordinates)
- release point height (m)
- release point diameter (m)

A.5 Emission factors

A review of published emissions was conducted in support of this study. The substances considered include NOx/nitrogen dioxide, PM_{10}, NMVOCs and methane. Although there are other substances that may be emitted to air from a shale gas facility (see Section 2), the substances considered were selected due to both their relevance for Local Air Quality Management and the availability of data. Methane should not be treated like a local “air toxic” pollutant such as nitrogen dioxide and PM_{10}, which is why there is not an applicable AQO.

The majority of the published data reflect emissions associated with operations in the USA. To reflect the level of variability in the data, low and high factors were selected for most pollutants and sources; these were termed emission factor sets A and B respectively (EFA and EFB). Where only a single value of an emission factor was obtained for a source, the low factor was assumed to be 25% below that value and the high factor was assumed to be 25% above that value. To reflect the potential for stricter emissions controls in the UK, and especially to reflect the provisions of the NRMM Regulation, a third set of emission factors was selected – termed emission factor set C (EFC). Details of the factors adopted in the assessment are given in Table A.1.

Where an emission factor for NOx was identified, nitrogen dioxide concentrations where estimated by applying an assumed conversion of NOx to nitrogen dioxide of 70% for long-term concentrations and 35% for short-term concentrations. Detail on the methodology for calculating the emission factors is provided in Appendix B.

Table A.1 Emission parameters

Phase		**Drilling**					**Fracturing**					
Equipment		**Drilling rig generators**	**Drilling rig mud pump engine**	**Drilling rig engine**	**Drilling rig compressor package**	**Mud–gas separator**	**Fracturing pump**	**Fracturing blender**	**Fracturing control and recording van**	**Hydration unit**	**Sand chief**	**Water transfer pump**
Source		Point	Point	Point	Point	Point	Point	Point	Point	Point	Point	Point
Emission rates (g per second)	**NOx (EFA)**	0.63	0.63	0.63	0.76	n/a	2.1	0.20	0.041	0.23	0.056	0.16
	NOx (EFB)	1.05	1.05	1.05	1.26	n/a	3.6	0.34	0.069	0.38	0.093	0.26
	NOx (EFC)	0.07	0.36	0.36	0.05	n/a	1.2	n/a	n/a	n/a	n/a	n/a
	NO_2 (EFA)	ND	ND	ND	ND	n/a	ND	ND	ND	ND	ND	ND
	NO_2 (EFB)	ND	ND	ND	ND	n/a	ND	ND	ND	ND	ND	ND
	NO_2 (EFC)	ND	ND	ND	ND	n/a	ND	n/a	n/a	n/a	n/a	n/a
	PM_{10} (EFA)	0.015	0.015	0.015	0.018	n/a	0.051	0.085	0.0030	0.0090	0.0030	0.0060
	PM_{10} (EFB)	0.025	0.025	0.025	0.030	n/a	0.035	0.010	0.0030	0.011	0.0040	0.0080
	PM_{10} (EFC)	0.004	0.005	0.005	0.002	n/a	0.016	n/a	n/a	n/a	n/a	n/a
	VOCs (EFA)	0.025	0.025	0.025	0.030	5.5	0.084	0.027	0.015	0.10	0.012	0.040
	VOCs (EFB)	0.041	0.041	0.041	0.050	9.1	0.140	0.034	0.018	0.12	0.014	0.048
	VOCs (EFC)	0.020	0.020	0.020	0.024	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Modelling parameters	**Quantity**	3	1	1	5	1	15	1	1	1	2	2
	Height (m)	3	3	3	3	4.6	4	1.5	1.5	1.5	1.5	1.5
	Diameter (m)	0.15	0.15	0.15	0.15	0.10	0.35	0.15	0.15	0.15	0.15	0.15
	Temperature (°C)	343	343	343	343	93	343	400	400	400	400	400

Phase		**Drilling**					**Fracturing**					
	Velocity (m per second)	20	20	20	20	5	20	20	20	20	20	20

Phase		**Extraction**					**Flaring and venting (exploration and hydraulic fracturing)**		
Equipment		**Fugitive releases**	**Heaters**	**Dehydrator vents**	**Control and recording van**		**Flare**	**Venting**	
Source		Area (g per second per m^2)	Point	Point	Point		Point	Point	
Emission rates (g per second)	**NOx (EFA)**	n/a	n/a	n/a	0.041		n/a	n/a	
	NOx (EFB)	n/a	n/a	n/a	0.069		n/a	n/a	
	NO$_2$ (EFA)	n/a	0.019	n/a	ND		3.2	n/a	
	NO$_2$ (EFB)	n/a	0.031	n/a	ND		5.4	n/a	
	PM$_{10}$ (EFA)	n/a	0.0034	n/a	0.0030		0.84	n/a	
	PM$_{10}$ (EFB)	n/a	0.0056	n/a	0.0030		1.4	n/a	
	VOCs (EFA)	7.41×10^{-7}	0.0026	0.047	0.015		0.0024	0.079	
	VOCs (EFB)	1.23×10^{-6}	0.0043	0.079	0.018		0.0040	0.13	
	CH$_4$ (EFA)	5.12×10^{-6}	0.0026	0.021	n/a		0.020	0.59	
	CH$_4$ (EFB)	3.10×10^{-5}	0.0043	0.034	n/a		0.034	0.98	
Modelling parameters	**Quantity**	n/a	1	1	1		1	1	
	Height (m)	0.5	1.5	1.5	1.5		5.5	3	
	Diameter (m)	100m^2	0.1	0.1	0.15		2	2	

Phase		**Extraction**					**Flaring and venting (exploration and hydraulic fracturing)**		
	Temperature (°C)	15	260	93	400		1,023	15	
	Velocity (m per second)	1	20	20	20		15	15	

Notes: n/a = not applicable; ND = no data

A.4 Meteorological data and receptors

ADMS uses information characterising a set of meteorological conditions including wind speed, wind direction and atmospheric stability. A dataset was sourced from the Bingley meteorological station in West Yorkshire for the years 2013 to 2017, which was identified as being representative of typical meteorological conditions for an inland location within the Bowland–Hodder Shale Formation. Wind roses for Bingley for 2013 to 2017 are presented in Appendix C.

The model was used to provide estimated concentrations of NOx/nitrogen dioxide, PM_{10}, VOCs and methane across a gridded area covering 5km × 5km (40m grid spacing) and centred on the conceptual shale gas site. In addition, individual receptors were located along each 45° bearing, at distances of 100, 200, 300, 400 and 500m; these were included to represent the potential locations of ambient air quality monitoring stations. There were no receptors inside the site, as defined by the 100m × 100m area of assumed fugitive emissions.

It is important to note that these receptors were not designed to represent locations of long-term human exposure (for example, homes, schools, hospitals), but rather the concentration levels that would potentially be recorded by a monitoring station at these distances and directions from the centre of the site.

Concentrations were modelled for each hour in the year at each receptor in order to build up estimates of long-term and short-term concentrations.

- For long-term concentrations, the maximum annual mean value at each point from the 5 years was used as the representative long-term value for that point in the assessment.
- For short-term concentrations, the highest hourly average and percentile concentrations were taken from each year's estimates for a given point, to provide maximum short-term concentrations for that point.

A.5 Scenarios

A series of 6 scenarios were developed to represent key emissions situations associated with shale gas facilities. Details of the scenarios are given in Table A.2.

- Scenarios 1 and 2 represent flaring and venting emissions during exploration, based on emission factor sets EFA and EFB (although in practice, venting directly to the atmosphere is considered unlikely).
- Scenarios 3–6 represent emissions during the 3 core production phases (drilling, hydraulic fracturing and extraction) and include emissions from sets EFA, EFB and EFC.

Table A.2 Emission scenarios

Scenario		Emission factor set	Description
1	Flaring and venting (three-month period, during appraisal)	EFA	Flaring and venting sources were modelled for the first 3 months (1 January to 1 April) of each year (2013 to 2017). A full year of meteorological data was used for each model run. It was assumed that there would be 3 hours of venting (only), followed by 69 hours of flaring (only), with that pattern repeating for the entire three-month period. After the three-month period, all sources

Scenario		Emission factor set	Description
			ceased emitting pollutants, but the model was run for a full 12 months to determine the annual average. The EFA set of emission factors was used for both flaring and venting sources.
2		EFB	As Scenario 1, except that the EFB set of emission factors was used for both flaring and venting sources.
3	All sources for a 10 well site over a two-year period	EFA	Two years of consecutive meteorological data were used for each model run (for example, 1 January 2013 to 31 December 2014). The EFA set of emission factors was used for all sources. The progression of the 10 well sites was modelled as follows. • **Drilling**. All sources associated with the drilling rig (3 generators, 1 mud pump engine and 1 additional engine) were assumed to be operational for 12 hours per day (7am to 7pm) for the first 60 weeks. The air compressor package comprising 5 air compressor units, was assumed to be operational for 12 hours per day (7am to 7pm) in the first week of drilling for each well. The mud–gas separator was assumed to be operational for 1 hour every 2 weeks, from 10am to 11am, every second Tuesday. After the 60th week, it was assumed that drilling was complete and drilling equipment ceased to emit pollutants. • **Hydraulic fracturing**. Fracturing was assumed to begin at week 61 and to follow a six-week pattern until the end of the 104th week. It was assumed that the 15 fracturing pumps would operate 12 hours per day (7am to 7pm) for the first 5 days of each six-week fracturing cycle. It was assumed that all other fracturing point sources would operate 12 hours per day (7am to 7pm), every day, from week 61 through to week 104. • **Flaring and venting**. Flaring and venting cycles were assumed to begin at week 63. To enable the modelling study to be set up on a conservative basis, it was assumed that there would be 3 hours of venting (only), followed by 69 hours of flaring (only), with that pattern repeating from week 63 through to week 104. • **Extraction**. All fugitive emissions and point sources associated with the extraction phase were assumed to begin at week 67 and to run continuously through to week 104. These sources were modelled as being active 24 hours per day, 7 days per week.
4		EFB	As Scenario 3, except that the EFB set of emission factors was used for all sources.
5	All sources for a 4 well site over a two-year period	EFA	Two years of consecutive meteorological data were used for each model run (for example, 1 January 2013 to 31 December 2014). The EFA set of emission factors was used for all sources. The progression of the 4 well sites was modelled as follows. • **Drilling**. All sources associated with the drilling rig (3 generators, 1 mud pump engine and 1 additional engine) were assumed to be operational for 12 hours

Scenario		Emission factor set	Description
			per day (7am to 7pm) for the first 60 weeks. The air compressor package, comprising 5 air compressor units, was assumed to be operational for 12 hours per day (7am to 7pm) in the first week of drilling for each well. The mud–gas separator was assumed to be operational for 1 hour every 2 weeks, from 10am to 11am, every second Tuesday. After the 48th week, it was assumed that drilling was complete and drilling equipment ceased to emit pollutants. • **Hydraulic fracturing**. Fracturing was assumed to begin at week 57. A gap of 8 weeks was assumed to occur between the fracturing of each well. It was assumed that the 15 fracturing pumps would operate 12 hours per day (7am to 7pm) for the first 5 days of each six-week fracturing cycle. It was assumed that all other fracturing point sources would operate 12 hours per day (7am to 7pm). • **Flaring and venting**. Flaring and venting cycles were assumed to begin at week 59. To enable the modelling study to be set up on a conservative basis, it was assumed that there would be 3 hours of venting (only), followed by 69 hours of flaring (only), with that pattern repeating for each well. • **Extraction**. All fugitive emissions and point sources associated with the extraction phase were assumed to begin at week 63 and run continuously through to week 104. These sources were modelled as being active 24 hours per day, 7 days per week.
6	All sources for a 4 well site over a two-year period	EFC	As Scenario 3, except that the EFC set of emission factors was used for all sources. An extension to Scenario 6, involving the modelling of 2 nearby A roads to assess the influence of a nearby confounding source was also undertaken. This was a separate calculation and the influence of these roads is not represented in the results tables provided in Section 3, but is illustrated in Figure 3.7.

Appendix B: Determination of emission factors and model parameters

This appendix contains a detailed description of the emission factors used in atmospheric dispersion modelling, including source of information, calculations and assumptions.

Table B.1 Emission factor methodology

Phase	Equipment	Ref. (Figure A.1)	Determination of emission factors and parameters
Exploration	Flare	1	Emission factors for nitrogen dioxide and PM_{10} were obtained from NYSDEC (2015). Emission factors for NMVOCs and methane were obtained from a report by the Institute for Global Environmental Strategies (IGES) (Glancy 2013). All emission factors were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios. The flare temperature and effective flare height were calculated using the Ontario flare modelling guidance (Government of Ontario 2016).
	Vent	2	All emission factors (emissions of NOx, PM10 and NMVOCs) were obtained from the IGES report (Glancy 2013). All emission factors were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios.
Drilling	Drilling rig generators (3 units)	3–5	Emission factors for NOx, PM_{10}, NMVOCs and methane were calculated according to the equation: Emission factor = (engine rating in horsepower) × (average engine load) × (Tier 2 emission factor / emission factor) × (scaling factor) A typical drilling rig consists of anywhere from 3 diesel engines (all generator sets) to 7 diesel engines (2–3 generator sets, 2 mud pumps, top drive engine, 2 drilling floor engines). The total horsepower for all engines in the drilling rig varies from 2,700 to 5,400 (NYSDEC 2015). As a representative case, it was assumed that the conceptual shale gas site's drilling rig would consist of 5 diesel engines (3 generators, 1 mud pump engine and 1 additional engine) with a total horsepower rating of 5,000. For simplicity, it was assumed that each of the 5 engines would have an individual rating of 1,000 horsepower. Individual engine loading will vary considerably during the drilling phase. An average engine load of approximately 30% was determined for rigs operating in the Barnett Shale and Haynesville Shale, based on a sampling of average daily fuel consumption and total rig horsepower (NYSDEC 2015). To account for variability and to ensure a conservative approach, an engine loading of 50% was assumed. Tier 2 emission factors are provided in Table B.2. The EFA and EFB sets were scaled by
	Drilling rig mud pump engine	6	
	Drilling rig engine	7	

