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AIR QUALITY EXPERT GROUP

Impacts of Net Zero pathways on future air quality in the UK

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

This is a report from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of Agriculture, Environment and Rural Affairs in Northern Ireland, on the interactions between Net Zero greenhouse gas objectives and the future of air quality in the UK. The information contained within this report represents a review of the understanding and evidence available at the time of writing.

Front cover image credit:

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

Freephone Air Pollution Information Service 0800556677
Internet http://uk-air.defra.gov.uk
PB 14622

Terms of Reference

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

AQEG's functions are to:

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

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

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1. Introduction and scope of this report

There has been an important link historically between society's emissions of greenhouse gases and poor air quality. The co-emission of greenhouse gases and short-lived air pollution is well established in some sectors, including fossil fuel electricity production, industrial manufacturing, space heating, transportation, and agriculture. The UK commitment to a Net Zero greenhouse gas budget in 2050 creates major opportunities for delivering additional economic and environmental co-benefits including an improvement in ambient air quality in the UK. Although air pollution and greenhouse gases can have distinctly different impacts, on occasion the same pollutants contribute to both effects. Black carbon for example is both a contributor to poor air quality and is also a significant climate warming agent on global scales. Tropospheric ozone, formed from the reactions of methane, volatile organic compounds and nitrogen oxides is similarly both a greenhouse gas (when in the free troposphere) and an air pollutant at the planetary surface.

Since air pollution is a complex mixture of different chemical entities, the potential for low carbon strategies to generate cleaner air depends on which pollutant is being considered and the low carbon pathway and/or technology chosen. For some regulated air pollutants that are co-emitted with carbon dioxide (CO_2) during fossil fuel combustion, such as nitrogen oxides NO_x (defined as the sum of NO and NO_2), black carbon, polycyclic aromatic compounds and carbon monoxide, significant reductions in ambient concentrations might be anticipated as fossil fuel use decreases. Other pollutants such as secondary particulate matter (PM), ammonia (NH_3), non-methane Volatile Organic Compounds (VOCs), persistent organic pollutants and airborne metals have complex non-combustion sources and have less direct connections to national carbon budgets. For example, fine particles are generated by vehicles through the friction and abrasion of surfaces, irrespective of the propulsion system. In some cases, the future air quality effects of Net Zero will depend critically on how a replacement technology is used; hydrogen consumed in a fuel cell releases no air pollution, whereas hydrogen combusted in a boiler or engine potentially does.

For air pollutants, in contrast to greenhouse gas emissions, it matters if air pollutant emissions shift closer to areas of population (even if total national emissions decrease). For example, air pollutants from district heating biomass boilers can have disproportionate impacts on people close by compared with large power-generation facilities remotely located and with tall chimneys. The effects of poor air quality are felt immediately and are costly, so transitory pollution generated on the pathway to 2050 requires consideration and careful management, for example the localised impacts of major infrastructure projects or the use of intermediate fuels.

A final note is that whilst the societal impacts of air pollution emissions are more localised to the UK than the effects of greenhouse gases that the nation emits, there is still an important transboundary, international context to the control of air pollution. Improved air quality in the UK arising from national Net Zero action is likely to be amplified further if similar strategies are adopted more widely in Europe. The benefits of UK action on Net Zero are likely to extend to improving air quality in near neighbour countries downwind of the UK. The effects of coordinated international action to reduce greenhouse gas emissions are likely to be particularly significant for the further reduction in longer-lived air pollutants such as PM and ozone. These are pollutants that are already managed through international treaties such as the UNECE Convention of Long-Range Transport of Air Pollution, and Europe-wide low carbon commitments may increase the effectiveness of those air quality-motivated agreements.

1.1 Scope

In this short report, the Defra Air Quality Expert Group (AQEG) has evaluated the ***Further Ambition*** scenario developed by The Committee on Climate Change (CCC) in 2019.

See: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

An initial assessment has been made of the possible impacts on air quality, primarily from the perspective of five pollutants for which either ambient standards or national emissions limits exist (PM, NO_x, O_3, VOCs, NH_3). In this assessment AQEG has attempted to differentiate between uncertainty associated with the underlying science of a particular process or technology, for example ‘does an activity emit a particular type of pollutant, and if so in approximately in what quantities?’, and with the broader uncertainties that relate to the scale of uptake, implementation and mitigation.

The assessment by AQEG is essentially identifying ***hazards*** rather than ***risks***, and it is understood that for every action area within the Net Zero strategy some form of hazard mitigation is likely to be introduced, or the hazard managed through existing regulatory processes such as the permitting of emissions. In some cases, the technologies that are highlighted as part of a Net Zero pathway do not currently operate in the UK at industrial scale, notably for Carbon Capture and Storage (CCS), and there is potential for the emergence of unanticipated new hazards as a consequence of the materials used. In uncertain technology areas such as this, it is accepted that existing systems for risk assessment will be applied, and the hazards identified here may not catalyse into significant risk once mitigation is in place.

The exact details of the realisation of each action are often critical to whether the air quality effects might be positive or negative. In some areas the selection of a specific technology pathway or implementation strategy could potentially lead to sub-optimal outcomes, and worsened air pollution emissions compared to plausible counterfactuals. AQEG aims to highlight those areas where air quality emissions and outcomes should be a factor that is considered in Net Zero design and specification, and to guide thinking around which realisations of individual Net Zero proposals would bring the greatest beneficial improvements in air quality.

Encouragingly, for virtually all of the changes proposed on the CCC Net Zero pathway, positive, improved and better air quality outcomes can be envisaged.

The report does not explicitly address the broader issue of societal health benefits arising from Net Zero, although in some cases we do identify where low carbon technologies may have different air quality impacts in different geographic areas. In this report we do not weight changes in different pollutants by their specific health outcomes, but view reductions in ambient concentrations of all major regulated pollutants as equally valuable. Follow-on work jointly with the DHSC Committee on the Medical Effects of Air Pollution (COMEAP) is anticipated to refine further which actions would bring the largest health benefits to the UK. Our approach to identifying possible air quality effects is restricted to those that would be experienced in the UK, but it is important to appreciate the enormous impacts of the manufacture, transportation and disposal of goods (including clean technologies) from outside of the UK. There is clearly significant potential for the export of air pollution emissions, and by extension adverse air quality, to other countries as part of the decarbonisation transition.

Mapping the detailed air quality improvement measures currently set out in the 2019 Defra Clean Air Strategy on to potential pathways to Net Zero is considered beyond the scope of this report.

1.2 Approach

AQEG used a workshop (24/01/20) to discuss items within a Net Zero scenario provided by the CCC, followed up by collective evaluation of the outcomes through AQEG meetings. The participants in the workshop are listed in Annex 1, a mixture of AQEG members, *ex officio*, invited academics and representatives from Defra, Department for Transport, Public Health England, the Environment Agency, and Department for Business, Energy and Industrial Strategy. Each item in the Net Zero plan was considered from the perspective of possible impacts on five key air pollutants – PM, NO_x, O_3, VOCs, and NH_3. The possible effect of an action proposed in the Net Zero scenario on each of these pollutants was evaluated. In some cases, an action was anticipated to lead directly to a change in the emission and change in ambient concentrations of particular pollutants. In other cases, changes in emissions of particular species would impact on secondary pollutants such as O_3 and PM. The possible scale of the impact of each action was initially considered, although this generally carried very considerable uncertainty associated with the possible scales of uptake of a particular technology or approach and how it was implemented.

