Options for air quality research: drivers of future changes

Chief Scientist's Group report

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This report is the result of research commissioned by the Environment Agency's Chief Scientist's Group.

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If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Dr Robert Bradburne
Chief Scientist

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We thank the project steering committee, which comprised of air quality experts from across the Environment Agency.

Executive summary

Air pollution has negative impacts on both human health and ecosystems. The nature and makeup of air pollution in the UK has changed over time in response to changes in emitting activities and sources. The drivers of change include developments in industrial processes, combustion technologies, fuels, legislation, and other socio-economic factors. It can be expected that the drivers of air quality, and the significance of different drivers, will continue to change in the future.

The Environment Agency regulates the largest and most potentially polluting industrial-scale sources of air pollutants, so it needs to foresee and manage the impact on its regulation of changing air quality drivers. This scoping study has developed a shortlist of topics that are likely to represent significant drivers and changes of air quality that will affect regulation over the next few decades. The study has then reviewed these topics to identify the future needs of the Environment Agency for research and evidence to inform its regulatory decisions.

Within this project, a quantified scoring mechanism was used to prioritise identified topics, which were then verified during a workshop involving the Environment Agency project steering committee. The aim of this activity was to identify topics with potentially high impact on future air quality, but where the existing evidence and applied research studies were relatively limited. Where those topics aligned with the regulatory remit of the Environment Agency, they were adopted into the shortlist for further consideration. The shortlisted (high priority) drivers and changes for air quality in the UK that are of most relevance to the Environment Agency have been identified as:

1. Ethylene oxide (EtO) emissions from medical sterilisation facilities
2. Battery manufacture and disposal
3. Deployment of carbon capture and storage (CCS) technologies
4. Perfluorooctane sulfonate (PFOS) and other per- and polyfluoroalkyl substances (PFAS)
5. Antimicrobial resistance
6. Urban impacts of ammonia (NH_3) emissions, including the contribution to urban particulate pollution from rural ammonia emissions, and the use of ammonia as a fuel
7. Bioaerosols
8. Emissions of nitrogen oxides (NOx) from hydrogen combustion, and contributions to climate change
9. Cold air drainage of air pollutants in katabatic flow

The significance of these topics to the Environment Agency may be determined by several factors. These include the pollutant(s) affected, the expected timescale, and the spatial distribution of the source/activity. In turn, such factors will determine the impacts on public health and/or ecosystems. By collating the evidence around these factors and impacts of future air quality drivers and changes, it was possible to evaluate the implications for the Environment Agency in terms of its regulatory remit and research needs.

The study produced an overview of the shortlisted topics against these factors to determine which topics may be appropriate for research to support regulation. Potential research needs are identified in each case. Where a topic is at an early stage that still needs basic research, investigation by the Environment Agency to inform regulation may be premature. Alternatively, topics that are at a more advanced stage may warrant prompt investigation by the Environment Agency, particularly where the topic is emerging but has yet to be applied or evaluated in a UK setting.

1. Introduction

This report presents a structured review of scientific issues that are expected to arise for air quality in England up to 2050. It will be used by the Environment Agency within its remit as a regulator to inform strategic planning for air quality research commissions and in-house studies within the next 5 years. The review was commissioned in the context of continuing, recent and emerging factors that affect the management and regulation of air quality, including:

- technological developments associated with the emissions, dispersion and impacts of air pollutants
- decarbonisation policies that can affect air quality as well as greenhouse gases
- changes in public behaviours that alter the activities causing air pollutant emissions
- changes in policies and practices due to the UK's departure from the European Union

The Environment Agency regulates the largest and most potentially polluting industrial sources of air pollutants, and so it needs to foresee, regulate and manage these processes. A broad review covering different aspects and activities, including land use, urban and rural situations, new fuels, altered climate and new pollutants has been carried out, considering the potential impact on human and ecosystem health, including crops.

Specifically, the objectives of this research were to:

- review the general outlook for changes in air quality, drivers and regulation, including where local air pollutant emissions may increase significantly or where reductions in pollution in other sectors shift focus to Environment Agency regulated sites and processes. Note that the future regulatory remit of the Environment Agency, particularly with regards to the deployment of new technologies, remains unknown
- establish priority air quality topics by considering estimated significance and whether they fall under the scope of the Environment Agency's regulatory jurisdiction
- evaluate existing scientific understanding of these priority topics, and identify research requirements for establishing a robust evidence base on which regulation and policy can be built

The review considers the health of people and ecosystems, including crops, because both are drivers for air quality regulation. It also looks to identify emerging topics, pollutants and substances with evidence of airborne risks.

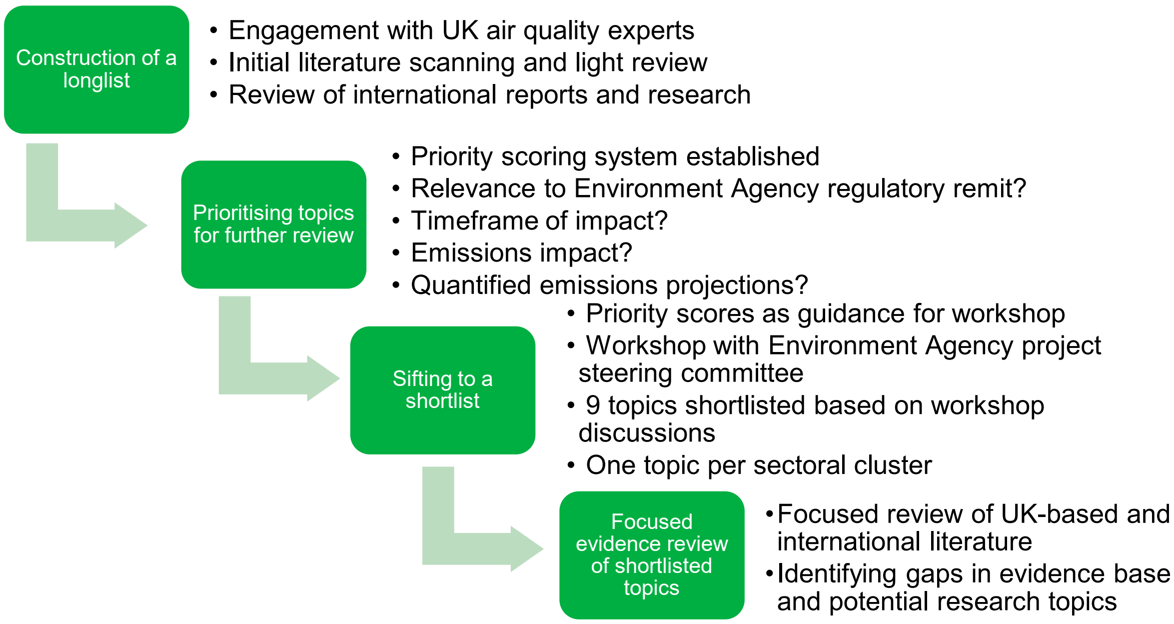
2. Approach

The evidence review was structured as 4 main stages, as illustrated in **Figure 1**:

1. The construction of a longlist of potential air quality topics.
2. Developing and applying metrics to determine the priority of each topic.
3. Sifting to a shortlist through scoring metrics and engagement with the Environment Agency Project Steering Committee.
4. Focused literature review to understand the existing evidence base in more depth.

The first stage of the review involved collating and assessing information on air quality drivers, changes and pressures from various sources, including UK experts, literature scanning, and reviewing major international reports and research. Each topic was then scored based on set criteria to identify those that could be considered highest priority for future Environment Agency research. The criteria used included relevance to the Environment Agency's existing regulatory remit, timeframe, emissions impact and projections, and confidence in the evidence base. Recognising that a scoring system is inevitably a simple approach, the initial scores were then used in conjunction with discussions with the Environment Agency project steering committee, to define the 9 priority topics. Existing evidence for each of the 9 shortlisted topics was then collated and summarised, and major gaps or uncertainties in evidence that could form the basis of research projects identified.

Figure 1: Flowchart of the approach used for the evidence review into drivers and changes in air quality



2.1 Constructing a longlist of air quality topics

The first stage of this review collated and assessed information on air quality drivers, changes and pressures by gathering evidence from a range of sources, including:

- **Engagement with well-regarded UK experts on air quality**. As a part of this process, experts across a range of disciplines were engaged to identify topics and offer insight into emerging sources, pollutants and components of air, as well as the potential implications of 'fast change' policies such as net zero. Given the crossovers between this project and a concurrent Environment Agency project (RDE155)[1] (Environment Agency, 2023e), both of which involved consulting air quality experts, engagement was coordinated to minimise duplication of effort and to speed up the consultation process. A total of 18 air quality experts were identified through existing contacts of both project teams. The experts spanned a range of disciplines, including research into the health impacts associated with air quality, emerging pollutants, monitoring and modelling of air quality, and industrial emissions legislation. Questions were circulated to identified experts and responses collated in relation to:
    - identifying any new sources and/or technologies of concern that will add pressure to future air quality emissions
    - how emerging sources and technologies might alter the management needs of air quality in the UK in terms of priority pollutants and/or pollutant speciation, and the spatial distribution of air quality concentrations
    - emerging topics that require significant improvement to the existing knowledge base
    - regulated emissions sources that are likely to vary across decades
    - evolution of air quality research needs over the next decade
    - specific reports and documents that could be included in this review
- **Review of international reports and research**, particularly across the United Nations Economic Commission for Europe (UN/ECE) and US air quality communities. For example, the Task Force for Emissions Inventory and Projections, a group established under the UN/ECE Convention on Long-range Transboundary Air Pollution to improve the quality and consistency of air pollution emissions inventories and projections recently released a questionnaire to air quality experts across Europe to identify priorities for future emissions inventory reporting and methodologies. Results from this survey were provided to the project team for this study and used to identify potential topics that are currently being considered elsewhere in Europe by air quality experts.

[1] This partner monitoring, modelling and integration project focused on the Environment Agency's evolving assessment capability through a review of available and potential future assessment needs and applications.

- **Literature scanning and light review**. Given the time constraints for the project, a full in-depth literature review was not possible when developing a longlist of priority topics. Instead, light-touch research was carried out, reviewing any existing summary documentation or previous studies on the potential changes to air quality over the coming decades. For example, this included simple web-based searches and a review of the current UK National Atmospheric Emissions Inventory (NAEI) projections.

2.2 Prioritising topics for further review

Once collated, each topic was categorised in terms of:

- thematic area, which represents the type of air quality issue identified, such as emerging sources, emerging pollutants and components of air, behaviour shift, net zero policy implementation, or use of new fuels
- sectoral clusters, such as industrial sources, transportation, waste management, agriculture, or residential
- pollutants concerned

Once categorised, each item in the longlist was scored using set criteria to identify topics that could be considered highest priority for future Environment Agency research. The criteria were:

- **Relevance to the Environment Agency's existing regulatory remit[2]**. A score of 10 was given to directly relevant topics. A score of 5 was given to topics that could potentially fall under the Environment Agency's remit in future; this includes considerations of the full lifecycle of impacts, from manufacture to disposal. A score of 0 (zero) was given to topics that clearly fell into the remit of other public sector agencies, so that the Environment Agency is unlikely to lead on these topics.
- **Timeframe**. Scores of 3 were given to topics that are likely to affect air quality in the short term, 2 for the medium term, and 1 for the long term. Timeframes were assigned semi-quantitatively, with short term reflecting topics with an air quality

[2] The Environment Agency's remit has principally been to regulate industrial-scale processes. Historically, these have been mostly combustion plants, such as power stations, refineries and chemical industries. In recent decades, this has extended to waste management and intensive agriculture sites. Additionally, in the past decade, the Environment Agency has taken more responsibility for national air quality monitoring network management. Therefore, the Environment Agency's remit is not static. For the purposes of this study, however, the remit has been defined as mostly focusing on ambient air pollutants and components of air that are discharged from localised (Environment Agency-permitted) sites, and on impacts on outdoor receptors.

impact that is broadly expected to be of importance by 2030, medium term by 2040, and long term by 2050.

- **Emissions impact**. Scores of 5 were given to topics that could be identified as having a high impact on emissions, 3 for a medium impact, 2 for an unknown impact, and 1 for a low impact.
- **Quantified emissions projections**. Scores of 3 were given to topics where there is limited quantified understanding of emissions through projections, and 0 (zero) where projections already exist.
- **Coverage in references:** If a topic was referenced in several sources, then it was considered high priority and received a score of 2, whereas topics with more limited reference information were given a score of 1. Expert judgement was used to semi-quantitatively allocate scoring under this category.
- A low **confidence rating** in the evidence base was given a score of 3, with medium and high confidence given scores of 2 and 1, respectively. Confidence ratings were based on expert judgement of the project team, on the basis of available literature found on initial review, and on opinions of consulted experts.

Initial scores were developed through expert judgement of the project team.

The purpose of the numerical scoring was to highlight topics within the likely remit of the Environment Agency, while also favouring topics that are potentially high impact with a less developed evidence base. It is fully understood that there are limitations to the scoring process. But it supported the next step, of holding prioritised and efficient communications and engagement activities with the Environment Agency, in order to select topics for shortlisting.

2.3 Longlist scores

Table 1: shows the scores for each topic within the longlist. Note that given the timescales of the project, a thorough assessment of each criterion was not possible, and interpretation of existing literature is necessarily qualitative or semi-quantitative and relies on expert judgement. Therefore, scores may not be representative of all available research and were regarded with a degree of uncertainty in the later stages of the project. In the final stage of the project, more thorough research is carried out for the shortlisted topics only, refining understanding presented in the longlist.

