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Effects of net-zero policies and climate change on air quality

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Effects of net-zero policies and climate change on air quality
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Cover image Fossil fuel power stations in the English Midlands on a winter morning. These are being replaced by renewable sources of electricity, notably by offshore wind turbines. © pro6x7.

Contents

Policy priorities

The combination of net-zero policies to tackle climate change will accelerate current progress towards clean air in the UK. Options within the range of control measures to achieve net-zero present an opportunity to choose win-wins for climate and clean air and avoid measures which slow the clean-up of the air we breathe.

Expected evolution of critical air pollutants under net-zero measures and climate change

Particulate matter

Outdoor population exposure and effects of particulate matter (PM) on human health are expected to decline as a result of control measures already enacted and many net-zero policies. However, PM will still pose a significant health risk through to 2050 and effects due to indoor exposures will become more important. Additional efforts to reduce PM will therefore be required.

Ozone

Effects of ozone (O_3) on human health and ecosystems/crop production are expected to remain at similar levels to those of 2020 through to 2050, driven mainly by global O_3 background, which in turn depends substantially on natural and anthropogenic methane (CH_4) emissions and other ozone precursors, including wildfire emissions. International action to reduce CH_4, in combination with national efforts, offer an effective control measure.

Nitrogen

In the absence of large reductions in ammonia (NH_3) from agriculture, UK emissions of NH_3 are expected to grow in response to a warmer climate and will dominate nitrogen deposition and effects on ecosystems and contribute substantially to human health effects through to 2050. Control measures on NH_3 emissions at the UK scale would be effective in mitigating this risk.

Nitrogen dioxide

Emissions and effects of nitrogen dioxide (NO_2) on human health in the UK are expected to decline steadily over the next 20 years as a result of net-zero policies and control measures already enacted.

Net-zero measures which may require mitigation to protect air quality

Combustion of biomass

Combustion of biomass has the potential to lead to reduced net greenhouse gas (GHG) emissions relative to fossil fuels, but could lead to air pollutant emissions, especially particulate matter with a diameter less than 2.5 µm ($PM_{2.5}$).

Cultivation of crops for biofuels

Increased cultivation of fast-growing crops for biofuels may, depending on the land use change, lead to increased biogenic volatile organic compounds (BVOCs) emissions, downwind O_3 and secondary organic aerosol formation.

Hydrogen as a combustion fuel

Use of hydrogen as a combustion fuel has the potential to increase emissions of nitrogen oxides (NO_x), a precursor to O_3 and $PM_{2.5}$.

Executive summary

Climate change and air pollution are related issues that merit a co-ordinated policy response. Climate change presents a demonstrable and rapidly growing threat to humanity and nature, while air pollution is estimated to account for around seven million premature deaths per year globally[1] and more than 28,000 per year in the UK[2].

While the UK has the clear target of net-zero GHGs by 2050 to address climate change, there is, so far, no equivalent pathway of air pollutant emission targets through to 2050.

The establishment of more specific net-zero policies for the next three decades provides an opportunity to consider climate change and air quality together and achieve the twin goals of cleaner air and net-zero GHG emissions.

Effects of climate change on air quality

Before examining impacts of net-zero policies, the report considers how climate change itself is expected to affect air quality in the UK by influencing emissions, atmospheric processing and transport of many pollutants. Some of these effects are likely to slow or temporarily reverse improvements in air quality. They are also likely to lead to changes in the seasonal and geographical variations in air quality.

- In summertime, more frequent and intense heat waves are likely to lead to more episodes of O_3 and PM. This reflects the build-up of local emissions under stagnant meteorological conditions along with increases in precursor emissions from vegetation and soils, more moorland fires, and inflow of pollutants from mainland Europe. In contrast, wintertime air quality is likely to improve as the cold stagnant conditions that lead to pollutant accumulation are expected to become less frequent.
- The responses of air quality to climate change will vary across the UK, with the southeast more exposed to stagnant meteorological conditions, high temperatures and continental inflow. The difference between urban and rural air quality is expected to narrow in response to changes in both emissions and meteorology.
- Changes in temperature, humidity and precipitation will alter the emissions, formation, processing and removal of PM, affecting its composition and distribution. While increased removal by rainfall is beneficial, greater formation of PM from organics and NH_3 is a concern.
- Emissions of NH_3, CH_4, BVOCs and soil NO_x are expected to increase with temperature, creating an additional motivation to reduce such emissions now. Reducing NH_3 emissions would decrease PM concentrations and benefit biodiversity by reducing the deposition of reactive nitrogen on sensitive ecosystems.
- O_3 will remain an important global and regional pollutant throughout the period to 2050 and beyond. Climate-driven increases in input from the stratosphere, increased formation from climate-sensitive precursor emissions, especially of CH_4 from wetlands, and increased wildfires will lead to increased O_3 in many parts of Europe. In the UK this will be offset by greater O_3 destruction in air from the Atlantic, a consequence of a warmer, more humid atmosphere. International action to reduce CH_4 and other O_3 precursors would therefore be a win-win for climate and air quality.

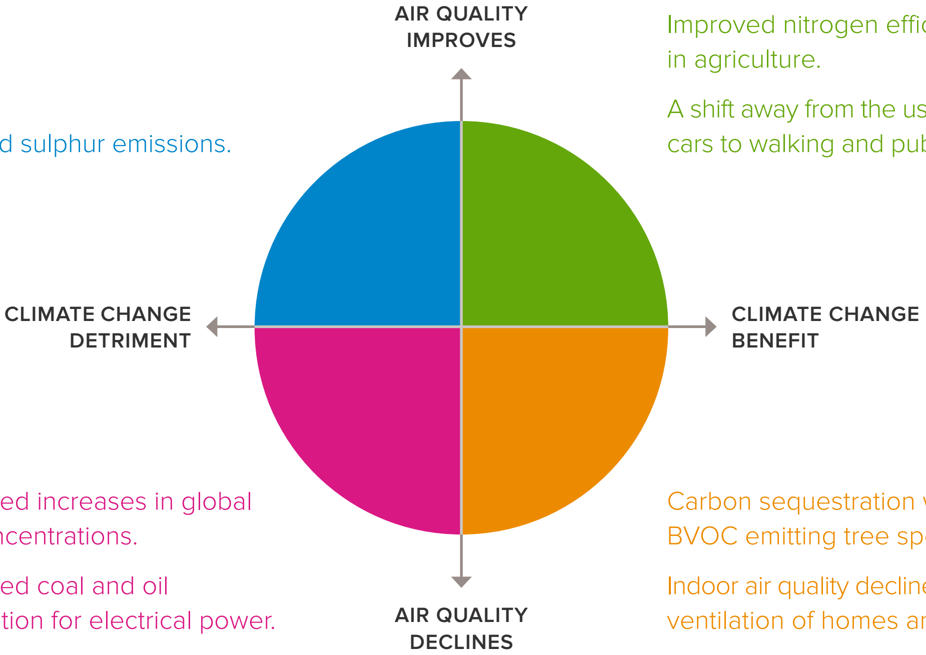
Effects of net-zero measures on air quality
The transition to net-zero will deliver significant improvements in air quality as a co-benefit. The policy challenge is to maximise these improvements while retaining the GHG mitigation. Many of the actions taken to achieve net-zero are unequivocally positive for air quality. In other areas, action can be taken to enhance the air quality benefits, often through small changes. In a small number of areas, net-zero measures may have adverse impacts on air quality that require mitigation or swapping those measures for others that have no adverse effects on air quality (see Figure 1).

The short atmospheric lifetimes of most air pollutants mean that positive health benefits start as soon as the source of pollution is removed, providing a rationale for the prioritisation of net-zero measures that also deliver significant air quality co-benefits.

FIGURE 1

Effects of policies on air quality and climate change

Net-zero measures have a range of impacts on air quality and climate change, providing incentives to maximise benefits for both. This figure illustrates the different responses of air quality and climate change to examples of net-zero measures and controls on air pollutant emissions.



Electrification of transport and home heating with wind and solar power.

Carbon sequestration with low BVOC emitting tree species.

Improved nitrogen efficiency in agriculture.

A shift away from the use of passenger cars to walking and public transport.

Reduced sulphur emissions.

Continued increases in global CH$_4$ concentrations.

Continued coal and oil combustion for electrical power.

Carbon sequestration with high BVOC emitting tree species.

Indoor air quality declines with reduced ventilation of homes and offices.

Combustion of biomass or hydrogen increases NO$_x$ and PM$_{2.5}$.

Opportunities with clear co-benefits

- Replacing fossil fuel derived electricity with decarbonised electricity will lead to substantial reductions in emissions of NO_x and sulphur dioxide (SO_2) and hence in $PM_{2.5}$ and O_3.
- 'Active travel' measures that encourage a shift away from car use to walking, cycling and public transport provide both decarbonisation and improvements in air quality, as well as health benefits that extend beyond improving air quality. Reducing demand can decrease emissions that are challenging to address through technology alone, such as non-exhaust PM from road vehicles and aviation jet turbine emissions.
- Improved efficiency in the management of nitrogen in the agricultural system has the potential to reduce NH_3, nitrous oxide (N_2O) and NO_x emissions in most cases. This would feed through into lower concentrations of $PM_{2.5}$ on a regional scale and a reduction in nitrogen deposition onto ecosystems. Measures to reduce dairy and red meat consumption would reduce NH_3 and CH_4 emissions, contributing to cleaner air and the net-zero target, as well as benefiting health.

Opportunities to enhance net-zero policies to benefit air quality

A transition to a fully battery electric vehicle fleet should bring significant improvements in urban air quality, benefiting many disadvantaged areas. However, emissions of non-exhaust particles from friction and abrasion such as from tyre, brake and road surface wear, and the resuspension of road dust, will continue to be a significant source of $PM_{2.5}$ emission, even from a fully electric vehicle fleet. These emissions could increase if average vehicle mass and numbers were to increase, as it may with larger batteries. This ongoing air quality issue can be mitigated by use of regenerative braking, smoother driving through vehicle autonomy, and the use of new pollution control technologies such as particle capture from brake callipers and low emission tyres.

In addition, one consequence of the reduction in urban NO_x emissions is an increase in O_3 concentrations because of a reduction in the chemical suppression of O_3 that takes place via reaction with nitric oxide (NO). The benefits of NO_2 reduction are likely to outweigh any O_3 disbenefit at the roadside, but this effect should be recognised, and regional O_3 pollution mitigated through policies that also reduce O_3 precursor emissions of volatile organic compounds (VOCs).

Net-zero measures that may require mitigation to protect air quality

- Carbon capture and storage (CCS) technologies may involve the consumption of large volumes of chemicals needed for the carbon dioxide (CO_2) stripping process. Possible fugitive emissions of volatile chemicals used in CCS can be controlled through the application of process after-treatment, and by selecting the materials on the basis of low toxicity and environmental impacts.

- While the expansion of decarbonised and nuclear infrastructure to replace fossil fuel assets will lead to air quality improvements, the transition period may have air quality impacts as a result of the temporary use of back-up power facilities, such as diesel farms, to supply capacity in peak periods, as well as construction activities. Mitigations can be introduced to manage such impacts, including enhanced requirements for after-treatment of combustion sources and dust suppression during construction.

- In the residential sector, technologies such as heat pumps and photovoltaics lead to unequivocal local air quality improvements. However, use of hydrogen or biogas boilers would likely lead to some emissions of NO and NO_2, which could be mitigated through enhanced requirements for emissions control and possibly new after-treatment technologies. Minimising leakage of hydrogen will maximise the climate and air quality benefits.

- Indoor air quality can be influenced, either positively or negatively, by net-zero measures. Delivering better indoor air quality in homes, workplaces and public buildings will require independent strategies as it is also influenced by human behaviours, product standards for buildings and furnishing materials, and the use of consumable products.

- Increased cultivation of fast-growing crops for biofuels and the planting of trees to create green urban spaces could lead to increased biogenic VOC emissions, leading to additional O_3 and secondary organic aerosol formation. These impacts can be significantly reduced through use of low-emitting species, such as cultivars of beech and lime, while avoiding large-scale planting of high emitting cultivars of species such as willow and oak.

- Actions on agricultural emissions should avoid ‘pollution swapping’ to deliver air quality benefits. For example, a switch away from ammonium nitrate fertilisers to urea could increase NH_3 emissions, although partial mitigation is possible through reduced overall consumption and improved farming practices.

- Combustion of biomass can reduce net GHG emissions relative to fossil fuels but could lead to air pollution emissions. After-treatment of emissions from biomass is likely to be cost effective at industrial scale, but possibly less effective at reducing emissions from domestic wood burning stoves or pellet boilers. Avoiding the use of biomass combustion in areas of high population density will be a key mitigation.

- Many of the key pollutants are secondary in nature, being formed in the atmosphere rather than emitted directly, including much of $PM_{2.5}$ and all O_3. These pollutants often have a non-linear relationship to their precursor emissions. In general, the term 'non-linearity' refers to a less than proportionate decrease in the secondary pollutant when the precursor emissions fall. Reducing the secondary emissions thus depends on continued action on the relevant primary emissions. For example, sustained reductions in emissions of NH_3 and NO_x are likely to be needed before substantial UK-wide reductions in resulting secondary PM are experienced. As $PM_{2.5}$ has a longer atmospheric lifetime than NH_3 or NO_2, this will demand continued international cooperation to reduce transboundary transport of pollution.
- Aviation has limited options for decarbonisation and thus for the foreseeable future it seems likely that airports will remain hotspots for air pollution due to emissions of PM, NO_x and VOCs from aircraft, as well as from road traffic and ground operations.

Areas for ongoing investigation

Effects of poor air quality on human health due to PM will likely remain despite the gradual reduction in exposure. There is strong evidence of adverse effects at exposures well below current levels and no identified safe lower concentration limit. The differential toxicity of particles is currently not well understood, which makes it challenging to determine the health impacts of changes in PM composition.

As emissions of pollutants continue to decline from historically dominant sectors such as power generation and road transport, where the emissions are generally well-quantified, a larger proportion of the remaining emissions will originate from diffuse sources where emissions are often not well quantified, such as cooking, ad-hoc burning and agricultural emissions. These changes will require further work on the UK National Atmospheric Emission Inventory (NAEI).

The changes in pollutant concentrations expected through to 2050 will have implications for their measurement in terms of the appropriate locations of monitoring sites and the relative importance of different source types. For example, there may be less need for roadside monitoring sites as vehicle exhaust emissions diminish.

Introduction

While climate change is having increasing impacts as a result of rising levels of GHGs, air pollutants are damaging human and environmental health. Some air pollutants also contribute to climate change, by absorbing thermal radiation and warming the climate system or reflecting incoming solar radiation and cooling the climate. Many sources of air pollutants, such as fossil fuels used for power, transport and heat, are also emitters of the main GHG, CO_2, through combustion. It is expected therefore that reducing combustion of fossil fuels will improve air quality as CO_2 emissions decline. There are many different sources of GHGs and hence a range of policy options to reduce emissions. This presents an opportunity to choose policies which maximise the benefits for air quality at the same time as achieving the desired trajectory towards the target of net zero GHG emissions.

The air in the UK has been substantially contaminated by pollutants (listed in Table 1) for over two hundred years. Over time, the pollutants that threaten human health and the environment have changed considerably from a mixture dominated by those co-emitted with GHGs from the combustion of fossil fuels to the current range of emissions that are derived from a broader range of sources, including some which are not co-emitted with GHGs.

From the time of the Industrial Revolution until the mid-20th century, coal smoke and SO_2 were the major constituents of the pollutant mix, along with NO_2, hydrochloric acid (HCl), NH_3, and PM from industry. These pollutants were responsible for extensive human health problems in the UK and for transport and deposition of pollutants across borders, including acid deposition throughout Europe, especially in Scandinavia.

Controls to address urban smoke and SO_2 problems, notably the 1956 UK Clean Air Act and Europe's UN Economic Commission for Europe's (UNECE) Convention on Long-range Transboundary Air Pollution in 1979, resulted in large reductions in emissions from urban coal combustion and sulphur compounds respectively. The improved air quality and reduced transboundary exchange of pollutants following these controls were important policy successes, but issues remained. In the 1990s, the UK faced growing air quality and human health problems, again centred on urban areas, but this time mainly due to transport related emissions of PM and NO_2 as well as O_3 episodes. Vehicle emissions of NO_x and VOCs have been largely addressed by a series of policy interventions, gradually reducing exhaust and fuel-related emissions from diesel and petrol vehicles.

By 2020, the burden of air pollution in the UK had been greatly reduced relative to the 20th century (see Figure 11). The only primary pollutant whose emissions have changed little is NH_3, which remains a substantial contributor to secondary PM and to nitrogen deposition and eutrophication of ecosystems throughout the UK.

The changes in composition of the air over the UK reflects policy initiatives implemented in the last five decades. While PM and its effects on human health remain an issue, especially in urban areas, the composition of PM emitted from vehicles has changed from exhaust-dominated sources in the late 20th century to non-exhaust emissions at present. VOC emissions are no longer mainly derived from vehicles and have declined by 50% since their peak in 1990. NH_3 from agriculture now contributes substantially to secondary inorganic PM. Agriculture is also an important source of two major GHGs, CH_4 and N_2O. Reducing the activities that lead to NH_3 emissions, notably livestock farming, therefore also presents an opportunity to reduce these GHG emissions.

CH_4 also contributes to poor air quality through the formation of tropospheric O_3. There are therefore a number of possible pathways towards a cleaner environment, which differ in their relative contributions to improved air quality and mitigation of climate change. This is the policy space that this report will explore – seeking to identify areas which maximise the air quality benefits while contributing to GHG emission reduction targets.

The context for the report includes a legal imperative to achieve net-zero GHG emissions in the UK by 2050, and plans for cleaner air, freshwater and ecosystems within the UK Environment Bill. The timing and options for these two processes are not co-ordinated. Unlike the clear target for net-zero GHG emissions in 2050, year-specific target emissions for the individual pollutants from 2020 are defined only to 2030 within the UNECE Gothenburg Protocol. There is no clear pathway of pollutant emission targets through to 2050, nor is there a clear priority within the five target pollutants considered ($PM_{2.5}$, NH_3, NO_2, SO_2 and non-methane volatile organic compounds) along the trajectory to a cleaner atmosphere in 2050.

In the absence of measures to consider both air quality and climate change together, opportunities to achieve the twin goals of clean air and net-zero GHG emissions will likely be missed. It is important to appreciate that climate change and air quality, while related, represent distinctly different areas of policy; solutions for one are not always beneficial for the other. Some policy choices may deliver GHG reductions while degrading air quality and vice versa.

The objectives of this report are to:

- provide evidence on structural, technical and behavioural solutions that can potentially address climate change and air quality together;
- raise awareness of net-zero policies which may have negative and/or unexpected impacts on outdoor and/or indoor air quality;
- outline evidence on how climate change affects air quality;
- identify air pollution sources that will not be tackled by net-zero measures and therefore require additional policy measures.

Changes in climate influence the emissions and the physical and chemical processing of pollutants in the atmosphere, including the primary pollutants and the products of their reactions and thus their atmospheric lifetimes and travel distances. These interactions are explored, and quantified where possible, in chapter 1 of the report. The report will identify the effects of these interactions at global and regional scales for each of the main air pollutants (O_3, CH_4, NO_2, NH_3, PM and VOCs). The effects of climate change on UK air quality through changes in atmospheric circulation and weather patterns will also be considered, drawing on recent research and synthesis.

Chapter 2 discusses the effects of policies to achieve net-zero on air quality, identifying net-zero policies with clear co-benefits for air quality, areas in which net-zero policies may be enhanced to benefit air quality and net-zero measures that may require mitigation to protect air quality.

Chapter 3 synthesises the effects of climate change and net-zero policies on air quality to provide insights on their combined consequences for human health and ecosystems and identifies priorities for policy development to maximise improvements in air quality and climate change.

TABLE 1

The air pollutants considered in the report, their sources, effects and atmospheric lifetimes

Pollutant	Sources	Negative effects	Atmospheric lifetime
NO_2	Combustion: transport, industry, and domestic and commercial heating	Human health: premature mortality; ecosystems: eutrophication; climate change due to ozone formation	<1 day
NH_3	Agriculture: livestock waste and fertilised cropland	Human health: as a component of PM leading to premature mortality; ecosystems: eutrophication; climate change through PM	A few hours
VOCs	Volatile organic fuels, solvents, industrial and domestic products, and vegetation	Human health: as components of PM leading to premature mortality; photochemical production of O_3 in the atmosphere which damages human health and ecosystems, and reduces crop yields	Hours to days for non-methane organic compounds (CH_4 lifetime ~10 years)
PM	Primary PM emissions from combustion, vehicles, industry, construction. Secondary PM from atmospheric processing of primary gaseous emissions (VOCs, NH_3, NO_x, SO_2)	Human health: premature mortality; climate: some PM cools the climate by increasing the Earth's albedo, eg sulphate, while other PM, eg black carbon, likely warms the climate	A few days
O_3	Formed by photochemical processes in the atmosphere from NO_x and VOC emissions	Human health: premature mortality; ecosystems: reducing plant biodiversity and the productivity of crops; enhancing climate change	Several weeks in the free troposphere

Chapter one
Effects of climate change on air quality

Left
Large scale wild fires have been a global feature of recent years and are both a source of air pollutants and CO_2. © David Fowler.

Effects of climate change on air quality

Key messages

Air quality in the UK is improving due to measures to reduce emissions. However, changes in the climate directly influence the emissions, atmospheric processing and transport of many pollutants. Although the net effect of these changes remains uncertain, it is clear that some are likely to slow or temporarily reverse improvements in air quality.

- O_3 will remain an important global and regional pollutant to 2050 and beyond. Climate-change driven increases in input to the troposphere from the stratosphere, increased formation from climate-sensitive precursor emissions and increased global CH_4 concentrations will lead to increased O_3 in many parts of Europe, although over the UK this will be partly offset by lower O_3 concentrations in air from the Atlantic.
- More frequent and intense heat waves are likely to lead to more episodes of high O_3 and PM in summertime. This reflects the build-up of local emissions under stagnant meteorological conditions along with temperature-driven increases in natural precursor emissions from vegetation and soils, increased occurrence of moorland fires, and inflow from mainland Europe. In contrast, in wintertime, air quality is expected to improve as the cold stagnant conditions that lead to pollutant accumulation are expected to become less frequent.
- Changes in temperature, humidity and precipitation will alter the emissions, formation, processing and removal of PM, affecting both its composition and distribution. While increased scavenging by rainfall is beneficial, greater formation of PM from increased emissions of organic compounds from vegetation and NH_3 is a concern. Addressing the expected increase in NH_3 emissions due to climate change would reduce PM concentrations and have an added benefit for biodiversity.
- The relative importance of mainland European sources for UK air quality would increase if stagnant conditions become more frequent, particularly for O_3 and PM during pollution episodes, which may cover areas much wider than the UK. While changes in the occurrence of stagnant conditions remain very uncertain, it is thus important to consider UK air quality in a wider international context and to encourage cooperation on control strategies across Europe.
- The responses of air quality to climate change will vary across the UK, with the southeast more exposed to stagnation, high temperatures and continental inflow. UK-average changes may therefore hide large regional effects. The difference between urban and rural air quality is also expected to narrow in response to changes in both emissions and meteorology.
- Climate change is likely to increase emissions of the major O_3 precursor CH_4 from natural sources such as wetlands, while anthropogenic releases from agriculture and other sources are also expected to rise in many scenarios. International action to reduce CH_4 emissions, the major contributor to background O_3 production, would therefore be a win-win for climate and air quality.

1.1 Introduction

Overview of climate change

Over the past 250 years the global climate has been changing, largely as a result of anthropogenic emissions of GHGs such as CO_2, CH_4 and N_2O. These GHGs absorb heat radiated by the Earth's surface, hindering the outflow of energy and warming the planet.

The simplest metric for this change is the global mean surface air temperature, which has increased by about 1.2°C since preindustrial times[3]. The temperature change varies by geographical location and season, and has been accompanied by changes in atmospheric transport patterns, vegetation and ice cover, cloud cover and precipitation that reflect adjustments in the global climate system.

Without climate mitigation and under plausible scenarios for global development, global surface temperatures are projected to be more than 3°C higher than in pre-industrial times by 2100. Even if GHG emissions were greatly reduced to stabilise atmospheric concentrations with immediate effect, global surface temperatures are still expected to increase by a further 0.6 °C over the coming century due to the thermal inertia of the climate system. This committed climate change has consequences for air quality that will continue to affect us into the future.

Relevance of climate change for air quality

In contrast to the long-lived GHGs, most of the pollutants responsible for poor air quality are short-lived, with lifetimes ranging from a few hours to several weeks. The principal drivers of poor air quality are local and regional emissions, along with local and synoptic meteorological conditions which govern the transport and fate of these pollutants.

There is also an influence from background pollutant concentrations upon which local and regional sources build, and while these make a minor contribution for short-lived pollutants such as NO_x, they can have a substantial effect for longer-lived pollutants such as O_3 and PM.

Climate change strongly influences many of the processes governing air quality. Changes in temperature and precipitation drive changes in both natural and anthropogenic emissions of key pollutants and their precursors. Changes in weather conditions alter the chemical transformation of pollutants and their build-up over populated regions, while changing weather patterns bring air from different origins that is influenced by different emission sources. The potential for changes in climate to have detrimental impacts on air quality without any changes in current anthropogenic emissions is sometimes termed the 'climate change penalty' on air quality[4], although we note that not all changes are detrimental to air quality.

Climate change may also affect the frequency and severity of major air pollution episodes and its effects under these conditions may differ substantially from its effects on average pollution levels. In this chapter we summarise the key effects involved, with a focus on those influencing air quality in the UK.

Interaction of air quality and climate

Historically there has been a close relationship between emissions of GHGs and air pollutants, as both have increased as a consequence of economic and industrial development. Combustion processes are responsible for most of the anthropogenic emissions of CO_2, and are also the dominant source for some air pollutants and their precursors, including NO_X, carbon monoxide (CO), many components of PM, and some VOCs. However, there has been some decoupling of these emissions recently as measures to improve air quality have led to controls on emissions of SO_2, NO_x, VOCs and PM from vehicles, power plants and industrial sources, independent of measures to reduce GHG emissions. Many of the control measures follow international agreements as part of UNECE protocols to reduce the long-range transport of air pollutants between countries, and of EU directives[5]. Moreover, shifts towards renewable energy generation driven by climate goals have led to co-benefits for air quality as air pollutant emissions have been reduced along with CO_2[6].

Despite their relatively short lifetime, many air pollutants also play a role in influencing climate, either through direct interactions with radiation, such as PM and the greenhouse gas O_3, or indirectly, such as NO_X, which governs O_3 production, serves as a precursor of nitrate aerosol, and influences the chemical removal of greenhouse gases such as CH_4 in the troposphere. Tackling sources of air pollutants that warm the climate system, like O_3, CH_4 and black carbon, can have substantial benefits for the climate, although reductions in SO_2 associated with reduced coal combustion will very likely lead to increased warming due to lower levels of sulphate aerosol. While these interactions of air quality and climate are important, they have been reviewed extensively elsewhere[7]. In this chapter, we focus on the impacts of climate change on air quality, but note that changes in air pollutants have already contributed to past changes in climate.