Phase	Equipment	Ref. (Figure A.1)	Determination of emission factors and parameters
			a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios. The EFC set were derived from the NRMM Regulation. An exit velocity of 20m per second was assumed. Other emission parameters (stack height, stack diameter and exit temperature) were obtained from NYSDEC (2015).
	Air drilling compressor package	8–12	Emission factors for NOx, PM_{10}, NMVOCs and methane were calculated according to the equation: Emission factor = (engine rating in horsepower) × (average engine load) × (Tier 2 emission factor / NRMM emission factor) × (scaling factor) A typical compressor package for air drilling comprises 5 diesel engines with a total horsepower rating of 3,000 (NYSDEC 2015); this value was assumed for this study. An engine load of 100% was assumed, although this would be a conservative estimate, as air compressor engines are usually operated at less than full load (NYSDEC 2015). Tier 2 emission factors are provided in Table B.2. The EFA and EFB sets were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios. An exit velocity of 20m per second was assumed. Other emission parameters (stack height, stack diameter, and exit temperature) were obtained from NYSDEC (2015).
	Mud–gas separator	13	Emission factors (emissions of NOx, PM_{10} and VOCs) and other emission parameters (stack height, stack diameter, exit velocity and exit temperature) were obtained from NYSDEC (2015). The emission factors were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios. The mud–gas separator source is only operational during a gas kick event, which occurs when a gaseous zone is encountered during drilling and some gas is returned with the drilling fluid; this gas is separated from the mud and vented for safety reasons. Although gas kicks are unplanned and sporadic occurrences, it was assumed that a 1 hour gas kick event would occur at the conceptual shale gas site once every 2 weeks; this is likely to be conservative based on the literature (NYSDEC 2015). Due to the design of the mud–gas separator, it is likely that some methane would also be vented during the gas kick event; however the emission factors from NYSDEC (2015) do not include a value for methane emissions.
Hydraulic fracturing	Fracturing pumps (15 units)	14–28	Emission factors for NOx, PM_{10}, NMVOCs and methane were calculated according to the equation:

Phase	Equipment	Ref. (Figure A.1)	Determination of emission factors and parameters
			Emission factor = (engine rating in horsepower) × (average engine load) × (Tier 2 emission factor / NRMM emission factor) × (scaling factor) It was assumed that each fracturing pump has a rating of 2,250 horsepower (Alamo Area Council of Governments 2015). A representative average engine loading of 75% was assumed, based on literature sources (Alamo Area Council of Governments 2012). Tier 2 emission factors are given in Table B.2. The EFA and EFB sets were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios. An emission velocity of 20m per second was assumed. Other emission parameters (stack height, stack diameter, and exit temperature) were obtained from NYSDEC (2015).
	Fracturing blender	29	Emission factors for NOx were obtained from Rodriguez and Ouyang (2013). The NOx emission factors were scaled by a factor of 0.75 for low emission factor scenarios (EFA) and by 1.25 for high emission factor scenarios (EFB). Emission factors for PM_{10} were obtained from Rodriguez and Ouyang (2013), which already included values for low and high emission scenarios. Emission factors for NMVOCs were obtained from Alamo Area Council of Governments (2015) which already included values for low and high emission scenarios.
	Fracturing control van	30	
	Hydration unit	31	
	Sand chiefs (2 units)	32–33	
	Water transfer pumps (2 units)	34–35	
Extraction	Heaters	36	Emission factors for nitrogen dioxide, PM_{10} and NMVOCs were obtained from NYSDEC (2015) and emission factors for methane were obtained from the Alamo Area Council of Governments (2015). The EFA and EFB sets were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios.
	Dehydrator vents	37	Emission factors for NMVOCs and methane were obtained from NYSDEC (2015). The EFA and EFB sets were scaled by a factor of 0.75 for low emission factor scenarios and by 1.25 for high emission factor scenarios.
	Extraction control van	38	Emission factors were assumed to be equivalent to those of the fracturing control van operated during the hydraulic fracturing phase.
	Fugitive releases	n/a	Emission factors for NMVOCs and methane were obtained from Glancy (2013); these included values for low emission factor and high emission factor scenarios.

Table B.2 Tier 2 emission factors for reciprocating engines using gas oil

Pollutant	**Emission factor (g per GJ)**
NOx	942
PM_{10}	22.4
NMVOCs	37.1
Methane	not available

Source: EEA (2016, Table 3-19)

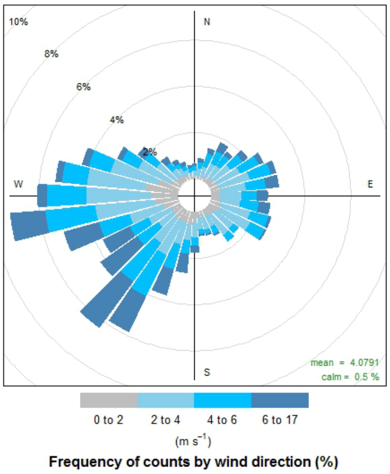
Table B.3 NRMM Regulation exhaust emission limits

Emission stage	**Engine sub-category**	**NOx (g per kWh)[1]**	**PM mass (g per kWh)[2]**
Stage V	NRE-v-6 and NRE-c-6 [1]	0.4	0.015
	NRE-v-6 and NRE-c-7 [1]	3.5	0.045
	NRG-v-1 and NRE-c-1 [2]	0.67	0.035

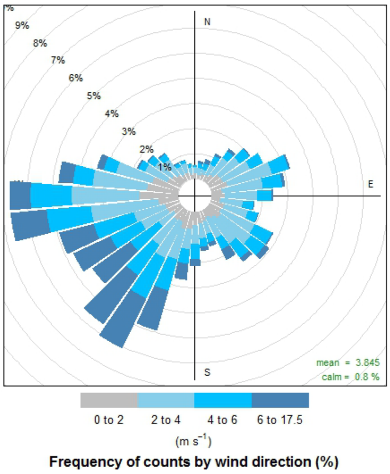
Notes:
[1] European Parliament and Council of the European Union (2016, Table II-1)
[2] European Parliament and Council of the European Union (2016, Table II-2)

Appendix C: Wind roses of Bingley meteorological data used in the atmospheric dispersion modelling, 2013 to 2017

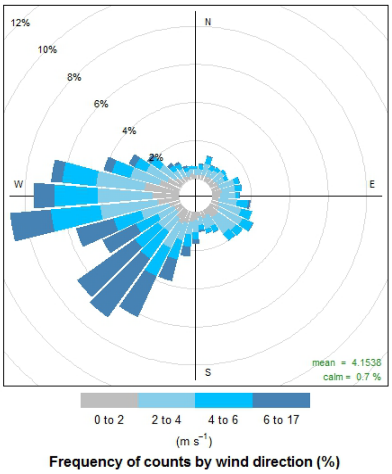
2013



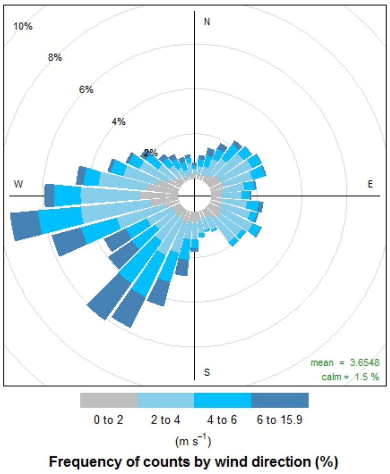
2014



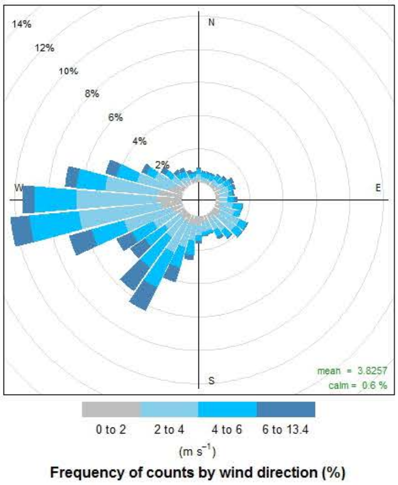
2015



2016



2017


14%
12%
10%
8%
6%
4%
2%
N
W
E
S
mean = 3.8257
calm = 0.6 %
0 to 2
2 to 4
4 to 6
6 to 13.4
(m s^{-1})
Frequency of counts by wind direction (%)

Appendix D: Short-term concentration and dispersion plots

D.1 Short-term concentration plots

Figures D.1 to D.3 illustrate the expected short-term variations in PM_{10}, NMVOC and methane concentrations, respectively, during the most important phases under Scenario 6 over the two-year period. The plots use coloured histograms to show the incremental impacts due to each phase, but the histograms are superimposed so the combined impacts of concurrent phases are not shown. The corresponding plot for Nitrogen Dioxide is shown in Figure 3.9 above.

For Figure D.3, there was limited literature data available on methane emissions during the drilling and fracturing phases, so it was not possible to identify appropriate methane emission factors to use for these phases. The dispersion modelling therefore only included emissions of methane during the extraction and flaring/venting phases i.e. from about day 400 onward.

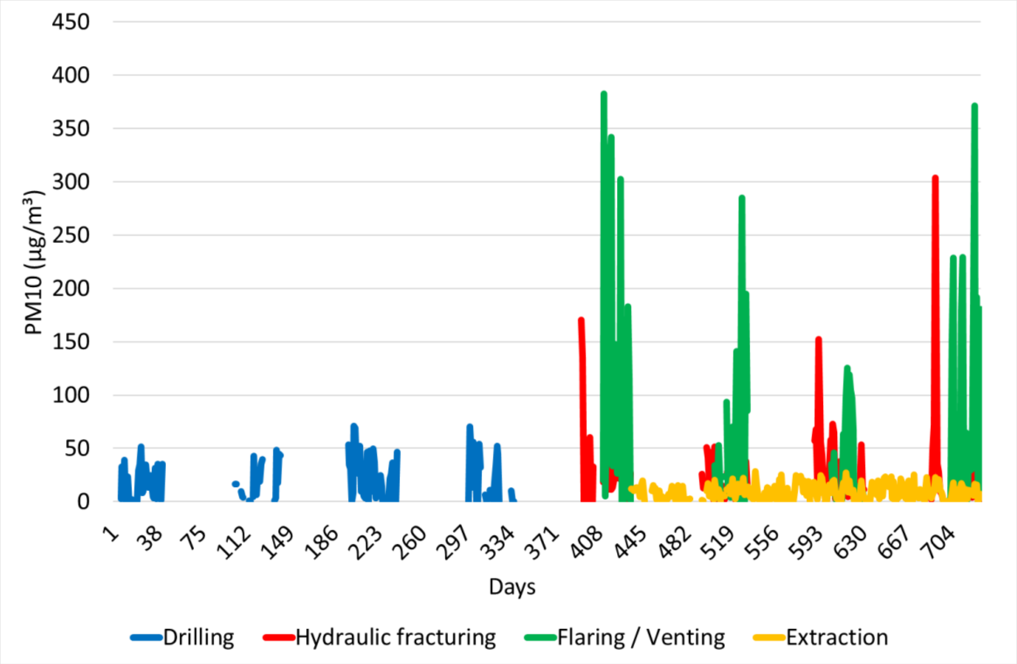


Figure D.1 Short-term variations in hourly average PM_{10} concentrations at the worst case receptor location under Scenario 6

Notes: The receptor is 100m north-east.
2016 to 2017 meteorological data

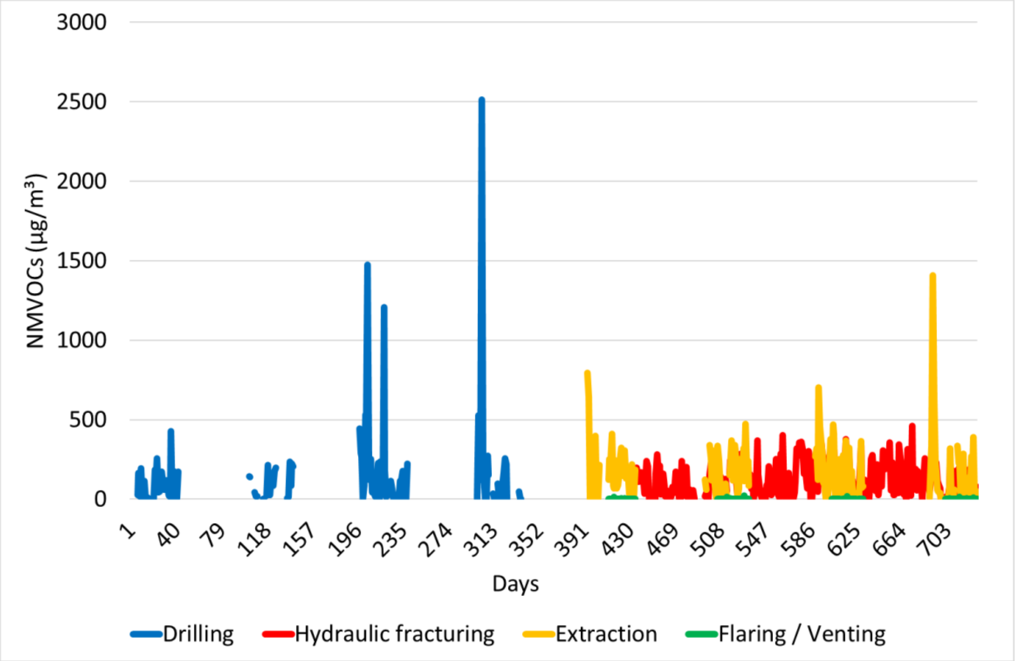


Figure D.2 Short-term variations in hourly average NMVOC concentrations at the worst case receptor location under Scenario 6

Notes: The receptor is 100m north-east.
2016 to 2017 meteorological data

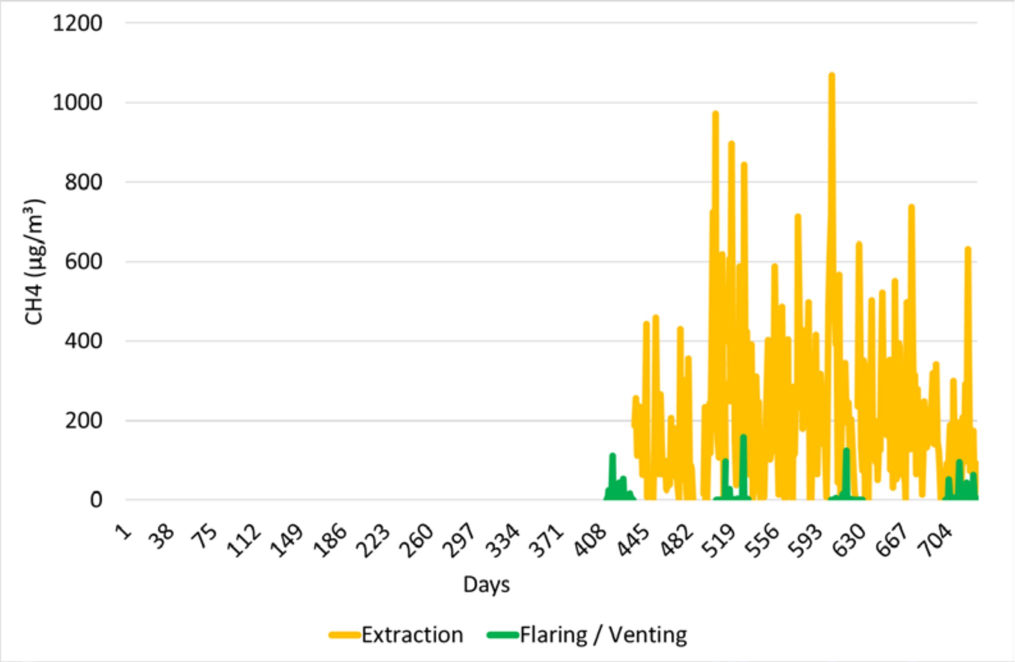


Figure D.3 Short-term variations in hourly average methane concentrations at the worst case receptor location under Scenario 6

Notes: The receptor is 100m north-east.
2016 to 2017 meteorological data

D.2 Dispersion plots (Scenarios 3–6)

Figures D.4 to D.19 illustrate the long-term and short-term concentrations of nitrogen dioxide, PM_{10}, NMVOCs and methane under Scenarios 3–6.