Table 1: Longlist scores for each air quality topic under set criteria

Topic	Sectoral cluster	Environment Agency remit?	Timeframe	Emissions impact	Quantified emissions projections	Referenced widely?	Confidence rating	Priority score
Cumulative (aggregate) pollutant exposure	Other	Yes	Short-term	Unknown	None identified	Yes	Low	23
Ethylene oxide (EtO)	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Low	22
Battery manufacture and disposal	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Low	22
Condensable primary organic aerosol emissions	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Development of measurement technologies improving understanding of wider range of air pollutants	Other	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Changes to the activity scope of industrial emissions reporting	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Changes to the pollutant scope of industrial emissions reporting	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Medium	21

Topic	Sectoral cluster	Environment Agency remit?	Timeframe	Emissions impact	Quantified emissions projections	Referenced widely?	Confidence rating	Priority score
Changes to the reporting thresholds of pollutants under industrial emissions reporting	Industrial sources	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Per- and polyfluoroalkyl substances (PFAS)	Residential	Yes	Short-term	Unknown	None identified	No	Medium	21
Carbon capture and storage (CCS)	CCS and BECCS	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Bioenergy with carbon capture and storage (BECCS)	CCS and BECCS	Yes	Medium-term	Unknown	None identified	Yes	Medium	21
Cold air drainage of air pollutants (katabatic flows)	Industrial sources	Yes	Short-term	Unknown	None identified	No	High	21
Perfluorooctane sulphonate (PFOS)	Industrial sources	Yes	Medium-term	Unknown	None identified	No	Medium	20
Short-chained chlorinated paraffins	Industrial sources	Yes	Medium-term	Unknown	None identified	No	Medium	20
BDE-99 (2,2’,4,4’,5-Pentabromodiphenyl ether)	Industrial sources	Yes	Medium-term	Unknown	None identified	No	Medium	20

Topic	Sectoral cluster	Environment Agency remit?	Timeframe	Emissions impact	Quantified emissions projections	Referenced widely?	Confidence rating	Priority score
Amines from carbon capture	CCS and BECCS	Yes	Long-term	Unknown	None identified	Yes	Medium	20
Nitrogen oxides (NO_X) from hydrogen combustion (H_2) – energy generation	Energy generation	Yes	Long-term	Unknown	None identified	Yes	Medium	20
Microplastics (airborne)	Other	Potentially	Short-term	Unknown	None identified	Yes	Low	18
Antimicrobial resistance (AMR)	Agriculture; Waste; Residential	Potentially	Short-term	Unknown	None identified	Yes	Low	18
Ultrafine particulates	Transport	Potentially	Medium-term	Unknown	None identified	Yes	Low	17
3D Printing	Industrial sources	Yes	Medium-term	Low	Yes	Yes	Medium	17
Hydraulic fracturing/fracking	Energy generation	Yes	Long-term	Medium	Yes	No	Medium	17
Trends in pollutants and sources implied by UK air pollutant projections to 2040 for industrial sources	Industrial sources	Yes	Long-term	Medium	Yes	Yes	High	17

Topic	Sectoral cluster	Environment Agency remit?	Timeframe	Emissions impact	Quantified emissions projections	Referenced widely?	Confidence rating	Priority score
Urban impacts of ammonia and wider mitigation options	Other	Potentially	Short-term	Unknown	None identified	Yes	Medium	17
Cloud storage	Industrial sources	Potentially	Short-term	Unknown	None identified	Yes	Medium	17
Bioaerosols (biological aerosols)	Agriculture; Waste; Residential	Potentially	Medium-term	Unknown	None identified	Yes	Low	17
Trends in pollutants and sources implied by UK air pollutant projections to 2040 for energy generation	Energy generation	Yes	Long-term	Low	Yes	Yes	Medium	16
NO_X from H_2 combustion – residential	Residential	Potentially	Long-term	Unknown	None identified	Yes	Low	16
Antifungals	Residential	Potentially	Medium-term	Unknown	None identified	No	Low	16
Ammonia as a particulate matter (PM) source	Agriculture	Potentially	Short-term	Medium	Yes	Yes	Medium	15
Net zero pathways and climate policy implementation	Other	Potentially	Long-term	Unknown	None identified	Yes	Medium	15

Topic	Sectoral cluster	Environment Agency remit?	Timeframe	Emissions impact	Quantified emissions projections	Referenced widely?	Confidence rating	Priority score
Mould	Residential	No	Short-term	Unknown	None identified	Yes	Low	13
Intensification of dairy/beef	Agriculture	Potentially	Medium-term	Medium	Yes	Yes	High	13
Supply chain impacts	Other	No	Short-term	Unknown	None identified	Yes	Low	13
Tyre wear	Transport	No	Medium-term	Unknown	None identified	Yes	Low	12
Ammonia fuel in road transport	Transport	No	Medium-term	Unknown	None identified	Yes	Low	12
Lithium battery thermal run-away emissions	Transport	No	Medium-term	Unknown	None identified	No	Low	11
NO_X from H_2 combustion – mobile	Transport	No	Long-term	Unknown	None identified	Yes	Low	11
Vehicle brake wear	Transport	No	Medium-term	Unknown	None identified	Yes	High	10
Reduced travel and modal shifts	Transport	No	Long-term	Medium	None identified	Yes	High	10
Ammonia as a maritime fuel	Transport	No	Long-term	Unknown	None identified	Yes	Medium	10
Autonomous/electric vehicles	Transport	No	Long-term	Unknown	None identified	Yes	High	9

2.4 Approach to sifting to create a shortlist

While the scoring system offered a semi-quantitative understanding of the priority topics, it should be recognised that this system cannot be calibrated to provide a completely unbiased view of the priority topics at the scale of the performed review. It is also appreciated that, while difficult to represent in a quantitative way, the views of experts represent important input into prioritising different topics. Therefore, the initial scores were used as a platform to inform discussion during a workshop with the Environment Agency project steering committee, and to give traceability to the shortlisting process. It was the outputs of these discussions that defined the final topic selection for the shortlist.

Two further criteria for the overall makeup of the shortlist were agreed, that:

- at least one topic from each sectoral cluster should be included in the shortlist
- the shortlist should include topics that were both:
  - focused on specific and/or emerging pollutant groups and components of air
  - more general topics or themes that may have a more wide-ranging impact on future air quality

In some cases, topics in the longlist were combined or rephrased as they were deemed topics of interest in general, but were only relevant to the Environment Agency if considered across a full lifecycle. For example, ammonia (NH_3) is considered a candidate fuel to replace fuel oil and gas oil in the shipping sector. While emissions from the combustion of the fuel were considered outside of the Environment Agency's remit, the production and distribution of the fuel are of greater relevance, and the topic description was altered to reflect this more clearly. In addition, when there was significant overlap in topics that could be summarised more neatly as a single topic item, this change was made. For example, nitrogen oxide (NO_X) emissions from hydrogen combustion in energy generation, residential settings and transport were considered to have sufficient overlap to be considered as a single topic within the shortlist.

Some topics that scored highly in Table 1: were deemed more relevant to the concurrent Environment Agency project (RDE155) studying monitoring and measurement techniques, and were instead passed to that project team for consideration. These topics were 'Cumulative pollutant exposure' and 'Development of measurement technologies'. Cumulative pollutant exposure has, therefore, been specifically included as a shortlisted topic in the RDE155 project report. The development of measurement technologies was considered inherent to RDE155 as a whole and, therefore, did not need including specifically.

A final shortlist was then agreed with the Environment Agency project steering committee before progressing to the next stage of the project. The full shortlist was:

1. EtO emissions from medical sterilisation
2. Battery manufacture and disposal

3. Deployment of CCS technologies[3]
4. PFOS and other PFAS[4]
5. AMR
6. Urban impacts of ammonia emissions, including the contribution to urban particulate pollution from rural ammonia emissions, and the use of ammonia as a fuel[5]
7. Bioaerosols
8. NO_X emissions from hydrogen combustion, and contributions to climate change[6]
9. Cold air drainage of air pollutants in katabatic flow

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[3] This topic merges the longlist topics of CCS, BECCS, and amines from carbon capture.
[4] This topic merges the longlist topics of PFOS chemicals and PFAS chemicals.
[5] This topic merges the longlist topics of ammonia as a PM source, ammonia in road transport, and ammonia as a maritime fuel.
[6] This topic merges the longlist topics of NOx from H_2 combustion – energy generation, NOx from H_2 combustion – residential, and NOx from H_2 combustion – mobile.

5. Research option scoping

For each topic in the shortlist, research options were then developed through a more detailed review of existing evidence for each topic. Given the short timescales, a formalised literature review was not feasible and not employed. Instead, the review began by considering systematic reviews and grey literature published on the topic, before searching primary literature to collate relevant information, and documenting where there were apparent gaps in the literature. Further information was collected on:

- expected timescale of impact
- relation to the Environment Agency's regulatory remit and actions taken by other environment agencies internationally if available
- further search for quantified projections of emissions
- commentary and interpretation of the likely spatial distribution considerations
- public health impacts of exposure
- ecosystem health impacts of exposure
- mitigation potential, including abatement and mitigation methods deployed internationally if available
- public interest and engagement on the basis of related articles and blogs

Where international primary or grey literature was used, the project team sought to transpose the conclusions to England, such as when considering the spatial distribution of emissions. The review was focused not only on identifying available information, but also on identifying what evidence could not be readily found. Gaps in the evidence base would then form the basis of research options for each topic. Equally, comparisons between similar papers were made when applicable. If large differences were identified, this was also considered a suitable basis for research options.

Summary findings for the shortlisted topics are given here, with full tabular assessments of each shortlist topic provided in Annex A.

5.1 EtO emissions from medical sterilisation

EtO is a gas that volatilises rapidly and is toxic in large quantities. It is mainly used in the manufacture of other chemicals, in particular ethylene glycol, which is used to make antifreeze and polyester. It is also used for sterilising medical instruments and these facilities can be located in mixed-use areas, and, therefore, in close proximity to residential areas.

Recent work in the US has recognised a substantially increased toxicity of EtO exposure (US EPA 2016). Based on this US assessment, the Environment Agency has recently proposed changing the long-term Environment Assessment Level (EAL) in air for EtO from 0.0184μg/m^3 to 0.002μg/m^3 as an annual mean (Environment Agency, 2023d).

In December 2021, the US Environmental Protection Agency (US EPA) extended the Toxics Release Inventory (TRI) reporting requirements for EtO releases and other waste management activities to 29 contract sterilisation facilities (US EPA, 2021). In April 2023, the US EPA proposed to significantly strengthen and update existing US Federal Clean Air Act standards for EtO emitted into the air from medical sterilisation facilities (US EPA, 2023a).

Emissions of this pollutant from large industrial sources are already regulated by the Environment Agency. However, the importance of medical sterilisation facilities and their locational context in England, along with their expected emissions of EtO and monitored concentrations in their vicinity, needs to be better understood to determine whether regulation of these sources is required.

5.2 Battery manufacture and disposal

At present, most environmental concerns relating to lithium-ion battery (LIB) manufacture are regarding water discharges. However, thermal runaway events and fires can occur during production, which have been shown in tests to release a wide range of toxic pollutants, including nickel, cobalt, copper, manganese, hydrochloric acid (HCl), hydrogen cyanide (HCN), hydrogen fluoride (HF), phosphoryl fluoride (POF_3), hexane, propylene, $PM_{2.5}$ and PM_{10} (Sun and others, 2016; Larsson and others, 2017). Releases of these pollutants from LIB fires in landfills are also of concern (Mrozik and others, 2021).

There has been limited research into these activities and their potential impacts on air quality in the UK. Existing studies of the scale and scope of LIB fires should be reviewed to assess their applicability to battery production facilities in England. Studies specific to expected situations in facilities in England once commercial LIB production is underway may then be needed, along with an assessment of the spatial and temporal occurrence of fires so that such studies can be scaled to a national impact. Similarly, an assessment of (i) the volume of domestic LIBs sent to landfills, and (ii) the expected future prevalence of landfill fires will be needed given the importance of LIBs for triggering, amplifying and prolonging landfill fires (Mrozik and others, 2021).

Detailed monitoring of concentrations of pollutants released during LIB fires in the vicinity of battery production facilities and landfills can be used to improve future exposure assessment. This will help inform the evaluation of human exposure risk in nearby populations.

5.3 Deployment of carbon capture and storage (CCS) technologies

The UK government’s 2021 Net Zero Strategy outlined the role that engineered greenhouse gas removal (GGR) technologies would need to play in supporting decarbonisation by 2050. Direct air carbon capture and storage (DACCS) and Bioenergy with carbon capture and storage (BECCS) are identified as the priority applications for CCS technology within the strategy.

CCS brings the potential to alter the quantity and profile of air pollutant emissions from the UK energy sector. While ammonia is the main degradation product, amines such as nitrosamines and nitramines, which are carcinogenic (Robles, 2014), can also be emitted. The review of this topic is focused on whether the broader science and research base (in the UK) is robust, but also whether there are any obvious gaps in the ongoing research being carried out by both Defra and the Environment Agency to assess the air quality risks associated with the release of amines from the process.

A 2015 Scottish Environment Protection Agency (SEPA) study (SEPA, 2015) identified knowledge gaps in terms of:

- nitrosamines/nitramines toxicity
- existing background levels of amines and their reaction products (in the UK)
- sampling and analysis techniques for amine compounds, particularly nitrosamines
- monitoring methods

The study also identified that the UK had not set EALs or Environmental Quality Standards (EQS) for the compounds of interest at that stage, although this had been progressed in other countries.

Since then, in the UK, there is research work ongoing by both Defra and the Environment Agency to assess the air quality risks associated with these compounds, including final stage research in partnership with various consultants on amines modelling and to inform the development of EALs for these substances.

Elsewhere, a pilot study (Sustainable OPEration of post-combustion Capture plants - SCOPE) led by private industrial partners but part-funded by the German Ministry for Economic Affairs and Energy is already researching "to close gaps in existing scientific, technical, environmental and societal knowledge regarding emissions from carbon scrubbing, in addition to effectively minimising such emissions and their impacts on the environment".

As such, there appears to be a strong emerging scientific basis on the impacts of amine scrubbing within CCS processes, as well as developments in how to measure and monitor amine compounds in and around CCS plant.

However, there remains a lack of background monitoring for amine concentrations at UK level. Linked to this, there is a potential need for local modelling and consideration of potential receptors, for example, at-risk communities and environments based on the likely location of UK carbon capture and usage (CCU) plant within the next decade.

This will enable the Environment Agency to monitor/measure and regulate air pollutants and potentially toxic nitrosamine and nitramine releases from future CCU operators in the UK.

5.4 Perfluorooctane sulfonate (PFOS) and other per- and polyfluoroalkyl (PFAS)

PFAS are a group of environmentally persistent synthetic chemicals, which includes PFOS, that are resistant to water, oil, and heat. These resistant properties have meant that PFAS have been used across a range of applications for decades, including in fire-fighting foams, metal plating, and in consumer products like carpets, waterproof clothing, and upholstery. Repeated exposure to PFAS has been demonstrated to have adverse effects on people's health and ecosystems. PFAS risks arise at multiple stages in its lifecycle, during manufacture, use and disposal. PFAS are emitted intentionally or unintentionally as fugitive emissions. Given the persistent nature of PFAS chemicals, accumulation risks are important to consider, such as build-up in soils impacted by atmospheric deposition from local sources.