The UK in a global context and roadmap for chapter one

While the drivers of climate change are largely global in scale, the controls on air quality involve local, regional and global factors. We focus here on impacts on air quality in the UK, but note that this is influenced by wider scale changes over western Europe and by changes in atmospheric dynamics and composition on hemispheric and global scales. It is therefore important to consider changes affecting UK air quality in a global context. We start by summarising changes in climate and transport patterns on global scales, along with those affecting the UK, in section 1.2, and then describe the consequences for global atmospheric composition and UK air quality in section 1.3. We consider the anticipated changes in air pollution episodes, which govern much of the detrimental impact of air quality on health and the wider environment, in section 1.4, and then summarise the air quality changes and policy implications in section 1.5.

BOX 1

Overview of climate influences on air quality

Emissions: changes in climate alter the natural emissions from soils, vegetation, wildfires and lightning, and may influence anthropogenic emissions directly, eg through solvent evaporation, or indirectly, eg through behavioural changes.

Processes: changes in temperature, humidity, light and precipitation have an impact on the photochemical production, destruction and deposition of atmospheric pollutants, altering their atmospheric abundance and lifetime.

Transport: changes in circulation and weather patterns bring air from different source regions and alter transport from the stratosphere, while changes in local meteorology alter the accumulation and dispersion of freshly emitted pollutants.

Background: changes in background atmospheric composition due to GHG emissions can impact air pollutants on a regional scale, eg O_3 produced from oxidation of CH_4.

Image:
Snow, here on the Lammermuir hills in Scotland, is becoming a less common feature of winter weather in the UK as winters become warmer and wetter. © David Fowler.

1.2 The changing climate

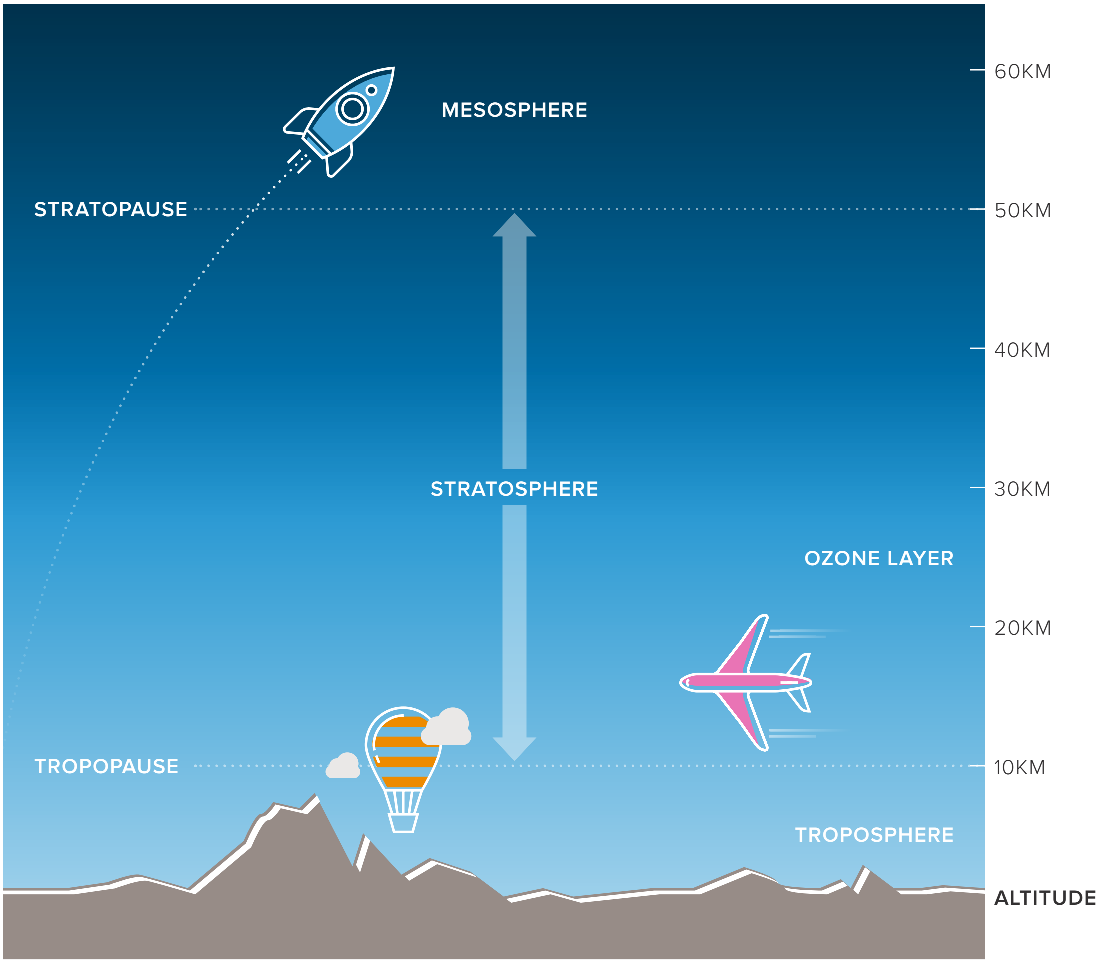
1.2.1 Global-scale climate change

Changes in large-scale climatological patterns

Changing atmospheric concentrations of GHGs and aerosols have led to changes in heating and cooling at the surface of the Earth, and to variations in surface temperature. Patterns of temperature change over specific regions and periods drive changes in atmospheric dynamics, and influence the large-scale climatological patterns that characterise the Earth's climate system. One of the strongest effects is seen in the Tropics, which have experienced a broadening associated with greater poleward extension of the Hadley Circulation – a pattern of circulation of air from near the Equator towards the poles and back – of the order of 1.1° in latitude per decade[8]. This has been accompanied by a poleward shift in the Subtropical jet streams, fast-flowing winds near the boundary between the stratosphere and troposphere. These trends are expected to continue through the 21st century[9] and may have implications for the climate in mid-latitude regions such as western Europe.

FIGURE 2

Illustration of the atmosphere and its layers



Stratospheric circulation

Changes in atmospheric emissions of GHGs also affect the slow, large-scale overturning of air in the stratosphere known as the Brewer-Dobson circulation. This leads to changes in the exchange of air and pollutants across the tropopause, the boundary between the stratosphere and troposphere. Increases in GHGs have led to a strengthening in the stratospheric circulation, and model studies suggest that this is likely to lead to a 3% increase in cross-tropopause transport per decade, increasing stratospheric O_3 inputs to the troposphere[10].

Shifting transport patterns: the North Atlantic Oscillation

The most important large-scale circulation pattern at northern mid-latitudes affecting the UK is the North Atlantic Oscillation (NAO). Particularly dominant in winter, this is the north-south variation in surface pressure over the Atlantic, with a large pressure difference characterised by a strong westerly flow and a smaller pressure difference marked out by a more meandering flow. There is some evidence, albeit with substantial uncertainty, that climate change will lead to a more positive NAO, and hence stronger westerly air flow and a northward shift of the storm track[11]. This has implications for the transport of pollutants from distant sources to the UK.

Understanding of the seasonal changes in circulation patterns is more robust. Climate models show a poleward shift of the westerlies in the North Atlantic in summer and autumn[12], but the signal is much less clear at other times of year[13]. In wintertime, strong jet streams following more northerly paths are typically associated with greater rainfall over the northern UK. However, there is still substantial uncertainty concerning many aspects of regional atmospheric circulation change in the northern hemisphere[14].

Blocking anticyclones

A key feature of meteorology influencing the UK is the presence of ‘blocking’ high pressure systems over continental western Europe caused by displacements in the Polar Front jet stream. These quasi-stationary anticyclones typically persist for one to two weeks, and cause the mid-latitude depressions that dominate the weather over the UK to take a more northerly path towards Scandinavia. These blocking systems bring dry, stable weather conditions over western Europe that are characterised by low wind speeds, clear skies and an absence of precipitation. Over the UK, winds under these conditions are typically from the east or southeast, bringing freshly polluted air from continental Europe. The slow wind speeds lead to relatively stagnant meteorological conditions that support the accumulation of pollutants from local emissions, adding to the effect of the imported pollutants from Europe.

In wintertime, blocking anticyclonic conditions are typically stable and cold and support the formation of winter smog in low-lying areas, trapping primary pollutants close to the surface. With strong local emissions of smoke from domestic and industrial fires, these conditions led to the formation of major smogs in London until the 1950s, before widespread coal combustion was addressed through the 1956 Clean Air Act. In contrast, in summer, warm and sunny conditions support efficient photochemistry and secondary pollutant production, and are typically responsible for rapid O_3 formation and the development of major oxidant pollution episodes. A strong relationship between summertime heatwave periods and extreme pollution events has been clearly demonstrated[15].

A notable example occurred during the heatwave of summer 2003 over Europe, when O_3 concentrations reached the highest levels seen since the 1980s[16]. Similar events occurred in the summers of 2006 and 2018. Reductions in emissions of NO_x and VOCs in Europe since 2000 have reduced peak O_3 concentrations in the UK over the last two decades, but summer peaks continue to expose the UK population and ecosystems to damaging levels[17]. These conditions are also typically associated with the highest concentrations of PM in the southern UK, especially in the spring when lower temperatures favour the presence of ammonium nitrate. The frequency, location and persistence of anticyclones over the continent are therefore important drivers of O_3 and PM exposure and effects in the UK.

The expected warming of the climate is projected to bring an increase in the frequency and intensity of summertime heatwaves and dry periods. However, changes in transport patterns are more difficult to assess with a high level of confidence. The frequency of summertime blocking in the northern hemisphere is expected to decrease, although the magnitude of the changes remains very uncertain[18].

The extent of the impacts of climate change on air quality

The extent of the impacts described above depends strongly on the assumed level of GHG emissions and thus the scenario for global socio-economic development that is followed. A suite of storylines spanning a wide range of different economic and development pathways has been developed to inform the Intergovernmental Panel on Climate Change (IPCC) climate assessments. The Representative Concentration Pathways (RCPs) define possible future trajectories of key greenhouse gases based on a specified radiative forcing level by 2100, and the main four pathways (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were used in the fifth IPCC Climate Assessment. These have now been supplemented by a more comprehensive set of storylines, the Shared Socio-economic Pathways (SSPs), which span a wider range of future conditions based on five global narratives balancing different approaches to adaptation and mitigation, each of which has a range of constituent storylines.

FIGURE 3

Summary of global climate scenarios[19, 20, 21]

Projected changes in global mean CO_2 and CH_4 concentrations between 2000 and 2100 along the RCP and SSP pathways, along with the corresponding changes in global surface air temperature since the preindustrial period. CO_2 and CH_4 concentrations are taken from the RCP and SSP public databases. Surface temperature changes are relative to 1850 – 1900 and are presented as median changes from Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations for the RCPs and from Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations for the SSPs[3].

Sources: SSP database 2017, RCP database 2009, IPCC 2013, IPCC 2021.

A brief summary of CO_2 and CH_4 concentration changes along these pathways and the likely corresponding changes in global surface temperature is shown in Figure 3. Of particular note for air quality, the changes in emissions of key pollutants and their precursors along the RCP pathways are less varied than those of GHGs, and most pathways show substantial reductions by 2100. In contrast, the SSP pathways span a broader range of pollutant emission trajectories that are more consistent with the corresponding greenhouse gas trajectories.

We focus here principally on the impacts of climate change until 2050, for consistency with national and international targets for net-zero climate policies and to permit direct comparison of the effects on air quality. However, we note that the large inertia of the climate system typically leads to relatively small changes between different climate change scenarios on this timescale, and hence we also consider changes over the second half of the 21st century where the differences between scenarios become much more apparent. The UK Climate Projections 2018 (UKCP18) explored the effect of climate changes over the UK along representative low-end (RCP2.6) and high-end (RCP8.5) pathways. We consider the same scenarios, supplementing these with insight from more recent studies applying SSP scenarios where available. However, we note that only the SSP1 scenarios (a world of sustainability-focused growth and equality) are fully consistent with net-zero climate commitments.

1.2.2 Changing UK climate

The changes in global climatology described above affect the UK both through modifications of atmospheric transport patterns and changes in the characteristics of the air that they bring. Changes in the strength and position of the jet stream over the Atlantic alter the flow that dominates conditions over the western coasts of the UK, leading to greater wintertime rainfall. In contrast, any change in stable anticyclones over western Europe could lead to greater occurrence of winds from the east and southeast, bringing cold air from the continent in winter and warm air in summer, increasing the chance of poor air quality.

The potential impacts of climate change on the UK were explored in the UKCP18[22], and key results are summarised in Box 2. UKCP18 focussed on changes expected by around 2070 following the RCP8.5 pathway, which corresponds to a global mean surface temperature rise of about 3.2 °C since preindustrial times. The overall picture is one of warmer, wetter winters, and hotter, drier summers for the UK. These are accompanied by a range of other changes such as reductions in soil moisture, particularly in the southeast of the UK, that may lead to increased drought in summertime. In contrast, in wintertime there is a strong reduction in snowfall, and an increase in both the frequency and intensity of rainfall, accompanied by a greater likelihood of flooding.

These changes will have direct implications for air quality. Increased winter precipitation is likely to be associated with good air quality, as the strong, generally westerly air flow in these conditions brings clean air from the Atlantic and higher wind speeds increase the advection and dispersion of domestic air pollutants. However, higher summer temperatures, lower wind speeds and sunny weather favour photochemical production of O_3 and the accumulation of PM, especially in urban source regions.

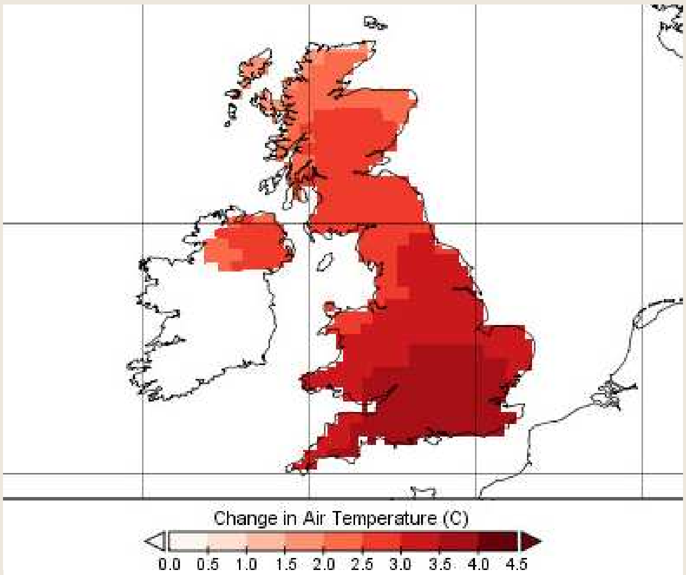
Image:
The Northern Hemisphere Jet Stream can be seen crossing Cape Breton Island in the Maritime Provinces of Eastern Canada. © NASA Johnson (CC BY-NC 2.0).

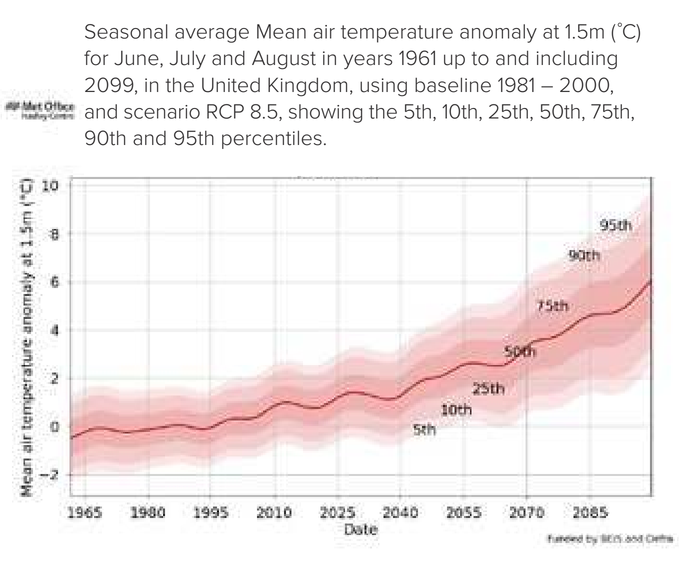
BOX 2

UK climate projections for 2060 – 2079 versus 1981 – 2000[23]

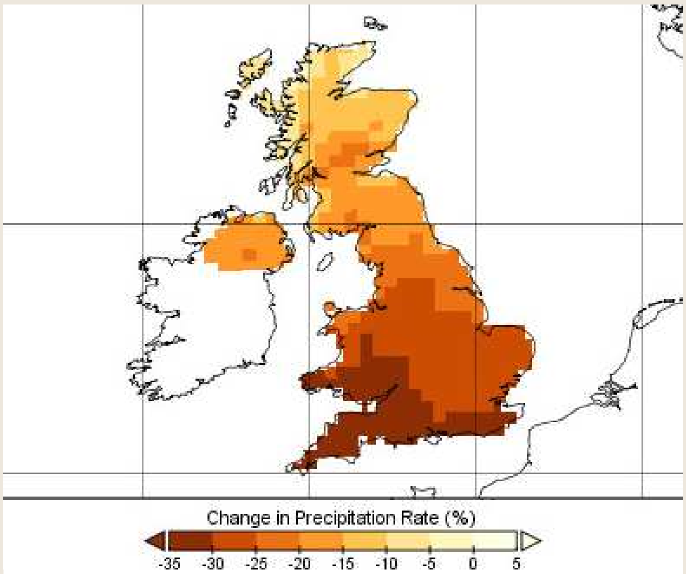
The UKCP18 predict an increased chance of warmer, wetter winters and hotter, drier summers along with an increase in the frequency and intensity of extremes. By 2070, along the RCP8.5 pathway seasonal temperatures are expected to rise 0.7 – 4.2°C in winter and 0.9 – 5.4°C in summer compared with 1981 – 2000. Precipitation is likely to increase in wintertime (ranging from a 1% decrease to a 35% increase) and decrease in summertime (ranging from a 2% increase to a 47% decrease).

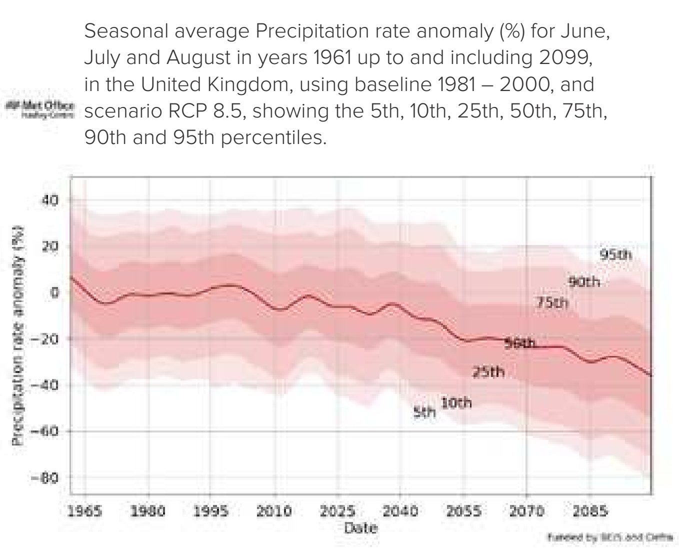
Summer temperature changes




Seasonal average Mean air temperature anomaly at 1.5m (˚C) for June, July and August in years 1961 up to and including 2099, in the United Kingdom, using baseline 1981 – 2000, and scenario RCP 8.5, showing the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

Summer precipitation changes

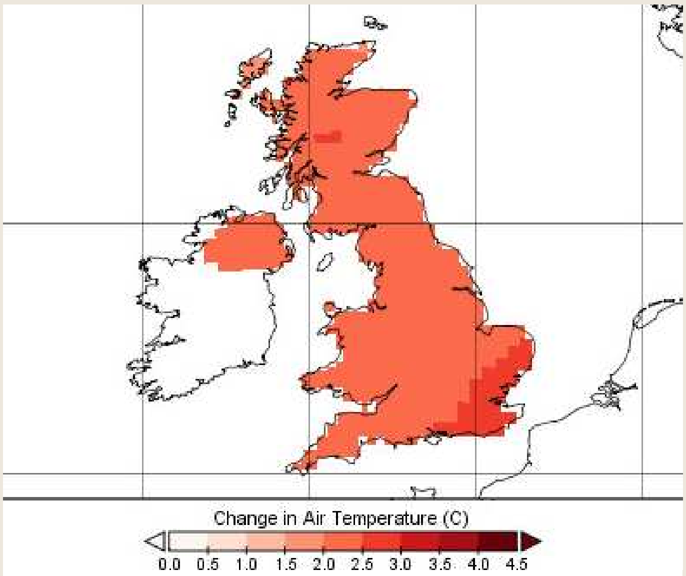


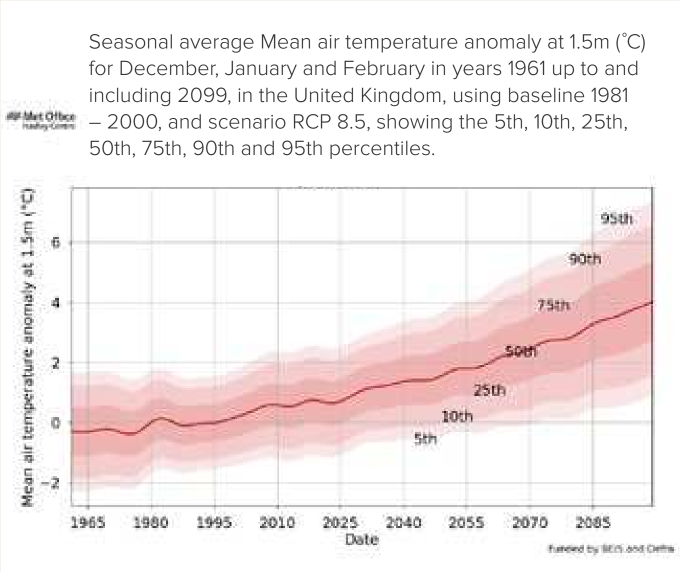

Seasonal average Precipitation rate anomaly (%) for June, July and August in years 1961 up to and including 2099, in the United Kingdom, using baseline 1981 – 2000, and scenario RCP 8.5, showing the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

Source: Met Office 2018.

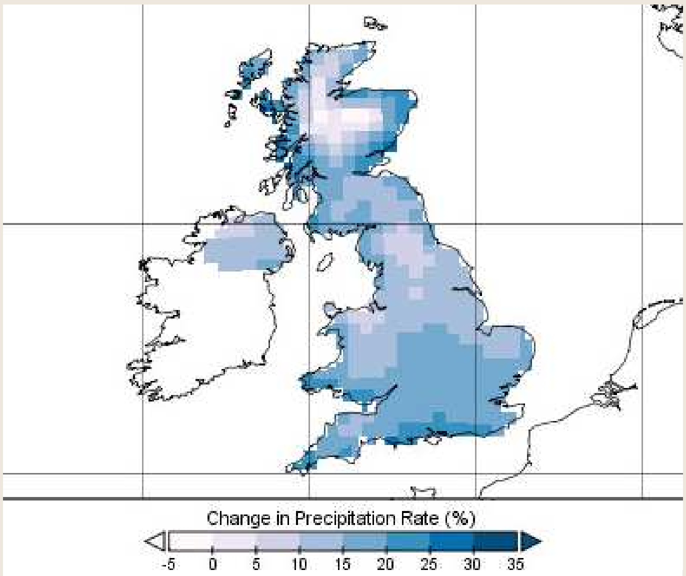
The temperature of hot summer days is expected to increase by 3.7 – 6.8°C, and the average frequency of hot spells where the maximum temperature exceeds 30°C for at least two consecutive days is expected to increase over the southern UK from once every four years to four times each year. Extreme rainfall is expected to increase and become 25% more frequent, with more high intensity frontal rainfall in winter, and more short high intensity showers in summer.

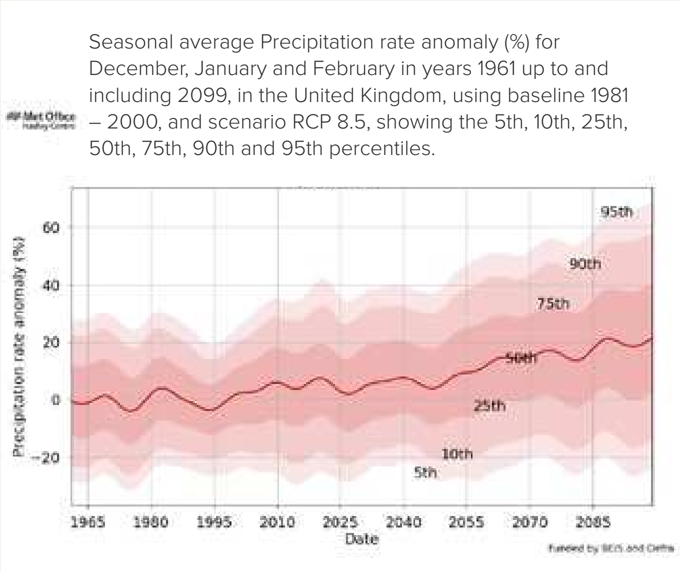
Winter temperature changes




Seasonal average Mean air temperature anomaly at 1.5m (˚C) for December, January and February in years 1961 up to and including 2099, in the United Kingdom, using baseline 1981 – 2000, and scenario RCP 8.5, showing the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

Winter precipitation changes




Seasonal average Precipitation rate anomaly (%) for December, January and February in years 1961 up to and including 2099, in the United Kingdom, using baseline 1981 – 2000, and scenario RCP 8.5, showing the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

1.3 How climate change affects air quality

In this section we describe first the impact of global climate change on long-lived pollutants which provide a global atmospheric background upon which regional pollutant changes build. We then focus on emissions, atmospheric chemistry and removal processes that occur at regional scales and typically control short-lived pollutants. This distinction based on scale and pollutant lifetime informs the different approaches to regulation which may be required for different pollutants, some of which can be adequately addressed on a local or national scale, while others require greater international cooperation.

1.3.1 Changes in global atmospheric composition

The geographical footprints of individual pollutants differ as a consequence of their atmospheric lifetimes and their sources. At the global scale the most prominent pollutant in surface air is O_3, in part because it has a longer atmospheric lifetime (several weeks) than most other key pollutants. The production of O_3 in the troposphere is closely connected to the concentration of CH_4. Both CH_4 and O_3 are GHGs and are also influenced by climate change. In this section we discuss the main contributors to poor air quality and effects of climate change on their sources in the coming decades.

Methane

CH_4 makes an important contribution to the radiative forcing of the climate as a GHG and also plays a major role in the atmospheric chemistry of air pollutants, in particular tropospheric O_3 production. Changes in climate influence the global CH_4 budget both through their effect on CH_4 sources and their influence on the main CH_4 sink through chemical oxidation in the atmosphere, which depends strongly on temperature and water vapour.

Anthropogenic sources are responsible for around 60% of current global CH_4 emissions, principally from fossil fuels and agriculture, while natural sources account for the remaining 40%, particularly wetlands[24]. Changes in the climate influence many of the source sectors, both anthropogenic and natural, with wetlands being particularly sensitive. Wetland emissions of CH_4 arise from the anaerobic decomposition of organic matter and prior to the Industrial Revolution wetlands were the main source of atmospheric CH_4. Global average atmospheric CH_4 concentrations have increased from pre-industrial values of 700 ppb to around 1900 ppb in 2020, with a rise since 2005 of about 5 ppb per year[25]. An extensive literature of measurements in field and laboratory conditions supports the conclusion that wetland CH_4 emissions increase with temperature although they also depend critically on the level of the water table as methanogens require anaerobic conditions[26].