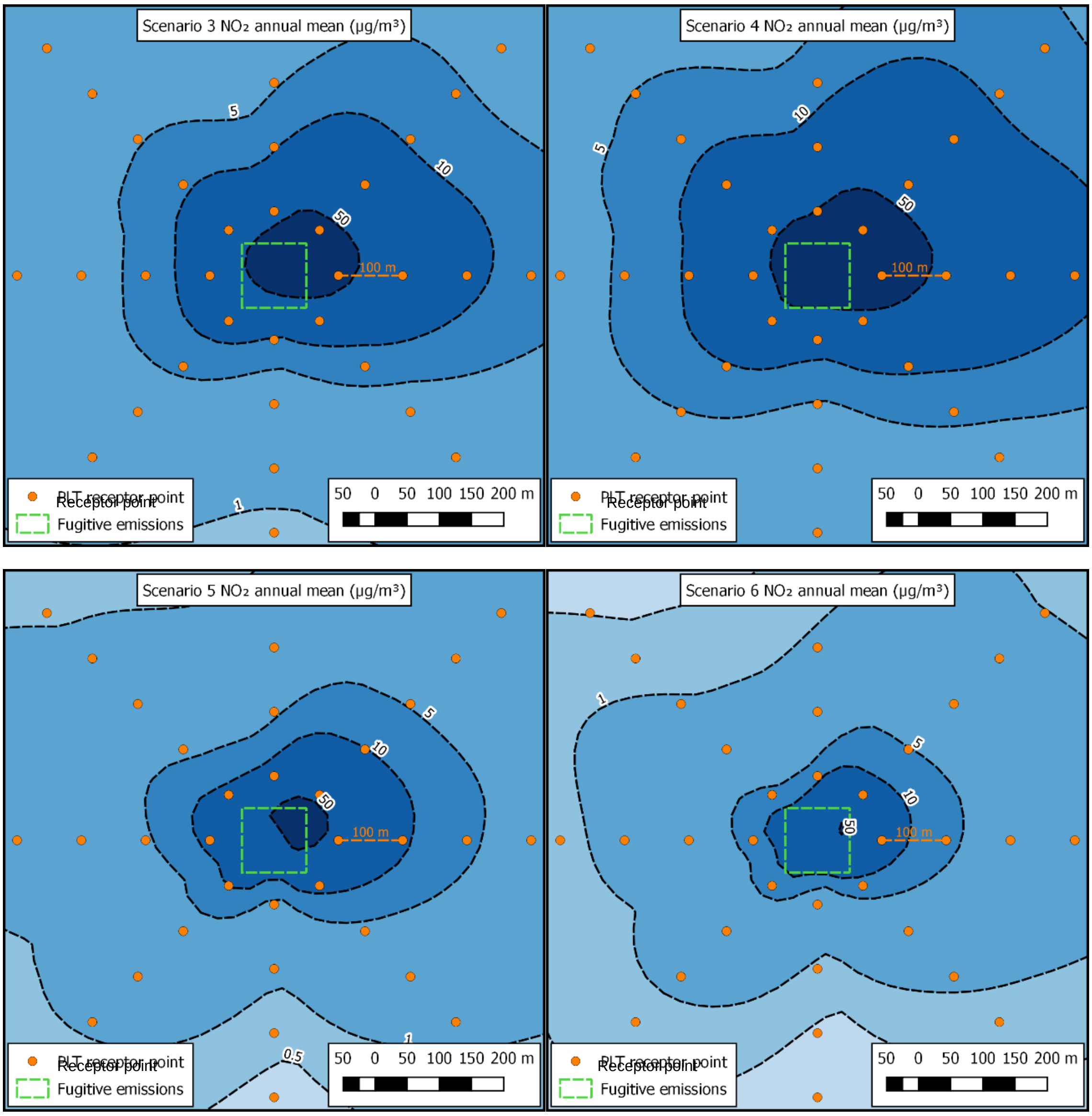


Figure D.4 Annual mean nitrogen dioxide concentrations under Scenarios 3–6 (near field)

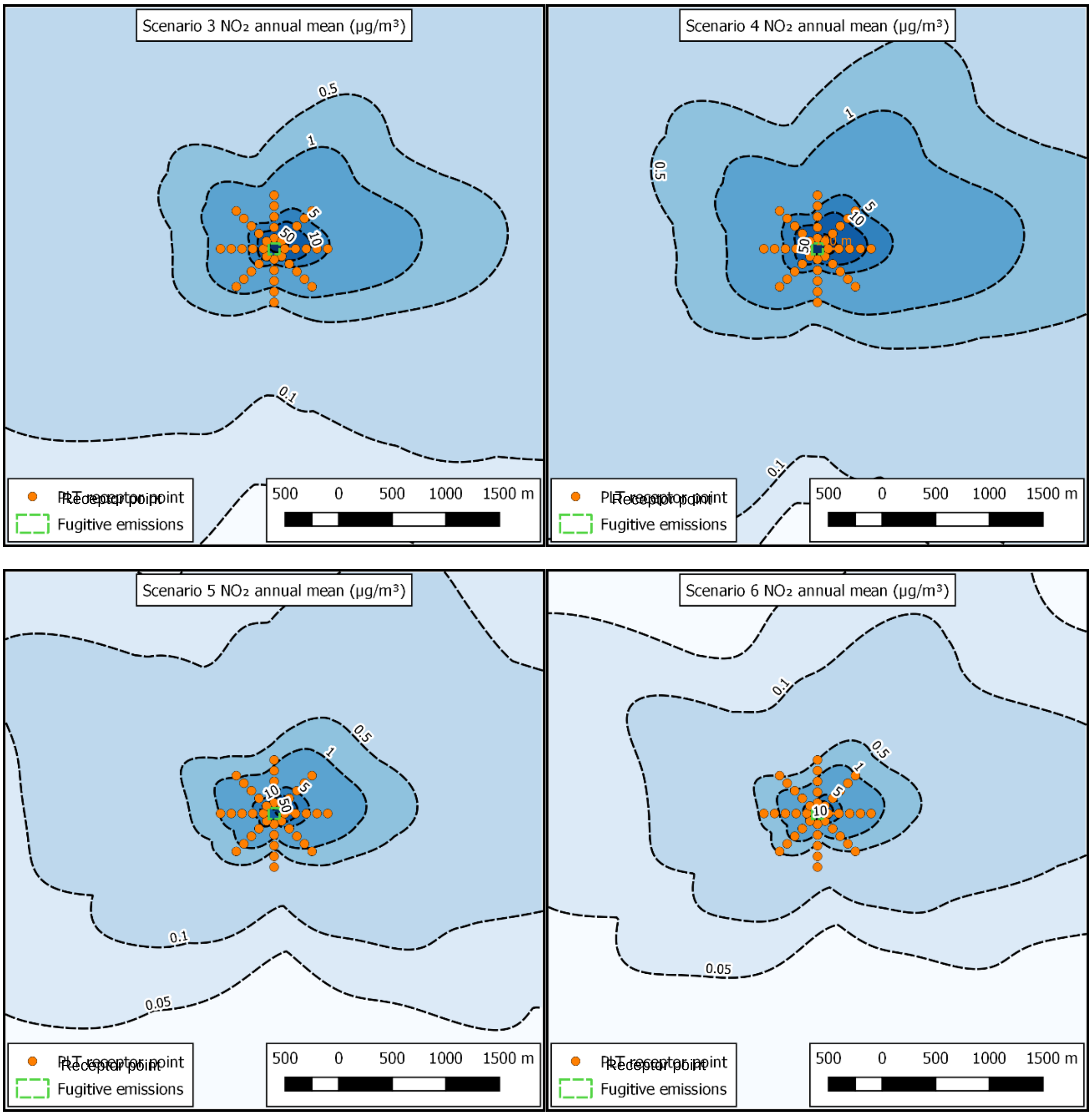


Figure D.5 Annual mean nitrogen dioxide concentrations under Scenarios 3–6 (wide)

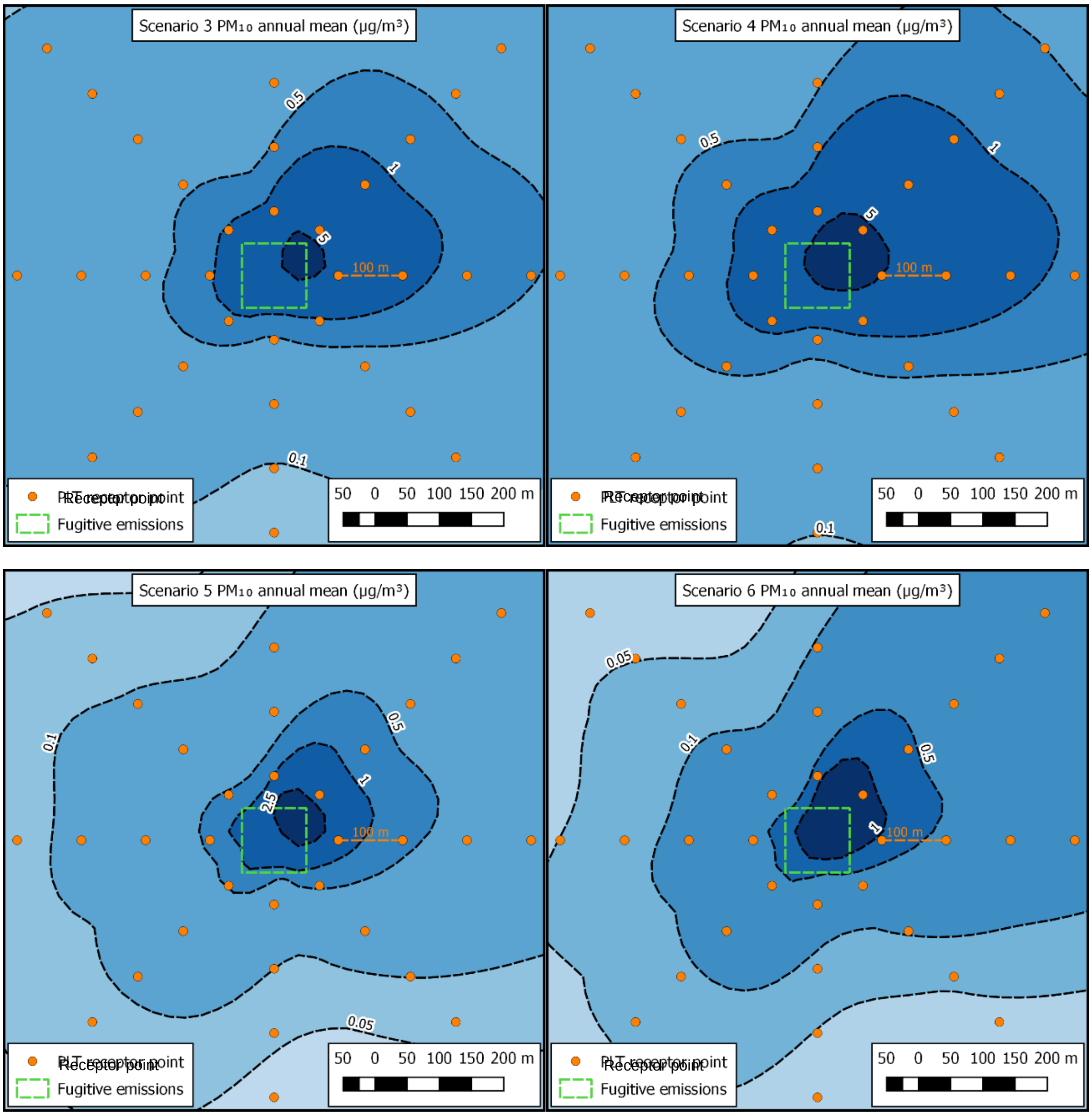


Figure D.6 **Annual mean PM$_{10}$ concentrations under Scenarios 3–6 (near field)**

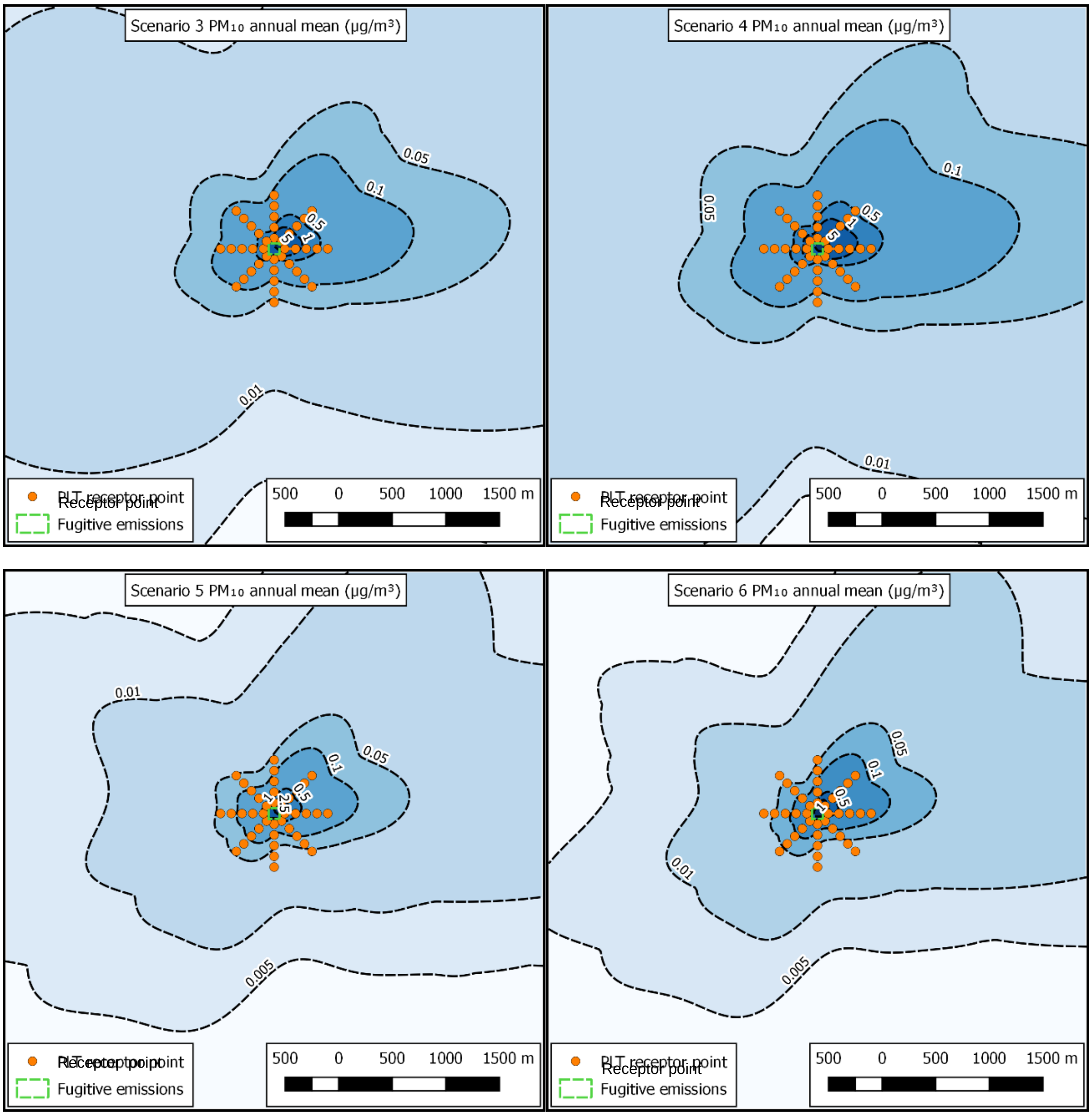


Figure D.7 Annual mean PM_{10} concentrations under Scenarios 3–6 (wide)