- A +ve notation was assigned when a Net Zero action was thought likely to lead to an improvement in air quality for that parameter (e.g. either emissions and/or ambient concentrations would be anticipated to reduce.)
- A neutral notation was assigned when the Net Zero action was not thought to directly impact air quality in either a positively or negatively manner.
- A -ve notation was assigned when the Net Zero action had the potential to lead to a detrimental effect on air quality for that parameter (e.g. either emissions and/or ambient concentrations would be anticipated to increase, if no mitigation was put in place.)

[In this analysis, there is no canonical counterfactual against which a comparison of air quality effects can be made. Where a range of different technological options are available for implementation, the possible change is measured against the best available alternative at the time the intervention would be made. For example, expansion in wind energy has unequivocal UK air quality benefits across multiple pollutants; the possible air quality hazard associated with other energy generation options in Net Zero, such as biomass CCS is then measured against wind as the counterfactual. In some areas there is only a single pathway or action proposed, and that is assessed against business as usual (BAU). For example, widespread forest planting is a standalone action so the air quality impact is measured against a BAU with no change in UK forest cover].

In many cases the introduction of a policy, process or technology had the potential to deliver a range of different air quality outcomes depending on exactly how it was implemented and the extent of mitigation. In many cases a –ve notation simply indicated that one *plausible pathway* for the action might led to a decrease in air quality, and this was generally expanded on in narrative for each action.

The assessment, therefore, provides a pessimistic view of the air quality hazards associated with individual actions. This is intentional, to ensure that those possible antagonisms between Net Zero strategies and air quality impacts are identified clearly and mitigated very early on in the design and implementation process.

A summary of the evaluation of each action is shown in Table 1 at the end of this report, including a short narrative description of key issues and potential mitigation. Several overarching themes emerged from this analysis of possible air quality impacts, and these are discussed further in sections 2-8, covering the areas of:

- Air quality impacts and the transition to Net Zero
- Impacts of transport fleet decarbonisation
- Food production and agriculture
- Forestry, biocrops and biogenic emissions
- Use of hydrogen (H_2) as a fuel
- Carbon capture and storage (CCS)
- Building energy efficiency

1.3 Key conclusions

- The implementation of Net Zero will lead to some immediate improvements in certain primary air quality parameters. However, due to non-linear formation, large reductions in ambient concentrations of secondary pollutants (PM and O_3) may not be fully realised until towards the end of the Net Zero transition.
- Air pollution has immediate adverse health effects on the communities where it is experienced, and care is needed to ensure that during the transition to 2050, air quality impacts are considered and minimised. For example, major low-carbon

infrastructure projects have the potential to create localised air quality problems during their development, whilst the use of transitionary fuels may cause pollution to rise temporarily in some locations.

- Decarbonisation of the road and rail transport fleet will bring very significant air quality benefits, reducing NO_x and VOCs in cities. This will improve air quality overall, particularly at the roadside. However, whilst primary PM emissions from engine and vehicle exhausts will decrease, PM from friction and abrasion (e.g. tyre and brake wear and resuspension of dust) will remain. These could plausibly increase if overall vehicle-miles driven were to increase, or if increases in emissions resulting from any greater average vehicle mass were not offset by decreases derived from regenerative braking and new mitigation technologies. Clean transport options within the Net Zero strategy, such as walking, cycling and public transport are integral to delivering optimal air quality benefits.
- There are positive reinforcing interactions between sustainable and lower greenhouse gas food production and improved air quality, particularly associated with reduced ammonia emissions from the agricultural sector. Lower ammonia emissions arising from lower farmed animal numbers, better fertiliser use practises, and improved waste management, may in combination with reductions from other sectors, lead to lower PM in both the urban and rural environment. Decreased nitrogen deposition to ecosystems would be a further benefit. Reductions in methane emissions from agriculture in the UK would have only modest impact on surface O_3 in the UK but would contribute positively to wider global improvements.
- Widespread forest planting and an increased role for biofuel crops means the potential impacts of natural (biogenic) emissions of VOCs should be considered. Increased emissions of VOCs can lead to growth in surface O_3 once mixed with NO_x that has been emitted from other sectors. Selection of low-emitting plant and tree species should be a key factor in the design of future land-use and bioenergy policies and should be considered in the Defra ‘Tree Strategy’, currently in preparation. Attention should also be paid to potential changes in soil NO_x and nitrous oxide (N_2O) emissions associated with any large-scale change in land cover.
- The wide-spread use of hydrogen as a replacement fuel could have variable impacts on air quality depending on how and where the fuel is generated and how it is used. Hydrogen used at industrial scales and in fuel cells are very clean options from an air quality perspective. However, the direct combustion of H_2 (or H-carriers such as ammonia) in domestic gas boilers or in engines would likely lead to similar (or lower) NO_x emissions than current fossil fuel combustion.
- Whilst there are considerable uncertainties associated with the possible future deployment of CCS in the UK, there is an ongoing requirement to apply regulatory risk assessment to ensure that there are no unintended air quality impacts arising from fugitive chemical releases from industrial capture processes.
- Widespread improvements in energy efficiency in commercial, public and domestic buildings have considerable potential for reducing energy demand. However, care is

needed to ensure that suitable construction materials, ventilation and air management is in place to avoid the unintentional accumulation of air pollution indoors. This is particularly relevant for PM, VOCs and the by-products of indoor chemical reactions. Poor indoor air quality is by no means an inevitable consequence of energy efficiency measures, but it is a factor that must be considered at an early phase of strategy development, including establishing clear indoor air quality objectives alongside those for energy efficiency.