Typically, PFAS are considered a water pollutant, but increasing consideration of the release of PFAS to air and the subsequent health impacts from inhalation is drawing greater attention.

The typical sources of direct airborne PFAS include:

- **Industrial emissions**: Many industrial facilities will produce, process or use PFAS chemicals, with associated emissions to the environment, including air. Typical relevant industries include metal finishing and plating, cable and wiring, building and construction, surfactant and fluoropolymer production, paper products and packaging, semiconductor, and textile industries (ITRC, 2022).
- **Firefighting**: Some firefighting foams designed for liquid hydrocarbon fires and vapour suppression can be major sources of local PFAS release to the environment (Roth and others, 2020). These particular foams are used for suppression, fire training, and vapour suppression. Elevated atmospheric concentrations can, therefore, be expected in locations around airports, refineries, chemical plants and military facilities where hydrocarbon fires are most likely to occur.
- **Incineration**: When products with PFAS in them are burned, as is relatively common in solid waste disposed of from industry (and non-industry to a lesser extent), the chemicals can be released to the air.
- **Landfills**: When PFAS-containing products are discarded into landfills, the products can leach out into the surrounding environment in various forms, including airborne gas and particles (Weinberg and others, 2011; Faust, 2022). The type and concentration of PFAS varies greatly among landfills due to variations in waste composition, with industrial waste expected to be the greatest source of PFAS.
- **Wastewater treatment plants**: These plants provide several pathways for PFAS release to the environment. Conventional treatment methods do not efficiently remove PFAS, while concentrations and type of PFAS differ by treatment site, with those that receive industrial wastewater discharges typically being associated with higher concentrations and subsequent release to air (ITRC, 2022).
- **Consumer product passive release**: PFAS can be released passively over time by products such as clothing, furniture and carpets (Faust, 2022).

Research options were considered for PFAS (and PFOS) emissions to air only.

A major obstacle for regulation of PFAS air emissions is the lack of standardised methods for measuring these substances. Other environmental agencies, like the US EPA, have been working to develop methodologies in recent years. Without well developed and tested measurement techniques, establishing meaningful UK regulations may be challenging. Another obstacle in handling the airborne contribution of PFAS exposure is that most studies into the health impacts of exposure and bioaccumulation of PFAS have focused primarily on exposure through ingestion of food and water containing PFAS chemicals. Disaggregation of the impact of inhalation of PFAS from wider exposure routes is not well studied. Additionally, there is insufficient research into the proportion of waterborne PFAS that is attributable to atmospheric deposition to surface waters.

Perhaps one area where research can be undertaken in the short term is to understand combustion of PFAS as a mitigation option. While evidence shows that PFAS chemicals can be broken down during combustion, there is a major gap in understanding the products of incomplete combustion which could include other dangerous chemicals and/or greenhouse gas emissions releases. Future studies to understand the products of combustion in conditions similar to typical incinerators may be needed to inform decisions of the abatement techniques industry needs to employ.

5.5 Antimicrobial resistance (AMR)

AMR refers to the gradual resistance of bacteria, viruses, fungi and parasites to current medicines. As resistance grows, the chances of disease transmission, severe illness and death increase due to difficulties in treating infection. AMR can occur naturally, but the main cause of AMR is the abuse or inappropriate use of antimicrobial drugs (WHO, 2021). Airborne transmission of AMR is a growing concern because of emerging evidence of long-distance transport of microorganisms with AMR (Environment Agency, 2020). Relevant airborne releases can arise from a variety of sources and environments, including hospitals, farms and wastewater treatment stations.

Internationally, there is much existing research into AMR as a component of ambient air. For example, smog in Beijing was found to contain antibiotic resistant bacteria in 2014 (South China Morning Post, 2016). The World Health Organization, the US Centers for Disease Control and Prevention (CDC) and numerous other international institutions have undertaken research on AMR and identified it as a topic of concern.

There is limited existing UK-based research into the impact of airborne AMR. O'Neill (2016) estimated that infections of multi-drug resistant bacteria would cause more deaths compared to cancer by 2050. The UK government has also developed a plan for AMR (HM Government, 2019).

AMR is not a traditional air pollutant, but rather a biological process. The Environment Agency has identified AMR as an important environmental issue and has regulations in the agriculture and healthcare industries. However, the specific consideration of AMR microorganisms as an air pollutant is not explicitly addressed, although it is often integrated into broader studies. In general, the evidence base on the impact of airborne AMR is insufficient given its potential impact on public health. The main continued knowledge gaps are:

- Additional measures and policies are needed to address the growing problem of AMR, including the development and implementation of new technologies, re-evaluation of existing policies, and publication of updated policies.
- Improved understanding of transmission dynamics of AMR within different environments. Research could be focused on the transmission pathways and mechanisms of AMR, especially in association with hydrological and climatic factors.
- Further improvements on the Global Antimicrobial Resistance and Use Surveillance System (GLASS), including enhancing surveillance capabilities in identifying emerging AMRs. Improved global collaboration in tackling the spread of AMR would also help fill in knowledge gaps with worldwide experts.
- Mitigation at source is usually more effective than alternative approaches. With the available surveillance data, identifying hotspots and source apportionment could be achievable. This would help to improve the understanding of AMR sources and better prevent the spread.

5.6 Urban impacts of ammonia and the use of ammonia as a fuel

Ammonia deposition can have adverse impacts on ecosystems through acidification and eutrophication. However, in an urban environment, ammonia (whether originating from agricultural or localised urban sources) often plays a crucial role in the formation of secondary Particulate Matter (PM), resulting in increased ambient concentrations and, therefore, impacts on human health. Recent policy analysis across Europe suggests that reducing ammonia emissions can often be a cost-effective way of reducing ambient concentrations of $PM_{2.5}$ in urban environments. However, at present, there is no ambient concentration limit value for ammonia in Europe.

Ammonia emissions are largely driven by the agricultural sector, chiefly from livestock and fertiliser use. Emission control measures are in place for agricultural sources, for both livestock management and the application of fertilisers to agricultural soils. For example, the Environment Agency regulates intensive pig and poultry units, and is responsible for permitting them (Environment Agency, 2023a). Abatement and emissions control options for ammonia have been extensively researched and developed across the last several decades, and Defra has published a Code of Good Agricultural Practice for Reducing Ammonia Emissions (Defra, 2018). However, new approaches to emissions control continue to be developed. For example, the potential to use trees as shelter belts to intercept ammonia and, therefore, abate impacts near intensive agricultural sources has been the focus of research in recent years. This may require a re-thinking of the approach to permitting, which favours discharge through ridge fans and chimneys to promote dispersion, but this may reduce the effectiveness of trees because air is diverted above the localised tree shelter belts.

However, other sources, such as road traffic, with the increased use of catalytic converters, may also represent important sources of ammonia emissions that have received limited study. Farren and others (2020) concluded that the UK inventory estimates of urban ammonia emissions for passenger cars may be underestimated by a factor of 17. In addition, emissions of ammonia from agriculture have been found to contribute significantly to $PM_{2.5}$ emissions in urban areas (for example, Kelly and others, 2023).

The maritime industry is presently challenged by increasingly strict air quality emission limits and climate legislation. Anhydrous ammonia has been identified as a possible long-term, net or near zero carbon fuel to be used for deep-sea cargo ships, as opposed to short-sea, passenger or inland waterway craft. Ammonia emissions through ‘ammonia slip’ can be anticipated. Ammonia slip is the unintentional release of ammonia and occurs when emissions control equipment is not operating properly, or there are unfavourable combustion conditions. These emissions, therefore, require management like those for ammonia slip in internal combustion engines (ICEs) fitted with selective catalytic reduction (SCR) after-treatment systems.

Ammonia as a maritime fuel has been studied in detail in recent years and there is a strong knowledge base on the safe handling of ammonia from its widespread use in the agricultural sector. Ammonia can be stored as a liquid at atmospheric pressure, which makes it easy to transport. This will prove critical if it is to be used to fuel deep-sea cargo ships.

Current production of ammonia is CO_2 intensive due to being largely produced by natural gas or coal. To be viewed as ‘green ammonia’, research and development is required to produce ammonia using renewable energies.

Within the Environment Agency’s remit, particular attention needs to be paid to the level of ammonia emissions that would be expected from future storage sites, and typical rates of leakage and dispersion patterns should be studied.

For urban ammonia, there is currently very limited research on other sources of ammonia away from the agricultural sector. Further research studies are required on the levels of ammonia emitted from cars, light-duty and heavy-duty vehicles (LDVs and HDVs), in addition to exploring risks associated with ammonia release from residential waste.

5.7 Bioaerosols

Bioaerosols (biological aerosols) are small airborne particles (ranging from 0.001 to 100µm in diameter) that originate biologically from plants or animals and can contain living organisms. Microorganisms, including viruses, pollen, bacteria and fungi may be present in bioaerosols. Bioaerosols are found everywhere; human sources of bioaerosols include Environment Agency regulated sites such as composting facilities, intensive farms (including livestock houses), sewage/wastewater treatment works (for example, aeration tanks), municipal landfill/solid waste, and mechanical biological treatment (MBT) systems. The presence of bioaerosols in the air can significantly contribute to the levels of $PM_{2.5}$ and PM_{10}.

There is a lot of research funded by Defra on the monitoring and regulation of bioaerosols. Examples include WR1121 ‘Monitoring bioaerosol and odour emissions from composting facilities', WR0617 'Small Area Health Statistics Unit (SAHSU), and the Bioaerosols and health pilot study' (Defra, 2011; Defra, 2014).

There are several gaps that should be addressed:

- More studies on long-term projections.
- Increased monitoring on how bioaerosol concentrations vary spatially and temporally.
- Further epidemiological studies on the health impacts of bioaerosols, not limited to respiratory diseases.
- Climate factors are also important to focus on because climate change will affect bioaerosol production and distribution, and this requires further study.
- Current mitigation strategies are focused on indoor bioaerosols control rather than outdoor air quality, so further research is needed.

5.8 Nitrogen oxide (NO_X) emissions from hydrogen combustion, and contributions to climate change

The future use of hydrogen in transport is not expected to be large (unless generated by a fuel cell). However, use of hydrogen in the residential sector is thought to be a potentially large future source of NOx emissions. However, neither of these source groups fall within the direct remit of the Environment Agency.

Instead, it is the upstream industrial activities associated with the generation and handling of hydrogen that are likely to be of greater relevance to the Environment Agency. NO_X and $PM_{2.5}$ are the main pollutants of concern in relation to the use of hydrogen as a fuel in industrial installations.

There is currently a lack of definitive information on the emissions that result from the industrial use of hydrogen and hydrogen-natural gas mixes for electricity and heat generation, and much of the information in the literature is derived from modelling studies.

- The technology and expertise are thought to be readily available in the UK to design, plan and implement pilot studies investigating the air pollutant emissions that could result from hydrogen and hydrogen-natural gas mixes in real-world industrial installations.
- A significant amount of preparatory work to support the specifications of the study could be achieved by first undertaking modelling studies. These would show how the combustion conditions, and, therefore, resulting emissions and performance of emissions control equipment might vary.
- Given that the most likely changes in the near future are associated with introducing a hydrogen-natural gas mixture into the gas mains supply, it would be sensible for the study to investigate how emissions vary across several different fuel mixtures.
- Damage and corrosion to boilers and emissions control equipment is also an important area to consider in the pilot study. Plant operators will wish to be reassured that the introduction of hydrogen (and any resulting changes that they

need to make regarding the combustion conditions) does not shorten the life of their equipment or machinery.

In addition to these potential impacts on air quality, hydrogen prolongs the atmospheric lifetime of methane, and is, therefore, classified as a secondary greenhouse gas (with a global warming potential of ~11). There is no requirement to estimate and report hydrogen emissions, but this is likely because current emissions are very small, and this may change in future years.

5.9 Cold air drainage of air pollutants by katabatic flow

In winter and spring, colder temperatures and low wind speeds increase cooling of the ground surface to create a cool layer of air that decreases mixing and dilution of pollutants, including odourous substances. On undulating terrain, the process of katabatic flow (or cold drainage flow) can allow the polluted layer to drift downhill, creating a persistent, concentrated region of pollution that could negatively impact public health. This may have an impact at a local level and may be of direct relevance to Environment Agency regulated sites under specific meteorological conditions.

This topic emerged following the discussions in the workshop with the Environment Agency project steering committee. The Environment Agency is interested in furthering its knowledge of cold air drainage flow of air pollutants due to its observed occurrence at the Walley's Quarry Landfill site in the West Midlands, notably flows of hydrogen sulphide (H_2S). This process is likely to affect other regulated sites, including landfill sites across the country and, therefore, provides the rationale for developing a stronger research base. Research on cold air drainage of air pollutants has principally been focused on analysing the meteorology surrounding the process of katabatic flow. However, in alpine settings, such as the European Alps, there has been analysis of how air pollutants are transported through the valleys (Gohm and others, 2009; Sabatier and others, 2019).

The science of katabatic flow is, therefore, well understood and need not be a priority for future research in the UK. Not well understood, however, are the specific impacts of katabatic flows of air pollutants from regulated sites in the UK. A review of studies undertaken in this area, and the role that this plays in a planning context in continental European countries, could prove to be valuable. It would also be possible to undertake an investigation of the topography surrounding selected UK point sources that are relatively close to population centres or sensitive ecosystems. Some simple air flow modelling would allow the potential impacts of katabatic air flow to be assessed, and an evaluation made of current risks. It would also allow opportunities for modifying topography to re-direct flows away from sensitive receptors such as housing. Of particular interest would be the extent to which changes in the local topography could change localised airflows. A specific example to consider would be the evolution of landfill sites, which are often concave when commissioned, but over their lifetimes change shape and typically become convex landforms.

Findings from such a study may indicate the need to add considerations or guidance for the planning and permitting stages of commissioning key point sources if the local topography proves to be important in directing katabatic air flow towards or away from receptors. An initial pilot investigation could be undertaken at several representative point source locations and would not require extensive resources. This topic should, therefore, be a research priority in the short term.

6. Discussion and summary

The objectives of this research were to review the general outlook for changes in air quality drivers and regulation, in addition to establishing a shortlist of priority air quality topics where Environment Agency research would be particularly useful.