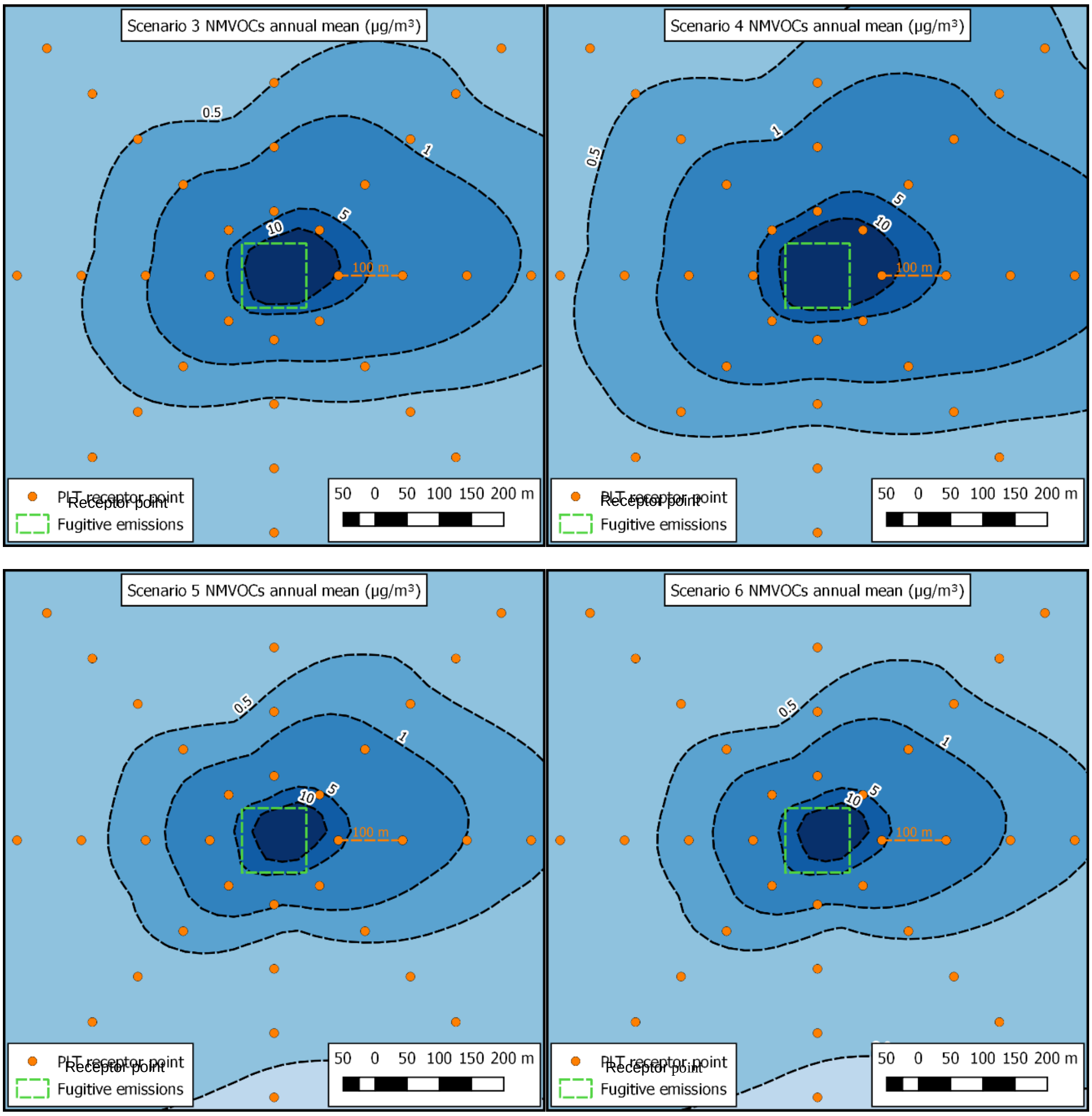


Figure D.8 Annual mean NMVOC concentrations under Scenarios 3–6 (near field)

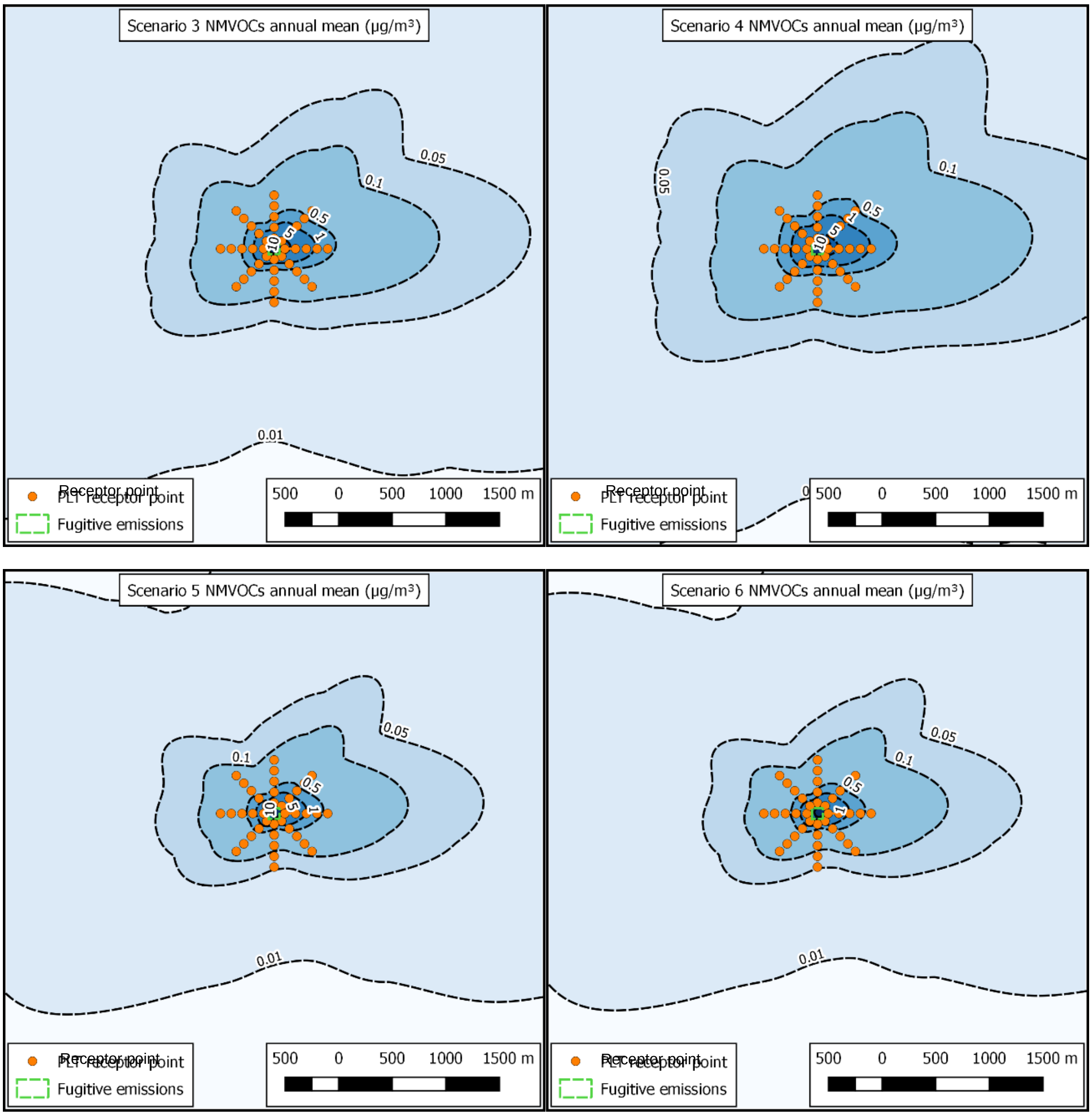


Figure D.9 Annual mean NMVOC concentrations under Scenarios 3–6 (wide)

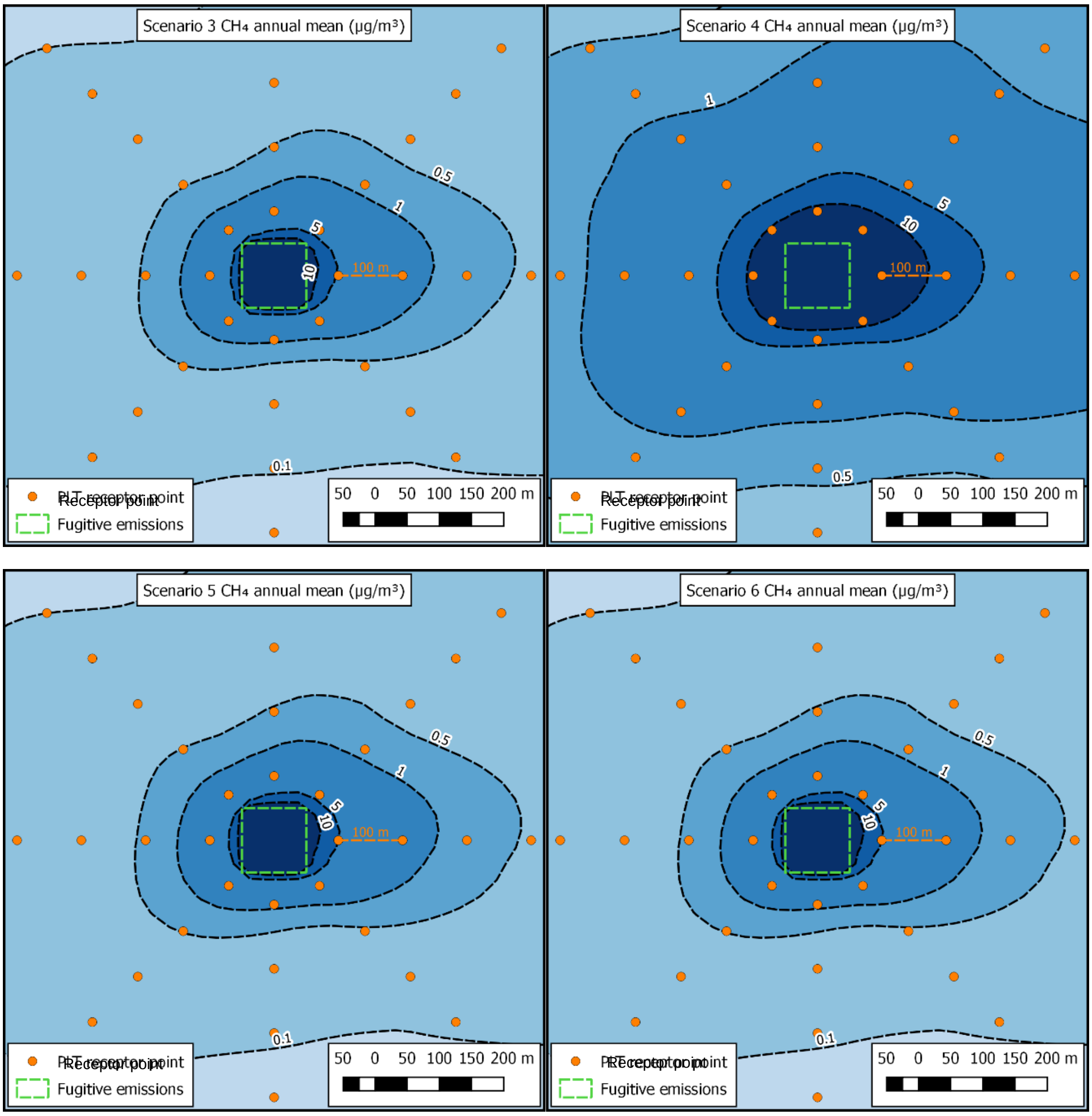


Figure D.10 Annual mean methane concentrations under Scenarios 3–6 (near field)