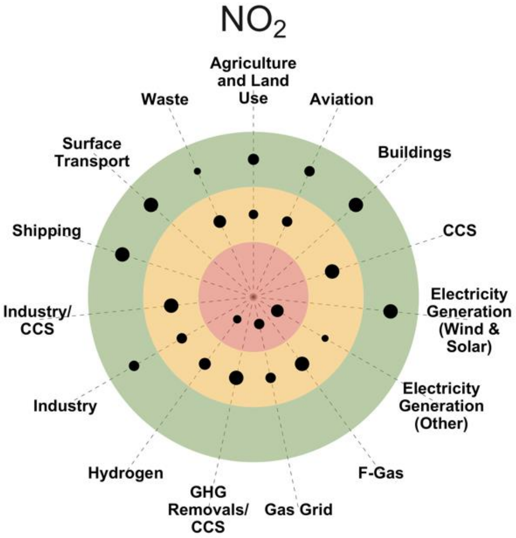
1.4 Potential impacts across emission sectors

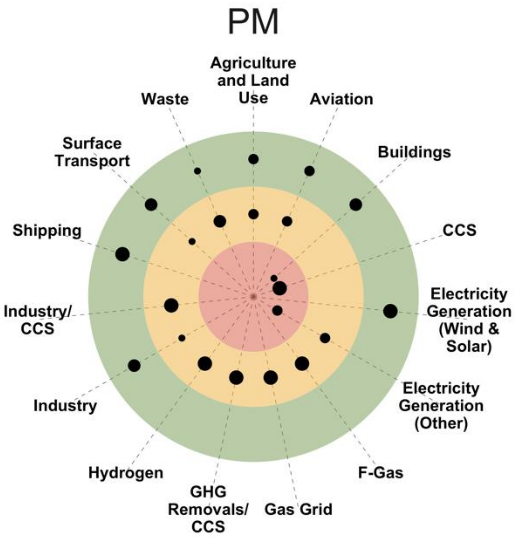
An analysis of the possible air quality implications of 47 individual actions to support delivery of a Net Zero carbon budget are given in Table 1 at the end of this report. These can be grouped into 15 different emission sectors. [Agriculture and land use; Aviation; Buildings; CCS; Electricity generation (wind and solar); Electricity generation (Other); F-gases; Gas grid; GHG removal / CCS; Hydrogen use; Industry; Industry / CCS; Shipping; Surface transportation and Waste].

A pictorial representation of this data is shown in Figure 1, placing the impacts of actions associated with each emissions sector into one of three coloured rings. In some instances, an emission sector is associated with a large range of possible Net Zero actions and interventions (e.g. Agriculture has 12), others have considerably fewer (e.g. Aviation only 2). The potential effect of the cumulative actions proposed in each emission sector is summarised for each of the five key air pollutants being considered here. The dots on the ‘dart-board’ show how Net Zero actions addressing each emission sector might impact on air quality – green means positively, orange is neutral and red negatively - if not mitigated. Large dots show that most, or all of the actions proposed for that sector may lead to an air quality change of given sign. A small dot indicates that a small number, or perhaps only one action for that sector has that particular air quality impact. Different actions proposed for each emissions sector may not always have the same sign in terms of air quality impacts, hence dots can appear in multiple rings for each.

In virtually all cases, dots appearing within the red ring, indicating negative air quality impacts, can be moved to either neutral or positive if suitable mitigating actions are taken.

Further details on possible mitigations are provided in the narrative for each action in Table 1. [Note: a small number of actions in the scenario are not evaluated since they effectively set out the necessary boundary conditions (such as total energy demand, H_2 production requirements), rather than prescribe a pathway to that end point]


NO_2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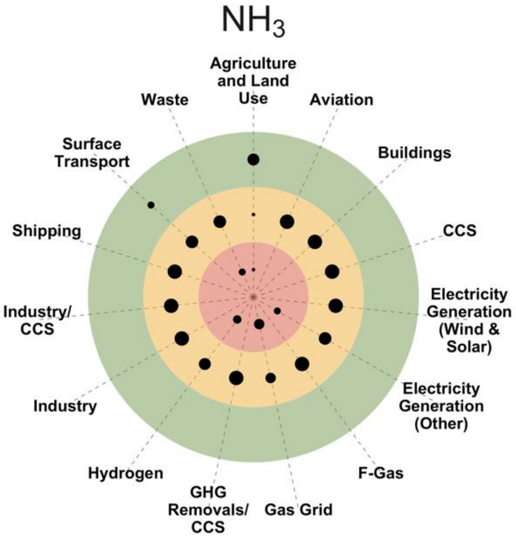
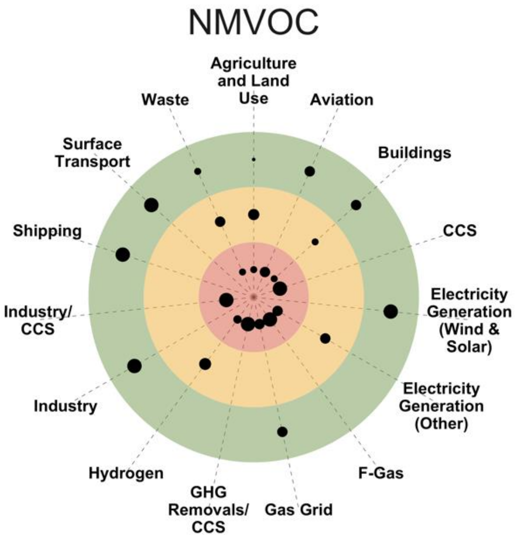
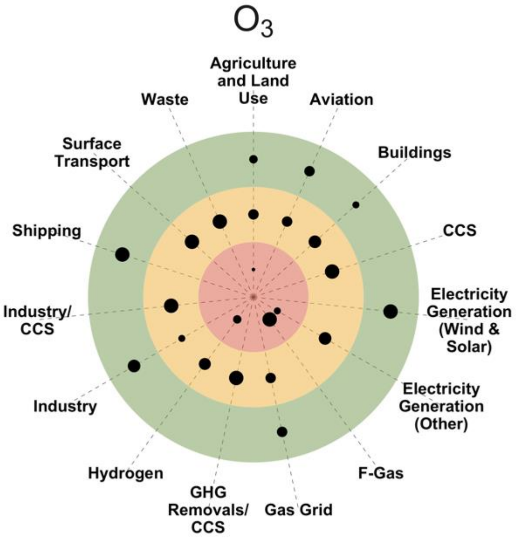

NH_3


NMVOC


O_3

Potental Air Quality Impact:

🟥 negative
🟨 neutral
🟩 positive

The figure shows for each of the five pollutants, the potential air quality impact (negative, neutral or positive) each sector could have. Power Generation has been split into renewable wind/ solar and other methods.

Larges dots indicate more or all actions with the sector have that effect. Small dots indicate perhaps only one action within that sector will lead to that effect.

*Carbon Capture and Storage (CCS), Greenhouse Gas (GHG).

Key areas of interaction between Net Zero strategies and UK air quality

2. Air quality impacts during the transition to Net Zero

The short atmospheric lifetimes of some primary emitted air pollutants, means, that positive benefits can potentially be generated very rapidly once a polluting source is removed or is replaced by a lower emissions alternative - a further incentive to pursue early introduction of low carbon approaches. Some replacement technologies in the Net Zero plan may feed in more slowly over decades, for example passenger fleet electrification or energy efficiency installations, and air quality benefits (for example roadside nitrogen dioxide NO_2) accrue in a step-wise fashion alongside CO_2 reductions. The air quality impact and benefits of the transition to Net Zero in 2050 is maximised the earlier those transitions begin and the more rapidly they are completed.

In some cases, the formation of secondary pollutants such as PM or O_3 is non-linear with respect to precursor emissions, and the greatest improvements in air quality may not come until well into the Net Zero transition period. For example, sustained reductions in the emissions of ammonia and NO_x are likely to be needed before large UK-wide, and transboundary reductions in resulting secondary PM are experienced. Similarly reducing O_3 as an air pollutant may require substantial reductions in both NO_x and VOCs.