From the 9 shortlisted topics, 3 broad topic groups have emerged:

- Newly or recently recognised air pollutants and components of air and/or processes of concern – includes CCS, PFAS, AMR and EtO.
- More established air pollutants with new aspects – includes ammonia, bioaerosols and landfill pollutants advected by cold air drainage.
- New fuels, products, and waste disposal routes – including hydrogen and LIBs.

While the focus of this study is on air quality impacts, it is important to recognise that the shortlisted topics are relatable to climate change and net zero targets, with the net zero fuels of hydrogen and ammonia, and the net zero process of CCS all having wider reaching impacts than air quality alone.

The wide-reaching impacts of these shortlisted topics present a multitude of research options for the Environment Agency to investigate further. Using ammonia as an example, future research options could include:

- furthering existing modelling work that identifies the agricultural ammonia contributions to $PM_{2.5}$ exposure
- use of ammonia as a maritime fuel, including risk of ammonia spills in port cities
- use of trees to abate agricultural ammonia from poultry, pigs, beef/dairy cows, to complement studies already being carried out by Defra

In the case of CCS, this is a topic that is already the subject of major international research initiatives. The Environment Agency could, therefore, choose to participate in these initiatives as an efficient method of furthering research in this area. By contrast, topics such as cold air drainage and PFAS deposits around Environment Agency-regulated sites can be viewed as more localised, and will be more suitable for Environment Agency-led research studies.

At first glance, it may appear that very prominent and well-established air quality concerns have been overlooked. For example, the Environment Agency receives more complaints on odour than any other environmental topic, yet this study chose not to include 'Odour' as a topic. However, public concerns about odour are indirectly addressed in this study, notably for cold air drainage of landfill-derived gas. Emissions of hydrogen sulphide (H_2S) have been responsible for odour complaints at Walley's Quarry, and this is detailed further in Annex A.

The shortlisted topics could be broadened to help the Environment Agency define a scope for future research. For example, LIB-induced fires at landfill sites could be extended as a research topic to an update of emissions from incident fires. This would reflect all disposed feedstocks as opposed to solely the initiating batteries.

This study has, ultimately, been focused on conventional source-dispersion-receptor aspects of air quality. When topics are considered for further research by the Environment Agency, it may be useful to consider societal issues as well, such as environmental justice. This could arise in situations where socio-economically disadvantaged groups live in closer proximity to Environment Agency-regulated industrial-scale processes and are, therefore, disproportionately impacted by them. This is a topic that is receiving attention from Defra and local authorities.

6.1 Options for future research

This section provides an overview of the readiness for future research of each shortlisted topic, all of which are detailed in Annex A.

For EtO, engagement with the US EPA and review of the 2022 TRI reporting for medical sterilisation facilities is an option that could be identified (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2023c). Further to this, there is a suggestion to establish the scope of the UK market. This could be through engagement with relevant operators to understand current procedures and mitigation measures in greater detail.

With air quality emissions from battery manufacture and disposal, existing studies of the scale and scope of LIB fires should be reviewed to assess their applicability to production facilities coming under the Environment Agency's geographical remit. In addition, detailed monitoring of concentrations of the pollutants released during LIB fires in the vicinity of battery production facilities and/or Environment Agency-regulated landfill sites, can be used to improve future exposure assessment. This will, in turn, help inform the evaluation of human exposure risk in nearby populations.

An assessment of the development of CCS technologies shows that there remains a lack of background monitoring for amine concentrations at UK level. Linked to this, there is a potential need for local modelling and consideration of potential receptors, for example, at-risk communities and environments, based on the likely location of a UK CCU plant within the next decade. Longer term, the Environment Agency may need to be ready to monitor and regulate air pollutant emissions and impacts from clusters of CCU plants, including monitoring and regulation of nitrosamine and nitramine releases.

For PFOS and PFAS, one area where future research could be undertaken in the short term is to understand combustion of PFAS as a mitigation option. While evidence shows that PFAS chemicals can be broken down during combustion, there is a major gap in understanding the products of incomplete combustion, which could include other dangerous chemicals and/or greenhouse gas emissions release. Designing a study to understand the products of combustion in conditions akin to typical incinerators and, therefore, what additional abatement equipment may be needed is high priority to inform decisions on what abatement techniques industry needs to employ.

With AMR, there is currently limited research on airborne AMR as an air pollutant, as it is often considered within a broader context. The mechanisms and drivers of AMR require further research. Additionally, aside from the biological research, there are several factors pertaining to environmental justice which could also lead to misuse and overuse of antibiotics, including social, economic and cultural factors that could be explored.

Future research on ammonia as a maritime fuel could assess the level of ammonia emissions that would be expected from future manufacture and storage sites, in addition to typical rates of leakage and dispersion patterns. For the urban component of ammonia, there is currently limited research on sources of ammonia away from the agricultural sector. Further study is, therefore, encouraged on emissions of ammonia from the transport sector, in addition to exploring the risks associated with ammonia release from residential waste.

Bioaerosols require further research to better understand long-term projections. This could result from monitoring bioaerosol concentrations, particularly close to receptors, and would provide further indication of the impact of bioaerosols on public health. Further epidemiological studies could also be carried out on the health impacts caused by bioaerosols that are not solely focused on respiratory diseases.

With NO_X from H_2 combustion, there is currently a lack of definitive information on the emissions that result from the industrial use of hydrogen and hydrogen-natural gas mixes for electricity and heat generation. Given that the most likely changes in the short to medium term are associated with introducing a hydrogen-natural gas mixture into the gas mains supply, it is suggested that a study could investigate how emissions vary across several different fuel mixtures. Furthermore, damage and corrosion to boilers and emissions control equipment is also an important area to be considered in the pilot study. Plant operators will wish to be reassured that the introduction of hydrogen will not shorten the lifespan of their equipment and machinery.

Finally, for the cold air drainage of pollutants from katabatic flow, additional study is encouraged to further understand the spatial and temporal scales that this topic would operate on. This will inform the Environment Agency of the level of risk to public health at its regulated landfill sites.

Annex A: Tabular assessment of shortlisted topics

EtO from medical sterilisation facilities

EtO from medical sterilisation facilities	
Theme	Emerging sources
Description and definition of scope	
EtO is a gas that volatilises rapidly and is toxic in large quantities. Its main usage is in the manufacture of other chemicals, in particular ethylene glycol which is used to make antifreeze and polyester. Because of its highly reactive nature it is also used for sterilising medical instruments that cannot be sterilised using steam or radiation. Medical sterilisation facilities can be located in mixed-use areas, such as in close proximity to residential areas. Recent work in the US has shown the risks of EtO exposure. For example, in December 2016, the US EPA's Integrated Risk Information System (IRIS) Program updated its cancer assessment for EtO (US EPA, 2016). The resulting substantially increased toxicity of EtO (60 times greater than previously understood) has drawn significant public and regulatory attention in the US to sources of EtO (for example, US EPA, 2023b). Based on the 2016 IRIS assessment, the Environment Agency has recently proposed changing the long-term EAL for EtO in air from 0.0184μg/m^3 to 0.002μg/m^3 as an annual mean (Environment Agency, 2023d). In December 2021, the US EPA extended the TRI reporting requirements for EtO releases and other waste management activities to 29 contract sterilisation facilities (US EPA, 2021). This decision was based on factors including chemical toxicity, proximity to population centres, a facility's history of chemical releases, and other factors the EPA Administrator deemed appropriate (such as potential environmental justice concerns). The US EPA has recently proposed to significantly strengthen and update US Federal Clean Air Act standards for EtO emitted into the air from medical sterilisation facilities, in particular addressing fugitive emissions (US EPA, 2023a). Emissions of this pollutant from large industrial sources with activities that are covered by the Environmental Permitting (England and Wales) Regulations (2016) are already regulated by the Environment Agency. However, the importance of emissions of EtO from medical sterilisation facilities and their locational context in England needs to be better understood.	
Pollutants affected	EtO

Expected timescale of impact	No significant change in the demand for sterilisation of medical equipment is expected. Health impacts range from acute (short-term) that are mainly relevant to exposure of workers in medical sterilisation facilities, to chronic (long-term) that are relevant to both workers or the general population living, working or studying near medical sterilisation facilities.
Relation to the Environment Agency's regulatory remit	Emissions of this pollutant from industrial installations with activities that are covered by the Environmental Permitting (England and Wales) Regulations 2016 are regulated by the Environment Agency. Medical sterilisation facilities would not currently be covered by these regulations. Regulated industrial facilities have to report annual releases to air of over 1,000kg per year of EtO to the Environment Agency Pollution Inventory (PI).
Quantified projections of emissions available	Not available.

Spatial distribution

Annual emissions of EtO from regulated installations should be included on the Environment Agency PI forms PI-1, PI-2, and PI-3 2012 where the reporting threshold of 1,000kg of emissions of EtO to air from a facility is exceeded (Environment Agency, 2012). Total reported amounts in England were reported for 2019, 2020 and 2021, although 26, 23 and 2 facilities reported that emissions of EtO were below the reporting threshold for these years respectively (Environment Agency, 2021a, 2021b, 2022).

However, the major industry sectors with regulated installations currently reporting EtO emissions are landfill and chemical. There is expected to be a small number of specialist medical sterilisation facilities across the country that are not currently subject to Environment Agency regulation or PI reporting requirements. These facilities are likely to be located in or near hospitals, or in light industrial estates or office parks and may, therefore, be nearer to residential areas than larger industrial facilities.

Public health impacts

Short-term impacts are most likely tied to worker exposure from existing use of EtO in medical sterilisation facilities. The acute effects of EtO in humans consist mainly of central nervous system depression and irritation of the eyes and mucous membranes. Chronic (long-term) exposure to EtO in humans can cause irritation of the eyes, skin, nose, throat, and lungs, and damage to the brain and nervous system. There also is some evidence linking EtO exposure to reproductive effects (US EPA, 2018a).

There can be long-term cancer impacts for workers or the general population if a person breathes in EtO in concentrations that might be found inside or nearby facilities where EtO is used over the course of many years (either a career or a lifetime). In December 2016, the US EPA's IRIS Program updated its cancer assessment for EtO, characterising it as "carcinogenic to humans" by the inhalation route of exposure based on: (1) strong, but less than conclusive on its own, epidemiological evidence of lymphohematopoietic cancers and breast cancer in EtO-exposed workers, (2) extensive evidence of carcinogenicity in laboratory animals, including lymphohematopoietic cancers in rats and mice and mammary carcinomas in mice following inhalation exposure, (3) clear evidence that EtO is genotoxic and sufficient weight of evidence to support a mutagenic mode of action for EtO carcinogenicity, and (4) strong evidence that the key precursor events are anticipated to occur in humans and progress to tumours, including evidence of chromosome damage in humans exposed to EtO (US EPA, 2016). All else equal, the unit risk estimate for EtO is nearly 60 times higher than it was prior to the 2016 IRIS update. An update in the risk value of this magnitude for a regulated pollutant is not typical.

The US EPA released its National Air Toxics Assessment (NATA) in August 2018 (US EPA, 2018b). Based on the 2016 IRIS update for EtO and 2014 emissions and meteorological data plus dispersion and exposure modelling, the NATA estimated lifetime cancer risks of 100 in a million or greater from breathing air containing EtO emitted from medical sterilisation facilities in multiple census tracts across the US.

The US (Agency for Toxic Substances and Disease Registry) has defined minimal risk levels (MRLs) for EtO of 0.4 and 0.07ppm for acute- and intermediate-duration inhalation exposure, respectively (US ATSDR, 2022). The Environment Agency has proposed a long-term EAL of 0.000002mg/m^3 (2ng/m^3) as an annual average (Environment Agency, 2023d). This is based on a lifetime total inhalation unit risk of 5.0 × 10-3 (μg/m^3) derived by US EPA (2016) for lymphoid and breast cancer combined, and an excess lifetime cancer risk of 1 in 100,000. This long-term EAL is considered protective of non-cancer effects from chronic exposures.

Ecosystem impacts

Because it is so reactive, EtO will not stay in the environment very long (Australian Government Department of Climate Change, Energy, the Environment and Water, 2022). EtO is converted to ethylene glycol when released. EtO is not persistent in air due to washout by rain and degradation by chemical processes. Short-term ecological effects of larger contaminations are death of animals including birds and fish, death of plants or low growth rates in plants. EtO has moderate acute (short-term) toxicity to aquatic life. Long-term effects on biota may include shortened lifespan, reproductive problems and lower fertility rates.

Mitigation potential

Emissions of EtO from medical sterilisation facilities to the ambient environment arise from sterilisation chamber vents and aeration room vents, as well as chamber exhaust vents and fugitive sources that include indoor EtO storage, EtO dispensing, vacuum pump operation, and pre- and post-aeration handling of sterilised material (US EPA, 2023a). Some or all of these sources may be controlled with abatement measures such as acid-water scrubbers, thermal oxidizer/flares, catalytic oxidizers, and gas-solid reactors (US EPA, 2023a).

The US EPA has set a National Emission Standard for Hazardous Air Pollutants (NESHAP) for commercial sterilisation facilities to limit the emissions of EtO (US EPA, 2006). Under the US Clean Air Act, the US EPA is required to regularly carry out a technology review of the current rule It has recently proposed, significantly strengthening and updating standards for EtO emitted into the air from medical sterilisation facilities, in particular addressing fugitive emissions (US EPA, 2023a).

Other potential mitigation methods could focus on alternative sterilisation methods that do not require the use of EtO. For medical sterilisation facilities, hydrogen peroxide gas plasma sterilisation is sometimes considered as a substitute for EtO. However, the effectiveness of EtO is higher, and this substitute would also need further research.

Public interest/engagement

There is high public awareness in the US of the health risks presented by EtO emissions, but this is more limited in the UK. Since the publication of the 2014 NATA showing increased long-term health risks from EtO emissions (US EPA, 2018b), state and local authorities in the US have conducted monitoring of EtO concentrations in ambient air around medical sterilisation facilities (for example, Colorado Department of Public Health and Environment, 2018; Village of Willowbrook, 2019). In December 2022, Earthjustice, a US non-profit public interest environmental law organisation, filed a lawsuit on behalf of various environmental NGOs against the US EPA over its failure to take legally required action to review on time the standards for EtO air emissions from medical sterilisation facilities (Earthjustice, 2022). The US EPA conducted extensive public outreach with communities near medical sterilisation facilities during 2022 (US EPA, 2023b) in advance of publishing a proposed new rule in April 2023 (US EPA, 2023a).