Given the extensive areas of high latitude wetlands, which are experiencing large temperature increases, and the possibility of emissions from clathrates as permafrost thaws, these regions are expected to remain an important and gradually increasing source of emissions through this century[27].

In addition to these changes in natural CH_4 sources, most future climate scenarios show substantial increases in anthropogenic CH_4 emissions associated with development pathways that lead to higher atmospheric CH_4 concentrations, highlighting the very limited regulation of CH_4 sources in all but the most stringent scenarios (RCP2.6, SSP1 and SSP2, see Figure 3).

Stratospheric Ozone

Transport of O_3 from the stratosphere is an important component of the budget of tropospheric O_3 and is projected to increase during this century. Two separate factors contribute to this increase. First, stratospheric O_3 is expected to increase in response both to removal of halogenated O_3 depleting substances, driven by the Montreal Protocol, and to the GHG-induced cooling of the stratosphere – which takes place alongside warming of the troposphere and the surface. Also, under the influence of increasing GHGs, models consistently predict a strengthening of the stratospheric Brewer-Dobson circulation and hence greater transport of air and pollutants from stratosphere to troposphere.

The build-up of halogenated O_3 depleting substances in the stratosphere in the second half of the 20th century led to depletion of stratospheric O_3. With the phasing out of these substances there are now signs of O_3 recovery[28]. This stratospheric O_3 destruction has been shown to have led to a decline in transport of O_3 from the stratosphere into the troposphere until the mid-1990s, partly offsetting an emissions-driven increase in tropospheric O_3 production[29]. From 1994 – 2010, despite a levelling off in precursor emissions, increased stratosphere to troposphere transport of O_3 drove a small increase in the tropospheric O_3 burden and this is projected to increase further during this century, with early studies suggesting an increase of about 3% per decade. While the transport of O_3 to the troposphere could rise by 20%, the effect on surface O_3 is likely to be more modest. Banerjee *et al.* (2016) calculate a late century increase in the contribution of stratospheric O_3 to middle latitude surface O_3 in the northern hemisphere of around 3 – 4 ppb under a high emissions scenario (RCP8.5), taking account of removal of O_3 depleting substances[30].

The abundance of stratospheric O_3 also affects the penetration of ultraviolet (UV) radiation into the troposphere and so influences OH production and tropospheric oxidation processes. Changes in surface O_3 over the UK due to reduced penetration of UV radiation associated with stratospheric O_3 recovery have not been quantified, but studies over the US suggest that reduced chemical production and destruction lead to lower surface O_3 in urban emission regions in summertime but to greater regional O_3, typically 0.5 – 1.0 ppb, by the end of the 21st century[31]. This regional O_3 increase is in addition to the increase associated with greater influx from the stratosphere.

Tropospheric Ozone

The response of tropospheric O_3 to climate change is expected to vary regionally and seasonally, reflecting the net effect of chemical, meteorological, dynamical, and physical processes[32]. One of the most robust responses is a decrease in O_3 in the remote lower troposphere where increasing humidity enhances O_3 loss[33]. In addition, in a warmer atmosphere, the thermal decomposition of peroxyacetyl nitrate, a relatively long-lived pollutant that acts as a reservoir of NO_x, reduces the transport of NO_x out of the surface boundary layer, decreasing overall O_3 production[34]. However, such photochemical changes may be offset by increases in natural precursor emissions, in particular from a greater prevalence of wildfires in boreal and mid-latitude regions[35]. While wildfire influence on O_3 remains poorly quantified, increased emissions will also enhance other regional pollutants, especially PM. BVOC emissions contribute to O_3 formation and are likely to increase in a future warmer climate. However, rising CO_2 and increasing drought conditions can lead to stomatal closure, limiting the magnitude of the response[36]. The removal of O_3 by deposition to the Earth's surface is also sensitive to climate change, with previous studies showing increased wintertime removal associated with declining snow cover and reductions in summertime removal under drought conditions[37], when stomatal closure increases near-surface O_3 concentrations[38]. The net response of surface O_3 to climate change is likely to reflect the balance of regional changes in sources and sinks, with increases in O_3 in source regions driven by climate-sensitive emissions, but decreases in remote, mainly oceanic regions where faster chemical removal dominates.

Studies of the impacts of climate change alone, with CH_4 concentrations invariant, have shown small increases in summertime O_3 of 1.0 – 1.5 ppb (2 – 3%) over continental western Europe by mid-century[39]. However, over the UK decreases of up to 0.5 ppb are projected, as the increase in O_3 from Europe is outweighed by lower background O_3 from the Atlantic associated with increased temperature and humidity which support greater O_3 destruction. Analysis of the climate change impacts on annual mean surface O_3 in the CMIP6 models shows a decrease of 1 ppb over the UK along the SSP3-7.0 pathway by 2050 and of 3 ppb by 2100 (see Figure 4). These decreases indicate that greater destruction over the Atlantic outweighs any increase in O_3 from changes in northern hemisphere emissions of BVOC, soil NO_x or lightning NO, at least over the UK, although we note that changes in wildfire emissions were not explicitly included in this analysis. The influence of global CH_4 concentration changes alone is shown in Figure 4b, and this ranges from a 2 ppb increase to a 2 ppb decrease in surface O_3 by 2050 depending on the CH_4 concentration pathway, which is dominated by anthropogenic emissions. We note that along the SSP3-7.0 pathway increased O_3 from high CH_4 concentrations outweighs the reduction in O_3 due to other climate changes, leading to a net increase following this pathway.

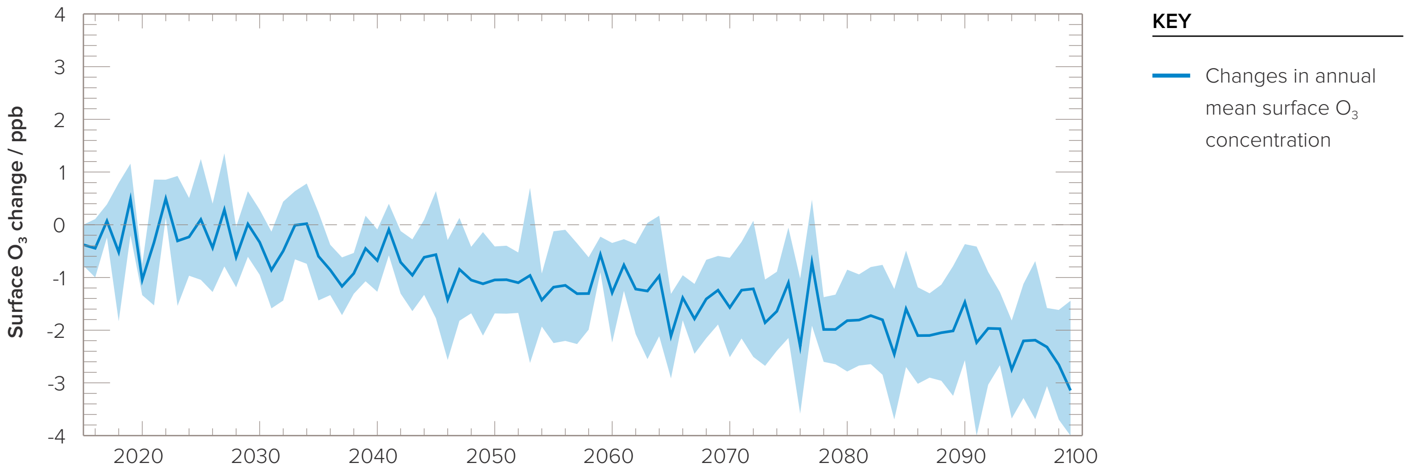
Image:
Lightning, a source of nitric oxide (NO) and nitrogen dioxide (NO_2) in the global atmosphere, is expected to increase with global temperature.
© mdesigner125.

FIGURE 4

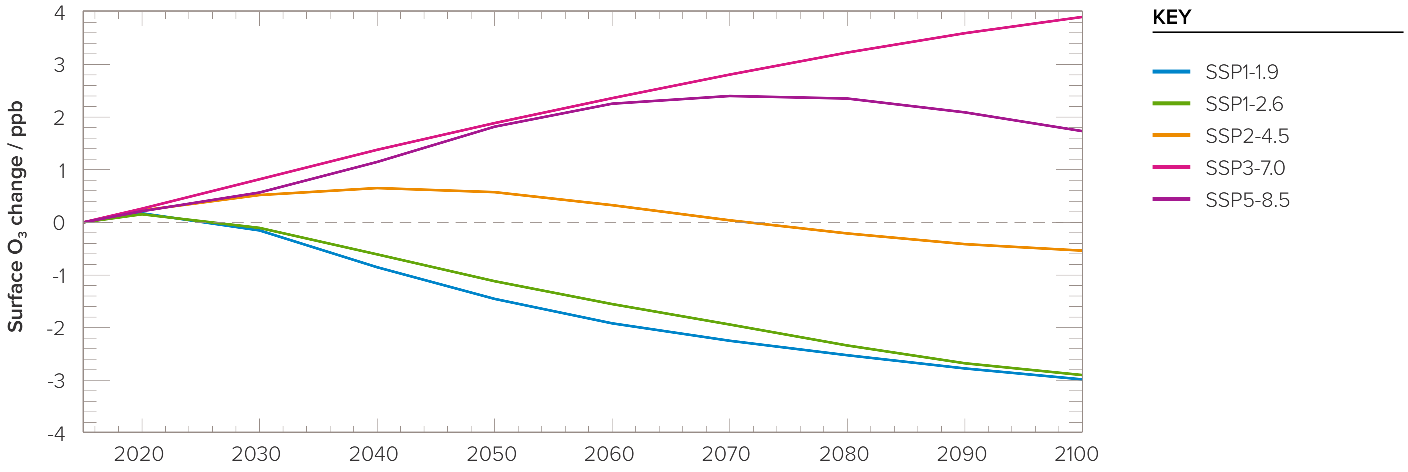
Changes in annual mean surface O_3 over the UK

Panel (a)[40] shows changes in annual mean surface O_3 over the broader UK region (50° – 60°N, 10°W – 5°E) due to the effect of climate changes alone in CMIP6 models following the SSP3-7.0 pathway. These represent differences in five models between simulations following the SSP3-7.0 pathway and those following the same pathway but with sea surface temperatures, sea ice cover and CO_2 concentrations constrained to present day levels. They reflect the effect of changes in meteorological variables and transport along with changes in natural emissions from biogenic sources, soil, and lightning, but not the effect of anthropogenic emissions, increased CH_4 concentrations or wildfires. Panel (b)[41] shows changes in annual mean surface O_3 over the UK due to changing global background concentrations of CH_4 alone, following a range of different SSP pathways under present-day climate.

(a) Surface O_3 change due to climate change



(b) Surface O_3 change due to CH_4 change



Source panel (a): Zanis *et al*. (2021), paper submitted.

Source panel (b): Turnock *et al*., 2018.

Other changes in background composition

Most future climate pathways are associated with substantial changes in global anthropogenic emissions of air pollutants. While the effects of these emissions are distinct from the effects of climate change alone, they may have a large impact on global tropospheric composition, and are likely to be the dominant cause of future atmospheric composition change along many of the pathways. To provide context to the climate-driven composition changes described above, we show the combined effect of climate-driven and anthropogenic emission changes on UK O_3 and $PM_{2.5}$ in Figure 5. These range from increases in annual mean surface O_3 of up to about 3.5 ppb by mid-century along the SSP3-7.0 scenario to decreases of more than 10 ppb along the low-end SSP1 scenarios where reduced emissions of pollutants and their precursors and CH_4 combine to reduce background O_3 substantially. In contrast, annual mean $PM_{2.5}$ decreases by about 1 $\mu g/m^3$ (~20%) along most scenarios, principally reflecting reductions in regional emissions.

1.3.2 Changes in UK air quality

Air quality in the UK is influenced by the impacts of climate change on transport processes, including changes in air mass origin and mixing, and on pollutant sources and sinks, including local emissions, chemical transformation, and removal processes. Here, we first summarise the expected influence of climate changes on these processes and then explore their implications for key pollutants.

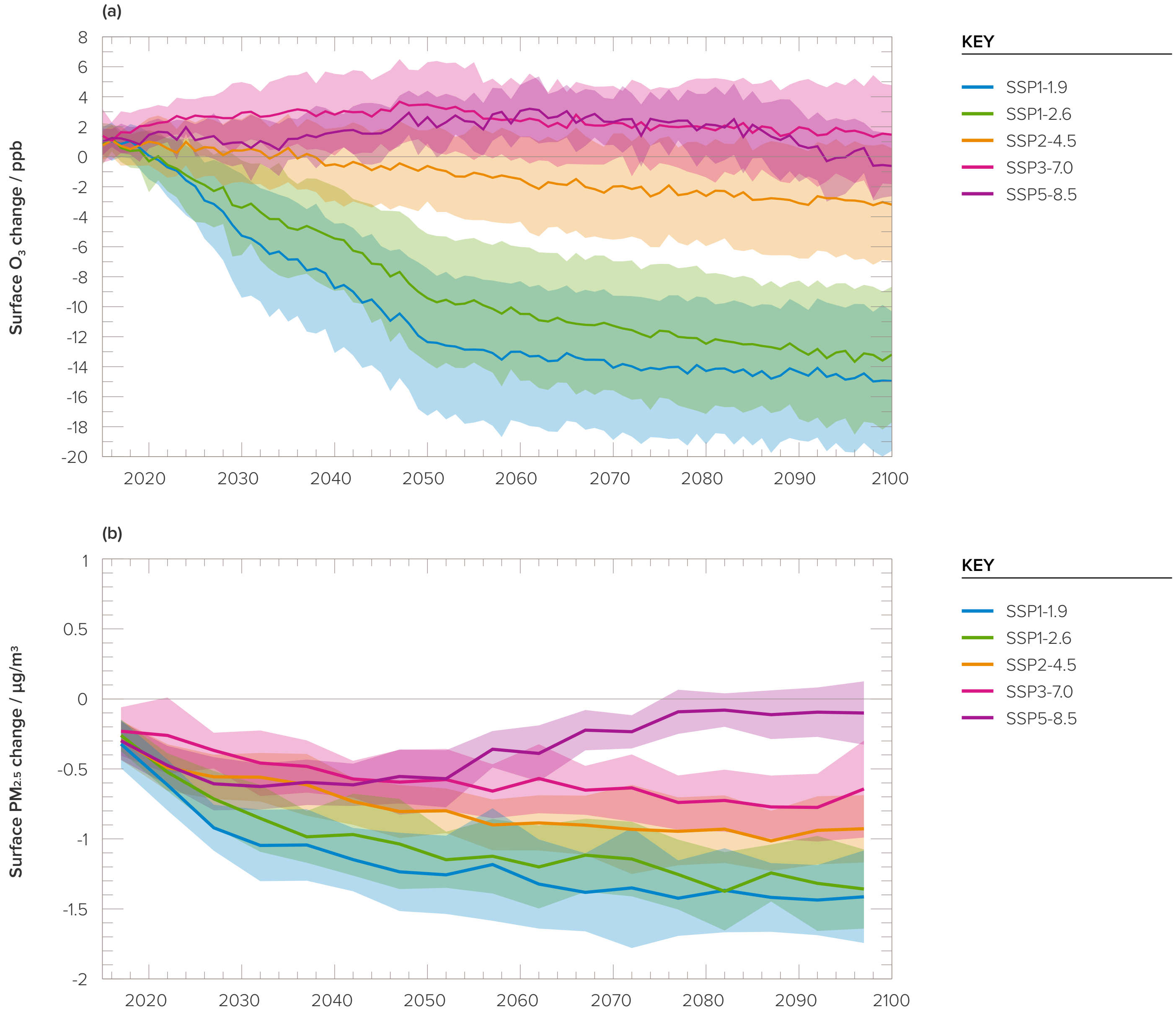
Regional and local transport and meteorology

The changes in northern mid-latitude transport patterns described in section 1.2.2 will lead to changes in the frequency of different air-masses arriving over the UK, with consequences for air quality. Any change in the frequency and intensity of continental anticyclones is likely to alter the inflow of polluted air from mainland Europe, and this may lead to elevated O_3, NO_x, and PM over the UK, even without emission changes. A northward shift in the North Atlantic storm track may bring more marine air from the southwest, and while this typically brings cleaner air to the UK, it can enhance levels of sea salt particles, and under some conditions can drive the recirculation of polluted outflow from continental Europe to western parts of the UK. Strong southerly flows, enhanced by high pressure over the Continent, can lead to transport of dust from the Sahara and smoke from wildfires in southern Europe. PM transported during these episodes contributes to poor air quality over the southern parts of the UK, and while minor transport events occur several times each year, major transport episodes occur every few years. Anticyclonic conditions over the UK typically lead to lower wind speeds and greater stagnation of air, allowing freshly emitted pollutants from local UK sources to build up to higher levels. It is also likely that changes in sunlight associated with increased cloud cover will influence formation of the urban heat islands that affect many of our larger cities. While there is substantial uncertainty in the extent of these changes, a weakening of urban heat islands, as suggested by UKCP18, may lead to reduced mixing of air close to the surface and thus to higher pollutant concentrations at street level, particularly at night-time[42].

FIGURE 5

Changes in surface O_3 and PM under future climate and emission scenarios[43]

Expected changes in annual mean surface O_3 (a) and surface $PM_{2.5}$ (b) over the UK region in CMIP6 models following five illustrative SSP pathways.



Source: Turnock *et al.*, 2020.

Sources and sinks of pollutants over the UK
Changes in climate affecting the UK, particularly the greater prevalence of hot, dry settled conditions in summer, are likely to alter the local sources and sinks of many UK pollutants. Higher temperatures are likely to drive increased emissions of BVOCs from vegetation and to increase emissions of NH_3 from agricultural land. Drier conditions in summer will lead to greater wind-driven emissions of surface soils and dusts, leading to increased PM concentrations. Summertime droughts are likely to lead to an increase in moorland wildfires, such as those occurring in the Pennines in summer 2018, which generate substantial emissions of NO_x, O_3, PM and other pollutants[44]. Increases in temperature and humidity drive increased photochemical activity, supporting more rapid chemical formation of oxidants such as O_3. However, these changes also alter the removal of some pollutants through photochemical and deposition processes. Rainfall is responsible for scavenging soluble gases and much PM, and changes in rainfall patterns are likely to lead to seasonal shifts in the efficiency of these removal processes. Through changes in vegetation and rainfall, climate change is likely to influence the removal of pollutants such as O_3 and NH_3 through dry deposition processes. In particular, summertime drought, which induces stomatal closure, is likely to reduce the dry deposition of O_3, as observed during the 2003 heat wave in Europe[45]. These episodes are likely to be more frequent as the summers become warmer and drier.

Changes in climate are also likely to influence UK anthropogenic emissions of pollutants indirectly through behavioural changes. These include increased use of air conditioning in summertime, changes in heating patterns in wintertime, and lifestyle changes affecting transport use and domestic emissions. They may also include changes in land use and agricultural practices driven by climate change. Many of these changes are likely to influence UK air quality, although their impacts have not been explored in detail to date.

NO_x and local O_3
Observation and modelling studies have demonstrated that the NAO has a substantial effect on wintertime pollutant levels over the UK[46]. Under the negative phase of the NAO, characterised by anomalously weak westerly flow, concentrations of NO_2 and key primary pollutants build up to higher levels than normal under relatively settled meteorological conditions. However, some secondary oxidants such as O_3 are maintained at low concentrations due to direct chemical removal by NO. In contrast, the positive phase of the NAO associated with stronger westerly flow leads to lower wintertime concentrations of primary pollutants, as pollutants are rapidly transported away from the UK. Concentrations of O_3 are typically higher than normal, reflecting background levels over the Atlantic. A more positive NAO under climate change may thus lead to lower levels of primary pollutants and higher O_3, although the extent of these changes remains uncertain.

Warmer, drier summertime conditions are expected to lead to greater occurrence of wildfires, particularly over moorland regions of Wales, Northern England and Scotland, and this will lead to additional local sources of NO, VOCs and PM and to local O_3 formation. NO emission from soils is temperature dependent and is also likely to increase, although this may be limited by reduced soil moisture under summertime drought conditions. Stronger summertime convection may lead to increased lightning, but the extent of these changes or their effect on surface NO_x remains uncertain.

Biogenic VOCs

Emissions of BVOCs may play an important role in air quality. The gas-phase oxidation of VOCs by the hydroxyl radical (OH) leads to the formation of peroxy radicals which oxidise NO and produce O_3. In addition, larger molecular weight BVOCs such as terpenes and sesquiterpenes (C_{10} and C_{15} compounds, respectively) may react with oxidants, such as O_3 and nitrate radicals, to produce lower vapour pressure products that condense to form secondary organic aerosol particles. These particles have detrimental effects on ground-level air quality and can influence the formation of clouds in the atmosphere[47].

Emission rates of BVOCs are highly plant species-specific and will change as the distribution of species changes, either naturally or as a result of land use change, such as the large-scale planting of trees for CO_2 removal. Emission rates depend on light intensity, leaf temperature, and concentrations of CO_2. Soil moisture and nutrient availability also influence BVOC emission rates, as may increases in ground-level O_3. Most studies suggest that BVOC emissions will rise in future, driven by increases in temperature, but severe drought in summertime and higher CO_2 concentrations may limit the extent of these increases. The major sources of isoprene in the UK are tree species such as spruce, poplar, willow and oak, and while the total source is small on a global scale (estimates range from 10 – 50 Gg yr^{-1} of a global total of about 550 Tg yr^{-1}) a 3°C temperature increase over the UK has been projected to increase these emissions by about 50%[48]. The current trend for urban greening as well as large scale tree planting, without regard for BVOC emissions, combined with the continuing emissions of NO and the increasing frequency of heat waves, suggests that BVOCs are likely to play an increasingly important role in poor air quality[49, 50].

Effects of climate change on emissions and atmospheric partitioning of NH_3

Emissions of NH_3 to the atmosphere occur when aqueous solutions containing ammonium are exposed to air. These solutions are found in vegetation, especially when recently fertilised, in animal excreta and a range of organic waste. The extensive use of inorganic nitrogen fertilisers over the last half century has increased emissions of NH_3 to the atmosphere. The global anthropogenic production of fertiliser nitrogen is now of a similar magnitude to the natural microbial fixation of atmospheric nitrogen[51]. The flow of reactive nitrogen through the global nitrogen cycle has roughly doubled since the early 20th century, and emissions of NH_3 now contribute substantially to the production of secondary inorganic aerosols, the long-range transport and deposition of nitrogen compounds and their effects on human health and ecosystems.

The effects of climate change on NH_3 are primarily on the emission process as the equilibrium between liquid and gas phase concentrations is highly sensitive to temperature. In principle, the volatilisation potential of NH_3 increases by a factor of three for a temperature increase of 10°C. Projected temperature increases over coming decades are therefore expected to increase NH_3 emissions, even without further increases in nitrogen use in agriculture. The scale of this increase is substantial, both in the UK and for global emissions, which may increase from the current annual total of 60 TgN/yr to 135 TgN/yr[52].

A further effect of a warming climate on NH_3 in the atmosphere is driven by the volatility of ammonium nitrate particles. Much of the gaseous NH_3 in polluted regions is rapidly incorporated into aerosols. With the recent decline in sulphur emissions, the NH_3 is present as ammonium nitrate following reaction with nitric acid.

As temperatures gradually increase, more of the NH_3 will partition to the gas phase, causing changes in the spatial patterns of deposition of gas and aerosol phase compounds. The effects of climate change on NH_3 are therefore substantial. The importance of NH_3 within the mix of air pollutants is growing and unlike many other pollutants, such as SO_2, NO_x and VOCs, emissions of NH_3 have not been subject to large reductions to improve air quality.

Particulate matter

There are a number of ways in which climate change may affect concentrations of airborne PM. Concentrations of secondary particles are affected by complex interactions between primary pollutant emissions, atmospheric circulation and temperatures[53].

Firstly, increased temperatures tend to reduce concentrations of ammonium nitrate, currently the largest single constituent of fine PM in many countries, including the UK, due to its increased dissociation into NH_3 and nitric acid vapour. Many organic components of airborne particles, both primary and secondary, are semi-volatile and have a greater tendency to enter the vapour phase at higher temperatures. This will make some constituents more available for oxidation, increasing the secondary organic component of the particles. Increased temperatures also favour the release of BVOCs into the atmosphere, many of which are oxidised to particulate phases, and an increase in biogenic secondary aerosol is expected.

A second major factor would be a change in synoptic scale atmospheric circulation patterns. Currently, the highest concentrations of secondary PM in the southern UK are often associated with air masses arriving from mainland Europe bearing high nitrate concentrations. If changes in circulation lead to an increase in the inflow of pollutants, increased concentrations would be expected. If the prevalence of southerly air flow increased, the UK could be affected more frequently by Saharan dust episodes.

Thirdly, climate change may lead to changed local patterns of wind, precipitation and atmospheric stability. Higher wind speeds lead to lower concentrations of primary pollutants, but have less effect on secondary pollutants. Precipitation is a sink for airborne particles, and hence increased winter precipitation would typically be expected to decrease particle levels, whereas drier summers would favour increased PM. The wind-driven suspension of surface dusts is another such potential regional impact.

The net effect of climate change on PM thus remains uncertain. While global model studies suggest that background PM concentrations over the wider UK region are likely to remain relatively constant under climate change (see Figure 5), few of these models yet fully incorporate the complex interactions outlined above and they are unable to resolve differences between urban and rural environments. However, given the influences outlined here, it is likely that there will be changes in the spatial and temporal distributions of PM associated with changing emission and scavenging processes, and changes in the composition of secondary aerosols, particularly associated with the increasing importance of atmospheric NH_3 concentrations.

1.4 Air pollution episodes

Many of the most severe impacts of poor air quality are caused by acute pollution episodes, characterised by short periods (usually 1 – 5 days) of elevated pollutant concentrations driven by stable meteorological conditions that allow pollutants to accumulate and transform. Some episodes are relatively localised and regional, while others occur over larger, international scales. They may be loosely characterised as:

i. Conditions favouring stagnation through accumulation of primary pollutants, for example NO_x and primary PM, predominantly in winter for the UK; and

ii. Conditions favouring photochemical production and accumulation of secondary pollutants, for example O_3 and secondary aerosol, predominantly in spring or summer.

Analyses predict that there will be significant variations in atmospheric stagnation events, with a likely increase in occurrence over populated areas globally[54, 55]. While the UKCP18 broadly predicts an increase in extremes as part of the trend to warmer, wetter winters and hotter, drier summers (see Box 2), research suggests the likelihood of more frequent summer heat extremes, and the consequent pollution episodes, at higher global mean temperatures[56]. The hot summer of 2003 (see Box 3) is predicted to become the norm as early as the 2040s.