It is worth highlighting that the development of the new low-carbon infrastructure needed to deliver Net Zero has some potential to create transitory problems associated with air quality, and particularly so for very large construction projects (e.g. nuclear power, new roads and rail). Such projects may have only modest impacts in terms of overall national emissions of air pollution (e.g. measured in tonnes of emission), but may themselves be significant perturbations to air quality concentrations in some localities. The effects of localised poor air quality even if only transitory, are real and substantial. Local air quality is a well-known issue within the construction sector, and a range of mitigations (e.g. emissions from off-road machinery, dust suppression etc) are already required. However, given the potential scale of infrastructure development needed for 2050, additional control measures for large infrastructure projects would likely be beneficial. The adoption of Net Zero, and the associated scale of development that may occur nationally, provides a motivation to go beyond current measures for air quality controls. There are likely opportunities to continue to reduce emissions from non-road mobile machinery, temporary electrical power, mining and construction and dust resuspension.

A further area of potential transitory and negative air quality impacts is the use of intermediary fuels and technologies over the early periods of strategy. Whilst many technological end points in 2050 are likely to be very low emissions from an air quality perspective, some pathways may temporarily create negative air quality impacts. For example, widespread zero emission district heating and power systems in 2050, including the use of fuel cells, may be delivered with transitional technologies possibly using higher emissions sources such as urban biomass combustion in combined heat and power applications.

3. Impact of road and rail transport fleet de-carbonisation

Electrification of the passenger vehicle fleet is already underway, and decarbonisation is predicted to be completed by 2050; for battery vehicles the UK Net Zero strategy identifies that electricity will come from zero carbon emission sources. There will be unambiguous benefits for air quality arising from the elimination of exhaust NO_x, with significant reductions in ambient NO_2 concentrations likely to be experienced at the roadside and in enclosed stations. A consequence of the elimination of the primary source of urban nitrogen monoxide (NO) from vehicle exhaust will be localised roadside increases in O_3. At present very near the road (within a few tens of metres) ambient O_3 is titrated (often completely) through reaction with NO, although over larger distance scales the O_3 is subsequently regenerated through photochemical processes. Although this might be viewed as a negative consequence of electrification, the overall air quality benefits of reducing urban NO_2 are likely to be much larger than the effects of roadside incremental increases in O_3.

The removal of internal combustion engine (ICE) passenger vehicles will fully eliminate remaining tailpipe PM emissions and any ammonia from exhaust gas after-treatments such as Selective Catalytic Reduction. Tailpipe emissions of VOCs would also be eliminated along with the evaporative and fugitive losses associated with the refuelling infrastructure. There may be some possible reduction in upstream refinery and extraction industries, although it is acknowledged these UK-based industries service a global market. For larger vehicles, decarbonisation is likely to come later than for passenger cars, possibly based around hydrogen fuels. The impact of this change on air quality will depend on whether H_2 is used in fuel cells, which are very low emission, or with H_2 as an engine combustion fuel, which would continue to generate NO_x emissions and require abatement systems. The former is considered more likely.

An important consideration relating to zero carbon transportation and air quality is that only a fraction of harmful air pollution originates from the tailpipe. For current ICE vehicles (e.g. EURO 6c and newer), the majority of PM emissions from each journey arise from friction, brake wear, tyre wear, road surface abrasion and the resuspension of road dust. There are some notable outstanding uncertainties in the prediction of future non-exhaust emissions effects. This includes the balance of increased vehicle weight (increasing tyre and road wear) traded-off against the benefits of regenerative braking (decreasing braking wear), and emerging vehicle PM reduction technologies, for example from capture from brake callipers and low emissions tyres. There are also wider uncertainties associated with the size of the vehicle fleet and total distance driven, in a future where relative costs-per-mile may be lower than today and UK population higher.

There are some plausible changes that could occur in ambient particle toxicity over the 2050 timeframe, as a greater proportion of UK urban PM comes from frictional wear, a source that is likely to contain enhanced amounts of trace metals. PM emissions will therefore remain an undesirable consequence of road transport even in 2050 under fully decarbonised scenarios. It is therefore critical that the other policy actions included in Net Zero that support transport modal shift, to options such as walking, cycling, and public transport are delivered to maximise the air quality and health benefits.

4. Food production and agriculture

Agriculture and food production feature prominently within the Net Zero strategy with an emphasis on reducing nitrous oxide (N_2O) and CH_4 emissions. Changes in future consumer behaviour, diets and farming practices have the potential to have significant beneficial effects on air quality. At present agriculture is the largest emission source of ammonia to the UK atmosphere, a chemical which undergoes reaction with acidic pollutants from other sources to form PM. A major fraction of UK PM is associated with ammonium nitrate, where nitric acid formed from combustion NO_x (for example from transport) has combined with ammonia from agriculture. Strategies to reduce fertiliser use and N_2O emissions have the potential to also deliver reductions in ambient ammonia and PM, as would any wider reduction in agricultural intensity.

The UK atmosphere contains an excess of ammonia at present and so sustained ammonia reductions are needed for significant PM benefits to begin to accrue. It should be noted that historically ammonia is the air pollutant that has been least successfully addressed in terms of emissions reduction, in the UK and across Europe more broadly. There is a strong argument for considering nitrogen reduction measures holistically, since measures to reduce atmospheric emissions of ammonia and N_2O could potentially lead to increased nitrogen releases as run-off to streams and rivers where increased nitrate concentrations cause harm to aquatic ecosystems. Some mitigation approaches to reduce ammonia emissions from agriculture, such as injecting slurry into soils rather than surface application methods may lead to increases in N_2O from soil due to enhanced soil nitrogen levels, especially if applied in wet potentially anaerobic soil conditions.

Reductions in the UK farmed animal population, a consequence of lower overall meat consumption patterns in some Net Zero scenarios, will have clear air quality benefits. Slurry and manure from ruminants, pigs and poultry are the dominant source of ammonia emissions in the UK, released from the animal housing, the manure/slurry storage at the farm or via emissions from land that has been fertilized with animal waste.

Lower animal numbers, possibly combined with improved animal diets and genetic manipulation, may also result in reductions in agricultural methane emissions. Reduced methane emissions can feed through also into reductions in wider tropospheric ozone. It should be noted that these ozone effects would be positive from an air quality perspective, albeit modest, and potentially spread over regional scales rather than the UK in isolation.

5. Forestry, bio-crops, and biogenic emissions

Changing how land is used in the UK is a major theme within the Net Zero strategy, including significant afforestation and some increase in the use of agricultural land for bioenergy crops, subsequently used in combination with carbon capture technologies (referred to as BECCS). Plants and trees are a source of VOCs to the atmosphere – biogenic volatile organic compounds (BVOCs) - and they interact with NO_x and sunlight to form photochemical O_3, particularly during the summer months. At present BVOCs are a relatively minor component of the total mass of VOCs emitted in the UK (perhaps 10-20%), but the high reactivity of BVOCs such as isoprene, means those emissions are disproportionately significant in generating surface O_3 in the rural environment.