Readiness for research and potential scoping options

Engagement with the US EPA as standards for EtO emissions from medical sterilisation facilities are revised, and review of the 2022 TRI reporting for medical sterilisation facilities is an option (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2023c).

The current TRI reporting threshold for on-site activities involving EtO is 10,000 pounds (4,536kg) per year. This threshold covers handling, usage and storage and, therefore, emissions to air may be substantially lower. The reported emissions from such facilities should be set against the current Environment Agency PI reporting threshold, which is 1,000kg per year, a figure that may mean medical sterilisation facilities are not captured even if medical sterilisation was a regulated activity.

Establishing the scope of the UK market and engagement with relevant operators to understand current procedures and mitigation measures is an option that could be explored. The importance of medical sterilisation facilities and their locational context in England, along with their expected emissions of EtO and monitored concentrations in their vicinity, needs to be better understood in order to determine whether regulation of these sources is required.

Battery manufacture and disposal

Battery manufacture and disposal	
Theme	Emerging sources
Description and definition of scope	
Most concerns relating to battery manufacture are for water discharges, but emissions of pollutants released to the air are produced by thermal runaway events and fires that can occur during production, during use and when batteries are disposed of in landfills. Fire tests have shown emissions of a wide range of toxic pollutants are generated. While battery use in transport applications is not part of the Environment Agency's remit, the manufacture of batteries in industrial facilities and the disposal of batteries in landfills takes place in facilities regulated by the Environment Agency. Emissions of pollutants from battery fires at these facilities can affect exposure risks in nearby populations. The incidence of battery fires can be expected to increase, driven by future increases in the use of electric vehicles powered by lithium-ion batteries (LIBs), which will drive increased manufacturing of LIBs. Increases in the number of LIBs sent to landfills will affect the future characteristics of landfill incident fires since LIBs can trigger, amplify and prolong landfill fires.	
Pollutants affected	Nickel, cobalt, copper, manganese, HCl, HCN, HF, POF_3, hexane, propylene, $PM_{2.5}$, PM_{10}.
Expected timescale of impact	Medium-term. To meet net zero targets, the growth in demand for electric vehicles over the coming decades will lead to an increase in the manufacture of LIBs, which will subsequently need careful disposal.
Relation to the Environment Agency's regulatory remit	The Environment Agency's Pollution Inventory (PI) reports on releases to air of inorganics, including hydrogen cyanide (HCN), as well as metals and compounds, such as copper and nickel, and other substance groups which include fluorides. All these releases are associated with battery manufacture and disposal (Environment Agency, 2022). Battery manufacture, usage and disposal is expected to grow significantly in the coming decades. While the Environment Agency does not have a regulatory remit over battery usage in transport, it will be primarily

	concerned with facilities that manufacture, recycle or dispose of (via landfill or incineration) batteries.
Quantified projections of emissions available	Not available.

Spatial distribution
Battery manufacturing facilities in the UK are located in the Midlands and the north-west. The UK Battery Industrialisation Centre is located in Coventry. The Envision AESC battery Gigafactory, located in Sunderland, opened in 2012. The Britishvolt battery gigafactory in Blyth is under construction and, despite falling into administration in early 2023, has since been bought out by the Australian company, Recharge who expects to open this facility within 2 years (Britishvolt, 2023). Also, Envision AESC is planning to construct another gigafactory in Sunderland (The Faraday Institution, 2022). With regard to battery fire testing facilities, there are a selection of labs in the UK which can perform flammability testing. The Health and Safety Executive (HSE) Science and Research Centre in Buxton, for example, is a new facility for battery abuse testing (HSE, 2022). There are a multitude of battery recycling facilities in the UK. Based on research, the West Midlands is the battery recycling heart of the UK (University of Birmingham, 2022). Some examples of battery recycling facilities include G&P Batteries, West Midlands and Ecobat Technologies (a global chain with many stores in the UK, such as in Bristol, Manchester, Glasgow). Landfills that the Environment Agency have regulatory responsibility for are more widely distributed across the country.
Public health impacts
When large LIBs, such as those used in electric vehicles, become internally damaged, they fall into a slow thermal runaway process which can lead to spontaneous combustion or release toxic gases and droplets of solvent. These gases include hydrogen fluoride (HF), phosphoryl fluoride (POF_3), methane (CH_4), ethylene, propylene and carbon dioxide (CO) (Sun and others, 2016; Larsson and others, 2017). Hydrogen fluoride (HF), when inhaled, can cause irritation to the eyes and nose, sore throat, cough, chest tightness, dizziness and, in large enough exposure, death (Public Health England, 2018). POF_3 is a reactive intermediate, which reacts with other organics or with water to produce HF. There is general uncertainty surrounding the toxicity of POF_3, though research on its chlorine structure suggests it could be a more toxic species than HF (Larsson and others, 2017).

Ecosystem impacts
Between April 2019 and March 2020, there were an estimated 250 fires in UK waste treatment facilities which could be attributed to small LIBs (Morris, 2020). Once disposed of, LIBs will leach their contents into surrounding soils and potential groundwater sources (Mrozik and others, 2021). In aquatic ecosystems, primary producers and microorganisms experience membrane damage from the oxidative stress created by the presence of metal oxides, metal and carbon-based nanoparticles in the water, which originate from battery disposal (Melchor-Martínez and others, 2021). Higher trophic level organisms can directly uptake the same nanoparticles or encounter them through ingestion of algae, filter feeders and benthic organisms. Nanoparticles then bioaccumulate through the trophic levels. Fish, exposed to these nanoparticles, have been shown to experience growth inhibition, delay in hatching and subsequent malformation of embryos (Melchor-Martínez and others, 2021).
Mitigation potential
At present, with the expected increase in demand for LIBs, the best-case scenario for their eventual disposal would involve high collection rates of the spent batteries, with an almost complete recovery of all the reusable materials which could be recycled back into the supply chain (Mrozik and others, 2021). To mitigate against illegal disposal and informal processing of LIBs, there will be a need to improve collection schemes, in addition to expanding and improving current recycling infrastructure, alongside appropriate legislation and regulations (Mrozik and others, 2021). Type testing on ‘second life’ LIBs will also be important to monitor risks of thermal runaway and the overall efficiency of the batteries should they be reused in an electric vehicle battery pack (Mrozik and others, 2021).
Public interest/engagement
In Wakefield, Yorkshire, more than 300 people objected to a proposed battery energy storage system (BESS) site (Yorkshire Post, 2022). Protestors believed the site posed a severe fire and explosive risk to the local area, which would subsequently emit large quantities of toxic pollutants into the surrounding environment. This followed a major explosion and fire that lasted an entire night at the Carnegie Road BESS in Liverpool in 2020 following thermal runaway of one of the four containers, each of which store 5MWh of energy (The Faversham Society, 2022). Concerns have been raised over the magnitude of the explosion and persistent fire, with future sites looking to store significantly more energy, for example the 700MWh battery at the Cleve Hill Solar Park development (The Faversham Society, 2022).

Readiness for research and potential scoping options
Existing studies of the scale and scope of LIB fires should be reviewed to assess their applicability to battery production facilities in England. Studies specific to expected situations in facilities in England once commercial production is underway may then be needed, along with an assessment of the spatial and temporal occurrence of fires so that these studies can be scaled to assess the national impact. Similarly, an assessment of the expected future prevalence of landfill fires as the volume of domestic LIBs sent to landfills increase will be needed since LIBs can trigger, amplify and prolong landfill fires (Mrozik and others, 2021). This might form part of a wider update to a previous Environment Agency review of landfill incident fires in general (Environment Agency, 2007), particularly as hotter and drier summers associated with climate change are likely to lead to increases in incident fires. Detailed monitoring of concentrations of pollutants released during LIB fires in the vicinity of battery production facilities and landfills can be used to improve future exposure assessment. This will help inform the evaluation of human exposure risk in nearby populations.

Deployment of carbon capture and storage (CCS) technologies

CCS BECCS	
Theme	Emerging sources
Description and definition of scope	
The UK government's 2021 Net Zero Strategy outlined the role that engineered greenhouse gas removal (GGR) technologies would need to play in supporting decarbonisation by 2050 (Department for Energy Security and Net Zero and Department for Business, Energy and Industrial Strategy, 2021). Direct air carbon capture and storage (DACCS) and Bioenergy with carbon capture and storage (BECCS) are identified as the priority applications for CCS technology within the strategy. CCS brings the potential to alter the quantity and profile of air pollutant emissions from the UK energy sector. While ammonia is the main degradation product, amines (as nitrosamines and nitramines) are of potentially greater concern, albeit emitted in smaller quantities. The review of this topic is focused on whether the broader science and research base is robust (in the UK), but also whether there are any obvious gaps in the ongoing research being conducted by both Defra and the Environment Agency to assess the air quality risks associated with the release of amines from the process.	
Pollutants affected	Ammonia, formaldehyde, nitrosamines and nitramines, amines, acetaldehyde, NO_X, carbon monoxide and total organic carbon.
Expected timescale of impact	Short- to medium-term. The Net Zero Strategy highlighted that BECCS applications in the power sector could be deployed by the late 2020s and help achieve the UK's Nationally Determined Contribution (NDC) by 2030. A pilot plant (part funded by a Department for Business, Energy and Industrial Strategy (BEIS) grant) opened in Northwich in 2022.
Relation to the Environment Agency's regulatory remit	The Net Zero Strategy identifies the need for regulation and abatement on emissions other than CO_2 from GGR technologies, specifically BECCS, biochar and wood in construction. However, it may be difficult to regulate due to the sector already progressing with preferred implementation

	technologies, for example, through amine use as a scrubbing agent.
Quantified projections of emissions available	BEIS has estimated a pathway to 2037 scenario for the GHG removal (negative) emissions, but to use this data, emissions rates per tonne carbon removed need to be established. Continuous measurement of ammonia in stack gas emissions appears the most likely way of validating carbon capture performance on a plant-by-plant level.

Spatial distribution

Engineered removals are likely to be located within or near industrial clusters, benefiting from access to CO_2 transport and storage infrastructure.

The government's 'Ten Point Plan for a Green Industrial Revolution' presents a goal to establish carbon capture, utilisation and storage (CCUS) in 2 industrial clusters by the mid 2020s, and to aim for 4 of these sites by 2030, capturing up to 10Mt of CO_2 per year (UK government, 2020). The plan suggests the development of these technologies alongside hydrogen to create transformative 'SuperPlaces' in areas such as the heart of the north-east, the Humber, the north-west and in Scotland and Wales.

The first UK industrial-scale CCU plant was opened by TATA Chemicals Europe in 2022 in Northwich. The plant uses emitted CO_2 from its combined heat and power plant to produce high grade sodium bicarbonate.

Public health impacts

A Scottish Environment Protection Agency (SEPA) study in 2015 highlighted that the amine solvents themselves are unlikely to be of significant public health concern in terms of air emissions, but there is a higher degree of uncertainty associated with emissions of amine reaction (degradation) (SEPA, 2015). Nitrosamines and nitramines are possible carcinogens. Environment Assessment Levels (EALs) or Environmental Quality Standards (EQS) have not been established in the UK or within the EU for most of the compounds of interest. Some EU member states have indicated their own environmental standards.

In the UK, there is research work ongoing by both Defra and the Environment Agency to assess the air quality risks associated with these compounds. This includes considerations such as reviewing:

1. which amine breakdown products are most likely to occur
2. atmospheric reaction studies to determine how, and for which substances, associated air quality impacts can be assessed, and modelling can occur

Ecosystem impacts
As with ammonia, amines are highly soluble in water and there are examples in the literature (for example, Rudneva and Omel'chenko, 2021) showing accumulation of nitrosamines within river ecosystems and fish species, with detrimental impacts linked to the carcinogenic, mutagenic and toxic properties of the substances. Typical impacts associated with air pollutants, dispersal and subsequent airborne deposition may occur. However, large-scale implementation of CCS technologies should reduce the impact of most primary air pollutants compared to the continued burning of fossil fuels. Overall, aqueous impacts of these substances to ecosystems are likely to be significantly higher than those from their airborne dispersion.
Mitigation potential
Use of CCS in power plants leads to a general energy penalty varying in the order of 15 to 25% depending on the type of CCS technology applied (European Environment Agency, 2011). Abatement systems to mitigate emissions of amines and amine reaction products to air are being developed. These systems could generate additional wastewater streams requiring additional treatment.
Public interest/engagement
Recently, the role of CCS facilities within the UK government's Net Zero Strategy (and linked outputs such as the most recent 'Powering Up Britain' - Net Zero Growth Plan) has gained prominence in the national media (HM Government, 2023). As of March 2023, the media has presented often critical viewpoints on the government's support of technology to capture and store CO_2 in undersea caverns, to enable an expansion of oil and gas in the North Sea. Continued reliance on the fossil fuel industries is highly controversial, even when plans for associated CCS activities are proposed to mitigate the impacts from a GHG emissions perspective.
Readiness for research and potential scoping options
The 2015 SEPA study identified knowledge gaps in terms of: • nitrosamines/nitramines toxicity • existing background levels of amines and their reaction products (in the UK) • sampling and analysis techniques for amine compounds, particularly nitrosamines • monitoring methods

SEPA was field-trialling an ambient air monitoring method developed by the Norwegian Institute for Air Research for nitrosamines at the time of its 2015 report. At that stage, the study also identified that the UK had not set EALs or EQS for the compounds of interest, although this had been progressed in other countries.

Since then, in the UK, there is research work ongoing by both Defra and the Environment Agency to assess the air quality risks associated with these compounds, including final stage research in partnership with Cambridge Environmental Research Consultants on amines modelling to inform the development of EALs for these substances. In addition, the Environment Agency is working with the National Physical Laboratory to identify knowledge gaps associated with measuring flue gas components from post-combustion capture processes. A review of emissions from post-combustion carbon capture using amine-based technologies has been completed (National Physical Laboratory, 2022) and field trials at a post-combustion capture facility are due to begin in August 2023.

Elsewhere, a pilot study (Sustainable OPEration of post-combustion Capture plants - SCOPE) led by private industrial partners but part-funded by the German Ministry for Economic Affairs and Energy is already researching “to close gaps in existing scientific, technical, environmental and societal knowledge regarding emissions from carbon scrubbing, in addition to effectively minimising such emissions and their impacts on the environment” (RWE, 2023).