BOX 3

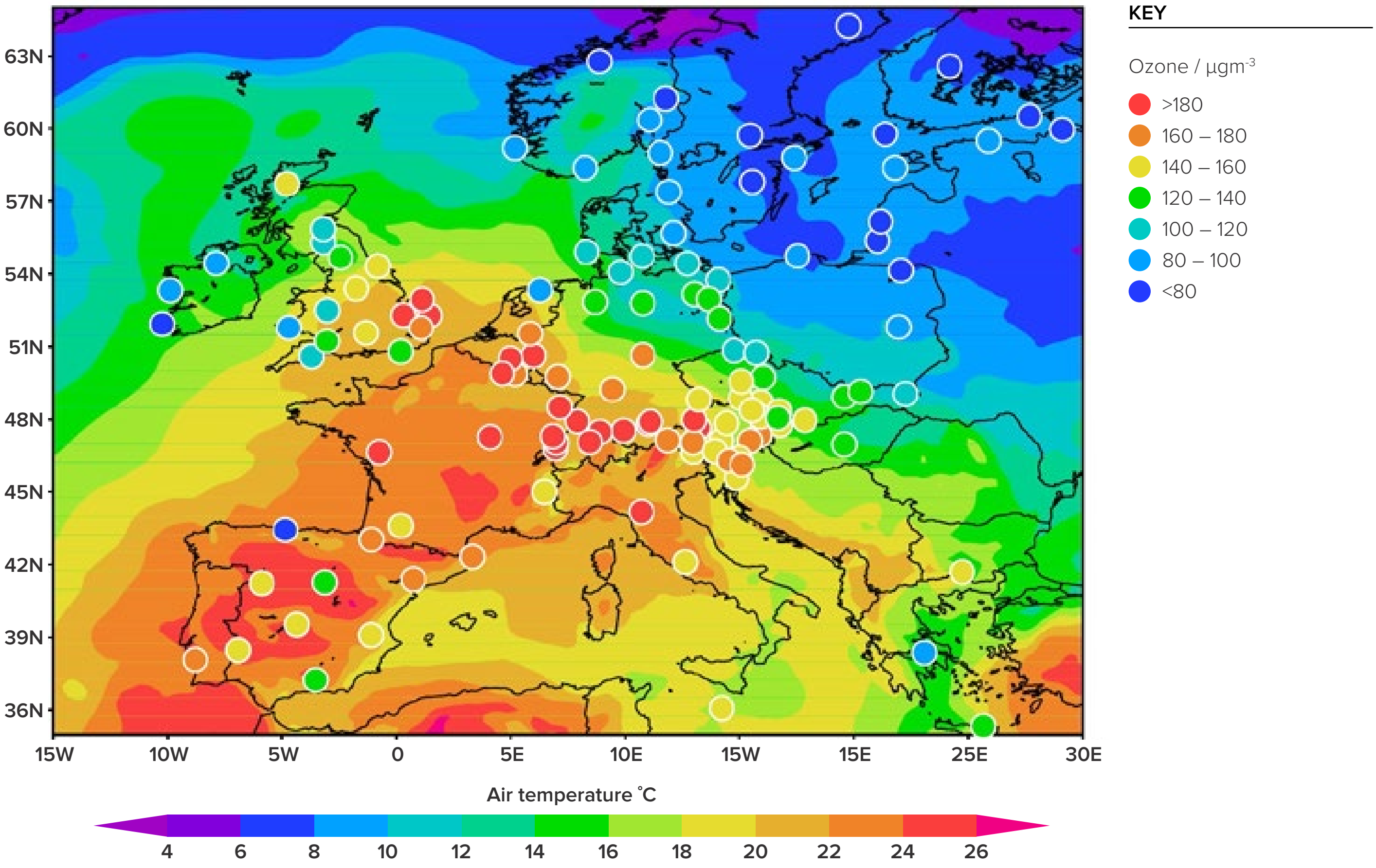
European heatwave of Summer 2003

A strong blocking anticyclone became established over western Europe in summer 2003, leading to an extended period of hot and dry conditions that included record temperatures over much of Europe in early August (including a then record 38.5°C in the southern UK). The stable conditions limited the mixing and dilution of pollutants, and the hot sunny conditions favoured photochemical processing of primary emissions, exacerbated by enhanced BVOC emissions[57] and by reduced dry deposition of oxidants to vegetation in the dry conditions. The heat and drought also led to major forest fires, particularly in Portugal, which provided an additional source of O_3 precursors and PM. High O_3 concentrations were measured across the southeastern UK over a 10-day period, peaking at 250 μgm^{-3} (125 ppb). The elevated ambient O_3 and PM_{10} (particles with diameters that are generally 10 micrometers and smaller) concentrations during the event were associated with 423 – 769 excess deaths across England and Wales, equivalent to about 20 – 40% of the total excess deaths over the period[58]. Events similar to the 2003 episode occur at frequent intervals: there were moderate O_3 pollution episodes in summer 2017 and 2018, while 2019 saw three summertime O_3 episodes, with 8-hour running mean O_3 exceeding 200 μgm^{-3}. These events were all associated with air masses originating over Europe and involved significant photochemical processing of primary emissions.

FIGURE 6

Daily maximum surface ozone over Europe on 6 August 2003

Daily maximum surface O_3 measurements (points) and mean 2pm temperature at ~1 km altitude (shading) across Europe at the peak of the heatwave on 6 August 2003. The figure reveals both the strong relationship between O_3 and temperature under hot, dry, stable conditions, and the continental scale of the O_3 episode.



Source: Figure adapted from Solberg *et al.*, 2008.

BOX 4

Wintertime stagnation episodes

An anticyclonic system over western Europe during early December 1991 led to an extended period of light winds, low insolation levels and temperature inversions accompanied by periods of wintertime fog. These conditions led to reduced dispersion across southeast England and favoured accumulation of primary pollutants. NO_2 levels exceeded 700 µgm^{-3}, the highest ever observed in London (and significantly higher than present day levels, reflecting emissions at the time). The episode was terminated by the arrival of a succession of frontal systems from the Atlantic bringing higher wind speeds and milder conditions[59].

The 1991 event was an extreme case, but was similar in scale to the 1952 episode that led to the Great Smog of London that may have caused as many as 10,000 excess deaths and that catalysed the development of the UK Clean Air Act in 1956. However, stagnation episodes of shorter duration recur at frequent intervals over different regions of the UK, for example in the northwest and Northern Ireland in 2010, across southern England and Wales in Jan 2017 when $PM_{2.5}$ levels exceeded 100 µgm^{-3} [60], and across the West Midlands in Dec 2019 when NO_x levels (primarily NO) reached 300 µgm^{-3} [61].

Projected meteorological changes are expected to lead to a change in the seasonal balance and relative severity of UK air pollution episodes, and in particular:

i. a decrease in poor air quality associated with wintertime stagnation events, typically characterised by elevated NO_x and primary PM levels; and

ii. an increase in summertime photochemical oxidant episodes characterised by elevated O_3 and secondary PM.

In terms of exceedances of current air quality objectives, these changes are expected to reduce exceedances of the hourly and annual mean objectives for NO_2, and to increase the likelihood of exceedances of the target for O_3 (100 µgm^{-3} as 8-hourly mean, and, to a lesser extent, the AOT40 [Accumulated O_3 exposure over a threshold of 40 ppb (=80 µg/m^3)] targets for ecosystems). The balance for PM in air pollution episodes is difficult to estimate, but over the annual cycle there will likely be a shift in ambient aerosol composition during episodes of elevated concentrations away from primary components and towards secondary (organic and inorganic) components, all else being equal. This may be accompanied by changes in PM toxicity during pollution episodes, although the sign of these changes remains uncertain.

1.5 Consequences of climate change for future UK air quality

We summarise the likely impacts of climate change on UK air quality for key pollutants in Table 2 and Figure 7. The table gives an indication of the expected impacts of changes in different climate processes on pollutant concentrations over the UK, while the figure provides a qualitative summary of the overall impacts on air quality. We outline the main impacts for the major pollutants, O_3 and PM, in Box 5. While we focus here on the effects of climate change alone, we highlight that associated changes in global anthropogenic emissions will alter the background concentrations of pollutants such as O_3, as shown in Figure 5, and that along many climate pathways these changes may dominate future changes in UK air quality.

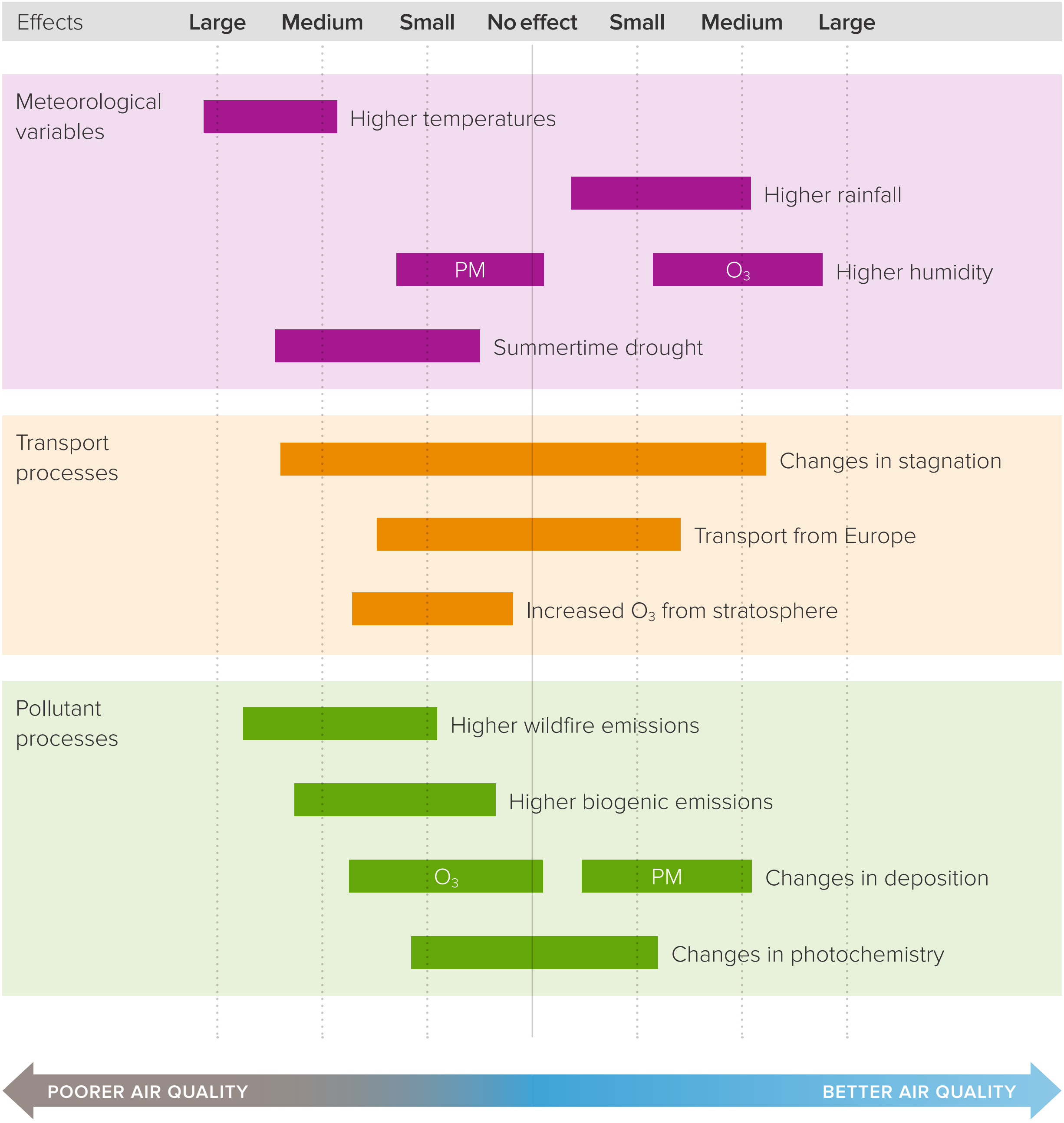
TABLE 2

Summary of key climate change impacts on UK air quality

Climate process	Surface concentrations over UK					Impacts
	NO_x	VOCs	NH_3	PM	O_3	
Wildfires	+	+		+	+	Affect global O_3 and PM, and local PM, NO_x, VOC and O_3
Wetlands/Permafrost					+	Increased CH_4 increases global O_3
Lightning NO_x emissions	+/-				+/-	Affects global O_3, but magnitude and sign of changes uncertain
Soil emissions	+				+	Increased NO increases global and local O_3
Vegetation emissions		+	+	+	+	Increased global and local O_3, local NH_3, VOC and PM
Stratospheric O_3 influx					+	Increased transport of O_3 from stratosphere
Stratospheric O_3 recovery					+/-	Slower tropospheric O_3 photochemistry due to O_3 recovery in the stratosphere
Higher temperatures	+	+	+	+	+	Higher emissions, greater PM and O_3 formation
Higher rainfall			-	-		More effective scavenging of PM
Higher humidity				+	-	Lower O_3 from Atlantic; greater PM growth
Changes in stagnation	+/-	+/-	+/-	+/-	+/-	Pollutants build up more, but changes in occurrence very uncertain
Regional transport				+/-	+/-	Changes in European influx uncertain; more dust, fires
Summertime drought	+	+		+	+	Reduced deposition of pollutants; more dust

FIGURE 7

Qualitative summary of the expected effects (span reflects uncertainty of outcome) of a range of climate changes on UK air quality



1.5.1 Regional impacts

Many of the changes in air quality associated with climate change differ substantially by region. Prevailing westerly flow makes the north and west of the UK more susceptible to changes in background composition over the Atlantic, while parts of the south and east are more greatly exposed to changes occurring over continental Europe. Summertime heatwave and droughts are likely to affect the southeast more greatly than other parts of the country, and greater accumulation of pollutants from UK sources in this region may be compounded by any influx of pollutants from Europe. Northerly and westerly regions are less exposed to these effects. In contrast, stronger westerly flow and greater wintertime rainfall may lead to a cleansing of western coastal regions, although the changes are likely to affect different pollutants differently. However, an increase in local sources such as summertime wildfires is likely to expose surrounding regions to poor air quality, and this may be a particular problem in population centres that neighbour moorland regions, such as those in northern England.

1.5.2 Urban/rural contrasts

Climate change is also likely to alter the balance of pollution between urban and rural regions, driven by differences in emission sources, local heating and land cover. Controls on vehicular and industrial emissions of NO_x and VOCs benefit urban regions most, while climate-driven increases in emissions of NH_3 from agricultural sources largely occur in rural regions. These changes in the distribution of key pollutants may be a particular issue for the composition and toxicity of PM, given the interaction of nitrate and NH_3, but the effects have not been explored in detail over the UK. The most probable outcome is a convergence of urban and rural concentrations of both O_3 and PM due to reduced primary emissions in urban areas, but sustained secondary particle formation affecting both urban and rural locations. Changes in urban heat islands, reflecting the thermal contrast between cities and surrounding regions, may also influence the dispersion of primary pollutants in urban regions, and while there is some suggestion in UKCP18 that this will weaken under future climate, the impact on air quality remains highly uncertain.

BOX 5

Summary of climate impacts on key pollutants

Ozone

Climate impacts on long-term average concentrations

In the absence of changes in anthropogenic emissions of precursors including CH_4, UK O_3 is likely to experience a small net decrease in concentrations to 2050 and beyond. This reflects a balance between increases in climate-sensitive precursor emissions (particularly BVOC, soil NO, and increased wildfires) along with greater stratospheric influx, and decreases due to reduced formation from transported nitrogen species and greater destruction associated with higher temperature and humidity.

Climate impacts on episodes

A greater frequency and intensity of summertime heatwaves is expected to lead to an increase in high O_3 episodes, particularly over the southeast of the UK. There may be an increase in the influx from mainland Europe during these episodes. Climate-driven changes in urban heat islands may affect urban O_3, but the magnitude of these changes remains uncertain.

Mitigation approaches

Regulation of anthropogenic CH_4 emissions globally would help reduce UK background O_3 as well as benefiting the climate. Management of climate-sensitive precursor emissions associated with wetlands, moorland fires, and biogenic VOC emissions associated with tree planting would be beneficial on both a UK and international scale.

PM

Climate impacts on long-term average concentrations

In the absence of anthropogenic emission changes, average PM concentrations are likely to remain stable, but changes in spatial and temporal distributions and particle composition are expected. These are associated with increased secondary formation, higher agricultural NH_3 concentrations and changes in scavenging due to rainfall. Most climate scenarios suggest long-term decreases in PM when accounting for expected anthropogenic emission changes.

Climate impacts on episodes

There is likely to be a decrease in primary particulate episodes associated with a decrease in the frequency of stagnation events in wintertime. However, there may be an increase in secondary PM associated with the increased frequency and severity of summertime heatwaves.

Mitigation approaches

Stronger regulation of agricultural NH_3 emissions is needed to balance the substantial climate sensitivity of these ‘natural’ sources, and further reductions would be valuable to reduce their importance in secondary particle formation.

Chapter two

Effects of net-zero measures on air quality

Left
Solar photovoltaic panels and a wind turbine in rural England. © huangyifei.

Effects of net-zero measures on air quality

Key messages

The transition to net-zero will deliver significant improvements in air quality as a co-benefit. Many of the actions taken to achieve net-zero are unequivocally positive for air quality. In some areas it is possible to enhance the air quality benefits through small changes in how net-zero policies are designed and implemented. In a small number of areas, net-zero measures may have adverse impacts on air quality that require mitigations, both technical and regulatory.

Opportunities with clear co-benefits

- The short atmospheric lifetimes of most air pollutants mean that positive health benefits begin to be generated immediately once the polluting source is removed. This would support the prioritisation and early introduction of those net-zero measures that will deliver significant air quality co-benefits.

- The replacement of fossil fuel derived electricity with renewable and nuclear energy generation would lead to substantial reductions in emissions of NO_x and SO_2. This would lead to reductions in $PM_{2.5}$ and O_3, which may benefit both rural and urban communities alike. It may also result in a substantial reduction in the transboundary transport of pollution.

- Net-zero action based around encouraging and supporting a shift away from use of passenger cars to walking, cycling and public transport offers significant opportunities for decarbonisation and would lead to long-term improvements in air quality, as well as bringing additional health benefits through increased physical activity levels.

- Improved efficiency in the management of nitrogen in the agricultural system has the potential to reduce NH_3 and NO_x emissions in most cases. This would feed through into lower concentrations of $PM_{2.5}$ on a regional scale and a reduction in nitrogen deposition to ecosystems. The adoption of diets with lower red meat and dairy consumption would also be expected to lead to reduced nitrogen and CH_4 emissions from livestock and their waste products, with additional air quality benefits.

Opportunities to enhance net-zero policies to benefit air quality

- The health impacts of air pollution can be highly localised and there are strategic opportunities for an ordering of net-zero investments to support a reduction in air quality-related health inequalities. Prioritising net-zero actions that also improve air quality in disadvantaged urban centres, such as by eliminating near-roadway NO_2 exposures through vehicle electrification, can potentially have health benefits larger than might be implied from the effect of the carbon savings alone.

- A transition to a fully battery electric vehicle fleet should bring significant improvements in urban air quality, with the greatest benefits arising if electricity is provided from clean, low carbon, low pollution sources. This should eliminate tailpipe emissions of NO_x and $PM_{2.5}$ as well as fugitive emissions related to the distribution and storage of fossil fuels. The benefits will be greatest in cities and near roadways.

- Non-exhaust emissions of particles from friction and abrasion such as from tyre, brake and road surface wear, and the resuspension of road dust, will continue to be a significant source of primary $PM_{2.5}$ emission, even from a fully electric vehicle fleet. These emissions could potentially increase if average vehicle mass were to increase, however this can be mitigated by use of regenerative braking, smoother driving through vehicle autonomy, and the use of new pollution control technologies such as particle capture from brake callipers and low emission tyres.

Net-zero measures that may require mitigation to protect air quality

- CCS technologies may involve the consumption of large volumes of chemicals, some novel, needed for the CO_2 stripping process. Possible fugitive emissions of volatile chemicals used in CCS can be controlled through the application of process after-treatment, and by selecting the materials on the basis of low toxicity and environmental impacts.
- An expansion in renewable and nuclear infrastructure will lead to air quality improvements over the next two decades. The transition period may however require the temporary use of back-up power, such as diesel farms, to supply capacity in peak periods and also lead to localised emissions due to construction activities. In both cases, mitigations can be introduced to manage air quality impacts, such as the application of enhanced requirements for after-treatment of combustion sources, and dust suppression during construction.
- Decarbonisation of homes is a major net-zero challenge and is likely to draw on multiple technical strategies including better building insulation, ground and air source heat pumps, photovoltaics, and hydrogen and biogas gas boilers. Technologies such as heat pumps and photovoltaics lead to unequivocal local air quality improvements. However, use of hydrogen or biogas gas boilers for home heating would likely lead to some emissions of NO_x, although these could be mitigated through enhanced requirements for emissions control and possibly new after-treatment technologies.
- Increased cultivation of fast-growing crops for biofuels may, depending on the land use change, lead to increased BVOC emissions, downwind O_3 and secondary organic aerosol formation. These impacts can be significantly reduced through careful selection of low-emitting species such as beech and avoidance of large-scale planting of species such as *Miscanthus*, *Salix* (willow) and *Quercus* (oak).

Image:
Oilseed rape, a crop used to produce biodiesel.
© georgeclerk.

- Future net-zero actions related to agricultural emissions would deliver maximum air quality benefits if they were designed to avoid pollution swapping. A switch away from the use of ammonium nitrate fertilisers to urea as an alternative could increase NH_3 emissions, although partial mitigation through reduced overall consumption and improved farming practices is possible.

- Combustion of biomass has the potential to lead to reduced net GHG emissions relative to fossil fuels, but could lead to air pollution emissions. After-treatment of emissions from biomass burning is likely to be efficient and cost effective when delivered at industrial scale, but possibly much poorer at reducing emissions from domestic wood burning stoves or pellet boilers. Avoiding the use of biomass combustion in areas of high population density will be a key mitigation.

Wider issues

- The formation of important secondary pollutants such as $PM_{2.5}$ and O_3 is non-linear with respect to their precursor emissions, and so the most significant improvements in air quality may not come until later in the net-zero transition period. As primary emissions of PM and NO_x decline, secondary particles will come to dominate population exposure, on average. Since $PM_{2.5}$ is relatively long-lived in the atmosphere this will demand continued international cooperation to reduce transboundary transport of pollution.

- The effects of fleet electrification and recent improvements in exhaust gas after-treatment technologies are already being reflected in decreases in urban nitric oxide emission concentrations across Europe. A consequence however is that urban O_3 concentrations are beginning to increase, as chemical suppression of O_3 via local reaction with the free radical nitric oxide is reduced. The benefits of NO_x reduction are likely still to outweigh any O_3 disbenefit at the roadside, but this switch between pollutants must be recognised, and regional O_3 pollution mitigated through policies that also reduce O_3 precursor emissions of VOCs, particularly from solvent-containing products.

- A reduction in air travel would reduce emissions of PM, NO_x, and VOCs from ground operations and road traffic in the vicinity of airports, in addition to reduced aircraft emissions associated with taxiing and take-off. For the foreseeable future it seems likely however that airports will remain hotspots for air pollution, relative to their surroundings, and generate wider impacts on air quality in regions downwind. While some plausible routes to decarbonise exist, for example using biofuels, or hydrogen-based fuels, combustion-related emissions of air pollution will persist.

- Indoor air quality can be influenced by net-zero policies, particularly those that lead to changes in buildings standards such as ventilation and methods of space heating. However, many aspects of indoor exposure will be independent of net-zero measures, and be influenced instead by human behaviours, product standards such as in buildings and furnishing materials, and the use of decorative and domestic consumable products. While net-zero measures provide a wide-ranging framework for improvement in outdoor air quality, delivering better indoor air quality in homes, workplaces and public buildings such as schools and hospitals will require independent strategies.

2.1 Introduction

In this chapter the likely effects of net-zero policies on air quality are discussed, including changes in transport, industry, agriculture (including forestry and land use change), buildings, infrastructure and energy generation. We also consider the impact of low carbon engineering and technological approaches in areas such as CCS, new fuels and energy efficiency.

2.1.1 The development of net-zero plans for the UK

In 2019 the UK adopted a legally binding target to reduce its territorial GHG emissions to net-zero by 2050 at the latest, following a recommendation from its statutory advisory body, the Committee on Climate Change (CCC)[62]. The CCC's advice was designed to inform the UK's contribution to the 2015 Paris Agreement on climate change, with the net-zero goal representing the country's 'highest possible ambition' as required by that accord. The adoption of the net-zero goal amended the target set under the UK's 2008 Climate Change Act, from a GHG reduction of at least 80% on 1990 levels by 2050, to a reduction of "at least 100%" by that date.

The greenhouse gas emissions covered by the Climate Change Act are CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (SF_6). Achieving net-zero GHG emissions by 2050 will entail reducing these emissions to a minimum, together with ways of removing CO_2 from the atmosphere to offset any emissions that remain. The level of climate change is ultimately a function of the cumulative emissions of long-lived GHGs (of which CO_2 is the primary contributor) and the rate of emission of short-lived GHGs (eg CH_4). UK climate change policy is to achieve net-zero CO_2-equivalent emissions accounting for both long-lived and short-lived gases. The UK's interim 2035 target (see below) also includes the UK's share of international aviation and international shipping (IAS) as well as GHGs released directly in the UK.

The Climate Change Act also requires medium-term 'carbon budgets' to be set for five-year periods on the path to 2050 to ensure that progress is made on track to the long-term goal. In December 2020, as required by the Act, the CCC recommended the Sixth Carbon Budget, setting the maximum allowed GHG emissions across the period 2033 – 2037. This is the first carbon budget set since the adoption of the net-zero target and as such it effectively sets the path for GHG emissions on the path to net-zero.

The CCC's recommended path for GHG emissions is front-loaded – the proposed budget level would require a reduction in GHG emissions of 78% in 2035 on 1990 levels (including IAS), which equates to a reduction of 63% on 2019 levels, with reductions faster in the first half of the period than in the second half. This same path for emissions was used as the basis for the CCC's advice that the UK's 'Nationally Determined Contribution' (NDC) for 2030 under the Paris Agreement should be for a reduction of 68% on 1990 levels.

The CCC's advice on the Sixth Carbon Budget presented five scenarios for reaching net-zero by or before 2050, including varying assumptions on the contribution of reduced consumption of high-carbon goods and services, such as red meat and aviation, and that of innovation in reducing costs and finding new ways to reduce emissions.

The CCC's 'Balanced Net-zero Pathway', seeks a way of reducing emissions while creating options to keep a range of routes to net-zero in play. This approach would keep cumulative GHG emissions to a level compatible with the temperature goal of the Paris Agreement, that of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C.

The CCC's Balanced Pathway entails further reductions in emissions from electricity generation – following a reduction of more than 50% since 2012, to almost eliminate these by 2030, largely through generation from zero-emission sources, such as wind, solar and nuclear. Zero-emission electricity is also of huge value in decarbonising other sectors through electrification over the period from now to 2050 – notably through the adoption of electric technologies such as electric vehicles and heat pumps in place of heating systems based on fossil fuels. Achieving net-zero also requires some contribution from the use of hydrogen and NH_3 as fuels where electrification is not feasible, together with significant changes to land use in the UK (Figure 8).