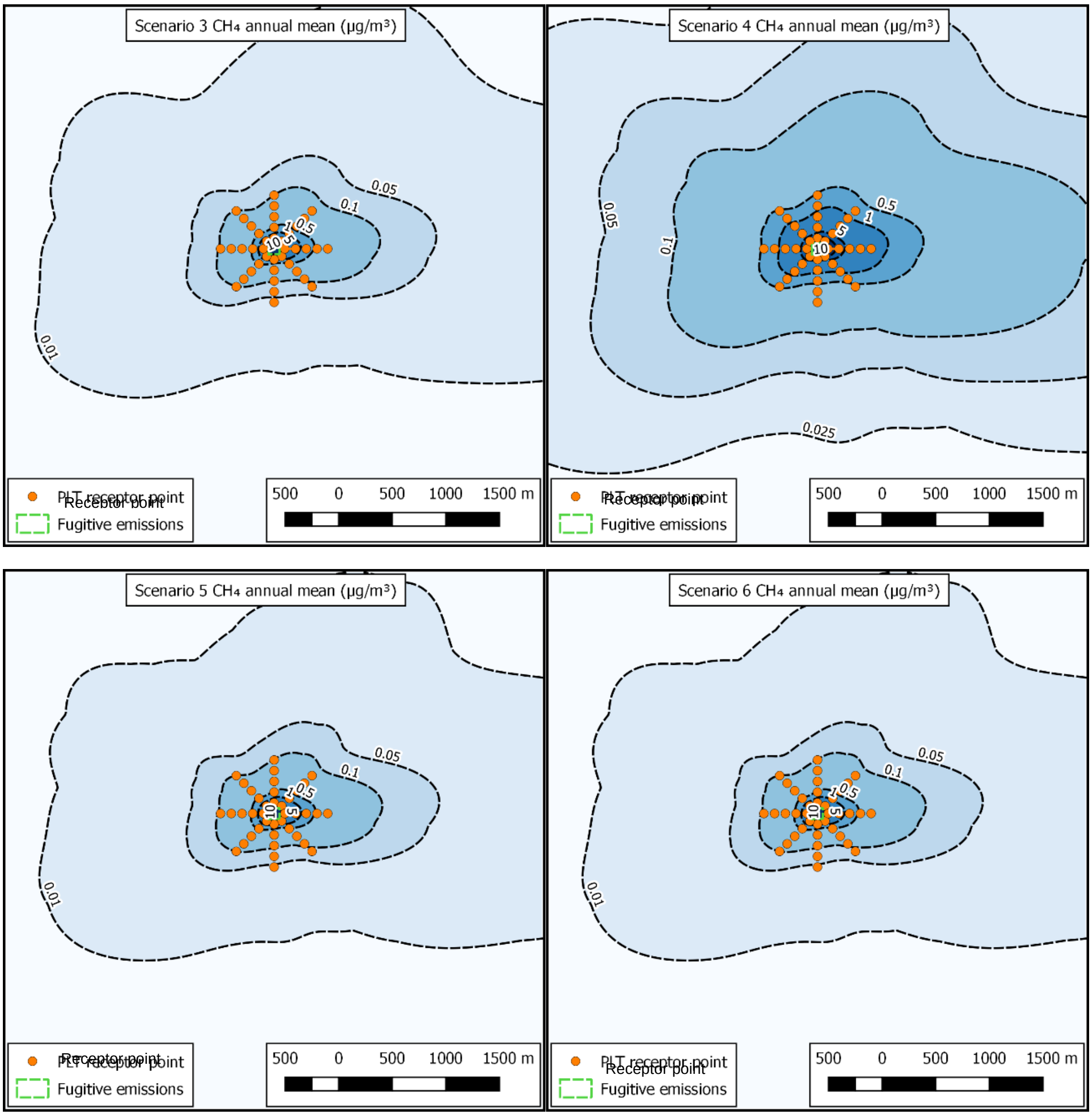


Figure D.11 Annual mean methane concentrations under Scenarios 3–6 (wide)

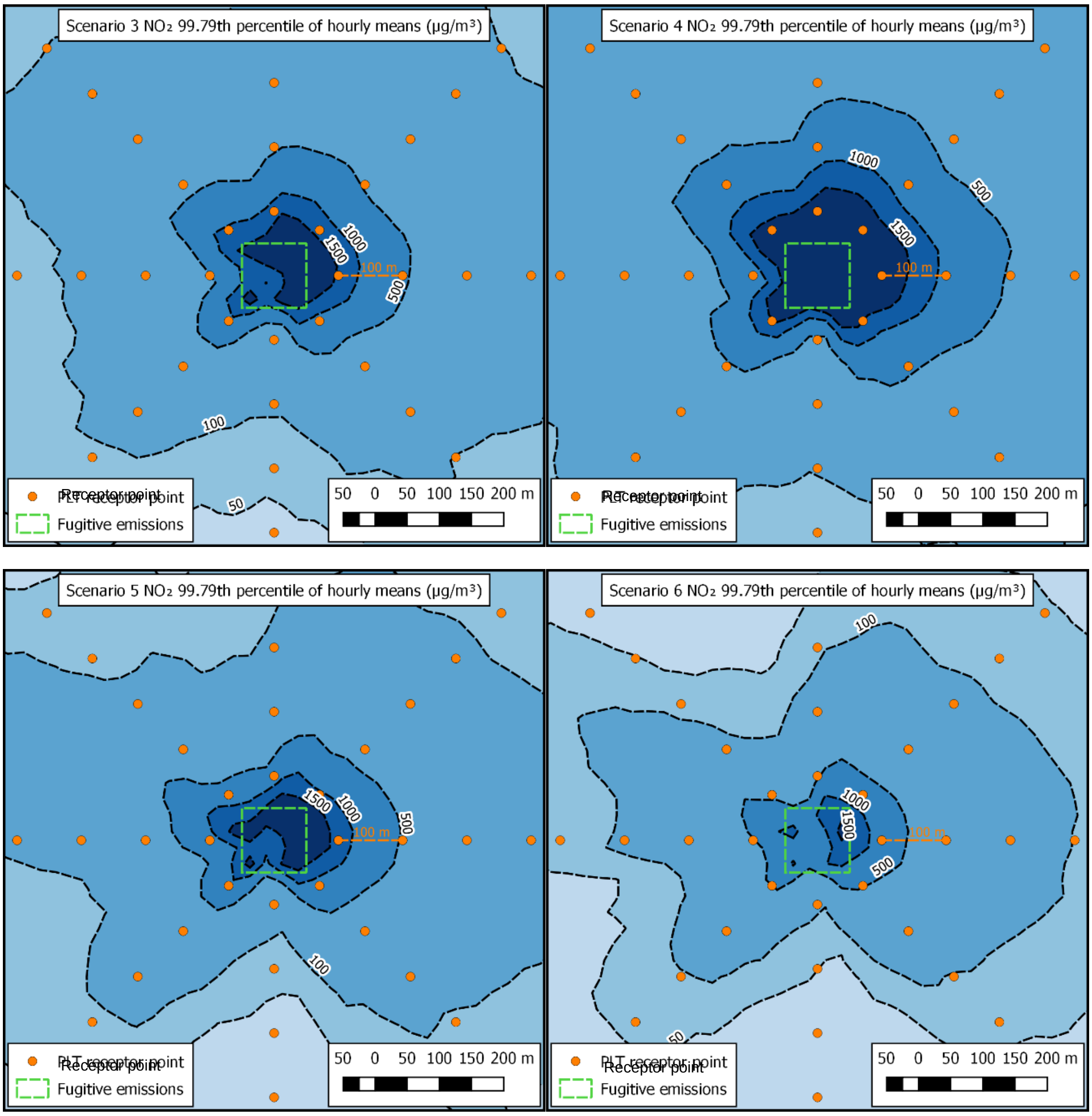


Figure D.12 Short-term nitrogen dioxide concentrations under Scenarios 3–6 (near field)

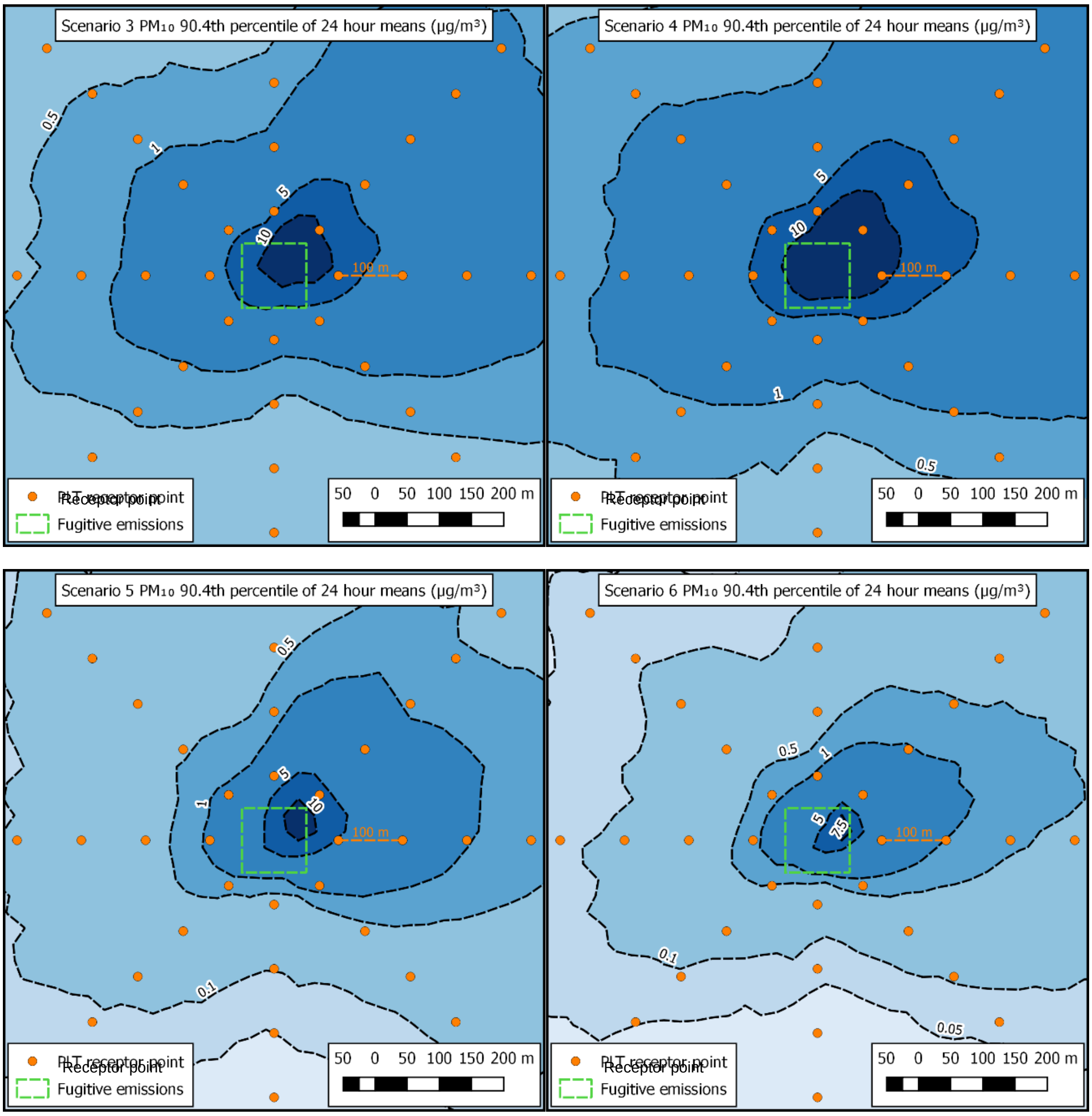


Figure D.13 Short-term PM_{10} concentrations under Scenarios 3–6 (near field)

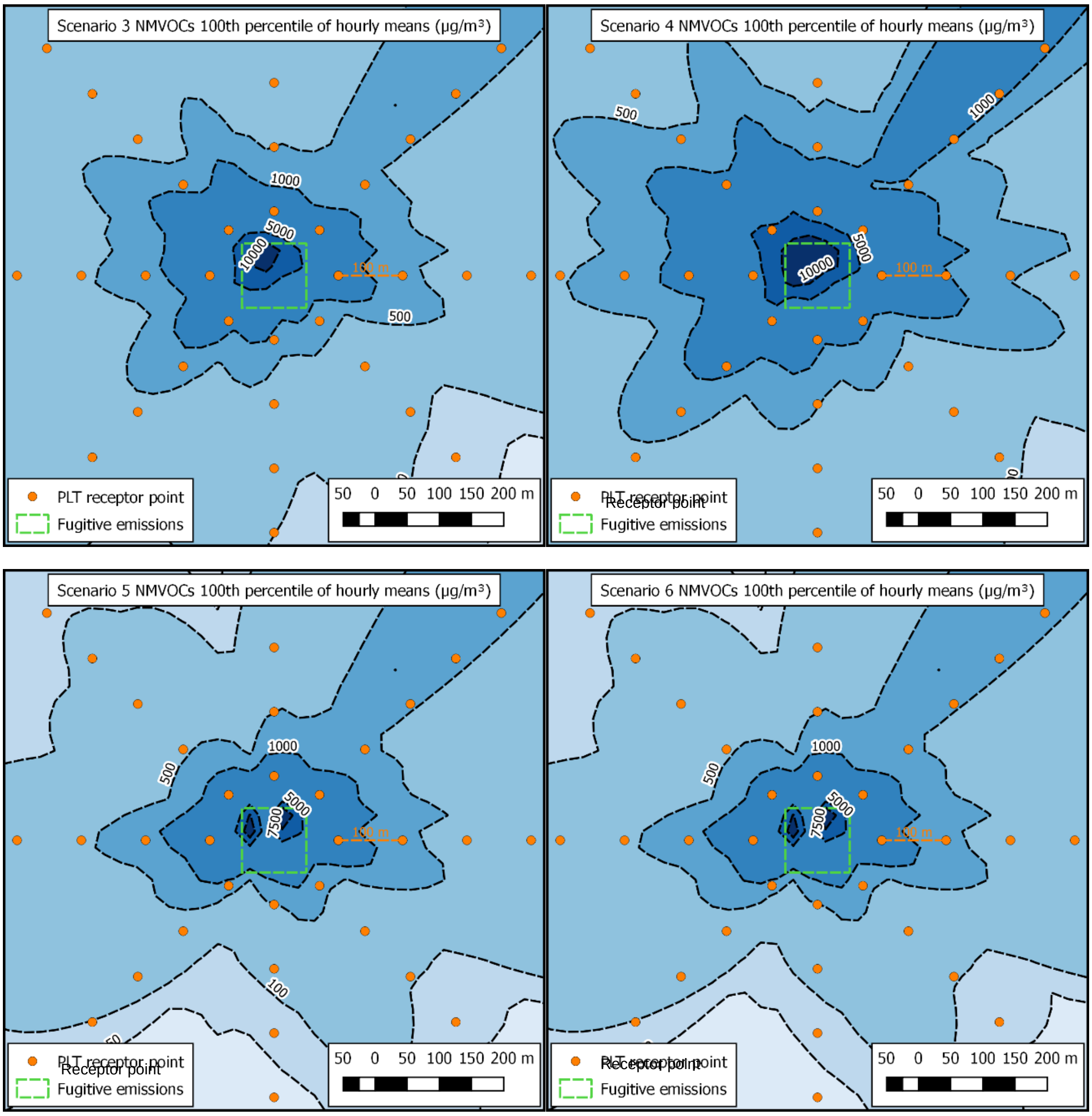
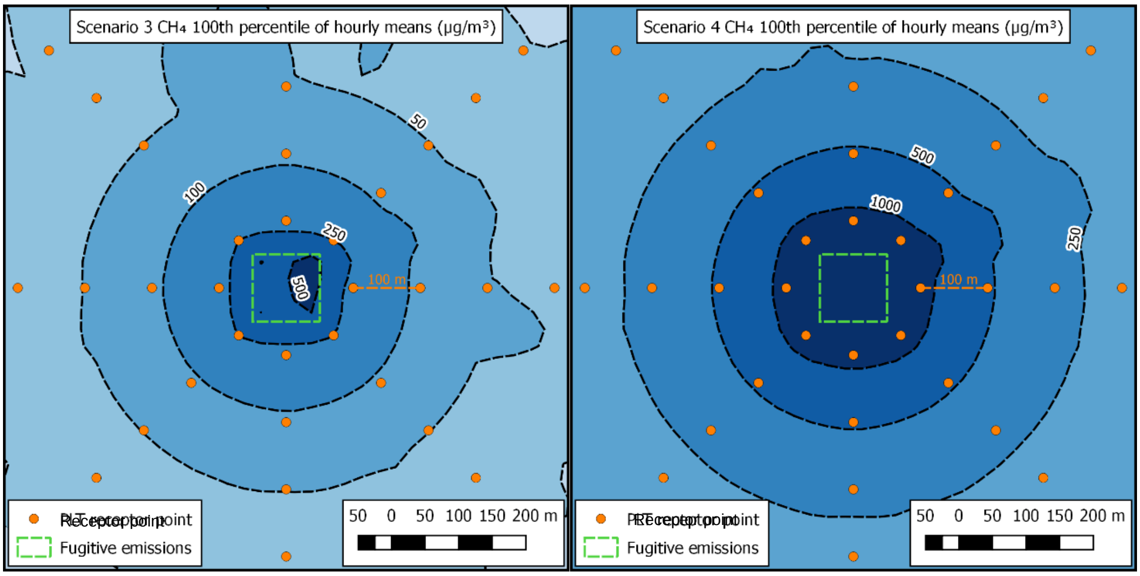