Whilst NO_x emissions are predicted to decline under Net Zero scenarios it is unlikely that it can be completely eliminated as a pollutant. The non-linear pseudo-catalytic nature of O_3 formation means that O_3 can be formed efficiently even at modest ambient concentrations of NO_x, assuming sufficient reactive VOCs, sunlight and water vapour are present. The future trajectory of ambient NO_x itself will in turn be critically tied to how hydrogen is used within the economy, whether it is combusted, and if so how, where and whether emissions after-treatments are used.

Higher ambient temperatures in the UK resulting from climate change itself are likely to increase BVOC emissions even without increased forest cover in the UK. The combination of increased temperature and forest area therefore creates the potential for significantly enhanced BVOC emissions, and by extension O_3 formation, unless emissions are managed through careful species selection strategies. Not all variety of trees and plants emit BVOCs and there is a well-established science on which tree-types are optimal if managing emissions is an objective. The Net Zero scenarios and their implementation need to embed this low-BVOC thinking into practical delivery, ensuring that where afforestation is undertaken, that minimization of BVOC emissions has been included in the design criteria.

Should increases in bioenergy crops become a major Net Zero pathway, then further factors beyond their potential BVOC emissions become significant. If crops require different fertiliser applications this might lead to changed soil ammonia and/or NO_x emissions, with possible impacts then on secondary chemistry to increases in PM. The 2050 scenarios are clear about the potential scope for bioenergy crops in either net zero, or net negative GHG configurations, when combined with CCS. It is important however to consider the possible air quality impacts of any transitional uses of biofuels on the way to 2050 which may not necessarily efficiently capture emissions. The use of bioenergy, particularly unabated urban wood-burning (including pellet boilers, stoves and open fires) has led to some well-documented urban PM problems where air quality has degraded, an unintended consequence of initially GHG-motivated interventions. A co-ordinated approach to Net Zero and the Defra Clean Air Strategy is important here as the latter has already identified possible measures to mitigate emissions from urban wood burning.

6. Use of hydrogen as a fuel

A growth in the use of hydrogen as a multipurpose fuel source is a major component of the Net Zero strategy, with both national production and consumption increasing dramatically over the next three decades. In this analysis our assumption is that it is generated from low carbon, low emission sources at an industrial scale and used as either H_2 or ammonia. In principle hydrogen is a very clean fuel from an air quality perspective, particularly so if used in combination with fuel cells, where no air pollution emissions arise. The widespread use of fuel cells creates very significant opportunities for air quality improvement in the UK, since it is essentially zero emissions from an air quality perspective. The use of hydrogen as a more traditional combustion gas, for example replacing fossil methane in the gas grid, or in engines, does however have the potential to generate a number of air pollutants, particularly NO_x, and secondary PM, via nitrates.

It should be noted that hydrogen itself is a reactive gas in the atmosphere that has the potential to generate O_3 on regional scales. Like methane, leakage from the gas network would be a critical factor in managing the impacts of fugitive losses to the atmosphere.

Hydrogen in the gas grid

The use of hydrogen as a replacement fuel in the UK fossil gas network, and more specifically as a means to eliminate methane and CO_2 from space-heating applications, potentially generates a range of different air quality impacts. The burning of hydrogen in smaller domestic boilers, and other similar natural gas- burning appliances, is likely to be possible given modest modifications to existing technologies. This would also likely lead to similar or lower NO_x emissions to those emitted when using methane fuel currently. The economics of domestic boilers are such that it would not likely be cost-effective to include chemical or catalytic abatement measures for NO_x, as currently occurs on vehicles, however the use of high efficiency burners would be one method of NO_x mitigation. The use of hydrogen as a significant energy source for domestic and commercial space heating would potentially lead to those remaining NO_x emissions (albeit lower than today) being located in higher population density areas.

An unambiguous benefit of the replacement of fossil gas with hydrogen would be the elimination of VOC leakage from the current gas distribution network. Around 10-15% of fossil methane gas is comprised of other VOCs such as ethane, propane and butane. The use of hydrogen within the national gas network would completely eliminate emissions of these VOCs, with benefits experienced as lower O_3 concentrations.

Using hydrogen in engines

Exhaust emissions arising from hydrogen combustion in engines is an area of some uncertainty. Burning hydrogen can generate NO_x and other oxides of nitrogen, hydrogen and oxygen, plus a large amount of water. It is likely that a highly lean combustion approach would be employed to maximise efficiency coupled to existing technologies of Exhaust Gas Recirculation and Selective Catalytic Reduction to control NO_x. Hydrogen could well be an attractive option for large mobile industrial machines with limited range, or for applications that are remote where electrification is not possible. This type of large plant use of hydrogen would likely benefit from existing know-how and technologies used to manage NO_x (and other pollutant) emissions.

The use of ammonia as a transport medium for hydrogen at industrial scales is predicted, and this is identified as possibly a key bulk fuel for sectors such as international shipping. Whilst fugitive emissions of ammonia would in principle impact air quality negatively, through PM formation, the highly toxic nature of pure ammonia is likely to lead to stringent controls on its handling and storage and systemic leakages would not be anticipated, although this remains an uncertainty until more evidence is available.

Burning ammonia in an internal combustion engine does present some challenges since it has a higher auto-ignition temperature compared with common fossil fuels. In practice, this means that a higher compression ratio and / or charge heating might be required in combination with a high energy ignition source to facilitate combustion. An alternative approach may be to ‘seed’ the combustion with a different, more combustible fuel. Applications in development have used fossil fuels such as diesel or natural gas to create an initial burn and initiate ammonia combustion. However, this erodes the carbon benefit of the application. Ammonia also has a relatively slow flame speed, and this can result in lower engine efficiency and increased likelihood of incomplete or unstable combustion at light loads. To counter this in spark ignition engines the seeding of ammonia combustion with hydrogen, catalytically cracked from the original ammonia supply is being explored. Diesel pilot ignition can be used in compression ignition applications (although this can no longer be considered zero-carbon) most likely in a diesel-like combustion cycle, again requiring an exhaust gas after treatment system.

7. Carbon Capture and Storage

Considerable uncertainties exist around the scale, technologies and economics of carbon capture and storage, although at present a significant component of the future UK carbon budget assumes CCS in the energy mix. This includes removing CO_2 from traditional fossil fuel use, and in net-negative configurations *via* the capture of emissions from biofuels. From an air quality perspective, a general assumption is that efficient large-scale CCS would have effective emissions abatement included within the plant infrastructure and be regulated, permitted and monitored in a similar manner to large combustion plant infrastructure at present. There are however multiple variants of CCS (both pre- and post-combustion) and there is no clear consensus on which is likely to be the most effective, technologically or economically.