The CCC's analysis has taken into account opportunities to improve the health of the UK population alongside reducing GHG emissions. The Expert Advisory Group on Health that the CCC convened to help inform its Sixth Carbon Budget considered the positive and negative effects on health of reducing GHG emissions, including air quality, diet, warmer homes and the exercise benefits of walking and cycling. This group helped the CCC to make judgements on the balance of mechanisms to reduce GHG emissions that were included in the scenarios. Although this group was also tasked with collating quantitative evidence on the health benefits accruing from these measures, its conclusion was that the available data are not currently of sufficient quality to do this robustly across the full range of health impacts, highlighting a need for further research.
The Expert Advisory Group on Health also concluded that aggregate measures of health impacts are less useful than those that take into account the distributional impacts across UK society – both directly, such as exposure to poor air quality, and indirectly, such as impacts of climate policies on household energy bills, which affect how well homes are heated.

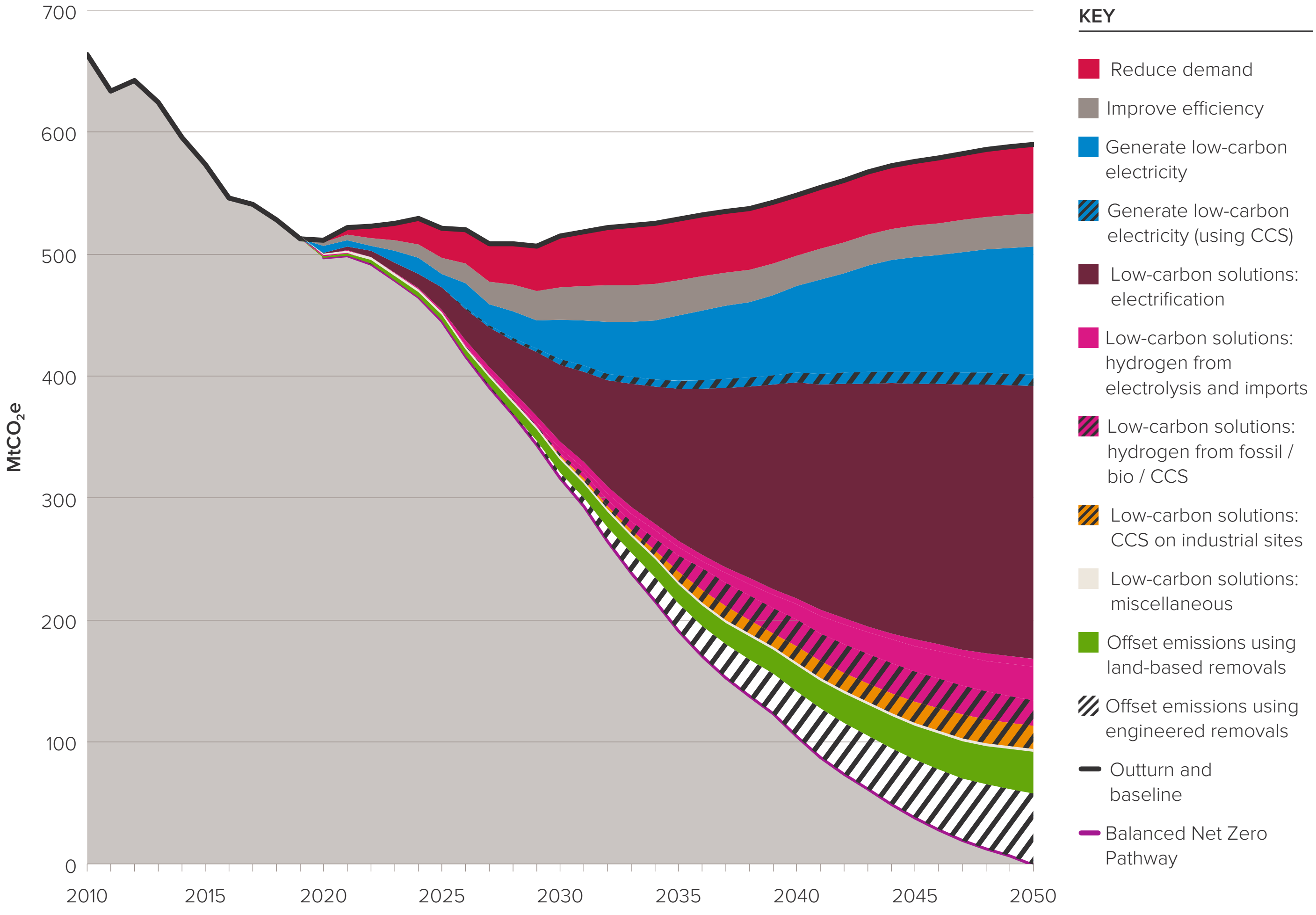
The CCC's pathways are also designed to exclude measures or structural changes that would be anticipated to make air quality significantly worse over the long-term, for example permanent shifts to combustion of biomass to heat buildings.

2.1.2 Links between greenhouse gases and air pollution

Activities which give rise to emissions of GHGs frequently also lead to the co-emission of other shorter-lived air pollutants that are harmful to ecosystems and public health. In general terms, the attainment of a net-zero greenhouse gas budget would be expected to lead to substantial change, overwhelmingly in the form of reductions, in emissions of other air pollutants[63]. This is a significant co-benefit arising from net-zero emission commitments. The exact nature of the links between GHG emissions and short-lived air pollution emissions are specific to individual processes and technologies, and different pollutants will be affected to different degrees by each intervention. These are explored further in this chapter.

FIGURE 8

Balanced Pathway for reductions in UK greenhouse gases to reach net-zero in 2050



Source: Figure adapted from CCC 2020, with further breakdown on CCS provided by the CCC.

Some air pollutants are common to both climate change and air quality strategies[64]. For example, black carbon is a significant contributor to climate change at global scales and is detrimental to public health if inhaled. Tropospheric O_3 is formed from the reactions of CH_4 or other VOCs and NO_x and is a radiatively active gas with climatic effect in the free troposphere and a harmful air pollutant at ground level. At hemispheric scales the budget of tropospheric O_3 is itself strongly influenced by atmospheric CH_4 concentrations and any future reductions in exposure to O_3 will in part depend on reducing CH_4 emissions[65].

A wide range of pollutants are co-released along with CO_2. The most obvious connection between climate-oriented action to reduce CO_2 and an air quality gain is the parallel reduction of combustion-related pollutants such as NO_x, carbon monoxide, black carbon (and other PM), SO_2 and polycyclic aromatic hydrocarbons (PAH), all of which are directly released from burning fossil fuels. Several key emission sectors are expanded on in later sections, for example those associated with primary energy production, space heating, and transportation. In some combustion-dependent systems the co-benefits of net-zero on air quality are substantial and clear cut. For example, the electrification of road transport will substantially reduce CO_2 emissions and largely eliminate NO_2 as a problem pollutant at the roadside in cities. In some cases, the outcome is more complex – a reduction in coal combustion will reduce sulphur emissions, improving air quality, but this may also reduce current climate cooling that arises from aerosols.

Some air pollutants are linked to GHG emitting processes in less direct ways. VOCs are released to air from many sources including leakage in the natural gas network and the fugitive evaporation of gasoline[66]. Both are a secondary consequence of current technologies that depend on carbon-based energy. In a transition to net-zero where these traditional fuel sources are replaced, the collateral emissions associated with them may also be eliminated as a beneficial by-product.

The connections between GHG emitting processes and co-emitted species that give rise to secondary air pollutants such as PM are more complex, and the scale of co-benefits less certain. The climate impacts of agriculture and food production are significant, as are the detrimental air quality impacts that arise from agricultural emissions of NH_3, which goes on to combine with acidic air pollutants to form PM, leading to eutrophication and wider ecosystem damage. Changes in farming practices and diets more generally, if designed well, may reduce greenhouse gas emissions and harmful PM, as well as leading to other environmental gains in ecological and aquatic systems.

While the atmosphere contains many thousands of individual chemical pollutants, the metrics used in a regulatory and legal context to outline what is good air quality are relatively narrowly defined. Progress on air quality is typically judged against changes observed in the atmospheric concentrations of a small basket of pollutants. Air quality can be measured against attainment of a limit value, for example an ambient concentration that must not be exceeded, or an objective to reduce concentrations year on year over a broad area, expressed as an annual rate of reduction. Both bring health benefits, with the latter type of objective important since harm occurs even at very low concentrations.

Most high profile is PM, where air quality is very frequently defined by the operational metric of $PM_{2.5}$ – broadly those particles with an aerodynamic diameter smaller than 2.5 micrometres. Alongside $PM_{2.5}$, concentrations of NO_2 and O_3 are the two other most commonly used metrics. SO_2 is also of direct health relevance, although its concentrations have greatly declined across the UK since 1980. Although $PM_{2.5}$ is the most commonly used metric for particle air quality, the composition of particles is in practice very complex, comprising variable amounts of organic and inorganic chemicals derived from direct emissions or from atmospheric processing. The differential toxicity of these individual components remains uncertain.

The impact of net-zero measures will be quantified first and foremost against how those climate interventions change the ambient concentrations of $PM_{2.5}$, NO_2 and O_3. Too narrow a focus, however, hides a substantial degree of complexity, and this may not necessarily capture all the impacts. Net-zero may lead to reductions in pollutants that are primarily thought of as precursors to secondary air pollutants, or reduce the environmental and health burden of longer-lived persistent organic pollutants such as metals, PAHs or polychlorinated biphenyls. The impacts of pollutants such as PAH and polychlorinated biphenyls can manifest in different ways to other pollutants, for example raising long-term cancer risk, even though they are present in air in only very small amounts[67].

In considering the impacts of net-zero on air quality it is important to also consider possible impacts on, or the creation of, emerging new pollutants in air, or the changes that may occur in other parameters, such as the size distribution or the chemical composition of PM. These more subtle impacts remain uncertain, since there is uncertainty regarding the possible differential health impacts of different sub-components of PM[68], or indeed how PM may respond to changes in natural precursor emissions[69].

2.1.3 Emissions changes, exposure and inequalities

One notable difference between the impacts of greenhouse gases and reactive air pollutants is that there can be substantial differentials in effects depending on where emissions occur. The long-lived nature of greenhouse gases (a century or more for CO_2 and N_2O and a decade for CH_4) means that they become well-mixed at a global scale. Thus, the benefits from the reduction in the emission of one molecule of CO_2 is essentially the same no matter where that occurs geographically. The much shorter lifetimes of most air pollutants (lifetimes of a few hours to several weeks) lead to considerable variability in their distribution and reductions in emissions generate different benefits for air quality depending on where they occur. The most significant air quality health co-benefits arising from net-zero depend therefore not only on the size of emission change but the location of the reduction. Net-zero actions that lead to a reduction in air pollution emissions in densely populated urban centres may have the potential to be more significant in changing exposure than reductions occurring in more remote locations.

A differential in possible exposure change does not negate optimising net-zero with air quality policy, since rural-sited emissions contribute to background levels and go on to cause wider scale harm, but it may influence local cost-benefit analysis. In some cases, a local reduction in emissions of one pollutant, for example NO_x, can lead to local increases in another, such as O_3, and so the interconnectedness of the different components of air pollution needs to be considered[70].

In the next section on the sectoral impacts of the net-zero transition on air pollution emissions it is thus important to keep in mind where changes in emissions are likely to occur and whether this is likely to amplify benefits (or disbenefits), if these occur close to where people live.

Exposure to air pollution, and the health impacts arising, are currently unequally distributed across society. Figure 9 shows how exposure to the pollutant NO_2 in London is distributed as a function of levels of crime, income, health deprivation, disability and living environment. Those in the lowest deciles (1 being the most deprived) tend to experience the highest pollution, while those in the higher deciles the least. Since NO_2 is relatively short-lived as a pollutant, its health impacts occur close to the point of emission, at present near to roads, while the links between deprivation and longer-lived pollutants such as $PM_{2.5}$ can be less pronounced. Nonetheless analysis by the Office for National Statistics, has shown a significantly higher exposure to ten-year averaged $PM_{2.5}$ for communities with higher percentage black, Asian and minority ethnic (BAME) communities[71].

This differential in the impacts of poor air quality creates some opportunities for net-zero climate actions, and the associated prioritisation and ordering of investment, to be directed to support a reduction in health inequalities. An early focus on net-zero actions that lead to reductions in air pollution emissions in disadvantaged urban centres could potentially have health benefits much larger than might be implied from the effect of the carbon savings alone.

2.2 Sectoral analysis of potential impacts on air quality

In this section some of the major sectors to be addressed by net-zero strategies are considered from an air quality perspective, and some of the key issues, opportunities and possible threats identified. Where possible the likely broad impact on air quality is described (benefit, disbenefit or neutral), along with a brief description of: why this effect may occur; when the impact is likely to be realised; the scale of the possible impact and significance; and the potential for mitigation, avoidance or optimisation through technological or policy modification.

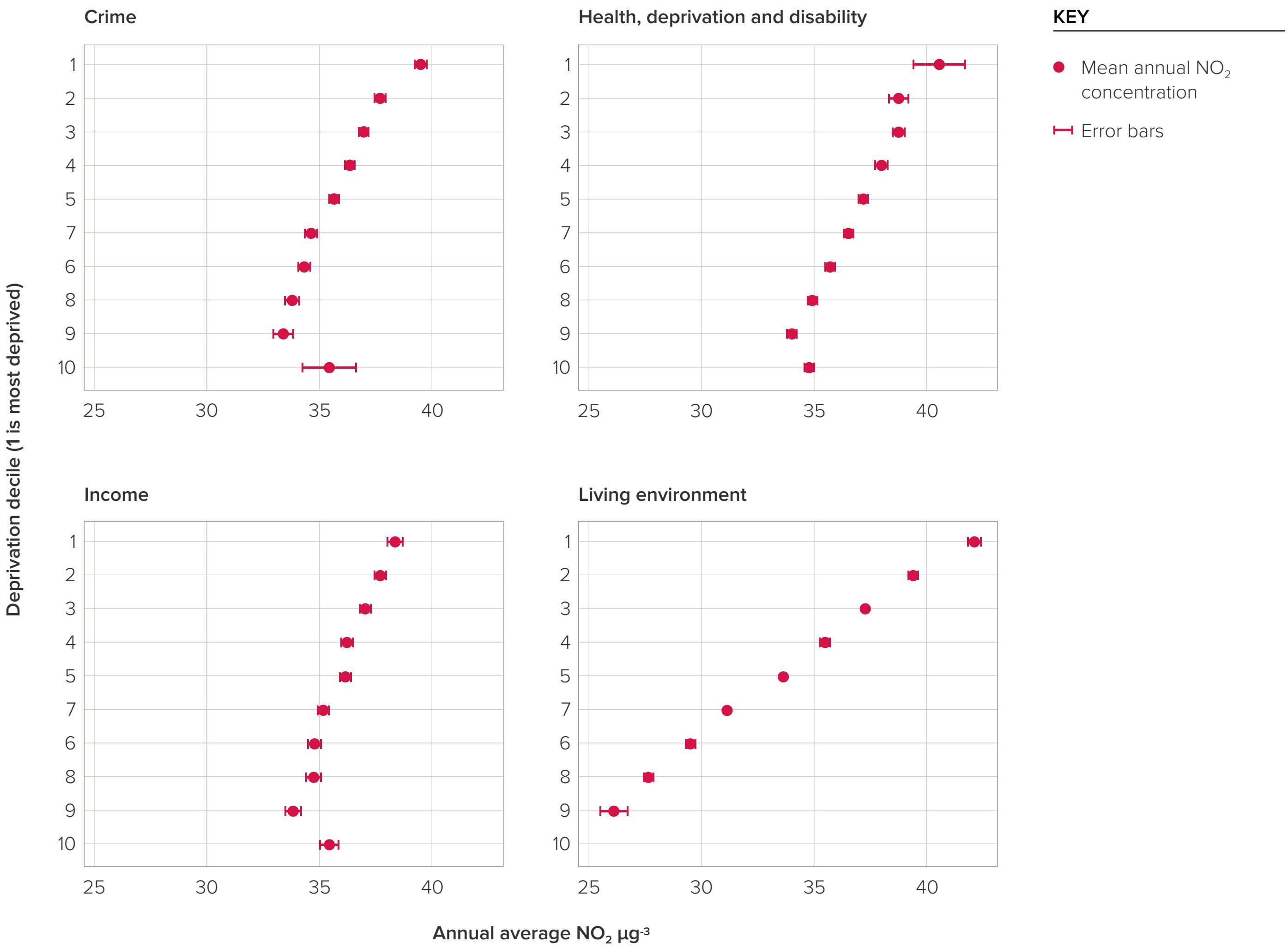
2.2.1. Electrical energy supply sector

Projected UK electricity demand for 2050 under the CCC's carbon budget scenarios ranges from 550 to 680 TwH, with a central (balanced) prediction of 610 TwH, incorporating efficiency gains[55]. This compares with actual UK electricity demand of around 300 TwH in 2019[72]. The near doubling of demand is driven primarily by the extension of electricity use including vehicle electrification, residential and non-residential heat and power demand, alongside manufacturing, construction and fuel supply. A key aspect of the non-renewable or continuing combustion-related capacity to meet this demand is the use of CCS abatement technologies at power plants – gas-fired facilities until they are phased out and biomass-fired units – to prevent release of CO_2 from combustion.

FIGURE 9

Mean annual NO_2 concentration in 2018 for selected domains of deprivation in London[73]

Mean annual NO_2 concentration (2018) for each deprivation decile of selected domains of deprivation across all Lower Layer Super Output Areas (LSOA) in London. A deprivation decile of 1 represents the most deprived 10% of all LSOAs nationally. Error bars represent one standard deviation above and below the mean.



Source: Air Quality News 2021 (based on data from the London Atmospheric Emissions Inventory and the Ministry of Housing, Communities and Local Government).

Under the CCC scenarios, the demand for power to 2050 will be met by significant shifts in electricity generation including (i) the phase out of unabated (ie not using CCS) generation from fossil fuels, conventional coal and gas; (ii) the trajectory, potentially of growth and then reduction, of low carbon generation in the form of gas or bioenergy coupled with CCS (gas-CCS or BECCS, respectively), and use of hydrogen in gas plants; (iii) significant expansion of wind and solar capacity; and (iv) changes in nuclear power provision. All of these have impacts on air quality and further effects may arise from offshore and non-UK power generation and imports, from changes in fuel sourcing (including gas and bioenergy) and, indirectly, from infrastructure development and construction.

Coal-fuelled power generation without carbon abatement is due to be phased out by 2025 in the UK. Existing UK coal plants are scheduled to close, or to convert to gas- or biomass-fuelled operations. This contrasts with the global picture, where reductions in coal-fired electricity output in Europe and the US are offset by growth in China, India and other Asian countries[74]. The phase-out will have a beneficial impact on air quality as combustion of coal produces a number of gaseous and particulate air pollutants, including NO_x, SO_2, acid gases (eg HCl), VOCs and a range of other gaseous and particle pollutants including heavy metals (eg mercury), dioxins, furans and PAH, which may accumulate in soils, sediments and organisms.

The 2050 net-zero trajectories for electricity generation considered by the CCC all include components of generation provided by natural gas or biofuel combustion, coupled with CCS technologies (both gas-CCS and BECCS) from 2025 onwards.

Combustion of natural gas releases NO_x, SO_2, VOCs, CO and PM, although generally in lower quantities than most other fossil fuels.

CCS technologies may increase certain air pollutant emissions, per unit of electricity generated, compared with the equivalent plant used without capture technology. These increases arise from the energy required for CO_2 capture, compression, transport and storage; emissions from the additional fuel combustion at the CCS facility (which may require up to 25% more energy per unit electricity produced); and indirect emissions relating to fuel and CCS solvent supply and treatment chains[75]. The impact of CCS upon individual pollutants depends upon the fuel source and CCS approach: retrofit post-combustion carbon capture using amine-based methodologies requires SO_2 and PM emissions to be essentially removed (as per current flue gas desulphurisation) for amine-based CCS chemistry to function; NO_x emissions are anticipated to scale with the primary energy demand to run the capture unit. If an amine-based approach is used, such as mono-ethanolamine, this may result in increased emissions of NH_3 from amine-based solvent degradation / solvent slip, affecting PM formation, and local fugitive emissions of amines, nitrosamines (potential carcinogens) and other organic nitrogen species. In the case of NH_3, these additional CCS-related emissions will be small, estimated at less than 6% Europe-wide, compared with NH_3 from agriculture.

Changing fuel sources for natural gas and biofuel-powered generation may affect air quality. In the case of gas-fuelled generation, fugitive emissions during extraction, processing and transport of CH_4 and VOCs will affect regional and hemispheric O_3, organic aerosol and wider oxidative processing.

These may particularly affect air pollution where terrestrial hydraulic fracturing is the process used to extract the natural gas, including fugitive gas emissions and local supply chain emissions, such as from compressors, energy and transport.

Increased cultivation of fast-growing crops for biomass combustion, for example *Miscanthus* and *Salix* (willow)[76], may, depending on the nature of the land use change, lead to increased BVOC emissions and downwind O_3 and secondary organic aerosol formation[77]. As electricity generation from renewables and transport electrification reduces NO_x emissions, changes will occur to the O_3 production sensitivity (the number of O_3 molecules produced per unit of NO_x) and the relative policy impacts of controlling NO_x or VOC emissions.

Substantial expansion in renewables, primarily wind and solar, forms a key component of the projected UK net-zero electricity generation trajectory, supplying 90% of demand by 2050, compared to 22% of generation in 2018. Alongside tidal and hydropower, these approaches have only minor negative impacts on air quality – almost entirely relating to construction – but then deliver very substantial long-term benefits from the displaced fossil-fuel combustion generation emissions of NO_x, PM, SO_2 and VOCs. Nuclear power provided 17% of UK electricity generation in 2019 with around 9GW of capacity; much of which is set to be retired in the next one to two decades.

The contribution of nuclear generation is a key uncertainty in net-zero electricity generation pathways, due to a combination of cost, political and technical factors, with potential generation ranging from 5 to 10 GW by 2050 across the CCC trajectory scenarios.

The transition of a small proportion of gas-fired electricity generation to hydrogen fuelled operation (10 – 20 TwH, with the hydrogen derived from electrolysis, or CH_4 reformation with CCS) will lead to reductions in SO_2, CO and VOC emissions, direct and fugitive, at the power plant, compared with fossil-fuel combustion generation, but will remain a source of NO_x formed through the thermal decomposition of nitrogen in air under high temperature combustion[78].

Interconnections which transfer electrical power between the UK and neighbouring countries have a current capacity of 6 GW or around 8% of UK generating capacity and

Image:
Harvesting a 4-years old willow plantation. Lignovis GmbH, CC BY-SA 4.0 creativecommons.org/licenses/by-sa/4.0, via Wikimedia Commons.

this is projected to increase significantly by 2025, with Ofgem projecting a doubling. The displaced air pollution impacts of interconnection supply depend upon the type of generation used. Historically much imported electricity has been purchased from France which has a predominantly nuclear grid.

2.2.2 Transport sector

Decarbonising the transport sector will bring substantial air quality benefits, in particular reducing tailpipe NO_x, PM, and VOCs in urban areas, where the population's exposure is greatest. The benefits would be most significant at the roadside. However, there are challenges that require consideration and potential mitigation.

The ban on sale of new gasoline and diesel fuelled cars and vans by 2030 and full electrification of the fleet by 2050 will bring substantial air quality benefits with reduced NO_X and VOC emissions. The greatest public health benefits are derived if electricity comes from zero carbon emission sources. Not only would exhaust emissions of VOCs be eliminated but also the evaporative and fugitive losses associated with both the vehicles themselves and the refuelling and refining infrastructure[79].

Reductions in NO_X emissions will lead to increases in O_3 concentrations at roadside and urban locations because O_3 is removed through reaction with NO (as seen during the COVID-19 pandemic, Grange *et al.*, 2021), but this will be partially offset by lower rates of subsequent photochemical processes which lead to production of O_3 downwind. The impact of vehicle electrification on O_3 is complex but the local city scale air quality benefits of reducing urban NO_2 and exhaust-derived PM are likely to be larger than the effects of roadside and urban increases in O_3. The wider impacts of this shift are complex to evaluate, since less NO_x ultimately leads to lower PM and O_3 at transboundary scales, but the reduction in NO titration effects may lead to some increase in O_3, deposition and ecosystem impacts at the regional scale.

Electrification of heavy goods vehicles poses a challenge due to their heavy loads and long-haul journeys. This requires extremely fast high-powered charging facilities or on-road charging infrastructure such as overhead catenaries or embedded conductive road strips[80]. A zero-carbon alternative is hydrogen power, but this too would require refuelling stations[81]. The impact of hydrogen power on air quality will depend on whether the hydrogen is used in fuel cells, which are very low emission, or as an engine combustion fuel, which would generate NO_X emissions and require abatement systems such as exhaust gas recirculation and selective catalytic reduction[82]. Since heavy goods vehicles travel internationally, a consistent approach across Europe is required. Electrification or hydrogen fuel-cells are already viable options for buses which can recharge or refuel in the depot and thus offer the potential for improving air quality, particularly in urban areas.

While electrification or hydrogen power will virtually eliminate all PM exhaust emissions and NH_3 from exhaust gas after-treatments such as selective catalytic reduction, PM from friction and abrasion, including tyre, brake and road surface wear, and the resuspension of road dust, will remain[83]. It is plausible that these emissions could rise if average vehicle mass were to increase, for example due to use of batteries or fuel cells, should vehicle numbers increase, or overall mileage driven. However, there are measures that could offset this effect, including regenerative braking and new mitigation technologies such as capture from brake callipers and low emission tyres.

The impacts of increasing automation and self-driving vehicles is not yet clear, although it has the potential to lead to somewhat smoother driving styles which would reduce PM emissions from braking[84]. A possible confounding factor is vehicle weight, as fully autonomous vehicles may be heavier due to increased battery and processor payload and more substantial safety systems.

While some PM vehicle emissions will always remain due to friction, a modal shift to options such as walking, cycling, and public transport would deliver both air quality and health benefits.

Both further electrification of the railway network and the introduction of hydrogen fuel-cell powered trains to replace diesel-powered trains will improve air quality through reductions in NO_X, PM and VOCs. This will lead to some particularly beneficial gains where people and trains are both in enclosed stations, locations which can currently be hotspots for poor air quality[85].

Globally, shipping is responsible for around 3% of anthropogenic GHG emissions. It is also a major source of sulphur oxides (SO_x), NO_x and PM, having impacts on human health via long distance and transboundary transfers[86], as well as via local emissions and exposure, such as in ports[87]. Some maritime areas require abatement technology on shipping emissions to reduce impacts on human health (eg the Baltic). While international shipping is not directly addressed within the Paris Agreement, countries have agreed global targets for GHG emissions reduction through the International Maritime Organization. These include peaking and then reducing emissions to at least 50% below 2008 levels by 2050. Assuming a commensurate reduction in air pollutants (eg through increased fuel efficiency) a reduction in sulphur emissions and air quality benefits is expected, although this may have climate warming effects through a reduction in sulphate aerosols. However, under existing commitments regarding emissions intensity, little change can be expected in absolute emissions within the next decade. Where GHG emission reductions are achieved by fuel substitution, such as to NH_3, liquified natural gas or fuel cell hydrogen, there also remains significant uncertainty in terms of the relative impact on air pollutants and human health. Assessment of NH_3 use in maritime internal combustion engines, for example, indicates that it could have more negative impacts on human health than liquified natural gas[88].