In terms of short-term research need, there appears to be a strong emerging scientific basis on the impacts of amine scrubbing within CCS processes, as well as developments in how to measure and monitor amine compounds in and around CCS plant. However, there remains a lack of background monitoring for amine concentrations at a UK level. Linked to this, there is a potential need for local modelling and consideration of potential receptors, for example, at-risk communities and environments based on the likely location of UK CCU plant within the next decade.

The Environment Agency should stay connected to ongoing research, as it is currently in relation to the previously mentioned SCOPE project. It is likely that such research will allow greater understanding of the role of airborne releases and the role of monitoring, for example, aqueous versus inhalation based. In addition, further evidence is likely to be realised in terms of the specific breakdown products of concern to both human health and ecosystems.

Longer term, the Environment Agency may need to be ready to monitor/measure and regulate air pollutant and potentially toxic nitrosamine and nitramine releases from, and nearby to, future CCU plants in the UK. The National Permitting Service is receiving applications for permits now and will require stack emissions monitoring, but methods need to be assessed and chosen soon to support this.

PFOS and other PFAS

PFOS and other PFAS	
Theme	Emerging pollutants and components of air
Description and definition of scope	

PFAS are a group of environmentally persistent synthetic chemicals, which includes PFOS, that are resistant to water, oil, and heat. These resistant properties have meant that PFAS have been used across a range of applications for decades, including in fire-fighting foams, metal plating, and in consumer products like carpets, waterproof clothing, and upholstery. Repeated exposure to PFAS has been demonstrated to have adverse effects on people's health and ecosystems.

Typically, PFAS is considered a water pollutant, but increasing consideration of the release of PFAS to air and the subsequent health impacts from inhalation is drawing greater attention.

The typical sources of direct airborne PFAS include:

- Industrial emissions: Many industrial facilities will produce, process or use PFAS chemicals, with associated emissions to the environment (including air). Typical relevant industries include metal finishing and plating, cable and wiring, building and construction, surfactant and fluoropolymer production, paper products and packaging, semiconductor, and textile industries (ITRC, 2022).
- Firefighting – some firefighting foams designed for liquid hydrocarbon fires and vapour suppression can be major sources of local PFAS release to the environment (Roth and others, 2020). These particular foams are used for suppression, fire training, and vapour suppression. Atmospheric concentrations would be expected to be high in locations around airports, refineries, chemical plants, and military facilities where hydrocarbon fires are most likely.
- Incineration: When products with PFAS are burned, as is relatively common in solid waste disposed of from industry (and non-industry to a lesser extent), the chemicals can be released to the air.
- Landfills: When PFAS-containing products are discarded into landfills, the products can leach out into the surrounding environment in various forms, including airborne gas and particles (Weinberg and others, 2011; Faust, 2022). The type and concentration of PFAS varies greatly among landfills due to variations in waste composition, with industrial waste expected to be the greatest source of PFAS.
- Wastewater treatment plants: These plants provide several pathways for PFAS release to the environment. Conventional treatment methods do not efficiently remove PFAS, while concentrations and type of PFAS differ by treatment site, with those that receive industrial wastewater discharges typically being associated with higher concentrations and subsequent release to air (ITRC, 2022).

- Consumer product passive release: PFAS can be released passively over time by products such as clothing, furniture, and carpets (Faust, 2022).

Research options were considered when relevant to PFAS (and PFOS) emissions to air only. Presenting research options on water contamination and mitigation options are considered out of scope.

Pollutants affected	PFAS/PFOS
Expected timescale of impact	Short-term. PFAS emissions from industrial processes are already anticipated to be common, but trends to dispose of waste through incineration, particularly at energy from waste facilities, may mean that airborne PFAS emissions will increase over the coming decade. Given the longevity of PFAS in the environment, early action is needed to prevent substantial bioaccumulation.
Relation to the Environment Agency's regulatory remit	As an air pollutant, the primary sources of PFAS are from industrial processes and waste management, which are both directly related to the Environment Agency's regulatory remit. Reducing the use of PFAS in production will have the knock-on effect of reducing passive release from products that dictate levels of indoor air pollution through time as well. Other environmental agencies are beginning to take interest in regulating emissions of PFAS In the USA, some state-level environmental protection agencies have already introduced ambient air quality limits, while the US Environmental Protection Agency (EPA) has explicitly incorporated air quality considerations into its 5-year strategy (US EPA, 2021).
Quantified projections of emissions available	No quantified emissions projections were identified that were relevant for the UK on PFAS (or PFOS) emissions.

Spatial distribution

Given the range of sources of PFAS pollution, it follows that the public may be exposed to emissions in both outdoor and indoor settings. In general, indoor settings are expected to have the highest levels of concentration due to proximity to PFAS-containing products and lower ventilation rates.

The attention on PFAS air emissions in the USA is driven by results of studies that suggest that air deposition is an important pathway for surface water contamination. For example, Galloway and others (2020) found evidence of significant PFAS contamination in surface water samples that were concluded to be from a fluoropolymer manufacturing facility around 30km away. Models suggest that long-range transport of PFAS is also expected, with some studies suggesting only 5% of PFAS emissions from a point source will deposit within 150km of the facility (D'Ambro and others, 2021). This is supported by evidence of PFAS contamination in Arctic snow, likely the result of deposition caused by long-range transportation (Environment Agency, 2021c).

That said, concentrations are expected to be significantly greater around sources. Some wastewater treatment plants, for example, have shown concentrations of PFAS in ambient air to be 1.5 to 15 times greater than background reference levels (Hamid & Li, 2016), and 5 to 30 times greater at landfill sites (Ahrens and others, 2011).

PFAS is transported in the atmosphere in both gas and particle phases, which contributes to the long-range transportation. Partitioning from gas phase to particle phase is more favourable with increasing chain length and decreasing temperature (Faust, 2022). There is also evidence of longevity: Zhou and others (2021), found that PFOS was still the dominant PFAS compound in $PM_{2.5}$ in North Carolina in 2019 despite PFOS manufacture not thought to have occurred in the US since the early 2000s. Suspected sources in this case include emissions from legacy consumer products, fire-fighting foams that predate regulation, degradation of precursors in the atmosphere, and sea spray aerosol.

Public health impacts

The health impacts of PFAS exposure have typically focused on the impact of exposure through ingestion of water or food. Inhalation of airborne PFAS is not expected to be as harmful to public health. That said, drinking water is most likely contaminated in areas where source waters are downstream of manufacturing and industrial plants or waste sites containing PFAS through direct leaching into water and surface water deposition of PFAS. In general, the health impacts of PFAS include (Centre for Environmental Research and Children's Health, 2021):

- reproductive effects, such as decreased fertility and increased high blood pressure in pregnant women
- developmental effects or delays in children, including low birth weight, accelerated puberty, bone variations, and behavioural changes
- increased risk of some cancers, including prostate, kidney and testicular cancers
- reduced ability of the body's immune system to fight infections, including reduced vaccine response
- interference with the body's natural hormones
- increased cholesterol levels and/or risk of obesity

Research, however, is lacking in how different levels of exposure lead to different health effects and their respective severity. As such, the Environment Agency and the Health and Safety Executive (HSE) were asked by Defra to examine the risks posed by PFAS and to develop a regulatory management options analysis which will set out further options for managing the risks of PFAS chemicals. This analysis was published in spring 2023 (Health and Safety Executive, 2023).

Occupational studies have found that some workers in PFAS handling sectors, in this case firefighters, had higher geometric mean concentrations of PFAS compared to office workers.

Ecosystem impacts

Ecosystems are affected by PFAS emissions once deposited in waters (including air deposition to surface waters) and through soil contamination (which can be contaminated through contaminated rainfall).

In soil, PFAS contamination increases the pH of soil and increases litter contamination, while it reduces soil respiration and the prevalence of water-stable aggregates. In plants, exposure affects a number of biochemical activities in plant cells, such as photosynthesis, protein synthesis, and carbon and nitrogen metabolisms. Root uptake is considered the primary pathway of plant exposure (Li and others, 2022). Rates of bioaccumulation are also influenced by additional factors, including physiochemical properties of the exact PFAS chemical (for example, carbon chain length), plant characteristics and the broader environmental characteristics (for example, soil pH, salinity, temperature). As a result, international studies of the effect of PFAS bioaccumulation and impact on vegetation should not be considered directly applicable to the UK context. PFAS in UK soils is not routinely monitored at present (Environment Agency, 2021c).

It has been found that a huge range of animals are affected by PFAS, including fish, birds, reptiles, frogs, horses, cats, otters and squirrels. The Environment Agency has previously said the PFOS exposure, at least through water, should be considered ubiquitous to the environment, with PFAS in general considered widespread across British freshwaters (Environment Agency, 2021c). Researchers found that PFAS exposure in otters in England and Wales was associated with wastewater treatment works and the use of sewage sludge in farming. Some PFAS can remain in mammalian tissues for a long time, and field studies have demonstrated increasing levels of PFAS concentrations on progression along a food chain.

Mitigation potential

Industrial sources and incineration: When released from industrial sites, treatment pathways have focused on the breakdown of PFAS through combustion. Estimates of the temperature at which PFAS are broken down vary in the literature, and can range from 650 to 1,100°C (Michigan Department of Environment, Great Lakes, and Energy, 2019). While thermal incineration is currently considered the only effective destruction method, more data on incineration conditions and the products of incomplete combustion are needed. For example, the combustion of PFAS produces post-combustion gases that will contain hydrofluoric acid which will need to be handled with corrosive-resistant abatement equipment. Other products may be fluorinated greenhouse gases (Stoiber and others, 2020).

Landfills: Gas collection systems commonly employed at UK landfills should already reduce possible PFAS emissions to air (ITRC, 2022). Although municipal solid waste will contain PFAS due to its presence in consumer products, it is generally accepted that landfills that accept industrial waste will have higher concentrations (and, therefore, greater levels of emissions of PFAS) and so mitigation options should focus on individual sites.

Wastewater treatment: Mitigation options at wastewater treatment facilities have typically focused on methods for reducing contamination in water (ITRC, 2022). While the correlations to air emissions are not known, it may be expected that treatment methods that remove PFAS from solution onto solid media may also reduce emissions to air. Recent tightening of the water quality regulations (Drinking Water Inspectorate, 2021) on levels of PFOS and perfluorooctanoic acid will ensure that water companies will already be required to implement effective treatment methods to remove PFAS.

As with many other sources, prevention is more effective than mitigation. The move away from the use of PFAS chemicals in industrial processes and products, particularly in the US in the 2000s, has been shown to have already impacted bioaccumulation in the public. Biomonitoring surveys conducted by the National Health & Nutrition Examination Survey have found concentrations of PFOS reduced 6-fold across the US population, which is likely the result of the voluntary phase out of PFOS use in industry across the 2000s (New York Department of Environmental Conservation, 2020), although whether this is due to reduced air or water exposure is not stated.

Public interest/engagement

PFAS are garnering increasing attention from the public and media. Articles in national newspapers and environmental magazines (Ends Report, 2023; Greenly, 2023; The Guardian, 2023) cite examples from the USA in support of greater action on reducing exposure to PFAS, although admittedly the concerns are primarily to reduce concentrations in water. Airborne PFAS is less well covered, but it appears likely that the contribution of air deposition to surface water will soon draw interest.

Readiness for research and potential scoping options

A major obstacle for regulation of PFAS air emissions is the lack of standardised methods to measure PFAS air emissions. Other environmental agencies, like the US EPA has been working to advance methodologies (Ryan, 2019) in recent years. Without well developed and tested measurement techniques, establishing meaningful regulations may be challenging for the Environment Agency. Another obstacle in handling the airborne contribution of PFAS exposure is that most studies into the health impacts of exposure and bioaccumulation of PFAS have focused primarily on exposure through ingestion of food and water containing PFAS chemicals. There is little evidence of the impact of inhalation only, and little evidence of the proportion of waterborne PFAS that originated from atmospheric deposition to surface waters.

One area where research could be carried out in the short term is to understand combustion of PFAS as a mitigation option. While evidence shows that PFAS chemicals can be broken down during combustion, there is a major gap in understanding the products of incomplete combustion which could include other dangerous chemicals and/or greenhouse gas emissions release. Designing a study to understand the products of combustion in conditions similar to typical incinerators and, therefore, what additional abatement equipment may be needed is high priority to inform decisions of what abatement techniques industry needs to employ.

Antimicrobial resistance (AMR)

AMR	
Theme	Emerging sources
Description and definition of scope	
AMR includes resistance by microorganisms to all chemicals with antimicrobial abilities. AMR occurs when bacteria, viruses, fungi and parasites change over time and no longer respond to medicines, making infections harder to treat and increasing the risk of the spread of disease, severe illness and death. AMR can develop naturally, but the main cause of AMR is the abuse or inappropriate use of antimicrobial drugs. This can create an environment in which resistant microorganisms grow. Airborne AMR microorganisms have relatively limited research especially in the UK, but they are a growing concern, because they could be carried for long distances and cause infection. Airborne AMR occurs in a variety of environments, mostly hospitals, farms and wastewater treatment stations. In 2014, the smog in Beijing was found to contain antibiotic-resistant bacteria (South China Morning Post, 2016).	
Pollutants affected	PM_{10}, $PM_{2.5}$, NMVOC, NO_X, O_3
Expected timescale of impact	Medium- to long-term. Although AMR can be detected in the air, the health impacts may take longer to become apparent. One reason for this is that the development process of AMR allows it to persist in the environment. The timescale of the impact of AMR can be influenced by factors such as the types of bacteria involved, the level of exposure, and the populations affected.
Relation to the Environment Agency's regulatory remit	AMR is not a traditional air pollutant but rather a biological process. However, the Environment Agency has identified AMR as an important environmental issue and has regulations in agriculture and healthcare industries. Therefore, AMR could potentially become a focus for the Environment Agency's regulatory remit.

Quantified projections of emissions available	Not available.

Spatial distribution

There is not enough information on the spatial distribution of AMR in England. However, we can identify that AMR is more prevalent in particular locations, including hospitals, farms and wastewater treatment stations.

Public health impacts

According to Murray and others (2019), AMR is the leading cause of death worldwide, killing about 3,500 people every day. Airborne AMR, as mentioned above, could be carried to infect human and animals far away from the original sources. AMR would reduce the efficacy of current treatments and hinder future medicine development. AMR poses a threat to people of all ages, with young children found to be at particularly high risk. People with weaker immune systems, the elderly, and those with chronic illness are also vulnerable to AMR.