The most well reported area of intersection between CCS greenhouse gas reduction and air quality is around unintentional solvent (and by-product) emissions and this can be associated with both pre- and post-combustion CCS. The carbon capture process typically involves the use of an organic stripping solvent, with organic amines being the most well-reported in literature. Pilot scale CCS activities have shown the potential for the co-emission of trace amounts of organic amine as a by-product, including some highly toxic species such as nitrosamines. To address this, alternative novel CCS solvents with lower toxicity (for example oxygenated organic compounds) are emerging. There remains a general principle that by-product emissions from the solvent stripping process require careful evaluation, for both overall mass of VOC emissions (because of PM and their PM and O_3 forming potential) and specific direct chemical toxicity. Existing regulatory mechanisms would be expected to address this hazard through the permitting process.

8. Building energy efficiency

Improvements in buildings energy efficiency are anticipated to deliver considerable reductions in greenhouse gas emissions across commercial, public and domestic spaces. Increases in energy efficiency reduce space heating requirements, energy consumption and associated emissions. In the short term, reducing demand from gas boilers is directly beneficial for local air quality, with the potential for longer term complete elimination of air pollution emissions as heating systems transition away from fossil carbon sources. Increased buildings energy efficiency can however sometimes lead to reductions in air exchange rate and ventilation and an increase in air pollution indoors. Highly energy efficient buildings materials can themselves also be a source of indoor pollution.

Poor indoor air quality is by no means an inevitable consequence of energy efficiency measures, but it is a factor that must be considered at an early phase of strategy development, This should include establishing clear indoor air quality objectives for new and retro-fitted buildings alongside those for energy efficiency. Indoor air quality is however also affected by many factors that are not directly connected to greenhouse gases and energy efficiency. Creating better, more energy efficient buildings must be undertaken with foresight of other evolving social factors and reflect changing ways of working and living, including consumer patterns and preferences.

With increasing energy efficiency measures to reduce GHG emissions, such as draught-proofing and triple glazing, there may be an increased risk of indoor overheating in summer, which could lead to increased seasonal demand for electricity. Building energy efficiency measures need to be carefully considered so that potential negative impacts can be appropriately mitigated.

The Net Zero plan does not include any wood burning at domestic scale as a primary heating source in 2050, and this is clearly a positive air quality change since this is currently a large source of primary urban PM emissions. Current understanding of the consumption of wood for burning in homes is that it is used frequently for decorative purposes rather than as a primary source of energy. Implementation of this aspect of the Net Zero plan may need to consider factors beyond the provision of suitable alternative domestic energy sources, although clearly well-heated energy efficient homes should reduce the direct need for burning of wood or solid fuel. It is worth noting that some aspects of indoor air quality are entirely de-coupled from energy consumption, particularly emissions of, and exposure to

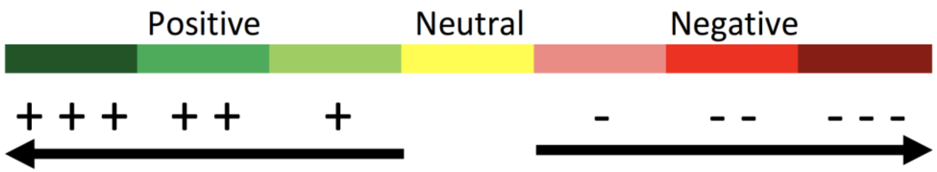
VOCs (and their by-products) from construction, professional and consumer products and standalone measures may be needed to control these.

The development of national indoor air quality objectives that could sit alongside those for future energy efficiency standards would be highly beneficial and ensure that effective management of the built environment was delivered in a joined-up way.

Annex 1. Workshop Attendees

NAME	ORGANISATION
SHAUN BRACE	Defra
JOHN NEWINGTON	Defra
SARAH MOLLER	Defra/AQEG
ROSE WILLOUGHBY	Defra
MOHAMED GHALAIENY	Defra
DAN MCGONIGLE	Defra
BILL PARISH	Defra
DONNA YATES	Defra
AMRITA KATARIA	Defra
LAURENT PIPITONE	Defra
SARAH REEVES	Defra
ALASTAIR LEWIS	AQEG, NCAS & University of York
EIKO NEMITZ	AQEG, UK Centre for Ecology and Hydrology
MARTIN WILLIAMS	AQEG, Kings College, London
GARY FULLER	AQEG, Kings College, London
BEN MARNER	AQEG, Air Quality Consultants
CLAIRE REEVES	AQEG, University of East Anglia
DAVID FOWLER	AQEG, UK Centre for Ecology and Hydrology
DAVID CARRUTHERS	AQEG, CERC
MAT HEAL	AQEG, University of Edinburgh
JAMES ALLAN	AQEG, NCAS & University of Manchester
DAVID CARSLAW	AQEG, University of York & Ricardo
TIM MURRELLS	AQEG, Ricardo
HELEN APSIMON	Imperial College
DAVID JOFFE	Committee on Climate Change
THOMAS ANDREW	Committee on Climate Change
JAKE LANGMEAD-JONES	Committee on Climate Change
PETER COLEMAN	Department for Business, Energy and Industrial Strategy
TIM DEVERELL	Department for Transport
ROSALIND MARSHALL	Department for Transport
KAREN EXLEY	Public Health England
ALISON GOWERS	Public Health England / COMEAP
HELEN MACINTYRE	Public Health England
AMANDA MACLEAN	Environment Agency
STEFAN GILLOTT	Defra / Kings College, London
ADAM VAUGHAN	Defra / University of York

Potential Air Quality Impact



Sector	GHG reduction measure	PM	NO_x	O_3	VOCs	NH_3	Narrative
Agriculture and Land Use	Natural gas demand replaced with low-carbon electricity; the majority of agricultural vehicles switch from diesel to biofuels by 2050.		+	+	+	+	Reductions in NO_x and VOCs expected, although neutral impacts on PM since non-exhaust emissions will remain.
Agriculture and Land Use	Widespread uptake of practices and technologies to improve nitrogen use efficiency.	+	+			+ +	Should lead to reductions in NH_3 and PM as a secondary effect. Small positive impacts for NO_x. Anaerobic digestates require controls. Reduced fertiliser use will reduce emissions from its manufacture and associated energy use.
Agriculture and Land Use	Livestock measures to reduce CH_4 emissions, such as the feed digestability for cattle and sheep. Assumed high uptake rate by farmers (75% of the maximum technical potential).			+		+	High uncertainty regarding NH_3 because it is not clear what is achievable, noting that very little progress made in the past. Animal numbers may be a more significant driver of emissions.
Agriculture and Land Use	Improved storage, management and application of manure. Assumed high uptake rate by farmers (75% of the maximum technical potential).	+ +	+	+ +	+	+ + +	High confidence that this would lead to multi-pollutant emission reductions, noting this is a relatively low-cost intervention.
Agriculture and Land Use	20-50% reduction in consumption and production of red meat and dairy. 15% of agricultural land freed up for sequestration, remaining land use for crops and livestock.	+ +	+	+ +		+ + +	This measure depends on incentivising farmers to use their land in other ways. Maintaining food production per capita is implicit in these measures, but broad air quality benefits are anticipated.
Agriculture and Land Use	Afforestation, 30-50 kha of new planting per year from the mid-2020s to 2050.	+	+	-	- -	+	Impacts on air quality depend on the type of trees planted; ideally selected for low BVOC emissions. There may be potential for trees to capture (and reduce) PM. Uncertainty over changes to soil NO_x emissions; however, if land-use is converted from farmland, then a net positive.
Agriculture and Land Use	Forest productivity, 80% of broadleaf woodlands are actively managed by 2030. Tree yields improve by 10-20%					-	May increase fertiliser use and NH_3 emissions to deliver efficiency gains in forestry activity.