While electrification is possible for small boats, most ships will require an alternative such as NH_3 (or hydrogen) for fuel-cells, internal combustion, or dual fuel or hybrid combinations[89]. Fugitive emissions of NH_3 are a potential risk, but this can be controlled, and will need to be, due to the toxicity of NH_3. As with hydrogen, the impact on air quality depends on whether the NH_3 is used in fuel-cells or combusted. The former would lead to substantial reductions in NO_X, PM and some reduction in VOCs and O_3, while the latter could lead to emissions of NO_X and PM, but slightly lower than are released from current technologies. As with heavy goods vehicles, international solutions to decarbonisation of transnational transport are needed to ensure the availability of compatible refuelling infrastructures.

Aviation has limited options for decarbonisation and so there is limited potential to change its impact on air quality. Use of hybrid-electric aircraft from the 2040s onwards and changes to aircraft design and air traffic management could offer small improvements in air quality but use of bio or synthetic fuels would likely lead to increased VOC emissions. Hydrogen and NH_3 fuelled jet engines are also under development for short-haul aircraft[90], although these would likely continue to lead to NO_x emissions[91], an issue of relevance both at airports and the wider atmosphere. Fuel cell powered aircraft offer more promise with regard to air quality in the longer term. Wider reductions in air travel would reduce emissions of PM, NO_X, VOCs and O_3 from ground operations and road traffic in the vicinity of airports. It seems likely that airports would remain hotspots for NO_x and ultra-fine particles in the near term, with negative impacts on O_3 pollution in the regions downwind.

2.2.3. Agriculture, land-use and food supply

In the land sector, effects on air quality may arise from afforestation or peatland restoration for carbon sequestration; change in crop varieties, including agricultural production of biofuels; and agricultural practices associated with animal management and waste, including possible impacts deriving from changes in demand.

The UK transition to net-zero in this area is primarily focussed around reducing GHG emissions from food production, coupled with enhanced carbon sequestration through woodland expansion and peatland restoration and an increase in bioenergy crop production.

With a finite land area, and a risk of offshoring of emissions if reduced food production leads to increased food imports, the aim is to combine improved productivity in some areas with changing food demand, particularly reduced red meat and dairy in diets. This may have the effect of freeing up additional UK land for uses such as carbon sequestration and energy crops, although these will inevitably have to compete alongside other demands for land.

Arguably one of the largest changes in UK land use will be in the form of woodland expansion. The UK CCC recommend an increase in tree planting from 13,000 hectares per year currently, to 30,000 ha per year by 2025, and to 50,000 ha per year by 2035. This woodland expansion will consist of a mixture of broadleaf and conifer tree species and in some areas has the potential to capture some of the NH_3 and particulate emissions from large point sources such as poultry farms, by offering a large surface area for pollution deposition.

It is important to note that the effects of tree-planting on the environment are complex and air quality is only one of many factors to consider. Trees can alleviate heat through shade and transpiration to support adaptation. They can have positive impacts on well-being and mental health, support drainage and water management, and enhance biodiversity. However, in terms of air quality, they can have both positive and negative air quality impacts depending on whether they are a source or sink for pollution.

For example, one potentially negative impact of woodland expansion on air quality is the enhancement of VOC emissions, such as of isoprene, and the resulting contribution to elevated ground level O_3 and secondary organic aerosols – a sub-component of $PM_{2.5}$ – concentrations in both rural and urban environments. Substantial increases in woody biomass combined with drier, hotter summers also raises the potential for more intense and widespread wildfires. In urban areas in particular, an expansion in the provision of green space would be expected to reduce air quality risks in many cases - reducing urban heat island effects and increasing surfaces for pollution deposition. However elevated VOC emissions from more vegetation have the potential to counteract these benefits to a degree. As such, the choice of vegetation for green space expansion in urban areas will be important to minimise unintended consequences. For example, beech trees may be preferred to oak to minimise VOC emissions. Finally, in areas where natural regeneration and 'rewilding' of land is used to enhance carbon sequestration, there is also the potential for colonising species such as ragwort to predominate and for pollen loadings to be increased as a result[92].

Peatland restoration – through blocking of drains and elevation of water tables – would be expected to have a minimal impact on local air quality, although may result in an enhancement in CH_4 emissions, and by extension a contribution to the reactive carbon pool available for tropospheric O_3 formation.

The UK's plans envisage an increasing area of energy crop production for BECCS, with a projected 30,000 ha per year by 2035 and crops such as *miscanthus* or short rotation coppice. The crop cultivation would be expected to have very limited direct impacts on air quality given the modest fertiliser inputs required for these crops, although some increase in VOC emissions may result. However, the combustion of these bioenergy feedstocks for BECCS could result in very considerable air quality impacts from NO_x and PM emissions in the absence of effective cleaning of flue gases.

For food production, the main implications of the net-zero transition for air quality arise from a reduction in ruminant CH_4 emissions, through measures such as improved animal health, improved breeding, feed additives and a reduced national herd, and an increase in the efficiency of nitrogen use in croplands to reduce N_2O emissions. For livestock, alterations in slurry and manure management aimed at reducing CH_4 and N_2O emissions have the potential to increase NH_3 emissions, and vice versa (ie 'pollution swapping'). For example, separation of solid and liquid waste is a proven strategy for reducing GHG emissions, but tends to markedly increase NH_3 emissions. Likewise, for slurry application to fields, injection (rather than splash plate application) serves to reduce NH_3 emissions but may result in enhanced N_2O emissions.

For croplands, improved nitrogen use efficiency would be expected to reduce NH_3 and NO_x emissions in most cases. Again though, there is significant potential for pollution swapping, such as through a switch away from ammonium nitrate fertilisers to urea. Such a change could reduce N_2O emissions but lead to enhanced NH_3 emissions, especially where this coincides with elevated temperatures.

Image:
Livestock, an important source of CH_4 and NH_3 emissions in the UK. © vm.

Reducing emissions of NH_3 generally has proved difficult and as most other pollutant emissions have declined substantially, NH_3 is gradually becoming a more important component of the pollutant mix across Europe, North America and East and South Asia. Additional sources of NH_3 will therefore make reductions in its emissions even more difficult to achieve.

2.2.4. The built environment

Improvements in the energy efficiency of buildings are expected to reduce greenhouse gas emissions across commercial, public and domestic spaces. Increases in energy efficiency reduce overall space heating requirements, energy consumption and associated emissions, either local or displaced. In the short term, reducing demand from gas boilers, the primary UK space heating source, is directly beneficial for local air quality, particularly in winter, reducing both NO_x and PM emissions. There is potential for complete elimination of air pollution emissions should space heating systems transition fully away from combustion sources, although this would likely take many decades to complete[93].

The exact mix of energy used, and mode in which it is used, are the key determinants of the final air quality benefits of net-zero in buildings. A number of options are proposed to replace fossil gas in boiler systems. Gas-based options include bio-derived CH_4, hydrogen, or some gas blend of the two. The retention of a boiler-based approach to space heating will retain some element of NO_x and PM emissions, since even hydrogen when combusted is a source of NO_x. The relative emissions of NO_x from hydrogen boilers, relative to natural gas, remains uncertain[94]. In a hydrogen gas grid future, should that grid be used to supply fuel cells in buildings, then the residual boiler NO_x and PM is also eliminated. It would be anticipated that new boilers designed for hydrogen fuels would as a minimum emit no more NO_x than those being used today, meeting the European Commission Ecodesign Directive, but could be engineered to perform better if there were regulatory drivers[95]. The replacement of CH_4 with hydrogen would also reduce emissions of CH_4 and VOCs such as ethane and propane which are released from leakage in the gas network.

Future use of hydrogen in a gas network could also have wider potential effects on both air quality and climate change. Use of hydrogen as a carbon-free fuel may lead to an increase in its atmospheric concentrations. The size of the increase would depend on the extent of hydrogen use and on the rate of leakage into the atmosphere, both of which are currently uncertain. Nevertheless, model calculations suggest some general trends associated with an increase in the concentration of hydrogen.

Any increase in the atmospheric abundance of hydrogen will lead to a decrease in the hydroxyl radical OH which is the major tropospheric oxidant, following the reaction, $H_2 + OH = H + H_2O$. The change in OH will lengthen the lifetime of CH_4, potentially offsetting some of the benefit of a switch to hydrogen. Model calculations indicate that the increase in the atmospheric abundance of hydrogen, on its own, will also lead to an increase in tropospheric O_3[96]. In the stratosphere, an increase in hydrogen will lead to a reduction in O_3 and an increase in water vapour, again with further potential impacts on atmospheric composition and climate.

Many other options for building space heating and cooling can also be implemented, for example heat pumps, direct grid electricity generated from low carbon sources, local solar photovoltaics or combinations of all three.

All of these lead to positive air quality outcomes, reducing NO_x, VOC and particle emissions in the urban environment. Increasing energy efficiency measures may increase the requirement for cooling in hot summer conditions, increasing the seasonal demand for electricity.

Energy efficiency measures in buildings can lead to reductions in ventilation, increasing the accumulation of air pollution from indoor sources. Highly energy efficient building materials can themselves also be a source of indoor pollution, releasing VOCs and more persistent pollutants such as fire retardants and plasticisers[97].

Such reductions in indoor air quality are not an inevitable consequence of energy efficiency, but must be considered at the design phase for new buildings and in the retrofit of existing building stock. Mechanical ventilation with heat recovery, is an approach that can both reduce energy demand and maintain good indoor air quality.

Indoor air quality more generally is an area where exposure to pollution is largely decoupled from action to reduce GHGs to net-zero. Social and behavioural factors that reflect changing ways of working and living, including cooking, consumer patterns, products and preferences can have larger effects on pollution indoors than energy infrastructure such as heating systems[98]. The move to greater home working and policies to phase out gas boilers and install heat pumps may have substantial effects on population exposure to air pollutants, increasing the importance of quantifying indoor exposure and effects. The use of domestic wood burners and open fires for aesthetic reasons remains an area of continued concern for both outdoor and indoor air quality[99].

2.2.5 Industrial emissions and waste

Changes in air pollution emissions from industry associated with the net-zero trajectory relate to decarbonisation through electrification, changes to industrial heat supply, and improved efficiency. The projected trajectories decarbonise the existing industrial base, rather than, for example, offshoring emissions through increased product and feedstock import. Air quality emissions changes associated with electricity generation are discussed in section 2.2.1. Industry GHG emissions are dominated (95%) by CO_2, followed by CH_4 (5%, half of which is attributed to leakage). Reductions in fugitive CH_4 loss from industrial processes will enable a modest reduction in VOC-driven O_3 formation.

Significant changes in industrial heat production are envisaged, from natural gas and oil to electricity and hydrogen for low temperature processes and solid biomass, hydrogen and electric kilns or furnaces for higher temperature process. While the net-zero trajectory envisages biomass combustion for power generation being used with CCS, elsewhere in industry, particularly in the NH_3, cement and iron and steel sectors, unabated biomass combustion may grow in the interim to 2050, with increases in PM emissions, compared for example with natural gas. Hydrogen has a significantly higher flame velocity than natural gas, corresponding to increased flame temperature and, in the absence of other adjustments, exhibits increased NO_x formation through the decomposition of nitrogen and oxygen in ambient air, known as the Zel'dovich mechanism. This may be mitigated through design to regulate flame properties, but there remains potential for industrial scale hydrogen-fuelled boilers to lead to increased NO_x emissions, particularly where these are retrofit designs prior to bespoke installations. As for space heating boilers, the overall future level of NO_x emissions from hydrogen use in industry may depend on the regulatory limits that are applied. There will be associated reductions in emissions of other natural gas derived air pollutants, VOCs, and (particularly in the case of fuel oil) PM and some sulphur containing pollutants.

Changes in practices for waste handling with potential air quality impacts include increased recycling, reductions in biodegradable waste sent to landfill and shifts in energy-from-waste combustion. Reduced landfill, through waste prevention, recycling and diverting biodegradable waste will reduce anaerobic CH_4 generation but only have a marginal impact on regional O_3 production. Landfill gases can also include NH_3, hydrogen sulphide (H_2S) and VOCs.

Wider shifts in the UK industrial base will also have air quality consequences – for example, reduced demand for petroleum products as the transport and power sectors are electrified implies reduced production and refining emissions, as well as changing demand with effects on metal processing and solvent use in chemical production and VOC release. Continuing global economic redistribution of heavy industry such as iron and steel, may effectively offshore local air quality penalties associated with their manufacture.

2.2.6 Behavioural and lifestyle impacts

The pathway to net-zero involves a series of behavioural changes in society, including reduced consumption of air quality-relevant products, such as red meat, solvents and fuels; changes in patterns of exposure to pollution, such as from greater homeworking; and insights gained from changes to GHG and air pollution emissions during the COVID-19 pandemic.

During the COVID-19 pandemic much of the reduction in national GHG emissions, (estimated at 13% in 2020) arose from enforced behaviour change in the transport sector. Emissions from the private car fleet were curtailed due to restrictions, though some rebound in private car emissions has been reported as a result of reduced public transport use. Electrification of surface transport over the coming decade should serve to reduce both NO_x emissions and exposure in urban areas, but in the shorter term any shift away from public transport towards private car use risks short-term increases in NO_x emissions and exposure given the current composition of the fleet which remains dominated by internal combustion engines.

Image:
Urban parkland provides important areas for recreation, wildlife and mitigates urban heat island and provides a sink for pollutants. It can also be a source of VOCs.
© NicolasMcComber.

COVID-19 has also resulted in different patterns of exposure to air pollutants, with lockdowns resulting in the temporary closure of schools and workplaces; and exposure being much more closely related to the internal and local external environments of people's homes. Homeworking and home-schooling therefore pose some potential additional risks to air pollutant emissions and exposure, such as through increased domestic solid fuel burning and local air quality impacts. These are balanced to a varying degree, depending on location, with a reduction in exposure to traffic emissions and, in particular, reduced exposure during commuting. Post-pandemic, it is anticipated that homeworking will continue at a higher level than before the outbreak, so some of these changes in types and levels of air pollution exposure may persist long-term. It is also possible that an increased awareness of indoor exposure to respiratory illness and its links to ventilation, may see a permanent increase in building air exchange rates[100].

Another behavioural change driven by COVID-19 has been increased use of green space. As noted above, enhancement of urban green space as part of net-zero policies has the potential to increase VOC emissions and ground level O_3 concentrations. Likewise, greater uptake of 'active travel' – cycling and walking, displacing private cars and public transport – has been a feature of COVID-19 responses and is aligned with the net-zero transition. More active travel would in theory lower emissions of air pollutants from transport, and increase physical activity which is generally inadequate across many high-income populations. It would also change patterns of exposure and may possibly increase commuting exposure risks, of particular relevance in highly polluted cities, but the health benefits of the exercise are considered to be greater than the disbenefits in exposure to pollution[101].

Of the other major behaviour changes expected as part of the net-zero transition, reduced ruminant red meat and dairy intake in diets is set to have one of the most significant, albeit indirect, benefits for air quality. Coupled with reduced food waste, such dietary changes would be expected to reduce emissions of CH_4 – a precursor to O_3 – from livestock and manure and would also reduce NH_3 emissions – a clear and substantial win-win[102].

2.3 Possible new pollutants from net-zero technologies

Technological innovation has historically often led to the creation and emergence of new forms of pollution. The emphasis that is placed on headline measures of air quality, defined as PM, NO_2 and O_3 can potentially draw attention away from the evaluation of new pollutants and unanticipated effects. While existing systems for regulatory and environmental risk assessment will without doubt be applied to new and emergent technologies, it is nonetheless valuable to identify examples of sectors of where new hazards could arise, although this does not imply that such hazards would crystallise as significant risks once mitigation was in place.

The adoption of CCS presents a substantial chemical engineering challenge if it is to be implemented at scale[103]. This typically involves the use of a stripping solvent to capture CO_2 from exhaust gases and the regeneration of that solvent in a closed loop cycle. To date organic amines have been the most common materials used. There has been some evidence that there can be fugitive emissions from such a process, in the case of amine capture leading to the atmospheric release of high toxicity nitrosamines in exhaust gases. While in overall VOC mass terms the releases have been trivial, from a toxicity perspective they have been of some concern[104]. Less harmful solvents are the subject of considerable research and development investment, but if used at national and international scale, the impacts of unintentional releases would undergo toxicological evaluation as part of the emissions permitting process.

Many of the solvents used in everyday products are a refining by-product of extractive fossil fuel and refining industries that service the currently huge global demand for liquid fuels. There has been growth in the use of non-fossil-based solvents[105], such as those extracted from, or based on, natural products, such as limonene, and bulk solvents based, not on carbon backbones, but other elements such as silicon, for example cyclic volatile siloxanes[106]. Global changes in fossil energy supply for net-zero may change the balance of materials used in non-fuel solvent products, with impacts on emissions, chemical reactivity and production of secondary pollutants or toxicity.

2.4 Timescales and the low carbon transition

The short atmospheric lifetimes, typically hours to weeks, of most air pollutants means that positive benefits occur very rapidly once a polluting source is removed. Some technologies for net-zero may feed in slowly over decades. For example, passenger vehicle electrification or improvements in energy efficiency, and air quality benefits, such as roadside NO_2, will appear alongside the CO_2 reductions. The air quality impact and health benefits of the transition to net-zero in 2050 will be maximised the earlier those transitions begin and the more rapidly they are completed. The benefits would be felt across a range of scales, spanning local benefits, for example from transport changes to national scale outcomes for slower-forming secondary pollutants, such as those arising from NH_3 from agriculture.

The formation of some secondary pollutants, such as PM or O_3, is non-linear with respect to the precursor emissions, and substantial improvements in air quality (reflected in ambient concentrations) may not materialise until well into the net-zero transition period. For example, sustained reductions in emissions of NH_3 and NO_x are likely to be needed before substantial UK-wide 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, both locally and at national/international scales.

The development of the new low-carbon infrastructure to deliver net-zero has some potential to create transitionary problems, from a few weeks to many years, associated with air quality, and particularly so for very large construction projects such as nuclear power and new roads and rail projects.

The effects of localised poor air quality, even if only temporary, can lead to immediate effects on health, such as increased hospital admissions[107]. Temporary and local air quality impacts are already managed by the construction industry. Controlling emissions from off-road machinery and dust suppression are part of best practice and can be legal requirements for development permissions[108]. 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 infrastructure development that may occur nationally, provides a motivation to go beyond current measures for air quality controls. There are likely to be opportunities to continue to reduce emissions from non-road mobile machinery, such as bulldozers and excavators, through: further exhaust aftertreatment; fuel switching; alternative approaches to temporary electrical power provision; and reducing dust emissions and resuspension.

A further area of potential transitionary negative air quality impacts is the use of intermediary fuels and technologies over the early stages of the progress to net-zero. While many technological end points in 2050 are likely to have 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 for a limited period that have higher emitting sources, such as urban biomass combustion in combined heat and power applications.

2.5 International dimensions to net-zero and emissions reductions

Many air pollutants have atmospheric lifetimes that are long enough for them to be transported over national and sometimes continental scales. Chapter 1 describes how meteorology affects the transport of air pollutants. Another international dimension of net-zero actions that needs to be considered is outsourcing of the production of both basic commodities and finished goods to other countries. The industrial production of goods is frequently associated with atmospheric emissions, and while embedded CO_2 associated with production is often quantified, air quality emissions are generally not. A specific example is the freeing up of additional UK land area for carbon sequestration and energy crops and the consequential increase in food imports. Not only might this increase offshore GHG emissions (rather than eliminate them) but also shift local air pollution and negative health effects to the producer country.

2.6 Air pollution emissions unaffected by net-zero measures

While many actions associated with net-zero will lead to a co-reduction in air pollution emissions and health benefits, there are a number of pollutants whose emissions are largely decoupled from greenhouse gas releasing activities. This is a significant factor that should not be lost in the wider discussion around climate and air quality co-benefits, since management of the latter will still require dedicated policies and interventions and will not be fully addressed through climate-orientated commitments and actions alone.

Natural or semi-natural emissions leading to air pollution may grow in significance (both in absolute and relative terms) in the UK over the next 50 years, including those of BVOCs which are linked to ambient temperature and forest cover extent. These include NO_x emissions from soil and combustion emissions from biomass burning, for example from moorland and peatland fires. These processes are sensitive to warmer UK summers under future climates and may increase in their significance as contributors to both $PM_{2.5}$ and O_3 on regional scales. Moorland fires during drought periods have already been seen to have significant impacts on some local communities in the UK. While it is anticipated that future concentrations of NO_x will be considerably lower than today, enhanced emissions of BVOCs in warmer summers would likely feed through into elevated O_3 on regional scales, compared to business as usual climatic conditions.

Some sectors of anthropogenic air pollution emissions are linked closely to behavioural trends, technologies and consumer products. The emissions of VOCs are shifting increasingly away from fuel-based sources and now arise predominantly from the combined consumption of refined volatile chemicals in manufacturing and domestic settings. Solvent consumption has grown steadily in the UK and other high-income countries over the last 20 years at a rate that is offsetting the rate of reductions in emissions from vehicle emissions and fuel use. This includes the increased use of solvent-containing domestic products such as personal care products, cleaning materials, decorative products and car care (such as de-icers). Compressed aerosols for example are now a larger source of UK VOC emissions than the entire gasoline vehicle fleet.

Cooking and food preparation, both in the home and in commercial premises, is a substantial source of air pollution in the urban environment. Emissions arise from the combustion of fuel if CH_4 gas is used as the heat source. Significant quantities of PM are generated from cooking with hot oils and fats and as a result of Maillard reactions when food is browned. VOCs are emitted during bread baking from yeast reactions, and terpenoids from the preparation of fruit. Many of these emissions will inevitably persist into the future, even if the source of heat for cooking shifts towards electricity.

2.7 Synthesis of the impacts of net-zero measures on air quality

Earlier sections provide an overview of the potential areas where net-zero actions may have an impact on air quality. The potential impact is described in large part only qualitatively since the future trajectories and implementation are very uncertain; indeed, often the technologies to be used have yet to be implemented at scale. Nonetheless it is useful to bring together this collection of impacts and apply some expert judgement of the possible scale of air quality impact, the direction of that impact, whether positive, neutral or negative, and the degree of uncertainty associated with the judgement.

An overview of all sectors is given in Figure 10. The figure provides an indication of the range of possible scale of effects, often wide due to uncertainties over the extent to which a particular technology or approach will be adopted, or because emissions from a given process are simply not yet known. The range can also indicate a wide range of possible choices in how an action is implemented. The estimates on direction of effects, uncertainties and scale are drawn from expert input to the UK's Air Quality Expert Group[109].

A notable difficulty in providing an overview of effects on air quality is the assignment of a counterfactual against which the net-zero pathway can be evaluated. Air quality benefits can be evaluated against a business as usual set of emissions, a continuation of the approaches used today, or against best available technology. If against business as usual, then all nearly all net-zero actions are positive for air quality. If compared against the best available technology (viewed from an air quality perspective) then different conclusions can be drawn. For example, the air quality impacts of biomass CCS would be positive compared to the business as usual/present day energy mix, but would appear negative if the counterfactual was wind or solar renewables. Figure 10 is an expert judgement on the potential scale and direction of impact on air quality of net-zero when compared to a business as usual scenario. Table 3 provides an accompanying short commentary for each item briefly summarising the underlying scale of the impact, the uncertainties and the impact of the action on reducing air quality inequalities.

FIGURE 10

Qualitative summary of possible effects of net-zero measures on air quality

Qualitative summary of possible effects on air quality of interventions and strategies in various sectors associated with delivering a net-zero greenhouse gas budget compared to business as usual. Table 1 provides an accompanying expert commentary on possible scale of effect, sources of uncertainty and impact of the effect on reducing air quality inequalities.

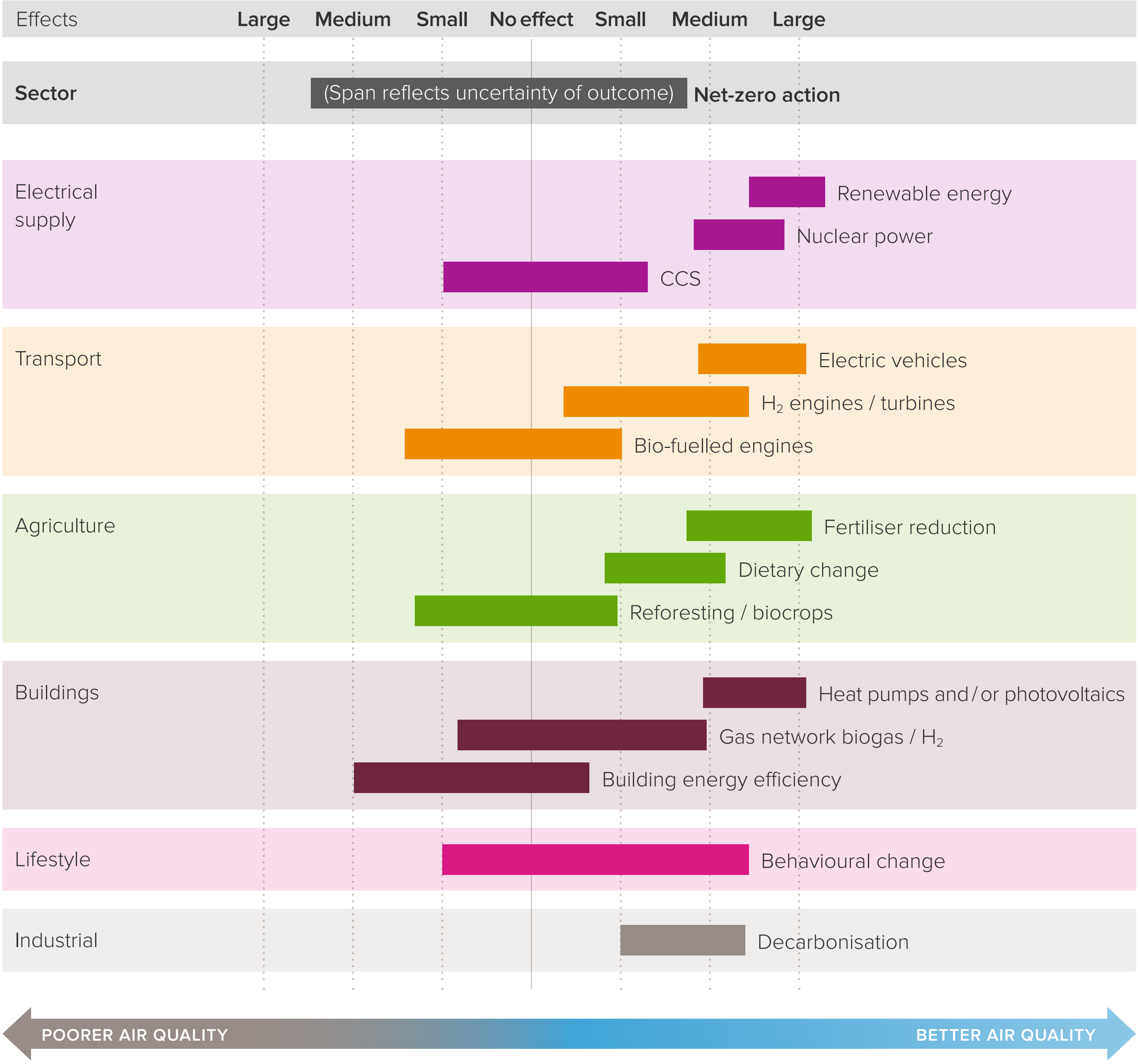


TABLE 3

Commentary on scale of effect, uncertainties and possible impact on air quality inequalities

Sector	Sub-sector	Commentary on scale of effect and uncertainties	Impact on reducing air quality inequalities
Electrical supply	Renewable power (non-combustion)	Large positive effect on air quality anticipated when displacing any combustion alternative. Low uncertainty in outcome since already in large scale use and future trajectory known with some confidence.	Medium Air quality impact is mainly a reduction in background and trans-boundary pollution, displaces fossil fuel generation located often away from population centres.
	Nuclear power	Large effect when displacing any combustion alternative. Larger uncertainties than renewables due to less clear implementation trajectory and degree of management of transitionary construction emissions.	Low May negatively affect some communities disproportionately during construction. There are however many other possible negative environmental impacts to be considered.
	CCS	Likely to be broadly equivalent to existing best available technology combustion power generation for air quality emissions, hence only modest impact on air quality. Uncertainties are associated with new chemical emissions, balanced against possible improvements in stack emissions controls.	Low Air quality impact is a reduction in background and trans-boundary pollution displaces existing fossil fuel generation located mostly away from population centres.
Transport	Electric vehicles	Large effect on NO_2 and VOCs when displacing any combustion alternative. Uncertainties in the extent to which non-exhaust emissions can be reduced through engineering, vehicle weight and miles driven.	High Largest benefits for urban populations, but also wider impacts to other communities. Some possible increase in urban O_3.
	Biofuels	Only modest direct impacts at point of use if fuels are used as direct replacements for liquid fossil fuels. Large uncertainties in the scale of uptake (eg by aviation) and possible supply chain emissions. Some increase in VOCs from biofuel crops is possible, increasing rural O_3.	Uncertain
Agriculture	Fertiliser reduction, and improved waste management	High confidence in large positive impacts on NH_3 arising if substantial emissions reductions occur, but considerable uncertainty in whether this can be delivered given previous difficulties in realising emissions reductions at the farm level.	Low Air quality impact is a reduction in background and trans-boundary pollution.