In addition, a study by O'Neill (2016) states that infections of multi-drug resistant bacteria would cause more deaths compared to cancer by 2050.

Ecosystem impacts

Aside from the influences on animals mentioned above, AMR would change the characteristics of microbials in the ecosystem and have negative effects on the environment. Transmission to soil and water systems could lead to a potential loss of biodiversity. The literature states that the most serious influence of AMR on ecosystems is its effect on the nutrient cycles. The disruption of microbials would lead to nutrient imbalances and productivity which could cause food production reduction and soil degradation.

Mitigation potential

In 2019, the UK government developed a national action plan to combat the issue of AMR (Department of Health and Social Care, 2019). The action plan includes 'Antibiotic Stewardship', an approach to promoting and monitoring the judicious use of antibiotics to preserve their future effectiveness and prevent AMR. The action plan promotes the responsible use of antibiotics.

Reducing the use of antibiotics is also another mitigation approach. This would require infection and disease prevention and control. Reducing or preventing the spread of infection would largely help mitigate AMR. This would require further biological and medical research.

Regarding environmental control, improvements and regulations on waste and wastewater treatment and use of antibiotics for agriculture are crucial to limit the release of antibiotics and AMR.

Antifungal resistance also raises further concern as a serious public health threat. The US Centers for Disease Control and Prevention (CDC) has developed a series of actions to prevent the spread of antifungal resistance. For example, the Antimicrobial Resistance Laboratory Network (AR Lab Network) has been developed to test antifungal susceptibility and discover resistant fungi (CDC, 2022a). Genetic sequencing is used to understand antifungal and antibacterial resistance mutations (CDC, 2022a). It is crucial to perform antifungal test for patients when their fungal infections are not improved with first-line antifungal drugs (Patterson and others, 2016). This would also help control and prevent spread of antifungal resistance.

Antivirals resistance is likely to develop for people who have compromised immune systems or who take long periods of antivirals to treat chronic viral infections due to misuse of drugs (Cleveland Clinic, 2022). To mitigate the antiviral-resistant viruses, it is crucial to first detect their occurrence. Genotypic antiretroviral resistance tests and phenotypic antiretroviral resistance tests are 2 blood tests for checking the drug resistance. Early flu vaccinations could also protect from antiviral drug resistance (CDC, 2022b).

As parasitic diseases are common and crucial to be controlled to ensure the health of animals, antiparasitic resistance is a more serious problem in animals, especially swine and poultry (FDA, 2023). The US Food and Drug Administration (FDA) develops the Antiparasitic Resistance Management Strategy that regulates use of approved dewormers, such as weight taping to control dosage used and 'Target Selective Treatment' to avoid deworming all animals (OIE, 2021; Stafford and others, 2009). Aside from minimising the frequency of using antiparasitic/anthelmintic drugs, rotating different modes of chemicals between dosing seasons for animals and drug combinations could also mitigate the resistance problem (Vercruysse and Claerebout, 2022).

Public interest/engagement

Public interest towards AMR is growing, especially since the Covid-19 pandemic. The World Health Organization (WHO) and the US Centers for Disease Control and Prevention (CDC) have raised awareness of AMR. There are public campaigns targeting the issue of overuse and abuse of antibiotics, such as the WHO's World Antibiotic Awareness Week. In the UK, there is also a high level of attention on AMR. On 23 October 2018, Public Health England (predecessor organisation to the UK Health Security Agency) proposed the 'Keep Antibiotics Working' campaign to increase the public awareness of AMR risks. The UK government developed a strategy to combat AMR in 2019.

Readiness for research and potential scoping options

AMR has been extensively studied under various scopes. WHO, US CDC and other institutions and organisations worldwide have performed a range of research on AMR as it is a topic of concern. WHO launched the Global Antimicrobial Resistance and Use Surveillance System (GLASS) in 2015 to tackle AMR. As mentioned above, the UK government has also developed an action plan for addressing AMR.

Despite its significance, there is currently limited research on airborne AMR as a component of air, as it is often considered within a broader context. There are some gaps remaining for AMR research:

1. The mechanisms and drivers of AMR require further research.

2. Aside from biological research, there are several factors that could also lead to misuse and overuse of antibiotics, including social, economic and cultural, which need exploring.

3. To effectively reduce AMR, it is crucial to implement further interventions and policies, including the use of emerging technologies. Additionally, re-evaluating current policies and issuing new ones can help to address this urgent issue.

Urban ammonia and the use of ammonia as a fuel

Emerging sources of ammonia (urban and fuel combustion)	
Theme	Emerging pollutants - Industrial and energy generation
Description and definition of scope	
Ammonia (NH_3) is, at present, unregulated in ambient air, with no limit values assigned in Europe. Regarding air quality concerns, the formation of secondary inorganic particles with atmospheric ammonia and acids such as sulphuric and nitric acid, significantly contribute to high concentrations of particulates in urban areas (Chatain and others, 2022). Ammonia emissions are largely driven by the agricultural sector, with livestock and fertiliser use. However, other sources, such as road traffic, with the increased use of catalytic converters, may also represent important sources of ammonia emissions that have received limited study. The maritime industry is presently challenged by increasingly strict air quality emission limits and climate legislation. Anhydrous ammonia has been identified as a possible long-term, net or near zero carbon fuel to be used for deep-sea cargo ships, as opposed to short-sea, passenger or inland waterway craft (European Maritime Safety Agency, 2022). Ammonia slip can be anticipated from this method and would, therefore, require management similar to ammonia slip in internal combustion engines (ICEs) fitted with selective catalytic reduction (SCR) after-treatment systems.	
Pollutants affected	Ammonia, NO_X, N_2O (for ammonia combustion), $PM_{2.5}$
Expected timescale of impact	Short-term for urban ammonia and wider mitigation options. Analysing the underestimated sources of urban ammonia is a growing research topic and likely to become increasingly important. Long-term for use of ammonia as a maritime fuel due to ongoing research and development projects which will support the development of standards and guidelines.
Relation to the Environment Agency's regulatory remit	The Environment Agency would have to manage and regulate sites where maritime fuel is stored. Any fugitive emissions/process emissions also fall under the remit of the Environment Agency. Not as clear for urban ammonia.

Quantified projections of emissions available	Farren and others (2020) concluded that the inventory estimates of urban emissions of ammonia for passenger cars are underestimated by a factor of 17. Other quantified projections are largely unavailable.

Spatial distribution

Ammonia gas does not remain in the environment for long as it reacts rapidly to create ammonium compounds.

It is centred around busy urban areas, with slow-moving traffic. There are 2 main sources of ammonia emissions from road transport; the first with catalyst-equipped petrol vehicles, and the second being light- and heavy-duty vehicles (LDvs and HDVs) which rely on SCR. Ammonia formation from 3-way catalysts results from the reduction of nitric oxide by hydrogen. SCR technology leads to ammonia slip as a result of either injection of excessive quantities of urea, low system temperatures or catalyst degradation (Suarez-Bertoa and Astorga, 2016).

A considerable increase in the absolute emissions of urban ammonia could provide a more efficient route to $PM_{2.5}$ formation. The quantification of significantly increased urban ammonia on $PM_{2.5}$ formation would, however, require detailed air quality modelling.

Public health impacts

Ammonia when inhaled in large concentrations is toxic. Inhaling low levels may cause irritation to the eyes, nose and throat. Higher levels can result in burns and swelling to the airways, in addition to lung damage which can be fatal (Public Health England, 2019).

Ammonia is also a precursor for secondary $PM_{2.5}$ and can have a large impact on ambient $PM_{2.5}$ concentrations. As such, it plays an important role in exposure to high levels of $PM_{2.5}$ and, therefore, the resulting human health impacts.

Ecosystem impacts

Emissions of ammonia can result in increased acid depositions and excessive nutrient levels in soils, rivers and lakes. This can then negatively impact forests, crops and other vegetation, as well as harming aquatic ecosystems (European Environment Agency, 2019).

Mitigation potential

For ammonia as a maritime fuel, SCR is expected to be used to control ammonia-slip, with possible additional catalysts required to control N_2O.

To mitigate the impact of urban ammonia resulting from road transport, an ammonia-slip catalyst can be used alongside an SCR catalyst to help reduce ammonia emissions from vehicles. Ammonia entering the ammonia-slip catalyst (ASC) is partially oxidised to nitric oxide, which subsequently reacts with not-yet oxidised ammonia, to produce N_2 following the usual SCR reaction schemes.

Public interest/engagement

There is a lack of public knowledge about ammonia outside of the agricultural industry. This is combined with a slightly negative perception of ammonia, pertaining to its toxicity when inhaled in large concentrations and its unpleasant odour (Guati-Rojo and others, 2018). The benefits of green ammonia need to be clearly outlined to the public should ammonia be used as a maritime fuel.

With urban ammonia, the topic is emerging and is not well known in the public domain. Further research is required before the potential effects of urban ammonia are communicated to the public.

Readiness for research and potential scoping options

Ammonia as a maritime fuel has been studied in detail in recent years and there is a strong knowledge base on the safe handling of ammonia from its widespread use in the agricultural sector. Ammonia can be stored as a liquid at atmospheric pressure, making it easy to transport, which will prove critical if it is to be used to fuel deep-sea cargo ships.

Current production of ammonia is CO_2 intensive due to it being largely produced by natural gas or coal. To be viewed as ‘green ammonia’, research and development is required to produce ammonia using renewable energies.

Within the Environment Agency’s remit, particular attention needs to be paid to the level of ammonia emissions that would be expected from future storage sites, and studies of typical rates of leakage and dispersion patterns should be further explored.

For urban ammonia, there is currently very limited research on the other sources of ammonia away from the agricultural sector. Further research studies are required on the levels of ammonia emitted from cars, LDVs and HDVs, in addition to exploring risks associated with ammonia release from residential waste.

Bioaerosols

Bioaerosols (biological aerosols)	
Theme:	Emerging pollutants and components of air
Description and definition of scope	
Bioaerosols (biological aerosols) are small airborne particles (ranging from 0.001 to 100µm in diameter) that originate biologically from plants or animals and can contain living organisms. Microorganisms, including viruses, pollen, bacteria and fungi may exist in bioaerosol. Bioaerosols are found everywhere; human sources of bioaerosols include regulated sites such as composting facilities, intensive farms, including livestock houses, sewage/wastewater treatment works (for example, aeration tanks), municipal landfill/solid waste, and MBT systems. Bioaerosols can contribute to $PM_{2.5}$ and PM_{10} in the air that are crucial for the Environment Agency to consider as the main pollutants.	
Pollutants affected	$PM_{2.5}$; PM_{10}
Expected timescale of impact	Medium-term. Bioaerosols influence human health based on various factors. Some have a short-term impact, for example, respiratory diseases, while some have a much longer term of impact, for example, chronic diseases and cancer. Therefore overall, bioaerosols could be considered as medium-term.
Relation to the Environment Agency's regulatory remit	The Environment Agency has permits that specify conditions related to bioaerosols. Monitoring and risk assessments must be completed. A site-specific bioaerosol risk assessment has to be carried out in regulated facilities following technical guidance notes for environmental modelling. Bioaerosol concentrations must be monitored if facilities are within 250 metres of a 'nearest sensitive receptor', the nearest place to the permitted activities where people are likely to be for prolonged periods, and the results of total bacteria as well as Aspergillus fumigatus must be submitted (Environment Agency, 2018).

Quantified projections of emissions available	Not available.

Spatial distribution
Specific information on spatial distribution of bioaerosols in England is not available. Bioaerosols are widespread and are found in both indoor and outdoor environments. Outdoor sources include soil, water, farms and waste. Bioaerosols are likely to be higher in rural areas due to agricultural activities. Indoor sources are influenced by humans and buildings.

Public health impacts
The composition of bioaerosols is complex and could contain allergens and toxins. Exposure to bioaerosols is associated with several health effects, such as infectious, respiratory, inflammatory and allergic diseases. Bioaerosols are only a concern at smaller particle sizes that penetrate more deeply in the lungs, as the larger particles are naturally filtered out in the upper airways (Douwes and others, 2003; Thomas and others, 2008). The most common response is that bioaerosols would lead to irritation and inflammation in the respiratory system, and subsequent respiratory diseases. The human lung is subjected to airborne pollutants and the exposure to bioaerosols decreases lung activity while increasing pulmonary inflammation (Robertson and others, 2019). Bioaerosols could also cause allergic reactions, rhinitis, hypersensitivity pneumonitis (HP)/extrinsic allergic alveolitis, allergic bronchopulmonary aspergillosis (ABPA), eye and skin irritations (Lacey and Dutkiewicz, 1994; Pearson and others, 2015). Bioaerosols, as they transmit in the air, can spread infectious diseases. The contact or inhalation of airborne bioaerosols are hard to control. It is also possible some bioaerosols such as fungi are toxic, and the contact or inhalation of certain types can lead to diseases in human and animals. Alternatively, the ‘hygiene hypothesis’ (first attributed in scientific literature during the late 1980s (Strachan, 1989) draws public attention to the potential benefits of microbial agents in enhancing atopic immune responses. Specific examples of this in more recent literature include the finding that through exposure to particular microorganisms in the earlier stage of life, immune tolerance could be established and protect from atopy and allergic asthmas (Martinez, 1999; Douwes and others, 2002; Douwes and others, 2003). However, it is also true that many scientific studies have since argued against the theory in terms of its overall influence and relevance to human health effects.

Ecosystem impacts

The ecological impacts of bioaerosols could influence the ecosystem in several ways. Bioaerosols could negatively impact biodiversity due to fungi and bacteria that could cause disease in animals and crop damages. Similar to AMR, bioaerosols also affect nutrient cycles, reducing productivity of plants. Plants and fungi release volatile organic compounds into the air that form secondary organic aerosols (Fröhlich-Nowoisky and others, 2016). The bioaerosols act as low-volatility organic vapours condensation nuclei in air (Fröhlich-Nowoisky and others, 2016; Pohlker and others, 2012). This affects cloud formation and may potentially influence Earth's radiative balance. Furthermore, bioaerosols are also likely to influence precipitation and ice nucleation (Joung and others, 2017; Fröhlich-Nowoisky and others, 2016). This would alter the global hydrological cycle and climate.