Figure D.14 Short-term NMVOC concentrations under Scenarios 3–6 (near field)



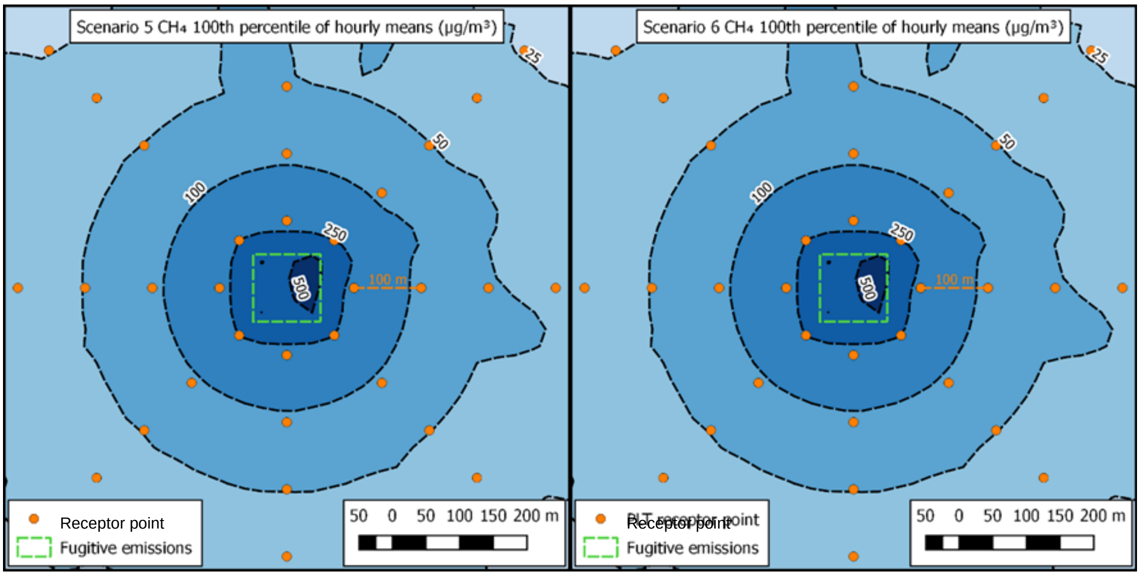
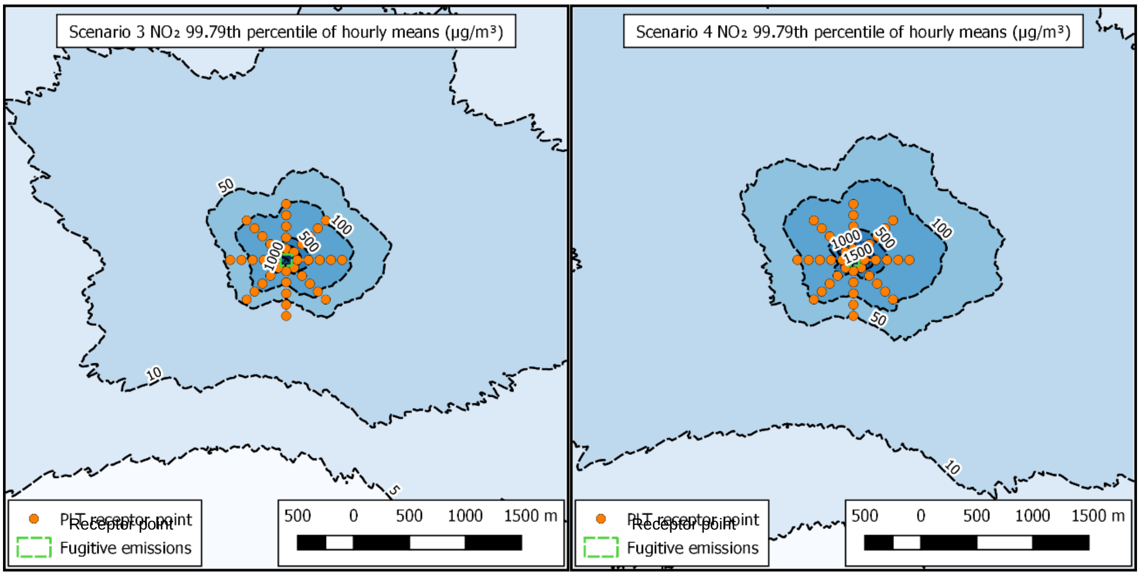


Figure D.15 Short-term methane concentrations under Scenarios 3–6 (near field)



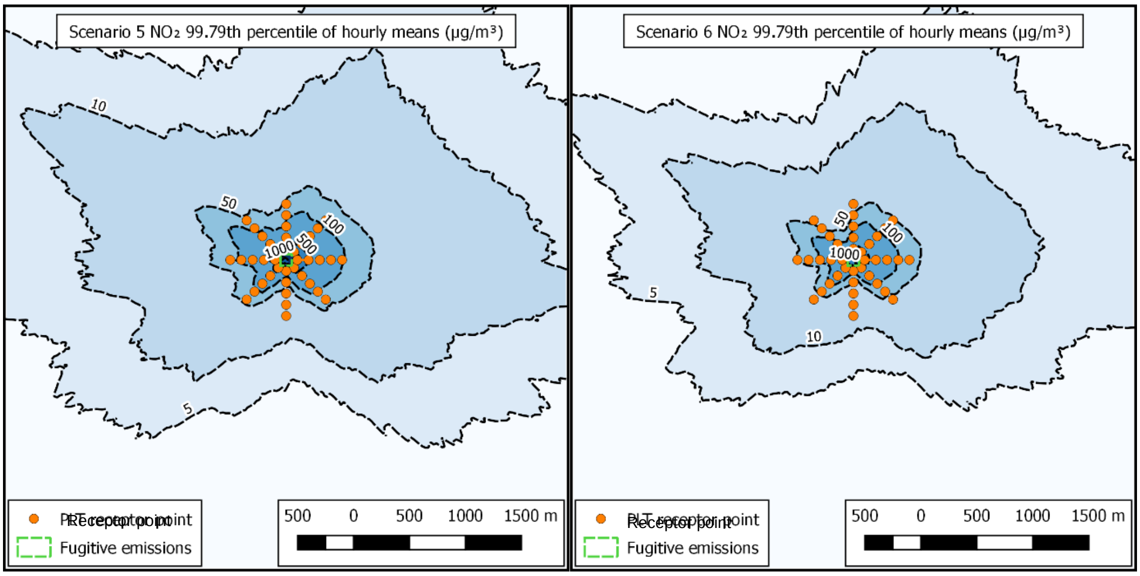
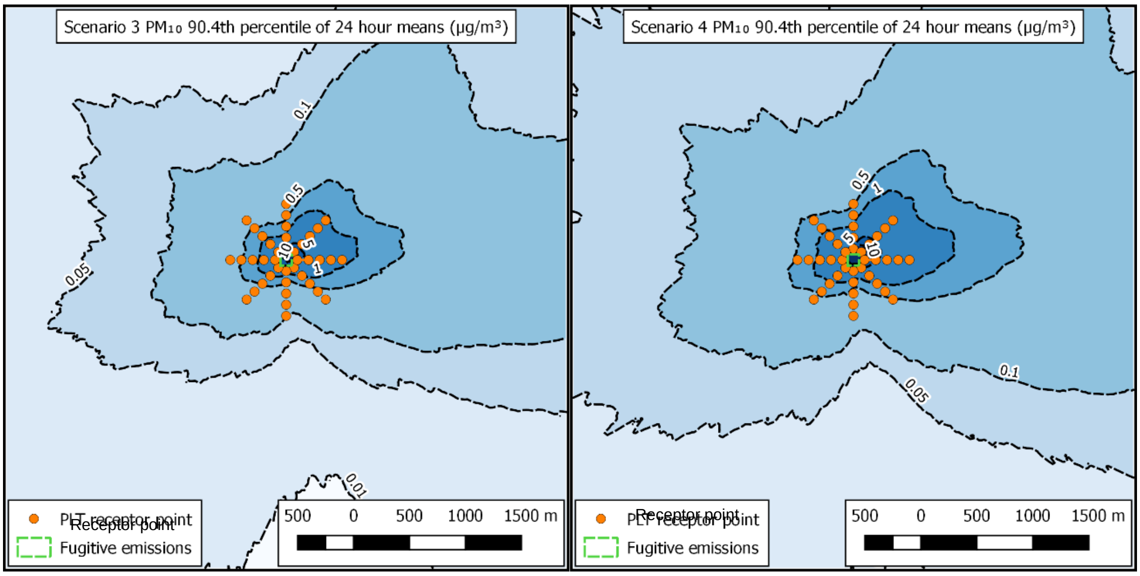


Figure D.16 Short-term nitrogen dioxide concentrations under Scenarios 3–6 (wide)



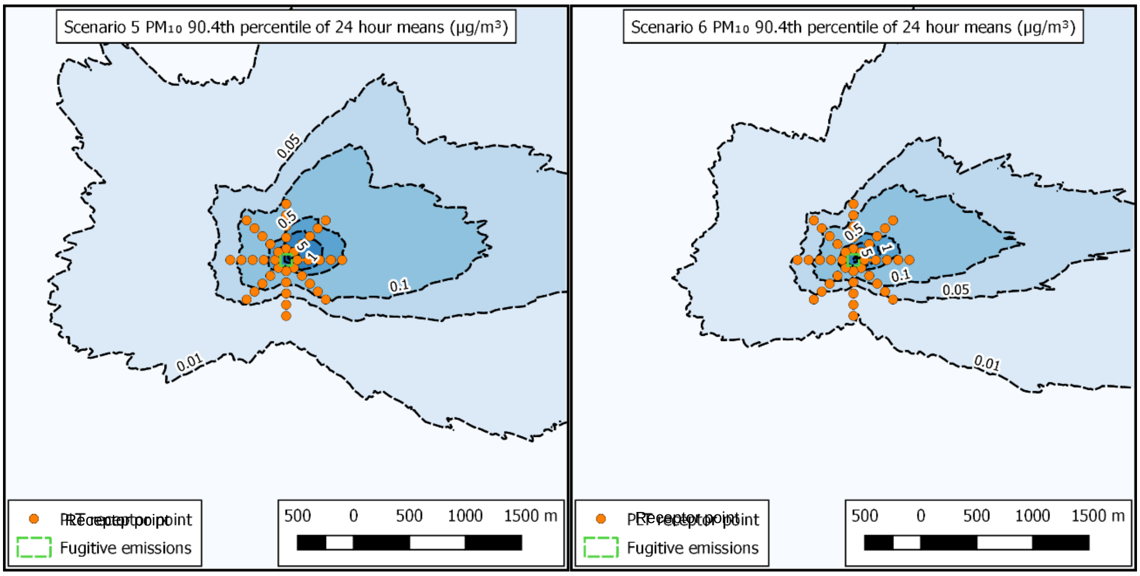
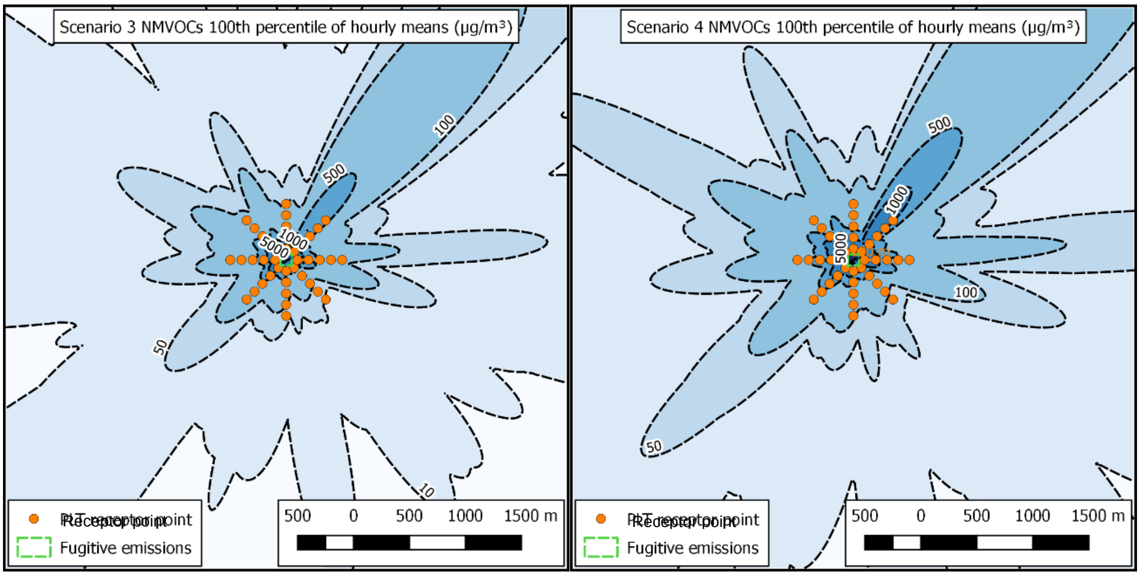