Sector	Sub-sector	Commentary on scale of effect and uncertainties	Impact on reducing air quality inequalities
Agriculture (continued)	Dietary change	High confidence that that dietary change would reduce NH_3 emissions, but also a high level of uncertainty about the likelihood of widespread population adoption of such a change.	Medium Air quality impact is a reduction in background and trans-boundary pollution.
	Reforesting, biocrops	The potential impacts on air quality are known with confidence, but the wide range of possible outcomes reflects uncertainties in the implementation, for example which tree or crop species are selected and whether low BVOC emissions are a requirement.	Medium Air quality impact is a change in background and trans-boundary pollution.
Buildings	Heat pumps and/or photovoltaics	High degree of confidence in the positive air quality benefits and potentially a large scale of impact if these are widely adopted. Improvements in PM and NO_x. Moderate uncertainty however over scale of uptake.	High Clear benefits for urban populations.
	Gas network biogas / hydrogen	Possible positive and negative impacts, depending on scale of uptake, how the gas is used (gas boilers or fuel cells) and the extent to which future technologies can reduce emissions, particularly for NO_x and fugitive emissions.	Medium to high Possible widening of inequality in exposure to NO_x if hydrogen boilers are used in high-density housing locations.
	Energy efficiency	A wide range of possible outcomes that could on balance be more likely negative for indoor air quality if widespread retrofitted energy efficiency measures lead to reduced buildings ventilation.	Uncertain Air quality effects may be outweighed by other factors like reduction in fuel poverty.
Lifestyle	Behavioural change	Wide range of possible outcomes, and uncertainty over the scale of uptake of individual actions, and which communities engage in behavioural change.	Uncertain
Industry	Decarbonisation	High degree of certainty that industrial decarbonisation would lead to improved air quality, particularly for some local communities, but considerable uncertainty of the scale of effect.	High Some possibly large gains for individual communities, although decarbonisation is very industry-specific so hard to predict air quality outcomes.

Chapter three

Climate and net-zero policy-driven changes in air quality and their effects on human and environmental health in the UK

Left
Electrification of the transport fleet is a key part of the delivery of net-zero and reduces air pollution.
© tongpatong.

Climate and net-zero policy-driven changes in air quality and their effects on human and environmental health in the UK

Key messages

- UK emissions of major air pollutants such as PM and NO_x have decreased considerably during the late 20th and early 21st century. Further decreases can be expected, which will be accelerated for most pollutants by net-zero GHG policies, resulting in decreased concentrations of many air pollutants and ensuring that the UK is on a path towards cleaner air in 2050.

- The actions taken to meet the net-zero target are expected to provide most air pollutant emission benefits in the near-term and less towards 2050.

- Net-zero policies that encourage behavioural change such as walking or cycling (‘active travel’) in place of driving – have direct benefits for air quality. Reducing demand has the important benefit of acting to reduce emissions that are hard to address through technology alone, such as non-exhaust PM from road vehicles and aviation jet turbine emissions.

- As emissions of pollutants continue to decline from historically dominant sectors such as power generation and road transport, where the emissions are generally well-quantified, a larger proportion of the remaining emissions will originate from small sectors where emissions are often not well quantified, such as cooking, ad-hoc burning and agricultural emissions.

- The reduced influence of primary air pollutants will make secondary pollutants such as O_3 and PM more important in the future. The complex non-linearity of secondary pollutant formation, and uncertainty in some of the underlying processes, means that careful attention should be paid to how changes in precursor emissions through net-zero policies affect future air quality.

- Emissions of NH_3, CH_4, BVOCs and soil NO_x increase with increasing temperature, which creates an additional motivation to reduce emissions of these pollutants to avoid the risk of increased emissions in a warmer climate.

- Effects of poor air quality on human health due to PM will remain despite the gradual reduction in exposure because no safe lower concentration limit has been found. While there remains uncertainty in the differential toxicity of PM, the composition of PM will continue to change over the coming decades through net-zero (and other) policies, which could influence human health.

- The decrease in urban sources of NO_x as a result of electrifying the vehicle fleet and reducing domestic gas combustion will tend to increase urban O_3 concentrations. Such increases in outdoor O_3 concentrations would also increase indoor O_3 concentrations with the potential to generate other pollutants through reactions with indoor air pollutants such as VOCs. From an air quality exposure perspective, indoor air pollution is important given the amount of time individuals spend indoors.

- The changes in pollutant concentrations expected through to 2050 will have implications for the measurement of pollutants in terms of locations of monitoring sites and the relative importance of different source types. For example, there will be less need for roadside monitoring sites as vehicle exhaust emissions diminish.
- Effects of eutrophication and O_3 on ecosystems will likely remain at similar levels to those of 2020, as exposure to O_3 and nitrogen deposition are projected to remain above thresholds for damage through the next three decades.
- Further improvements in air quality may be possible with additional policy measures. For example, NH_3 emissions contribute to PM and eutrophication and remain largely uncontrolled. Measures to reduce dairy and red meat consumption would reduce NH_3 and CH_4 emissions, contributing to cleaner air and the net-zero target, as well as potentially benefiting health.

3.1 Introduction

By 2020, the burden of air pollution in the UK has been greatly reduced relative to the 20th century, as shown in Figure 11. The only primary pollutant whose emissions have changed little is NH_3, which remains a substantial contributor to secondary PM and to nitrogen deposition and eutrophication of ecosystems throughout the UK.

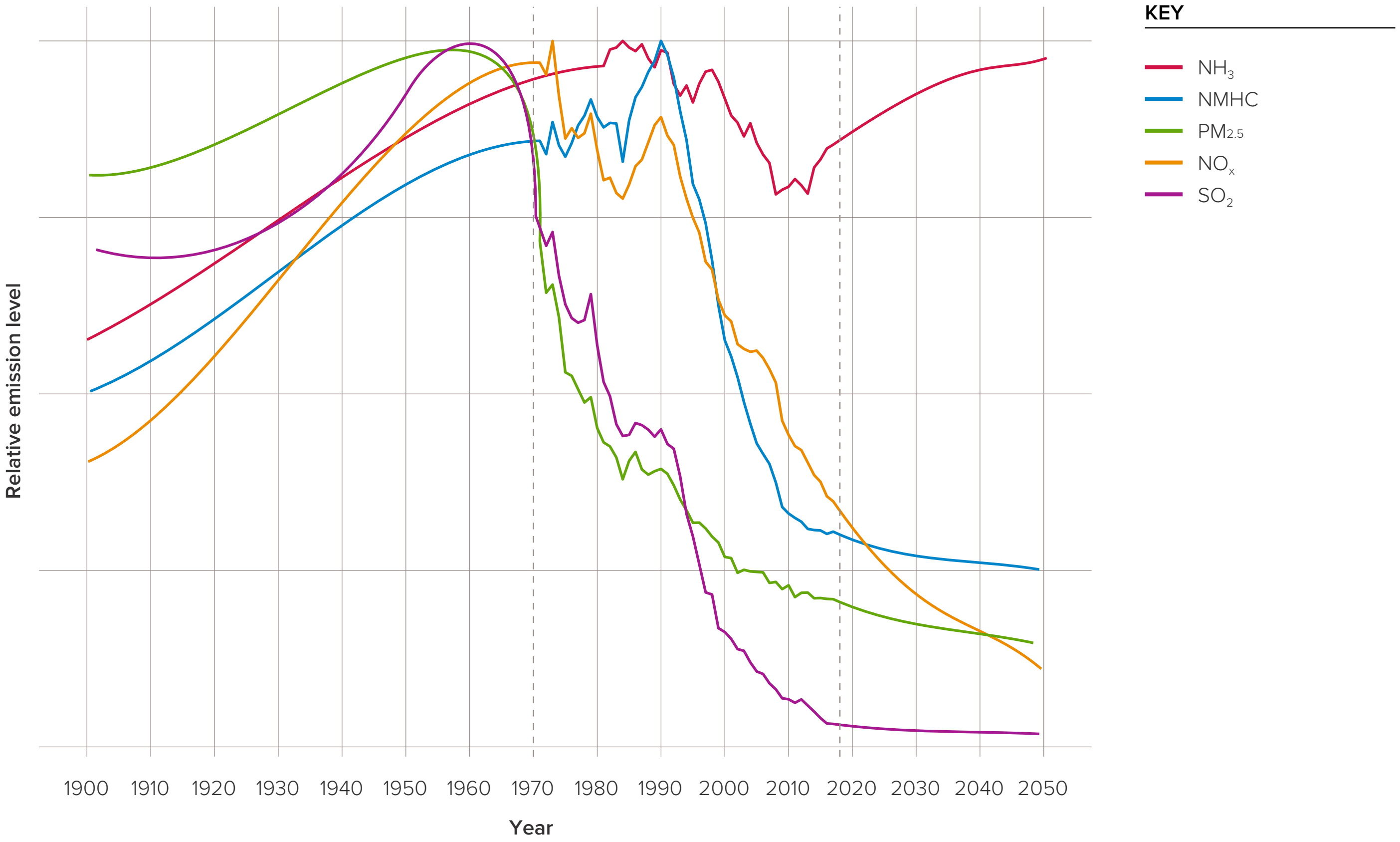
The changes in composition of the air over the UK reflects policy initiatives implemented in the last two decades. While PM and its effects on human health remain an issue, especially in urban areas, the composition of PM emitted from vehicles has changed from exhaust-dominated sources in the late 20th century to non-exhaust emissions at present. VOC emissions are no longer mainly derived from vehicles and have declined by 50% since their peak in 1990. NH_3 from agriculture now contributes substantially to secondary inorganic PM.

In this chapter the effects of climate change on emissions and atmospheric chemistry and the effects of policies to achieve net-zero emissions of GHGs by 2050 and their combined consequences for human health and ecosystems are brought together to identify priorities for policy development to maximise the improvements in air quality during this transition.

FIGURE 11

Illustrative relative trends in emissions of different air pollutants scaled from zero to maximum value[110]

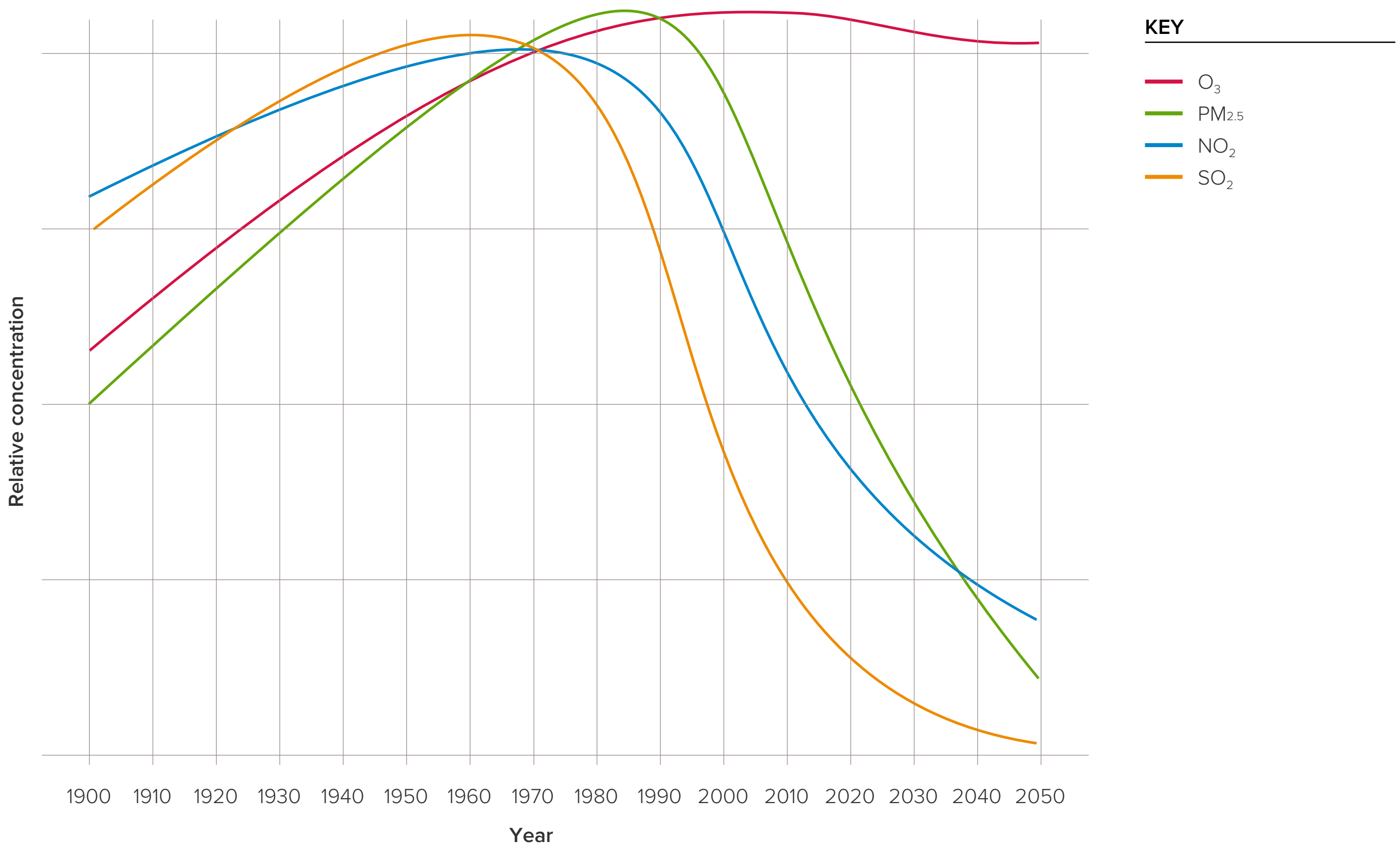
The 1970 – 2018 figures are based on UK National Atmospheric Emissions Inventory (NAEI) total emissions. Pre-1970 and post-2018 figures provide an indicative estimate of the trend. Note that the NAEI considers non-methane hydrocarbons (NMHCs) as a subset of wider VOC emissions.



Source: National Atmospheric Emissions 2021 (for 1970 – 2018 data). Pre-1970 and post-2018 are indicative estimates reflecting broad past and expected future trends.

FIGURE 12

Illustrative relative trends in population-weighted concentrations of different air pollutants scaled from zero to maximum value



Source: Indicative estimates reflecting broad past and expected future trends.

3.2 Under climate change and net-zero measures, which air pollutants will decline, which ones will increase, and which ones will not be affected?

While there are many uncertainties involved in projecting the UK's future air pollution and climate towards 2050, there are certain key themes that can be highlighted. A strong theme is the reduction in activities associated with the combustion of fuels which generate a very wide range of air pollutants. This is important because many primary pollutant emissions are simply eliminated and there is high confidence regarding the outcome in terms of emissions reduction. On the other hand, the shifting pollutant mix in the future will be towards non-combustion sources, which tend to be more difficult to control and many of which are strongly influenced by a changing climate.

For some pollutants and sectors, there are limits to the extent to which emissions can be further reduced through technological improvements. Examples include non-exhaust PM emissions from road vehicles and aviation jet turbine NO_x emissions. These challenges highlight the importance of the behavioural changes that can be driven by net-zero policies, for example reductions in demand for a polluting activity such as driving and its substitution by an increase in active travel. Demand reduction also has the benefit of acting to reduce emissions from sources where it is technologically challenging to reduce emissions, such as non-exhaust PM from vehicles. Here we examine the prospects, pollutant-by-pollutant.

3.2.1 NO_x emissions

NO_x emissions can be expected to decrease significantly relative to today due to net-zero and other policies. This reduction is driven by the transition to electric vehicles in the transport sector and eventual elimination of domestic gas combustion through the adoption of heat pumps. Bans are to be imposed on the sale of new petrol and diesel light duty vehicles from 2030 and diesel use in heavy duty vehicles from 2040 but it will take time for the maximum benefits to be realised because a typical vehicle has a lifetime of about 15 years. The significant further reductions in NO_x will be of greatest benefit to urban areas, given the proximity of road vehicle and gas combustion sources to populations. However, such controls will also reduce nitrogen deposition, O_3, and secondary PM formation.

While total UK emissions of NO_x can be expected to decrease, leading to associated reductions in NO_2 concentrations, not all sectors will contribute. As noted in Chapter 2, there are limited options for decarbonisation from aviation and so there is limited potential to change its impact on air quality. Even if there is a wholesale switch to biofuels, the combustion of fuels using gas turbines is likely to remain the main mode of propulsion. For this reason, there will likely be significant changes in the spatial distribution of emissions, with 'hot spot' areas remaining. Many large cities in the UK tend to have airports immediately outside their urban areas – or in the case of Heathrow for example, as part of west urban London. Airports will represent a continuing and potentially large source of pollutants such as NO_x and particle number concentrations. Indeed, in the case of an airport such as London Heathrow, which is located upwind of London, aviation emissions of some pollutants such as NO_x could dominate the total emissions burden in the city.

3.2.2 PM emissions

PM will likely remain important through to 2050 given the potential contribution from direct emissions, the significant influence of secondary PM and the contribution from natural sources, which will be more influenced by a warming climate. However, the evaluation of the effects of PM is challenging, given that many different properties of particles have potential impacts on human health, including composition and size distribution. Considering only particulate mass will not capture the changing composition of PM over time as different sources are controlled, nor the relative toxicity of the different components.

While the reduction, or elimination, of vehicle exhaust emissions will be a significant change relative to today, the same will not be true of non-exhaust emissions of brake, tyre wear and road wear. Even today, non-exhaust emissions from road vehicles dominate both the PM_{10} and $PM_{2.5}$ emissions from vehicles. Currently, the technological options to reduce these emissions are limited, except for regenerative braking systems used on hybrid and battery electric vehicles. As discussed in Chapter 2, if a move to electric transportation also increases vehicle weight or traffic activity, there is the potential for increased emissions of non-exhaust emissions. Given the importance of traffic-related emissions in urban areas, non-exhaust PM will represent a continuing and potentially growing source of exposure of urban populations to PM.

3.2.3 VOC emissions

VOC emissions include sources from which it will be difficult to realise significant reductions by 2050 relative to 2020. Emissions from some sectors are expected to decrease – for example from the use of petrol and diesel in transport fuels and fuel delivery infrastructure. However, indoor sources of VOCs, for example from personal care products, may well increase in their importance without changes to product formulations or reductions in use. The situation for biogenic emissions poses more of a risk for increased emissions because emissions of VOCs are highly temperature and species dependent. An increase in fast-growing crops for biofuels could lead to increased emissions of VOCs, for example, from the planting of *Miscanthus* and *Salix* (willow)[111]. These risks could be significantly reduced through the careful selection of species and cultivars such as *Fagus* (beech) and *Tilia* (lime), known to be low-emitting and resilient to climate change, as well as through land use management.

3.2.4 Ozone

O_3 will continue to be an important global and regional pollutant throughout the period to 2050 and beyond, unless global CH_4 concentrations decline substantially. Global CH_4 concentrations have increased steadily over the last decade from both anthropogenic and natural wetland sources. Inputs of O_3 from the stratosphere are also projected to rise (see discussion in Chapter 2).

Tropospheric O_3 has many different impacts on human health, ecosystems and climate. This is reflected in the numerous metrics that are used to describe it, from short-term health-based metrics to those aimed at protecting ecosystems. As an illustration, Figure 13 highlights some of these factors, showing hourly predictions of O_3 averaged across 53 UK sites in 2011 and 2050. For example, peak summertime concentrations are projected to decrease through continued regional NO_x and VOC reductions, whereas wintertime and annual mean levels are projected to rise, mostly due to reduced emissions of NO_x, leading to a net increase in the annual mean concentration. The mitigation of CH_4 emissions should be prioritised at an international level as a win-win for climate and air quality, as they constitute a precursor to O_3.

As seen in Chapter 2, the reduction in NO_x emissions, especially in urban areas, creates a potential trade-off with O_3 because less O_3 will be eliminated through its reaction with NO. This is likely to lead to a continuation in the rise that the UK has been seeing in urban concentrations of O_3 for many years. This is also expected to have consequences such as indoor reactions with VOCs resulting in the formation of other air pollutants such as PM and formaldehyde. NO_2 and O_3 are also associated with many impacts beyond health, such as those to ecosystems (see section 3.6).

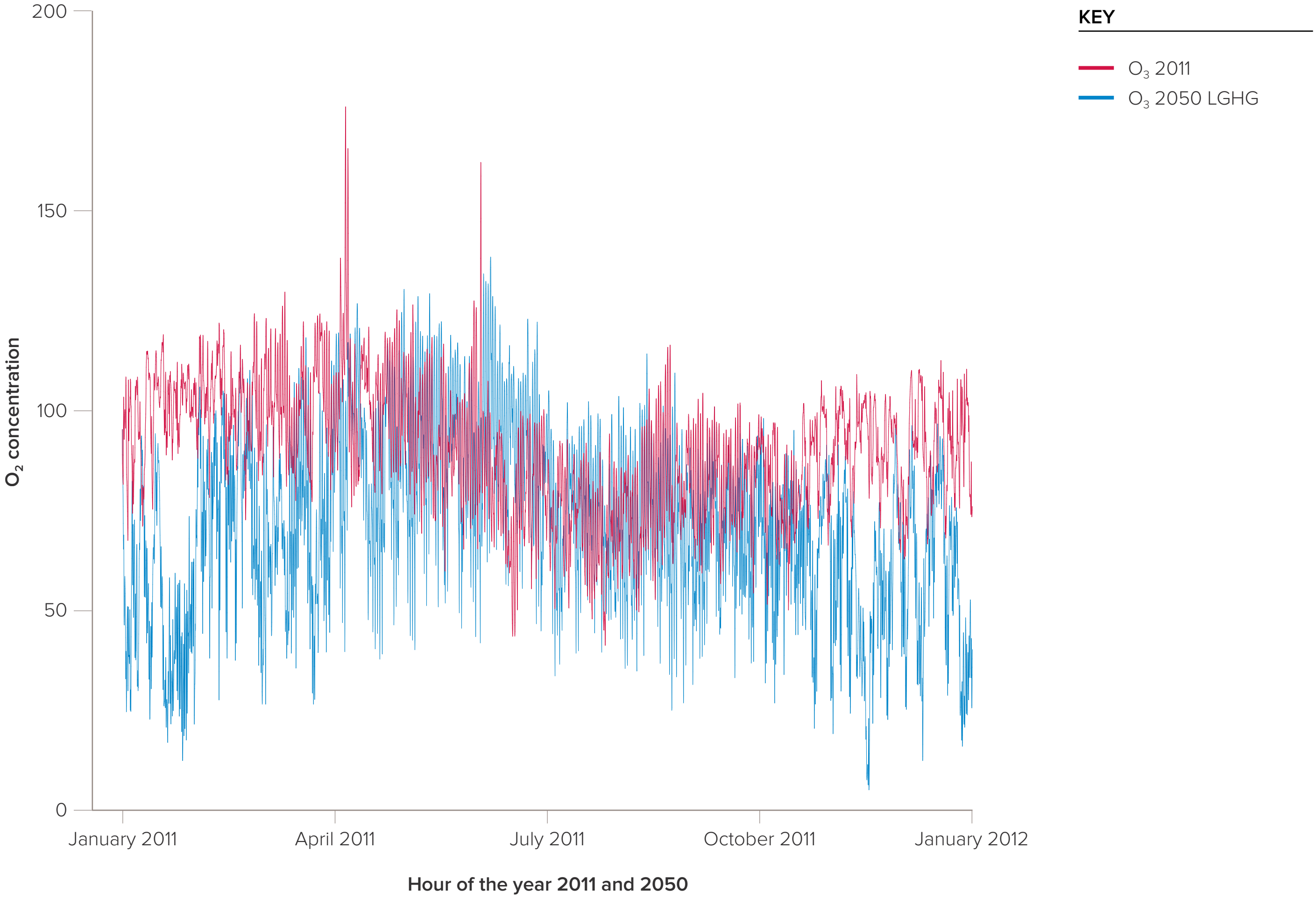
3.2.5 NH_3 emissions

Reducing NH_3 emissions has proved challenging over the past few decades in the UK. While there has been much focus on reducing emissions from the energy system, use of nitrogen-based fertilisers and other agricultural sources of NH_3 have continued to generate the majority of UK emissions. Reductions in emissions have been small relative to the scale of current nitrogen deposition in excess of ecosystem tolerance (critical loads). Considerable reductions in NH_3 emissions are required to improve air quality and ecosystem health. A principal concern related to NH_3 emissions is the potential to form $PM_{2.5}$. Changes in temperature, humidity and precipitation will alter the levels of emissions and the way they react with other pollutants in the formation, processing, and removal of PM. Reductions in SO_2 and NO_x will tend to result in more NH_3 being present in the gas phase, which would be further increased by higher temperatures. There is the potential for large increases in NH_3 deposition near emission sources such as livestock farming operations. Lower consumption of dairy products and beef would lead to reduced emissions of NH_3.