Sector	GHG reduction measure	PM	NO_x	O_3	VOCs	NH_3	Narrative
Agriculture and Land Use	Energy crops and short rotation forestry planted on 0.7-1.2 million hectares of agricultural land.				-		Willow is a significant VOC emitter, which would potentially give rise to ozone production. Needs to avoid fertilisation and select species for low VOC emission. High NH_3 emissions can arise from other short rotation crops so would require management.
Agriculture and Land Use	Trees planted on 10% of farm land and hedgerows extended by 40%.	+	+			+	Hedgerows have small beneficial impacts on PM, with other possible very small effects on VOCs emissions similar to afforestation.
Agriculture and Land Use	55-75% of peatland is restored and managed.			-			Peatland restoration reduces drainage and may increase CH_4 emissions, with implications for ozone formation; effects are likely small over UK.
Agriculture and Land Use	20-50% reduction in food waste by 2025.	+	+			+ +	Food waste leads to anaerobic digestate so reductions have direct benefits and may also reduce demand for food production with upstream benefits associated with reduced NH_3 emissions.
Agriculture and Land Use	Anaerobic Digestion.				-	-	Some air quality hazards associated with poorly managed anaerobic digestion, including fugitive emissions of VOC (possibly malodour) and NH_3 emissions.
Aviation	Limited growth of 60% higher than 2005 levels, with fuel efficiency improvements of 0.9% per year.	+	+	+	+		Reducing aviation growth may have some positive impacts on ultrafine PM, compared to uncontrolled growth. However, it should be noted that negative air quality outcomes continue to accrue and will potentially be higher than today. Reduced demand will also reduce emissions from road traffic activity and ground operations at airports.
Aviation	5-10% of aviation fuel used being bio or synthetic fuel.				-		Considerable uncertainty as to how emissions will change with the use of different fuel types in aviation. Some DfT evidence that black carbon emissions may reduce due to changes in the oxidation processes in the flame. It could also increase the amount of organic carbon produced either as VOCs or particulate due to the fuel being less pure.
Buildings (Residential and non-residential)	19 million homes supplied by low-carbon heat from; heat pumps, hybrid heat, H_2 boilers, and low-carbon district heating. Heating not supplied by biomass boilers.	+ + +	+ +		+		H_2 as a combustion gas for used for heating would impact NO_x emissions. If combined heat and power plants (CHP) are included, there is potential for higher NO_x, compared to fuel cells although likely lower than existing natural gas use.
Buildings (Residential and non-residential)	From the mid-2020s, all new homes built are ultra-high energy efficiency and widespread retrofitting of existing homes, reducing energy demand by 25% overall.	+ + +	+				Retrofits can significantly affect indoor environments. Designs need to account for keeping houses cool in summer. Reductions in air exchange to keep homes warm may reduce indoor air quality. Modern materials can be sources of VOC's in an indoor environment.

Sector	GHG reduction measure	PM	NO$_x$	O$_3$	VOCs	NH$_3$	Narrative
Buildings (Residential and non-residential)	Half of heat is from low-carbon heat networks and with the remaining half from heat pumps and improved energy efficiency.	-	+	🟨	-	🟨	Non-residential buildings will have similar impacts to residential; however, are more uncertain. Actions can reduce any effects in urban buildings; for example, optimising air intakes far from the road. Increased energy efficiency may increase indoor exposure to VOCs and PM, and may be a possible negative consequence.
Buildings (Residential and non-residential)	5 million homes and 46% of non-residential buildings supplied by low-carbon district heating.	+	+	+	+	🟨	Abatement of emissions generally easier at a single large plants than if emitted at home, so broadly positive benefits anticipated.
Carbon Capture and Storage (CCS)	CCS used across the economy for power generation, hydrogen production and industry.	-	🟨	🟨	- -	🟨	Each CCS solvent has a different potential for affecting air quality. Some CCS solvents generate carcinogens (VOC and PM) in pre- and post-combustion. These can be difficult to measure, due to toxicity. The technologies are known but not yet operating at scale in the UK or widely internationally.
Electricity Generation Double 2017 levels	Electricity demand increase.	Not assessed, boundary conditions					Under a 2020 'business as usual' scenario, this action in isolation would have the potential to have widespread negative impacts on air quality. However, the low-carbon emission 2050 energy scenarios (for example, powered by renewables /nuclear /CCS combinations) could have very significant positive impacts.
Electricity Generation Double 2017 levels	60-90% electricity generation from wind and solar.	+ +	+ +	+ +	+	🟨	Phase-out of combustion sources would have a range of benefits. This assessment ignores the transitional impacts of the manufacture and construction of the listed technologies.
Electricity Generation Double 2017 levels	6% electricity generation from bioenergy with carbon capture and storage (BECCS).	-	-	-	- -	-	Fast-growing plants have the potential to increase biogenic VOCs (and therefore ozone), depending on which species are grown. Localised increased NO$_x$ and PM emissions could arise from additional transport and pelletizing of plants to biofuels. Potentially some changes in ammonia emissions from fertiliser.
Electricity Generation Double 2017 levels	23% electricity generation from natural gas with CCS.	🟨	🟨	🟨	- -	🟨	Assessment assumes effective mitigation of combustion emissions such as NO$_x$ and PM as part of the CCS process. Main air quality impact from CCS capture solvents, relative to natural gas use without CCS.
Electricity Generation Double 2017 levels	4-11% electricity generation from nuclear.	-	-	🟨	🟨	🟨	The primary source of air pollution arises from long construction times (decades) needed to build a nuclear power plant. These include dust, temporary power and off-road vehicles. These impacts are likely to be localised to specific communities.
Electricity Generation Double 2017 levels	<1% electricity generation from flexible hydrogen/ammonia gas plant. (flexible gas plant, interconnection, demand-side response, battery storage, hydro storage, power-to-gas).	🟨	-	🟨	🟨	🟨	Any air quality effects are likely to be small. Back up power generation possibly involving combustion of H$_2$, would be expected to be located in rural locations.