Figure D.17 Short-term PM_{10} concentrations under Scenarios 3–6 (wide)



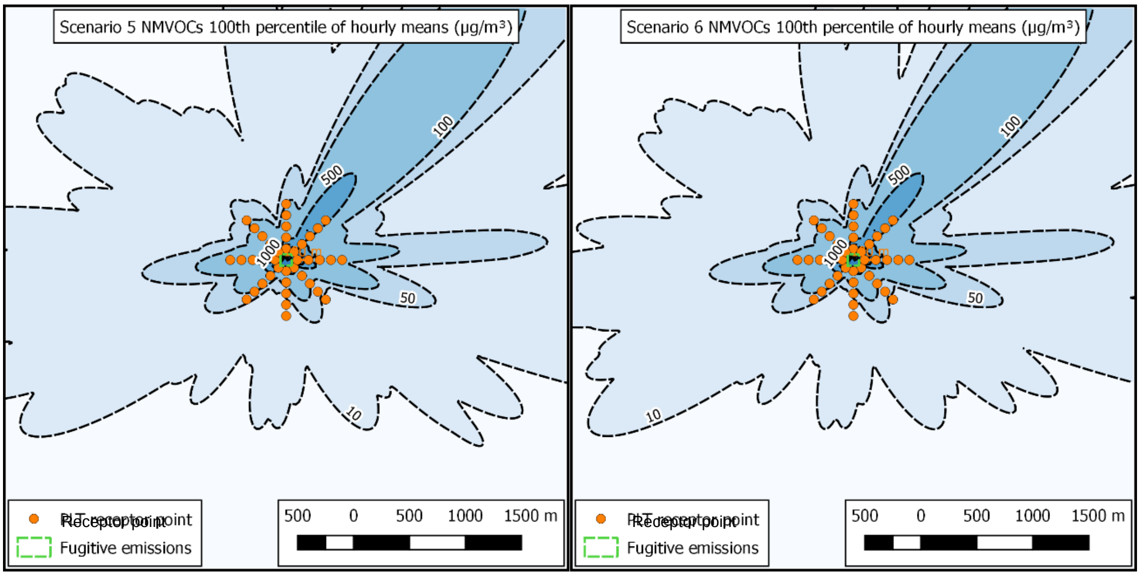
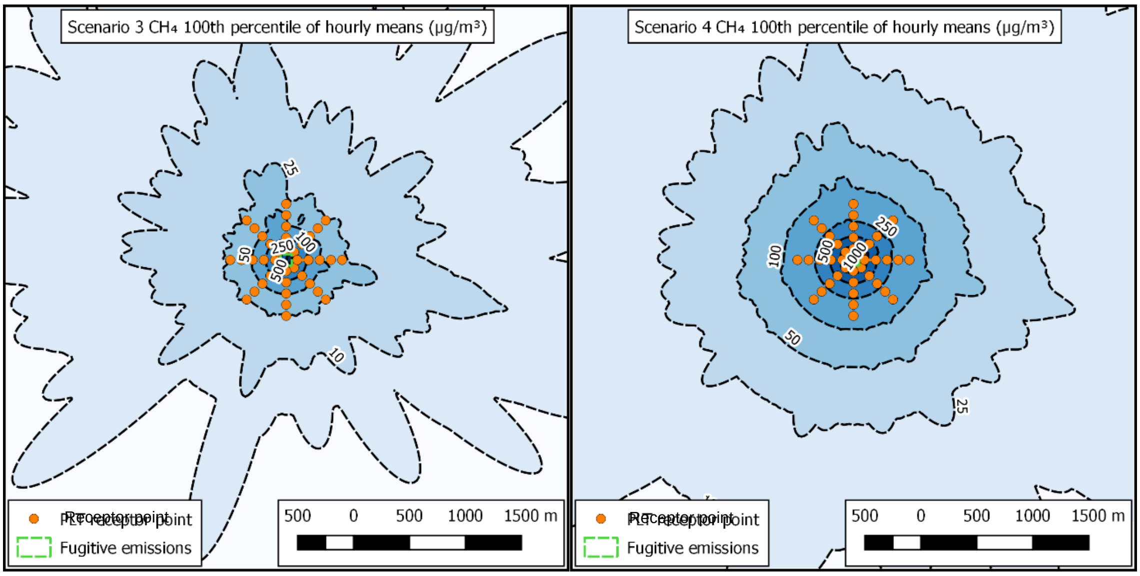


Figure D.18 Short-term NMVOC concentrations under Scenarios 3–6 (wide)



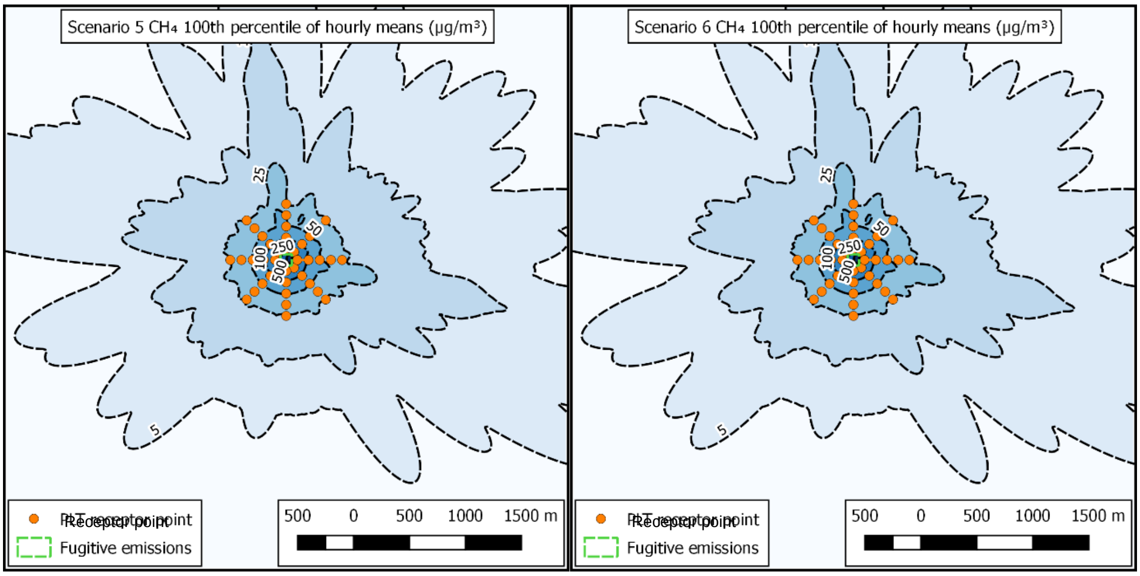


Figure D.19 Short-term methane concentrations under Scenarios 3–6 (wide)

Appendix E: Summary of ambient monitoring methods applicable to shale gas facilities

Table E.1 summarises the findings of the review of methods for ambient monitoring at shale gas sites, including:

- substances monitored
- sampling frequency
- duration of monitoring
- approximate costs
- any further comments and notes on any limitations

Note: The list of methods is not exhaustive. There are analysers using other principles, but these are not frequently used and so have been excluded.

Table E.1 Summary of methods for ambient monitoring at shale gas sites

Method	Substances	Sampling frequency	Duration	Approximate costs	Comments and limitations
Chemiluminescence	Nitric oxide and nitrogen dioxide	Continuous	1 minute average	£9,000 to £12,000	It is the reference method for this component (BS EN 14211:2012 ‘Ambient air. Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence’). Requires the use of a converter to convert the nitrogen dioxide to nitric oxide to make a measurement of total $NO_{x.}$ The efficiency of converter may degrade over time, which could have an impact on the quality of measurement and so requires regular checking and maintenance. Possible uncertainties caused by responses to other reactive nitrogen species on the measurement of nitrogen dioxide. This can be overcome by buying an analyser that uses a photoconvertor specific for nitrogen dioxide. There are units that are MCERTS certified for use for undertaking air quality measurements of NOx. Samples at a single point. To make measurements at multiple sample points, would require more instruments or a multiplexing sample system. Can be combined with other analysers to produce a monitoring system.
Cavity attenuated phase shift (CAPS)	Nitrogen dioxide	Continuous	1 minute average	£16,000	Enables a direct measurement of the nitrogen dioxide which does not involve a conversion step prior to analysis. Only measures nitrogen dioxide. This is an issue for situations where total NOx is also required. Samples are taken at one point.

Method	Substances	Sampling frequency	Duration	Approximate costs	Comments and limitations
Photo ionisation detector (PID)	Benzene – capable of measuring a variety other species (VOCs such as methane, formaldehyde)	Continuous	1 minute average	£2,000 to 6,000	Responds to other species (i.e. not specifically to benzene) dependant on the electron volt rating of lamp. Samples are taken at one point.
UV fluorescence	Sulphur dioxide	Continuous	1 minute average	£9,000 to £12,000	Reference method specific for sulphur dioxide (BS EN 14212:2012 'Ambient air. Standard method for the measurement of the concentration of sulphur dioxide by ultraviolet fluorescence'). Modern instruments include a hydro kicker to remove potentially interfering hydrocarbons.
Electrochemical	Multiple components including nitrogen dioxide, nitric oxide, carbon monoxide, sulphur dioxide, ozone	Continuous	1 minute average	£500 individual £8,000 for system	Cross interferences can be significant if compensation is not undertaken. These interferences include other gases, temperature and humidity. Advantages: instruments are small, cheap, portable and low powered, making it easy to deploy several at one time.
Flame ionisation detection (FID)	Methane	Continuous	1 minute average	£10,000 to £15,000	Technique will respond to other VOCs present in the sample, so there is a possibility of cross interferences. Can be used for methane and NMVOCs. Does not distinguish between species. Uses a flammable gas and so not intrinsically safe.
Fourier transformer infrared (FTIR)	Methane, sulphur dioxide, formaldehyde, benzene and other components	Continuous	1 minute average	£40,000	Capable of measuring many different components simultaneously. However, there can be issues with mixtures of components due to interpretation of complex spectra. One instrument enables measurement at a single point.
FTIR open path	Methane, sulphur dioxide, carbon dioxide, benzene, formaldehyde and other components	Continuous	1 minute average	£50,000 to £80,000	Can be used as a fence line monitoring device using multiple reflectors to measure along a variety of paths. Same issues as above.

Method	**Substances**	**Sampling frequency**	**Duration**	**Approximate costs**	**Comments and limitations**
Open path laser diode	Carbon monoxide, carbon dioxide and methane	Continuous	1 minute average	£20,000 per species	Very specific – provided the correct wavelength is chosen for analysis, the unit is not subject to interferences.
Non-dispersive infrared (NDIR)	Methane, carbon monoxide, carbon dioxide and nitric oxide	Continuous	1 minute average	£6,000 to £10,000	This measurement principle suffers from cross interference with water vapour and carbon dioxide. Single point sampling.
Differential optical absorption (DOAS) spectrometry analyser	NO_X, sulphur dioxide, formaldehyde and benzene	Continuous	1 minute average	£30,000 to £50,000	Dependant on concentrations to enable accurate analysis (that is, low concentration = long integration times). Need to use complete absorption spectrum to calculate concentration. This improves accuracy; minimum interferences.
Differential absorption LIDAR (DIAL)	NOx, sulphur dioxide, formaldehyde, benzene and others	Continuous	1 minute average	£80,000 to £500,000	Capable of measuring in 3 dimensions.
Cavity ring down	Methane, nitrogen dioxide, BTEX	Continuous	1 minute average	£30,000 to £40,000	Wavelength specific for each species measured. Single point sampling.
Cavity enhanced adsorption spectroscopy (CEAS)	NOx, sulphur dioxide, formaldehyde, benzene and others	Continuous	1 minute average	£35,000	Wavelength specific for each species measured. Single point sampling.
Gas chromatography (GC)	Various hydrocarbons (C4 to C16) – aromatic, aliphatic, containing oxygen, BTEX, nitrogenated, chlorinated	Continuous	Hourly average	£30,000 (BTEX) £60,000 to £100,000	Requires onsite supply of carrier gases. Species to be measured depend on column and detector.
GC mass spectrometry (GC-MS)	Various hydrocarbons (C4 to C16), aromatic, aliphatic, containing oxygen, BTEX, nitrogenated, chlorinated	Continuous	Hourly average	£100,000 to £250,000	Very specific – able to measure a large range of different compounds without need for columns. Able to easily resolve close peaks.
High and low volume samplers	PAHs, sulphur dioxide, acid gases, metals and so on	Short-term	–	£10,000 to £20,000	Requires subsequent analysis. Enables the deployment of a variety of media to target specific species.

Method	Substances	Sampling frequency	Duration	Approximate costs	Comments and limitations
Diffusion tubes	Nitrogen dioxide, sulphur dioxide, ozone and BTEX	Short-term	–	£5 to 25	Indicative long time averaging of samples highlights areas of high concentrations.
Analytical thermal desorption dual bed tubes	Benzene, other organic molecules and BTEX	Short-term	Hourly average	£80, plus analysis	Requires a pump to draw a sample through the tubes. Followed by subsequent analysis.
Optical light scattering	PM_1, $PM_{2.5}$, PM_4, PM_{10}, total suspended particulates (TSP), particle size distribution	Continuous	Hourly mean	£300 to £30,000	Some units have demonstrated equivalence, others have not. Makes assumptions for the physical characteristics of a particle when determining mass concentrations. These assumptions may not be correct for the particles being measured. Systems may be sensitive to effects of humidity. This design can be miniaturised for inclusion with portable systems.
Beta attenuation monitor (BAM)	PM_{10}, $PM_{2.5}$	Continuous	Hourly	£18,000 to £20,000	Used in conjunction with PM_{10} sampling head capturing all particulate matter at and below PM_{10}. Includes low level source. Demonstrated equivalence for MCERTS UK particulate matter.
Tapered element oscillating microbalance (TEOM) with filter dynamics measurement system (FDMS)	$PM_{2.5}$, PM_{10}	Continuous	Hourly	£22,000 to £25,000	Demonstrated equivalence for MCERTS UK particulate matter.

Notes: BTEX = benzene, toluene, ethylbenzene and xylenes

Appendix F: Case studies

This appendix presents 5 hypothetical case studies used to test the application of the proposed monitoring framework.

F.1 Case Study 1: Near-urban site, confounding source

A shale gas site, consisting of 15 vertical wells, is proposed for development in a near-urban environment. The site is located near an existing large-scale energy-from-waste facility, which has been conducting background air quality monitoring for several years. A dispersion modelling study has indicated a process contribution from the shale gas site of >1% of the long-term AQO for nitrogen dioxide at a nearby residential property. During the drilling phase, the local town centre is designated as an AQMA for nitrogen dioxide. Table F.1 provides a summary of the case study details.