Mitigation potential

In the UK, there is guidance in the biowaste and composting sector for monitoring bioaerosols, such as the M9 protocol (Environment Agency, 2018).

Several approaches can be used to reduce bioaerosols at source. For example, improvements in waste management, especially from farm wastes. For indoor bioaerosols control, ventilation systems with high-efficiency particulate air (HEPA) filters are useful in reducing bioaerosols, if used correctly.

Scrubbers are used to remove pollutants from air. Although the use of scrubbers is more common in mitigating odour, specifically designed scrubber systems, such as wet scrubbers are also able to remove bioaerosols, (Di Natale and others, 2018; Lee and others, 2021).

In the context of mitigating bioaerosols after they have been generated, disinfectants are widely used for mitigating indoor bioaerosols, as well as ventilation. Another mitigation strategy is to reduce/prevent bioaerosol exposure and disease transmission, including mask-wearing, physical distancing and barriers.

Public interest/engagement

The public interest is very high in areas near sites that have the potential to generate bioaerosols. Public perception and knowledge also increased during the Covid-19 pandemic because bioaerosols contribute to the transmission of respiratory viruses (Leung, 2021). The tragic death of Awaab Ishak due to the environmental mould pollution in 2020 also raised the public awareness of bioaerosols and pushed the UK government to deliver Awaab's Law for social housing (DLUHC, 2023).

Bioaerosols are not receiving a high level of attention compared to other air pollutants. Campaigns such as 'Clean Air Day' and 'Healthy Air' are promoting improved ventilation systems and cleaning, with a focus on bioaerosols as an indoor air pollutant. On January 23 2018, the Environment Agency released guidelines (Environment Agency, 2018) on monitoring bioaerosols in regulated facilities that handle biological waste. Scholars and researchers also have increasing interest in bioaerosols generated in hospitals and facilities, with ongoing research being conducted at the University of Leicester.

Readiness for research and potential scoping options

The current research and regulations on bioaerosols are limited, especially for emerging air pollutants. There are several gaps that need to be addressed.

Bioaerosols require further study of long-term projection and monitoring, particularly in relation to how concentrations and spatial distributions of bioaerosols impact on health. This may require further development of longer-term bioaerosol measurement methods.

Further epidemiological studies could be performed on health impacts caused by bioaerosols, not only limited to respiratory diseases. Experimental studies in model systems could help identify the health impacts of bioaerosols without confounding factors. This is key to identifying the causal associations of bioaerosols on health outcomes (Robertson and others, 2019).

Climate factors are also important to focus on because climate change would affect the production and distribution of bioaerosols.

Current mitigation strategies are more centred on indoor bioaerosols control rather than outdoor air quality. Although reducing exposure through actions such as mask-wearing would be effective, this is not always realistic in an outdoor setting. Therefore, it is crucial to develop mitigation policies and technologies for outdoor bioaerosols.

In outdoor areas, there is limited analysis of the background concentration of bioaerosols in unaffected areas, which is required to determine the level of bioaerosols above the average for an area (Robertson and others, 2019).

Nitrogen oxide emissions from hydrogen combustion, and contributions to climate change

NO_X from hydrogen combustion - energy generation	
Theme	New fuels
Description and definition of scope	
The future use of hydrogen in transport is not expected to be large (unless generated by a fuel cell). Use of hydrogen in the residential sector is thought to be a potentially large future source of emissions. However, neither of these source groups fall within the remit of the Environment Agency and are, therefore, not considered further. Upstream industrial activities associated with the generation and handling of hydrogen is likely to come under the Environment Agency's remit. However, the scope of this topic is the emissions resulting from the combustion of hydrogen, so upstream activities are not considered here. The focus is on the potential changes to NO_X and $PM_{2.5}$ from the use of hydrogen as a fuel in industrial installations. In addition, hydrogen prolongs the atmospheric lifetime of CH_4, and is, therefore, classed as an indirect greenhouse gas. This potential impact should, therefore, also be considered.	
Pollutants affected	NO_X, $PM_{2.5}$, PM_{10}
Expected timescale of impact	Short-term. It is unknown if/when significant amounts of hydrogen will be used as a fuel, but there have already been pilot studies in the UK investigating the practicalities and implications of mixing hydrogen into existing natural gas supplies (HyDeploy, 2023).
Relation to the Environment Agency's regulatory remit	The use of hydrogen as a fuel in industry could be extensive in future years. This could potentially range from relatively small boilers (inadvertently using a hydrogen-natural gas mix because that is provided through the gas mains supply) up to significant use in electricity generating stations (where more direct choices would be made about the extent to which hydrogen is used). So, it is sensible for the Environment Agency to gain an understanding of the potential emissions from the combustion of hydrogen and hydrogen-natural gas mixes, and, therefore,

	the extent to which these emissions differ from current natural gas combustion emissions.
Quantified projections of emissions available	Emissions from hydrogen combustion are not currently reported in the National Atmospheric Emissions Inventory (NAEI), or from other data sources. This is because official guidance material does not yet contain information on the relevant emission factors. A recent study by Aether Ltd suggests that NO_X emissions from hydrogen combustion may not differ substantially from those from natural gas combustion (Aether Ltd, 2023). It is suggested that the emissions control/mitigation technologies that are applied may be the most important factor in determining the emissions of NO_X and PM, but these are considered to be tentative conclusions. Further research is required before this can be definitively confirmed. Emissions of hydrogen by fugitive losses are not currently estimated, and hydrogen is unlikely to be included in emissions inventories until fugitive emissions (and resulting impacts on greenhouse gas emission totals) become significant enough to warrant further investigation.
Spatial distribution	
The spatial distribution of emissions will be comparable to existing natural gas combustion sources in the electricity generation and industrial sectors.	
Public health impacts	
As noted above, tentative conclusions from a recent literature review indicate that there may not be significant changes in emissions of NO_X and $PM_{2.5}$ caused by fuel switching from natural gas to hydrogen or a hydrogen-natural gas mix. If this is the case, then no significant change in public health impacts is expected. Little or no impact is expected from the impacts on greenhouse gas emissions arising from the fugitive release of hydrogen.	
Ecosystem impacts	

As above.

Mitigation potential

Options for emissions control are expected to be broadly the same as those currently used for natural gas combustion. There are reasons why emissions control technologies applied to hydrogen combustion might not perform in the same way as when they are applied to natural gas combustion (for example, different combustion temperatures), but differences are expected to be small compared to the overall effectiveness of emissions mitigation.

Public interest/engagement

Recent pilot studies investigating the benefits of using a hydrogen-natural gas mix in the residential sector have given rise to some concern from the public. For example, in Whitby, there was local backlash against proposals for the gas grid to be switched to hydrogen in 2025 for net zero trials (The Telegraph, 2023). But, given that the scope of this issue is limited to electricity generation and the industrial sectors, public interest is assessed as being generally low.

Readiness for research and potential scoping options

There is currently a lack of definitive information on the emissions that result from the industrial use of hydrogen and hydrogen-natural gas mixes for electricity and heat generation, and much of the information in the literature is derived from modelling studies.

The technology and expertise are thought to be readily available in the UK to design, plan and implement pilot studies investigating the emissions that could result from hydrogen and hydrogen-natural gas mixes in real-world industrial installations.

A significant amount of preparatory work to support the specifications of the study could be achieved by first carrying out modelling studies. These would show how the combustion conditions, and, therefore, resulting emissions and performance of emissions control equipment, might vary.

Given that the most likely changes in the near future are associated with introducing a hydrogen-natural gas mixture into the gas mains supply, it would be sensible for the study to investigate how emissions vary across several different fuel mixtures.

Damage and corrosion to boilers and emissions control equipment is also an important area to consider in the pilot study. Plant operators will wish to be reassured that the introduction of hydrogen (and any resulting changes that they need to make regarding the combustion conditions) does not shorten the life of their equipment or machinery.

Cold air drainage of air pollutants by katabatic flow

Cold air drainage of pollutants	
Theme:	Emerging sources
Description and definition of scope	
In winter and spring, colder temperatures and low wind speeds increase cooling of the ground surface to create a cool layer of air that decreases mixing and dilution of any odours and pollutants emanating from a landfill site, for example. On undulating terrain, the process of katabatic flow (or cold air drainage flow) can allow the polluted layer to drift downhill, creating a persistent, concentrated region of pollution that could negatively impact public health (Environment Agency, 2023b). The science behind katabatic flow is not novel, therefore, the scope of this topic is focused on the review of the flow of hydrogen sulphide (H_2S) from Walley's Quarry in the West Midlands. Environment Agency staff highlighted this example to the project team to include in the project shortlist to review the need for additional research as a result of this, and other potential examples around Environment Agency regulated sites.	
Pollutants affected	H_2S, NO_X, PM_{10}, $PM_{2.5}$, SO_2, benzene, toluene, ethylbenzene, Xylene (BTEX), CH_4
Expected timescale of impact	Short-term, currently occurring at landfills across the country and, therefore, requires a stronger research base for how to manage cold air drainage flow.
Relation to the Environment Agency's regulatory remit	The Environment Agency regulates the Walley's Quarry landfill site in the West Midlands, among several others, and it is within its remit to mitigate against the spread of foul odours and pollution to local populations (Environment Agency, 2023c).
Quantified projections of emissions available	Not available.
Spatial distribution	
Effects of cold air drainage flow will be limited to pollutant sites situated on high ground relative to surrounding local populations as pollutants will be at their most concentrated when the flow of air pools into valleys. Katabatic flow will occur most often in winter and spring when daylight hours are most limited, and temperatures are typically lower than the daily average.	

Public health impacts
Acute exposure to low concentrations of hydrogen sulphide (H_2S) can result in irritation to the eyes and respiratory tract (Public Health England, 2016). Between 500 and 1,000 parts per million (ppm), H_2S is toxic to humans, if inhaled. In concentrations of 1,000 ppm or greater, inhalation of H_2S can prove fatal (Health and Safety Executive, 2009).
Ecosystem impacts
H_2S has high acute (short-term) toxicity to aquatic life, birds and terrestrial animals. H_2S can also contribute to the formation of sulphuric acid in the atmosphere, leading to acid rain deposition.
Mitigation potential
At the Walley's Quarry landfill site, H_2S levels have been reduced through permanent capping and increased gas extraction and treatment (Defra, 2022). This decreased concentrations from around 6,500ppm in June 2021 to between 2,100 and 2,400ppm in early 2022. Continuing this capping and extraction, combined with regularly monitoring the levels of H_2S are detailed to be the best measures to reduce levels of H_2S at Walley's Quarry (Defra, 2022). Other approaches, such as in-situ aeration of landfill waste, iron scavenging, utilising sodium bicarbonate, and constructing a wall around the landfill were viewed as unrealistic and/or ineffective strategies to reduce H_2S levels at Walley's Quarry.
Public interest/engagement
The meteorological science of katabatic flow is well understood, but typically a focus on air pollutants has been limited to international (and in particular) alpine settings, such as the European Alps. There has, however, been an increase in public engagement on the topic at Walley's Quarry. There have been complaints and protests from the local community near Walley's Quarry regarding foul odours of H_2S. Newcastle-under-Lyme Borough Council also served a statutory nuisance abatement notice on Walley's Quarry Limited as a result of emissions of H_2S (BBC News, 2021).
Readiness for research and potential scoping options

Walley's Quarry will prove an important case study for understanding the implications of katabatic flow on local air quality. Existing research on cold air drainage has been primarily focused on the meteorology of the topic rather than its relationship with the in-air transportation of pollutants (Aghdam and others, 2019). Additional study is, therefore, important to further understand the spatial and temporal scales that this topic would operate on. This will, in turn, inform the Environment Agency of the level of risk to public health.

At Walley's Quarry there is also some evidence that katabatic flows have become more prominent as the landfill has changed shape/height over several years. It has changed over ~5 to 10 years from a depressed/concave quarry (where air was enclosed) to an upstanding/convex dome (from which air can 'spill' downslope/outwards). This raises a question about how 'full/high' a landfill should be raised in a situation with potential drainage flows towards residents.

Priorities for future research on cold air drainage of air pollutants should assess the site-specific consequences on public health, as opposed to launching national studies on the science of katabatic flow events.

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List of abbreviations

AMR	Antimicrobial resistance
ASC	Ammonia-slip catalyst
ATSDR	US Agency for Toxic Substances and Disease Registry
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
BESS	Battery energy storage system
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CDC	US Centers for Disease Control and Prevention
CH_4	Methane
CO	Carbon monoxide
DACCS	Direct air carbon capture and storage
Defra	Department for Environment, Food and Rural Affairs
DLUHC	Department for Levelling Up, Housing & Communities
EAL	Environment Assessment Level
EPA	Environmental Protection Agency
EQS	Environmental Quality Standards
EtO	Ethylene oxide
EU	European Union
FDA	US Food and Drug Administration
GGR	Greenhouse gas removal
GHG	Greenhouse gas
GLASS	Global Antimicrobial Resistance and Use Surveillance System
H_2S	Hydrogen sulphide
HCl	Hydrochloric acid
HCN	Hydrogen cyanide
HDVs	Heavy-duty vehicles
HF	Hydrogen fluoride
HSE	Health and Safety Executive

ICEs	Internal combustion engines
IRIS	Integrated Risk Information System
ITRC	Interstate Technology Regulatory Council
LDVs	Light-duty vehicles
LIB	Lithium-ion battery
MBT	Mechanical biological treatment
MRL	Minimal risk level
NAEI	National Atmospheric Emissions Inventory
NATA	National Air Toxics Assessment
NDC	Nationally Determined Contribution
NECR	National Emissions Ceiling Regulation
NESHAP	National Emission Standard for Hazardous Air Pollutants
NGO	Non-governmental organisation
NMVOC	Non-methane volatile organic compounds
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
OIE	World Organisation for Animal Health
PFAS	Per- and polyfluorinated alkyl substances
PFOS	Perfluorooctane sulphonate substances
PI	Pollution Inventory
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of ≤2.5μm
PM_{10}	Particulate matter with an aerodynamic diameter of ≤10μm
POF_3	Phosphoryl fluoride
ppm	Parts per million
SCOPE	Sustainable OPEration of post-combustion Capture plants
SCR	Selective catalytic reduction
SEPA	Scottish Environment Protection Agency
SO_2	Sulphur dioxide
TRI	Toxics Release Inventory
UN/ECE	United Nations Economic Commission for Europe
US EPA	US Environmental Protection Agency
WHO	World Health Organization

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