Sector	GHG reduction measure	PM	NO_x	O_3	VOCs	NH_3	Narrative
F-Gas	Switch from fluorinated-gases to low global warming potential alternatives in almost all areas, including widespread use of alternatives (e.g. isobutane, propane).	🟨	🟨	-	- -	🟨	Replacement of F-gases with VOC propellants. Refrigerants create the potential for increased emissions which may form surface ozone. Non-VOC alternatives would be optimal.
Gas Grid	Bio-CH_4 from anaerobic digestion injected into the gas grid.	🟨	🟨	🟨	- -	- -	CH_4 injected into the gas grid will still have the same leak potential, with the additional issue of NH_3 emissions from the digestion. Questions remain over where the products from the waste process will go after and the downstream impacts of the waste disposal.
Gas Grid	Displacement of natural gas in gas grid for home energy and transport, could be widespread or limited.	🟨	- -	+	+ +	🟨	Scope to include transportation and use for heating, with potental to reduce VOC emissions. NO_x emissions could be comparable or lower to gas boilers emission today. The scale of impact assumes using gas combustion boilers; however, using a fuel cell/heat pump would be highly beneficial towards reducing both VOC and NO_x emissions.
GHG Removals/CCS	1 Mt of direct air carbon capture and storage (DACCS) by 2050.	🟨	🟨	🟨	-	🟨	Potential impacts from possible organic solvents used during the process. Impacts assume clean energy is used to power the capture process.
Hydrogen Increase tenfold from 2017 levels (use in industry, gas grid and HGVs)	Demand: widespread Hydrogen (H_2) use in industry and use in other sectors (HGVs, gas grid).	Not assessed, boundary conditions					The use of H_2 may lead to increased NO_x emissions, depending on its application; however, the expectation is that H_2 will primarily be used in fuel cells. Use in domestic combustion boilers could give an adverse effect for NOx, but a positive displacement of VOCs.
Hydrogen Increase tenfold from 2017 levels (use in industry, gas grid and HGVs)	Production from methane (CH_4) reformation with CCS.	🟨	🟨	-	-	🟨	Impacts will dependant on which production methodology is chosen. Large scale production is likely to have well-controlled point source emissions. Increased VOC emissions may be associated with the process; however, large uncertainties remain as to which technology is used.
Hydrogen Increase tenfold from 2017 levels (use in industry, gas grid and HGVs)	Production using low-carbon powered electrolysis.	🟨	🟨	🟨	🟨	🟨	Assuming a low carbon energy source, no significant impact anticipated.
Hydrogen Increase tenfold from 2017 levels (use in industry, gas grid and HGVs)	H_2 imported from the international market, potentially transported as ammonia.	🟨	-	🟨	🟨	-	NH_3 is a toxic gas, requiring safe storage and transportation, although this is a well-established industry already. Likely a very small potential for fugitive NH3 emissions. Potential for increased NO_x emissions if used for combustion, but predicted use mainly focused on fuel cells.
Industry	Widespread deployment of H_2, electrification or bioenergy for stationary industrial heat/combustion in manufacturing sectors not treated with CCS.	+	🟨	+	+	🟨	Likely to have positive benefits for PM and VOCs. The impacts towards NO_x are more uncertain, depending on how the H_2 is used.

Sector	GHG reduction measure	PM	NO_x	O_3	VOCs	NH_3	Narrative
Industry	90% of off-road machinery switched to H_2 and electricity	+		+	+		Likely to have positive benefits for PM and VOCs. The impacts towards NO_x are more uncertain, depending on how the H_2 is used.
Industry	Reduced venting and leakage of CH_4 through gas recovery, reduced emissions completions, continuous monitoring, flaring where needed, and closure of parts of the gas grid.			+	+		Reductions in VOC emissions would be anticipated, with additional benefits (small) for ozone.
Industry	Emissions from fuel combustion in oil and gas production are reduced through a mix of CCS and electrification, with more CCS offshore and more electrification onshore.	+	+		+		Reductions in several pollutants would be anticipated, although offshore reductions would have only modest impacts on public exposure to pollution.
Industry/CCS	CCS in sectors with non-combustion process emissions (cement, lime, ammonia and glass) and 'internal' fuels produced by their feedstock (iron, petrochemicals and refining sectors).				-		Operating CCS requires energy, but the assumption is that clean sources will be used. For industrial processes, possibly some NH3 emissions. A possibility for temporary emissions during construction and retrofit phases. As for other CCS options, changes in VOC emissions are possible
Industry/CCS	BECSS in industry only to a limited extent where biomass is already used.				-		Only small effects anticipated since widespread adoption is not expected. As for other CCS options, changes in VOC emissions are possible.
Shipping	Almost all shipping fuel is ammonia (or hydrogen) by 2050.	+ + +	+ + +	+	+		Fugitive emissions of NH_3 are a risk; however, it can be controlled. SO_2 emissions possibly fully eliminated. Impacts assume all NH_3 is used in fuel cells, but some emissions of NO_x and PM may occur if combusted, but lower than current technologies.
Surface Transport	10% shift of vehicle miles to walking, cycling & public transport.	+ + +	+ +		+ +	+	Widespread positive air quality benefits, assuming suitable investment in urban infrastructure is made to facilitate this change.
Surface Transport	Ban sale of fossil fuel cars/vans by 2035. Full electrification of the fleet by 2050.	+	+ + +		+ + +		Elimination of NO_x and VOC emissions from vehicles are the significant benefits. Non-exhaust PM emissions could be further reduced with further technology improvements and managing vehicle weights. The impacts of vehicle automation are uncertain, potentially increasing power demand but leading to smoother lower PM emission driving.
Surface Transport	Almost 100% of Heavy Goods Vehicles (HGVs) being zero-carbon emitters by 2040 (via battery-electric, hydrogen, or hybrids with overhead power lines on major roads).	+	+ + +		+		Harder to achieve than for light-duty vehicles. How H_2 will be used is currently less clear; it could be used as a combustion fuel in large vehicles; greatest benefits arise with the use of fuel cell technology.

Sector	GHG reduction measure	PM	NO_x	O_3	VOCs	NH_3	Narrative
Surface Transport	Widespread rail electrification and switch to H_2 trains where electrification is not possible, by 2040.	+	+ +	🟨	+	🟨	Potentially the most significant benefits will be arounds train stations and travelling on trains. This will be primarily an occupational benefit for reductions in exposure, as well as some benefit for passengers.
Waste	Ban on biodegradable waste to landfill by 2025, diverted to biogas and energy generation from waste.	🟨	🟨	🟨	-	- - -	Risk of increased usage and therefore, increased emissions of VOCs and NH_3; however, options exist to manage emissions effectively.
Waste	41 TWh's of energy from waste fitted with CCS, majority of energy used for power.	+	+	🟨	+	🟨	Air quality impacts are largely dependent on the cleanliness of the combustion facility and capture, but reasonable to assume robust regulation and enforcement.
Waste	20% reduction in Nitrous Oxide (N_2O) and CH_4 emissions from wastewater treatment by 2050.	🟨	🟨	🟨	🟨	🟨	Likely to have only limited impacts on air quality.
Waste	70% recycling rate by 2025.	🟨	🟨	🟨	🟨	🟨	Likely to have only limited impacts on air quality.