Table F.1 Case Study 1 summary

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
Prior to baseline	Is the facility an ‘early adopter’?	No	not applicable
	What size is the facility?	10–20 wells	Enhanced: drilling and hydraulic fracturing – NOx Recommendation: minimum of 2 site boundary monitoring locations
	Is there is a high degree of interest/ concern from local residents?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at human receptor sites?	No	not applicable
	Is the facility located in close proximity to a confounding source?	<2km from a Part A permitted industrial facility	Enhanced: baseline – NOx, NMVOCs and PM_{10}/$PM_{2.5}$ Recommendation: undertake directional analysis to identify monitoring location with greatest signal strength. If available, review existing background air quality data collected by permitted industrial facility
	Does local ambient air quality data	No	not applicable

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
	indicate existing air quality issues?		
	Do the results of dispersion modelling show an insignificant impact at ecological receptor sites?	Yes	not applicable
Prior to drilling	No change to monitoring strategy		
Change in circumstances: Air Quality Management Area declared during Drilling			
Prior to hydraulic fracturing	Does local ambient air quality data indicate existing air quality issues?	Yes – <5km of AQMA	Enhanced: hydraulic fracturing, extraction and decommissioning – NOx and/or $PM_{10}/PM_{2.5}$ Recommendation: minimum of 2 site boundary monitoring locations Add at least 2 monitoring locations (non-automatic) within local communities
Prior to extraction	No change to monitoring strategy		
Prior to decommissioning	No change to monitoring strategy		

The monitoring strategy for Case Study 1 is summarised in Tables F.2 and F.3. The strategy is split into these tables in order to reflect the change in local levels of air quality following the designation of the AQMA. Tables F.2 and F.3 illustrate the monitoring strategy before and after the designation respectively.

The case study illustrates how the ambient air monitoring framework will require monitoring strategies to be updated to reflect any changes to background levels of air quality as indicated by the declaration of a new AQMA, specifically where this indicates an exceedance of an AQO. As shown above, this change in background air quality resulted in a more stringent monitoring strategy being adopted following the drilling phase. The case study also demonstrates the need to consider a more detailed baseline study in cases where another permitted industrial facility is nearby.

Table F.2 Case Study 1: monitoring strategy prior to designation of AQMA

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Baseline	SO_2, CO, O_3, PAHs, CH_4	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	• Directional analysis • Review existing background air quality data
Drilling	not applicable	SO_2, CO, O_3, PAHs, CH_4,	NOx	• >2 site boundary monitoring locations

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
		NMVOCs, PM_{10}/$PM_{2.5}$		

Table F.3 Case Study 1: monitoring strategy, following designation of AQMA

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Hydraulic fracturing	not applicable	SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs, PM_{10}/$PM_{2.5}$	• >2 site boundary monitoring locations • >2 monitoring locations (non-automatic) within local communities
Extraction	SO_2, CO, O_3, PAHs, CH_4		NOx, NMVOCs, PM_{10}/$PM_{2.5}$	• >2 site boundary monitoring locations • >2 monitoring locations (non-automatic) within local communities
Decommissioning	SO_2, CO, O_3, PAHs, CH_4		NOx, NMVOCs, PM_{10}/$PM_{2.5}$	• >2 site boundary monitoring locations • >2 monitoring locations (non-automatic) within local communities

F.2 Case Study 2: Small site, with nearby shale gas facilities

A developer plans to construct a small shale gas development consisting of 5 vertical wells. The site is located in a rural environment and dispersion modelling has indicated an insignificant impact at human and ecological sites. However, there are other shale gas facilities within 2km of the site which are currently operational. After the baseline phase, the developer decides to increase the size of the site to >20 wells. Table F.4 provides a summary of the case study details.

Table F.4 Case Study 2 summary

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
Prior to baseline	Is the facility an ‘early adopter’?	No	not applicable
	What size is the facility?	<10 wells	not applicable
	Is there is a high degree of interest/ concern from local residents?	No	not applicable

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
	Do the results of dispersion modelling show an insignificant impact at human receptor sites?	Yes	Reduced, baseline – all pollutants Reduced, extraction – all pollutants Reduced, decommissioning – all pollutants
	Is the facility located in close proximity to a confounding source?	<2km from a Part A permitted industrial facility	Enhanced, baseline – NOx, NMVOCs and PM_{10}/$PM_{2.5}$ Recommendation: undertake directional analysis to identify monitoring location with greatest signal strength If available, review existing background air quality data collected by permitted industrial facility
	Does local ambient air quality data indicate existing air quality issues?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at ecological receptor sites?	Yes	not applicable
Change in circumstances: Size increased from <10 wells to >20 wells after Baseline			
Prior to drilling	What size is the facility?	>20 wells	Enhanced, drilling, hydraulic fracturing and extraction – NOx, NMVOCs, PM_{10}/$PM_{2.5}$ Recommendation: minimum of 4 site boundary monitoring locations
Prior to hydraulic fracturing	No change to monitoring strategy		
Prior to extraction	No change to monitoring strategy		
Prior to decommissioning	No change to monitoring strategy		

The monitoring strategy under Case Study 2 is set out in Tables F.5 and F.6, which illustrate the change in monitoring strategy following the decision to increase the size of the development. Table F.5 and Table F.6 illustrate the strategy before and after the increase respectively.

Case Study 2 illustrates how the ambient air monitoring framework will require a strategy to be updated to reflect any changes to the size of the facility, specifically where an increase in the number of wells is proposed. As demonstrated above, the increase in well number resulted in a more stringent monitoring strategy being adopted following the baseline phase.

Table F.5 Case Study 2: monitoring strategy prior to increase in well numbers

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Baseline	SO_2, CO, O_3, PAHs, CH_4	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	• Directional analysis • Review existing background air quality data

Table F.6 Case Study 2: monitoring strategy following increase in well numbers

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Drilling	not applicable	SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	• >4 site boundary monitoring locations
Hydraulic fracturing	not applicable	SO_2, CO, O_3, PAHs, CH_4, NMVOCs, $PM_{10}/PM_{2.5}$	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	• >4 site boundary monitoring locations
Extraction	SO_2, CO, O_3, PAHs, CH_4	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	• >4 site boundary monitoring locations
Decommissioning	SO_2, CO, O_3, PAHs, CH_4, NOx, NMVOCs, $PM_{10}/PM_{2.5}$	not applicable	not applicable	

F.3 Case Study 3: Large ‘early adopter’ facility, close to designated habitat site

A large shale gas development consisting of 30 vertical wells is proposed in a rural setting where background concentrations are anticipated to be low. The site is one of the first of its kind in the UK. There are currently no air quality monitoring stations in the local area. Dispersion modelling has indicated that an insignificant impact at a designated habitat site cannot be confirmed. Table F.7 provides a summary of the case study details.

Table F.7 Case Study 3 summary

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
Prior to baseline	Is the facility an ‘early adopter’?	Yes	Enhanced: all phases – all pollutants

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
			Recommendation: minimum of 2 site boundary monitoring locations.
	What size is the facility?	>30 wells	Enhanced: drilling, hydraulic fracturing and extraction – NOx, NMVOCs, PM_{10}/$PM_{2.5}$ Recommendation: minimum of 4 site boundary monitoring locations
	Is there is a high degree of interest/ concern from local residents?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at human receptor sites?	Yes	Reduced: baseline – all pollutants Reduced: extraction – all pollutants Reduced: decommissioning – all pollutants
	Is the facility located in close proximity to a confounding source?	No	not applicable
	Does local ambient air quality data indicate existing air quality issues?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at ecological receptor sites?	No	Enhanced: drilling and hydraulic fracturing – NOx Recommendation: consider extending the monitoring strategy to designated habitat sites, focusing on substances identified as posing a risk to ecological sites under the Habitats Directive.
Prior to drilling	No change to monitoring strategy		
Prior to hydraulic fracturing	No change to monitoring strategy		
Prior to extraction	No change to monitoring strategy		
Prior to decommissioning	No change to monitoring strategy		

The monitoring strategy under Case Study 3 is set out in Table F.8. The strategy illustrates how the ambient air monitoring framework requires additional controls where the site is an early adopter, and is located in close proximity to a European designated habitat site. Case Study 3 is also an example of where the characteristics of a site may indicate the requirement for both reduced and enhanced monitoring approaches (that is, reduced monitoring for human health protection but enhanced monitoring for ecological protection). In this circumstance, the enhanced monitoring approach should be prioritised.

Table F.8 Case Study 3 monitoring strategy

Phase	**Recommended monitoring programme**			**Recommendations**
	Reduced	**Routine**	**Enhanced**	
Baseline	not applicable	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	>2 site boundary monitoring locations
Drilling	not applicable	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	>4 site boundary monitoring locations Monitoring at designated habitat sites
Hydraulic fracturing	not applicable	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	>4 site boundary monitoring locations Monitoring at designated habitat sites
Extraction	not applicable	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	>4 site boundary monitoring locations
Decommissioning	not applicable	not applicable	NOx, NMVOCs, $PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	>2 site boundary monitoring locations

F.4 Case Study 4: Medium site, local concerns regarding the development

A shale gas operator has proposed the development of a medium-sized shale gas facility consisting of 20 wells. Local residents have raised concerns about the potential effects of the facility on the local community. The site is in a rural setting, with residential properties located within 500m of the boundary. Dispersion modelling has indicated an insignificant impact resulting from emissions from the site. Table F.9 provides a summary of the case study details.

Table F.9 Case Study 4 summary

Development phase	**Assess/review site characteristics**	**Response**	**Variation from routine monitoring**
Prior to baseline	Is the facility an 'early adopter'?	No	not applicable

Development phase	**Assess/review site characteristics**	**Response**	**Variation from routine monitoring**
	What size is the facility?	10–20 wells	Enhanced: drilling and hydraulic fracturing – NOx Recommendation: minimum of 2 site boundary monitoring locations
	Is there is a high degree of interest/ concern from local residents?	Yes	Enhanced: drilling, hydraulic fracturing and extraction – NMVOCs Recommendation: minimum of 2 site boundary monitoring locations. Include measurement of odours or potentially odorous chemicals.
	Do the results of dispersion modelling show an insignificant impact at human receptor sites?	Yes	Reduced: baseline, extraction and decommissioning – all pollutants
	Is the facility located in close proximity to a confounding source?	No	not applicable
	Does local ambient air quality data indicate existing air quality issues?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at ecological receptor sites?	Yes	not applicable
Prior to drilling	No change to monitoring strategy		
Prior to hydraulic fracturing	No change to monitoring strategy		
Prior to extraction	No change to monitoring strategy		
Prior to decommissioning	No change to monitoring strategy		

The monitoring strategy under Case Study 4 is set out in Table F.10. The strategy illustrates how the framework may require additional controls where a site is attracting significant opposition from the local community to provide reassurance that the facility does not pose a significant risk to local air quality. Under such circumstances, the application of enhanced monitoring would be required for certain phases and recommendations are made for further monitoring of nuisance pollutants.

Table F.10 Case Study 4 monitoring strategy

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Baseline	SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	not applicable	
Drilling	not applicable	$PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs	• >2 site boundary monitoring locations • Include measurement of odours or potentially odorous chemicals.
Hydraulic fracturing	not applicable	$PM_{10}/PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs	• >2 site boundary monitoring locations • Include measurement of odours or potentially odorous chemicals.
Extraction	SO_2, CO, O_3, PAHs, CH_4	NOx, $PM_{10}/PM_{2.5}$	NMVOCs	• >2 site boundary monitoring locations • Include measurement of odours or potentially odorous chemicals.
Decommissioning	SO_2, CO, O_3, PAHs, CH_4	NOx, NMVOCs, $PM_{10}/PM_{2.5}$	not applicable	

F.5 Case Study 5: Medium site, located close to A-road

A medium-sized shale gas site consisting of 15 wells is proposed for an area of land adjacent to an A road. Dispersion modelling has confirmed an insignificant air quality impact is expected at human and ecological receptor sites. Following the first 5 years of operation, the operator decides to re-fracture the wells. Table F.11 provides a summary of the case study details.

Table F.11 Case Study 5 summary

Development phase	Assess/review site characteristics	Response	Variation from routine monitoring
Prior to baseline	Is the facility an ‘early adopter’?	No	not applicable
	What size is the facility?	10–20 wells	Enhanced: drilling and hydraulic fracturing – NOx Recommendation: minimum of 2 site boundary monitoring locations

Development phase	**Assess/review site characteristics**	**Response**	**Variation from routine monitoring**
	Is there is a high degree of interest/ concern from local residents?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at human receptor sites?	Yes	Reduced: baseline, extraction and decommissioning – all pollutants
	Is the facility located in close proximity to a confounding source?	Yes – <350m of a major roadway	Enhanced: baseline – NOx and PM$_{10}$/PM$_{2.5}$ Recommendation: undertake directional analysis to identify monitoring location with greatest signal strength
	Does local ambient air quality data indicate existing air quality issues?	No	not applicable
	Do the results of dispersion modelling show an insignificant impact at ecological sites?	Yes	not applicable
Prior to drilling	No change to monitoring strategy		
Prior to hydraulic fracturing	No change to monitoring strategy		
Prior to extraction	No change to monitoring strategy		
Change in circumstances: Decision to re-fracture taken after 5 years of operation			
Prior to re-fracturing	Adopt monitoring strategy applied during hydraulic fracturing phase		
Prior to decommissioning	No change to monitoring strategy		

The monitoring strategy under Case Study 5 is set out in Tables F.12 and F.13, and illustrates the change in monitoring strategy following the decision to re-fracture the existing wells. Table F.12 and Table F.13 illustrate the monitoring strategy before and after the decision.

Case Study 5 illustrates how the ambient air monitoring framework would require a monitoring strategy to be extended to reflect a decision to re-fracture existing wells. It also demonstrates how the framework would require more detailed analysis, where a confounding source (that is, a major roadway) is in close proximity to the site.

Table F.12 Case Study 5: monitoring strategy prior to decision to refracture

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Baseline	NMVOCs, SO_2, CO, O_3, PAHs, CH_4	not applicable	NOx, PM_{10}/$PM_{2.5}$	• Directional analysis
Drilling	not applicable	NMVOCs, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	NOx	• >2 site boundary monitoring locations
Hydraulic fracturing	not applicable	NMVOCs, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	NOx	• >2 site boundary monitoring locations
Extraction	NOx, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	not applicable	NMVOCs	

Table F.13 Case Study 5: monitoring strategy following decision to refracture

Phase	Recommended monitoring programme			Recommendations
	Reduced	Routine	Enhanced	
Hydraulic fracturing (re-fracturing)	not applicable	NMVOCs, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	NOx	• >2 site boundary monitoring locations
Extraction	NOx, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	not applicable	NMVOCs	
Decommissioning	NOx, NMVOCs, PM_{10}/$PM_{2.5}$, SO_2, CO, O_3, PAHs, CH_4	not applicable	not applicable	

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