FIGURE 13

Hourly ozone concentration in the UK in 2011 and for a 2050 scenario[112]

Low greenhouse gas scenario (LGHG); 80% reduction CO_2e by 2050; achieves interim carbon budgets (through the Fourth Carbon Budget, broadly consistent with the Fifth Carbon Budget); no constraint on nuclear beyond practical considerations eg construction timelines.



Source: Public Health Research 2018.

3.3 Which classes of air pollutants will require action beyond net-zero measures to improve air quality by 2050?

Chapter 2 highlights the fact that NH_3 emissions from food production have the potential to be reduced through different mitigation measures. However, NH_3 is likely to remain a major pollutant for many years to come. UK Emissions of NH_3 have fallen the least compared to significant combustion-related pollutants, with a reduction of only 13% from 1980 to 2018[113]. As highlighted in Chapter 1, there are several climate-related factors that could work against the effective reduction of NH_3 including increased volatilisation of surface emissions and partitioning into the gas phase of ammonium nitrate under warmer conditions. It is also worth noting that even if combustion related NO_x emissions are virtually eliminated by 2050, there are important natural sources of NO_x such as soils, wildfires and lightning that would provide a continued route to the formation of ammonium nitrate PM. Indeed, both soil NO_x and NO_x from wildfires would be expected to increase in a warmer world.

Reducing emissions of VOCs could also present challenges in the future. Over the past few decades, emissions of VOCs from road vehicles, which were the dominant source, have dramatically decreased through changes to fuels and the introduction of highly effective aftertreatment technologies such as the three-way catalyst. Other sectors will prove more challenging to address, such as emissions associated with the domestic use of products and the wide use of solvents across many different sectors. Biogenic emissions will play an increasingly important role in future, with potentially increased emissions due to a warming climate.

3.4 Future air pollution factors other than climate change and net-zero measures

Policies to reduce air pollution in parallel with the path to net-zero need to take account of a series of other factors beyond the relationships and impacts covered above. These include the challenges of transboundary pollution beyond UK control; the incidence of specific air pollution episodes; the non-linear relationship between primary and secondary pollutants; the timing of policy measures; and uncertainties around quantification.

3.4.1 UK-controllable component of air pollution

From a policy perspective, a principal consideration is the UK's capacity to control the sources of air pollution. There are several trends that suggest that the UK-controllable component of many air pollutants will diminish over time. For some sectors and pollutants, the UK has complete control over emission sources, such as NO_x emissions from road vehicles and exposure of populations to concentrations of NO_2.

In terms of NH_3, while significantly reducing emissions will be highly challenging, they are also inherently UK-controllable as NH_3 has a short lifetime (a few hours) in the atmosphere. In this respect, action taken to reduce NH_3 emissions is attractive and would result in multiple benefits including reduced $PM_{2.5}$ concentrations and nitrogen deposition.

However, for pollutants such as O_3 and PM, a very large component of the concentration is determined by non-UK sources, which means that even highly ambitious action taken in the UK to reduce precursor emissions that form O_3 and PM may have a negligible effect on concentrations within the UK. In the case of PM, European control of precursor emissions will directly benefit the UK, whereas global action is required to reduce concentrations of O_3. It should be noted, however, that neighbouring EU countries have similar ambitions to reduce both air quality and greenhouse gas emissions and the UK will benefit in terms of air pollution.

Additionally, as the UK exerts control where it can, such as in historically dominant sectors such as power generation and road transport, the UK-controllable portion of the emissions will shrink. There is the general challenge of reducing emissions from a large number of smaller emission sectors, some of which are inherently difficult to control, such as ad-hoc burning, and which may themselves increase in a warming climate. Challenges in exercising control over air pollution also include the growing importance of secondary pollutants and the uncertain and non-linear response of pollutant concentrations to changes in emissions – explored in section 3.4.3.

Finally, it is important to recognise that concentrations of pollutants will not reduce to zero even with ambitious emission reductions, due to natural source contributions and the influence of emissions outside the UK.

3.4.2 Expected changes in air pollution episodes

Air pollution episodes, periods of high pollution levels, such as smogs and summer O_3, are an important aspect of the impact that air pollution has on human health and are caused by the interplay of emissions and meteorology. The meteorological influence operates at both the small scale, such as in urban areas and under conditions of light winds and a stable atmosphere, and at a larger scale, such as the frequency of blocking high pressure systems flow from continental Europe. The winter smogs, dominated by SO_2 and PM, which were so characteristic of the mid-20th century are a thing of the past and the anticipated wetter, milder winters associated with a less stable atmosphere will further reduce the importance of winter episodes of elevated air pollutant concentrations.

Summertime episodes associated with secondary pollutants such as O_3 will remain important towards 2050 and could worsen due to higher summertime temperatures and reduced surface deposition. As noted in section 3.6, an increase in biogenic VOC emissions coupled with higher temperatures, could create conditions that would more likely lead to summer O_3 and PM episodes. Air pollution episodes exacerbated by a changing climate are likely to increase, for example those due to wildfires, in the UK and throughout the northern hemisphere.

3.4.3 Non-linear processes of air pollutants

A decline in emissions and hence airborne concentrations of primary pollutants will in most cases lead to a reduction in concentrations of related secondary pollutants. However, the decline in secondary pollutant concentration may not be proportional to the reduction of its precursor, a phenomenon known as non-linearity. In general, non-linearity works such that there is a less than proportionate decrease in the secondary pollutant as primary emissions decline. Hence it is likely that many secondary pollutant concentrations will not fall as rapidly as those of their main precursor. As discussed in the next section, the effects of these non-linear processes will depend on the prevailing air pollutant concentrations, which will change towards 2050.

3.4.4 Timing of policy measures

The timing of measures to reduce emissions on the transition to net-zero GHG emissions will be important for air quality. These will depend greatly on the trajectory of decarbonisation in different industrial sectors (Figure 14). For most sectors, a 50% reduction in CO_2-equivalent emissions is planned to be achieved in the early 2030s relative to 2019, which highlights that most emissions reductions will be achieved in the near-term rather than close to 2050.

Electricity generation

The presence of a comprehensive policy framework, available zero-carbon technologies and low costs mean that rapid falls in UK emissions from electricity generation can continue, although at a lower rate than the last decade as coal has been almost completely eliminated.

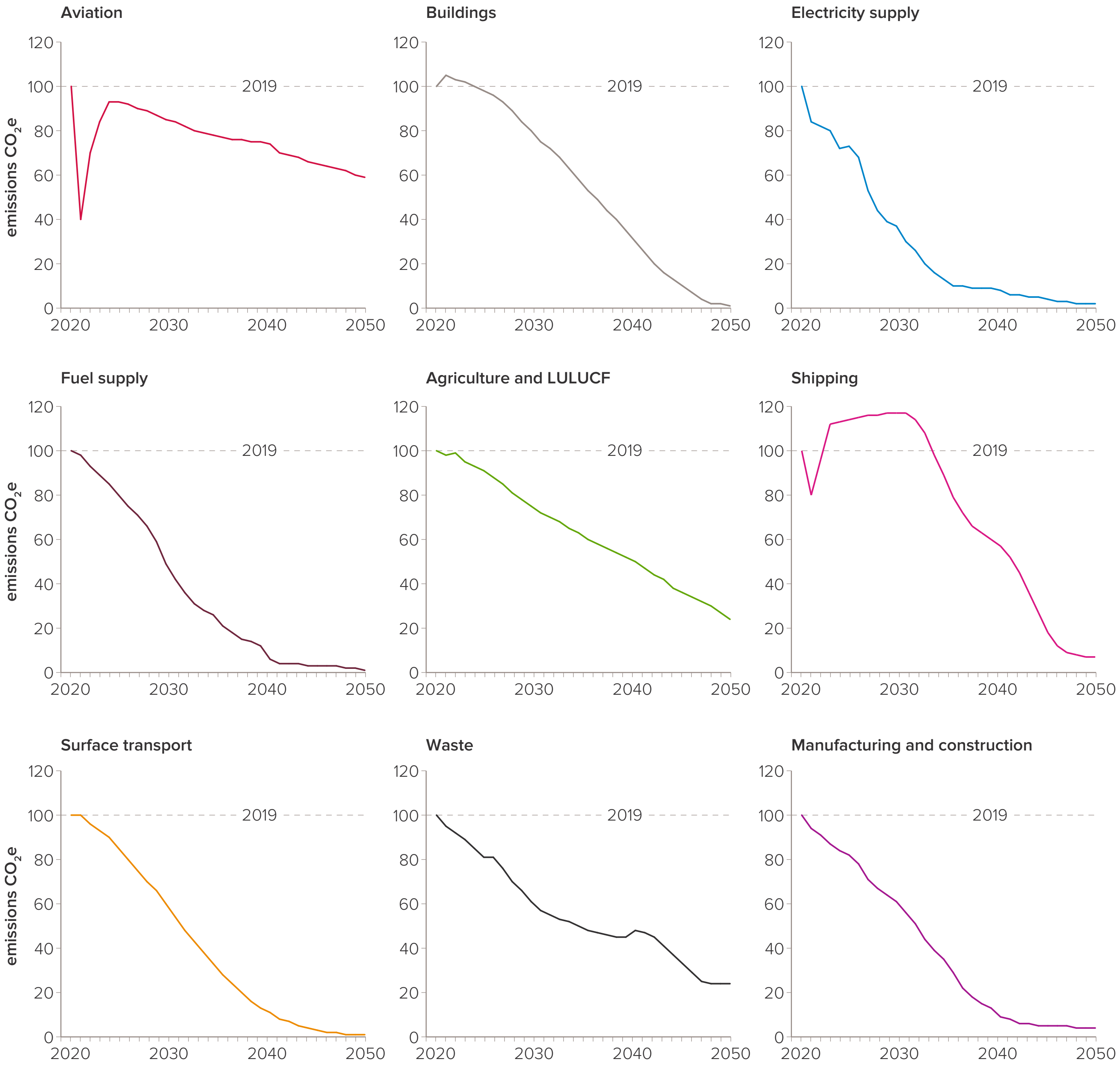
The UK Government has committed to deployment of 40 GW of offshore wind capacity by 2030 (a fourfold increase in installed capacity relative to today). The Sixth Carbon Budget projects an increase in solar capacity to 60 GW by 2035 (a six-fold increase in installed capacity relative to 2019). The CCC anticipates that the overall carbon intensity of electricity generation in 2030 will therefore fall to below 50 gCO_2 per kWh, compared to over 500 g/kWh in 2012 and 182 g/kWh in 2020. This would be achieved by completing the phase-out of coal-fired generation by 2024 and pushing generation from unabated fossil gas generation to the margins of the system (ie meeting demand only when renewable generation is unusually low, or demand is particularly high).

The CCC has recommended full phase-out of unabated) fossil generation by 2035, which will require further deployment of options that can achieve ‘dispatchable’ (or immediately accessible) roles in a low-carbon way, likely to be a combination of fossil gas generation with CCS and turbines combusting low-carbon hydrogen. Thereafter, the sector will continue to have a crucially important role in economy-wide decarbonisation through electrification in other sectors, chiefly transport and heat, to displace fossil fuel combustion, with electricity generation reaching 2 – 3 times current levels by 2050.

FIGURE 14

Change in sectoral emissions CO_2e in the balanced net-zero pathway compared with 2019 emissions

Aviation and shipping emissions are lower in 2020 due to COVID-19. LULUCF = Land use, land use change and forestry. The dips seen in the trends for aviation and shipping are associated with COVID-19 impacts.



Aviation

Buildings

Electricity supply

Fuel supply

Agriculture and LULUCF

Shipping

Surface transport

Waste

Manufacturing and construction

Source: Committee on Climate Change 2020.

Surface transport

The UK Government has committed to full phase-out of sales of new internal combustion engine light-duty vehicles, such as cars and vans, by 2030, with sales of such vehicles being limited to fully electric vehicles or, until 2035, hybrids with significant zero-emission capability. This will likely lead to the fleet of such vehicles having zero tailpipe emissions by 2050, given a typical vehicle lifetime of 15 years. The rate of electric vehicle purchase will need to grow strongly in the 2020s, but the peak rate of emissions reduction from electric vehicle adoption will not be achieved until every new vehicle is zero-carbon in the first half of the 2030s.

The Government's Transport Decarbonisation Plan also committed to a phase-out of smaller lorries to follow in 2035 with the largest lorries in 2040.

There are significant opportunities to reduce emissions more rapidly in the 2020s by reducing vehicle-kilometres travelled in such modes, such as by shifting to walking, cycling and public transport. Such opportunities tend to be greater in urban environments, meaning that urban air quality could benefit disproportionately from such changes.

The implementation of clean-air zones in cities can also accelerate adoption of electric vehicles and retirement of the highest-emitting internal combustion engine vehicles in urban areas in the 2020s.

Buildings

The UK Government has proposed a Future Homes Standard to be introduced by 2025, requiring new build homes to be future-proofed with low carbon heating and world-leading levels of energy efficiency. It has also consulted on a Future Buildings Standard for highly efficient non-domestic buildings.

A wider Heat and Buildings Strategy is expected to set out actions to reduce emissions from homes and other buildings. If a date for the phasing out of gas boilers were set for 2035, given a typical boiler lifetime of around 15 years, the profile of emissions reduction from buildings will have similarities to that for surface transport, with the fastest reduction in emissions being in the period 2035 – 45. However, the relatively high costs of heat pumps compared to fossil heating means that uptake of these technologies may lag that of electric vehicles by around five years. Early heat pump markets are anticipated to be in new homes and in properties off the gas grid, where current heating costs are higher. Any contributions from repurposing gas distribution networks to carry hydrogen will not be significant before 2030.

Significant improvements in buildings energy efficiency are anticipated in the 2020s and can contribute significantly to reducing GHG emissions but the impact on air quality will be more mixed. A phase-out of biomass boiler installations in the early 2020s, with a transition to fully zero-carbon solutions such as electrification, hydrogen and district heating would mean that the air-quality impact of such boilers would disappear by 2040.

Industry

Decarbonisation of industrial sites is site-dependent and will rely in many cases on infrastructure development, such as use of hydrogen or CCS, or upgrading, such as of the electricity grid. As set out in the Government's Industrial Decarbonisation Strategy, development of CCS and hydrogen infrastructure at the largest industrial clusters in the 2020s will enable rapid decarbonisation of those areas in the late 2020s to the mid-2030s. Switching to low-carbon solutions for smaller and more distributed industrial sites is anticipated to be more gradual over the period to 2040, with the potential to decarbonise to the fullest extent possible by 2040, well ahead of the overall 2050 net-zero date.

3.4.5 Quantification uncertainties

The quantification of emissions of air pollutants and their impacts will likely become increasingly challenging in future. First, emissions from major sources such as power stations and road vehicles will be greatly reduced. These sources are well-established and understood with many years of scientific development in quantifying emission rates, as well as their spatial and temporal characteristics. With the ongoing reduction in importance of historically dominant emission sectors, there will be a larger number of smaller sources that contribute to air pollution, which are often poorly quantified. Examples include emissions from cooking, wood burning and ad-hoc burning activities. Many such highly uncertain source types are not considered in the UK National Atmospheric Emissions Inventory. These sources will become relatively more important over time. Second, some of the impacts that a warmer, drier climate has on emissions are also potentially challenging to quantify, such as an increase in wind-blown suspension owing to drier surfaces.

Ambient measurements of air pollutants provide considerable insight into the influence that different sources have on pollutant concentrations. In 2021, for example, 41% of the UK national network sites were located at roadside locations, in part reflecting the importance that road vehicle emissions have had on human exposures over the past few decades. However, with diminishing road vehicle exhaust emissions and a wider range of sources contributing to concentrations of most pollutants through net-zero and other policies, it may be necessary to reconsider the location of measurement sites to provide information on the changing source contributions. For example, increasing the number of sites that measure PM composition, could lead to a better understanding of a wider range of source contributions, at the expense of the reduced measurement of NO_x and NO_2.

3.5 Likely consequences of air quality changes on human health: direct and indirect

3.5.1 Overview

While concentrations of many pollutants will decrease in working towards net-zero, the impacts on human health are more uncertain. The general move away from combustion of fuels through net-zero policies should lead to direct health benefits through the reduction of common primary pollutants such as NO_x, as well as a wide range of other pollutants such as metals, PM, PAHs and VOCs. The changes in emissions involved in achieving net-zero will continue to reduce mass concentrations of $PM_{2.5}$, which should have significant benefits in terms of human health. Although it might be expected that some PM components are more harmful to health than others, current studies do not take account of the possible differential toxicity of particles in terms of their composition and effects on health, which makes it challenging to determine any overall changes in health burden due to compositional changes. The focus remains on reducing particle mass and with no preferential targeting of specific components. However, the evidence related to these impacts could change over time, which could result in a more source-specific approach to the control of PM and its precursors.

Nevertheless, the known factors of particle composition and particle size distribution are important determinants of health impacts. These issues are of importance when considering the potential growth of natural sources such as wind-blown dust or wildfires that have markedly different compositions compared with PM generated from fuel combustion processes. The changing composition of particles from the late 20th century towards 2050 should also provide epidemiologists with an opportunity to quantify changing health impacts over the longer term and possibly to quantify the health impacts of changing composition over time.

It can be expected that as ammonium nitrate and sulphate concentrations decrease, there will be an increasing dominance of primary and secondary organic aerosol from sources such as cooking, biomass and biogenic emissions. The lack of evidence regarding relative toxicity of components of PM will need to be addressed in order to probe the impacts of this shift.

The transition away from gasoline and diesel as road fuels will significantly reduce outdoor exposures to NO_2. Other urban sources of NO_x and NO_2 – especially those related to natural gas combustion – will also likely reduce considerably. However, as discussed in section 3.2.1, it is possible that some notable ‘hotspot’ locations will remain, such as those near airports. Such hotspots highlight the need to evaluate health impacts at small spatial scales.

O_3 will present a continuing challenge to address given the difficulty posed in reducing concentrations, and as noted, in urban areas, reductions in NO_x will lead to increased O_3 concentrations. These issues were considered by Heal *et al*. which highlighted the continuing health burden of O_3 concentrations in the UK[114].

In all the considerations above, the issue of exposure is important. An important source of high exposure to pollutants is the indoor environment. In recent years there has been a growing recognition of the importance of indoor air quality, even if it remains difficult to quantify its specific contribution to adverse health outcomes. However, it seems likely that indoor air pollution will continue to grow in relative importance in the coming years as reductions in outdoor emissions continue. As discussed in Chapter 2, there is the potential (although not inevitable) to worsen indoor exposure to air pollutants through some actions to meet net-zero such as energy efficiency measures that reduce ventilation, or the introduction of new materials that are sources of indoor air pollutants. On the other hand, there will be reductions in indoor combustion emissions from cooking using natural gas and any emissions from natural gas fuelled boilers.

In addition to concerns over a direct increase of O_3 concentrations and its potential health impacts, there is also the potential for changes in indoor air chemistry through the generation of by-products. In this respect, the emission of indoor VOCs under conditions of higher O_3 concentrations could lead to increased concentrations of pollutants such as formaldehyde and the formation of secondary PM.

3.5.2 Future $PM_{2.5}$ and its effects on human health

Recent results of studies of air pollution and health impacts in the UK[115] looked at different future scenarios, some aimed at meeting the UK's 2050 Climate Change Act target of 80% reduction of CO_2e emissions by 2050, the forerunner of the UK's current net-zero emissions commitment. Population weighted mean NO_2 concentrations were projected to approximately halve (by between 51 and 60%) between 2011 and 2050, and $PM_{2.5}$ concentrations were predicted to decrease by between 42% and 44%, leading to annual average levels of 5 to 6 μgm^{-3}, in the scenarios that met the Climate Change Act targets. These predicted 2050 $PM_{2.5}$ concentrations met the 2005 World Health Organisation (WHO) guideline threshold of 10 μgm^{-3}, and are close to the new 2021 WHO guideline threshold of 5 μgm^{-3} [116].

As well as the lack of certainty associated with forecasting concentrations of $PM_{2.5}$ leading up to 2050, the extent of human health effects at reduced concentrations is also uncertain. Recently, the European ELAPSE project has considered the evidence for adverse health outcomes for $PM_{2.5}$, NO_2, black carbon and O_3, and specifically low-level pollutant effects[117]. The study reported "Significant positive associations, found between natural mortality and NO_2, natural mortality and black carbon and coronary events and NO_2". Importantly, it did not identify thresholds between $PM_{2.5}$ and health outcomes, concluding that "Long-term exposure to outdoor air pollution is associated with morbidity and mortality, even at low concentrations".

It should be noted that while associations were found at the lowest concentrations (below 10 µgm^{-3}), the study included data only from Norway and Stockholm, Sweden. Thus, those findings might not be generalisable to broader populations.

Finally, a systematic review of associations between long-term exposure to $PM_{2.5}$ and PM_{10}, and all-cause and cause-specific mortality was undertaken to help with updating World Health Organization guidelines[118]. The authors concluded that there was clear evidence that both $PM_{2.5}$ and PM_{10} were associated with increased mortality from all causes, cardiovascular disease, respiratory disease and lung cancer. Associations remained evident below the current WHO guideline exposure level of 10 µgm^{-3} for $PM_{2.5}$. Current and emerging health studies, in areas with $PM_{2.5}$ concentrations similar to or below those of the UK, provide evidence of the continued associations between $PM_{2.5}$ exposure and health outcomes, and support action to reduce $PM_{2.5}$ in the coming decades. The recent revisions of the WHO guidelines in September 2021 substantially reduce the guideline exposure level for $PM_{2.5}$ from 10 µgm^{-3} to 5 µgm^{-3}, which will act to provide a longer-term ambition for the continued reduction of $PM_{2.5}$ concentrations[108].

3.6 Implications of air quality changes for ecosystems and biodiversity

3.6.1 Effects of tropospheric O_3 on agricultural crops and natural ecosystems

Emissions reductions in the precursors for tropospheric O_3 in the UK and more widely through continental Europe and North America have changed the exposure of vegetation to O_3 over the last three decades. The peak concentrations in summer photochemical episodes have declined, reducing peaks in exposure of O_3 sensitive species. Projected combustion-related emissions are destined to decline further as vehicle fleet and home heating power sources are electrified. However, the reductions in peak O_3 concentrations are not matched by reductions in average concentrations, which have grown in recent decades and are strongly influenced by background O_3 imported into the UK westerly airflow from the Atlantic and are largely controlled by northern hemispheric sources of O_3 precursors. An increased frequency and intensity of summertime heatwaves in the future, coupled with an increase in wildfires, could lead to increases in peak O_3 concentrations, discussed in Chapter 1.

Current exposure of crops to O_3 is reducing yields in North America, Europe and Asia in the range 10% to 20%. Semi-natural species show a similar range of sensitivity to O_3 as crop plants. Effects on the wider plant community are therefore expected to be of a similar magnitude to those on agricultural crops. Even the most optimistic emission reduction scenarios will not prevent O_3 damage, estimated in the range 0.1 to 11% in 2030[119].

The exposure of UK crops to O_3 in recent years has been sufficient for this damage to reduce the yields of sensitive crops and natural species[120]. With projected O_3 exposures in the next three decades, O_3 will continue to reduce crop production and damage semi-natural flora in the UK through to 2050.

The contribution to the tropospheric O_3 burden from global CH_4 emissions is substantial[121]. As the natural sources of CH_4 are regulated by the climate, increasing with temperature, the effects of a changing climate on the terrestrial effects of O_3 remain an important issue globally and an important focus for further research and policy development.

3.6.2 Effects of reactive nitrogen deposition on plant diversity

Current global emissions of reactive nitrogen (those forms which are available to vegetation for growth and development when deposited to terrestrial surfaces) are roughly double those cycling through global ecosystems prior to the Industrial Revolution. Effects of the deposited of reactive nitrogen on natural and semi-natural ecosystems include changes in the competitive balance between plant species leading to reductions in biodiversity, which have been observed across Europe and North America[122].

Substantial reductions in emissions of oxidised nitrogen across Europe and North America have been achieved since the turn of the 21st century and in China since 2012[123]. However, emissions of reduced nitrogen as NH_3 have continued to rise globally and even in the few countries where reductions have been made, their scale has been small.

The process of emission of NH_3 to the atmosphere from soils and vegetation is very sensitive to temperature. Projections of future NH_3 emissions have not generally included this temperature effect so are likely to have under-estimated future concentrations[124]. The effects of deposited nitrogen on vegetation vary according to the form of the deposited nitrogen, with effects of gaseous NH_3 deposition on several species dominating the overall effects of deposited nitrogen[125].

The controls on emissions to achieve net-zero are mainly focused on combustion related emissions. Similarly, controls to improve air quality are mainly focused on transport and combustion related emissions. Thus, while reductions in emissions of oxidised nitrogen are destined to continue to decline, the prospects for reductions in emissions of non-combustion emissions such as NH_3 are very limited. With current projections of surface temperature changes over coming decades, global emissions of NH_3 have been projected to increase from 60 TgN/yr in 2010 to 135 TgN/yr in 2100.

Current effects of deposited reactive nitrogen on plant biodiversity are therefore destined to grow substantially, in part due to the effects of climate change and specifically due to the impact of increases in surface temperature on the processes regulating emissions of NH_3 from soils and vegetation.

Annex

Left
Planting new forests in large areas of rural UK will be a part of the delivery of net-zero. Choices of species to be planted will be important to minimise the emissions of VOCs, a significant source of O_3 and PM. © tbradford.

Acronyms

BECCS	Bioenergy with carbon capture and storage
BVOCs	Biogenic volatile organic compounds
CCC	UK Committee on Climate Change
CCS	Carbon Capture and Storage
COVID-19	Coronavirus disease 2019
CMIP5/6	Coupled Model Intercomparison Project Phase 5/6
DACCS	Direct air carbon capture and storage
GHG	Greenhouse gas
IAS	International aviation and international shipping
IPCC	Intergovernmental Panel on Climate Change
LSOA	Lower Layer Super Output Areas
LULUCF	Land use, land use change and forestry
NAEI	UK National Atmospheric Emission Inventory
NAO	North Atlantic Oscillation
NDC	Nationally determined contribution
NIHR	National Institute for Health Research
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter less than 2.5 µm
PM_{10}	Particulate matter with a diameter less than 10 µm
RCP	Representative concentration pathway
SOA	Secondary organic aerosol
SSP	Shared socio-economic pathway
UKCP18	UK Climate Projections 2018
UNECE	UN Economic Commission for Europe
VOCs	Volatile organic compounds
WHO	World Health Organisation

Chemical symbols

CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CH_4	Methane
H_2S	Hydrogen sulphide
HCl	Hydrochloric acid
Hg	Mercury
NO	Nitric Oxide
N_2O	Nitrous Oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NH_3	Ammonia
O_3	Ozone
OH	Hydroxyl radical
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
SO_x	Sulphur oxides

Glossary of terms

Air pollution
Air pollution refers to the presence of pollutants in the air that are detrimental to human and/or environmental health. It primarily consists of gases (such as nitrogen dioxide, ozone, sulphur dioxide, carbon monoxide, ammonia and volatile organic compounds) and particulate matter, made up of solid and liquid particles such as soot, dust and particles formed in the atmosphere from emitted gases.

Air pollution episodes
Periods of elevated atmospheric pollution.

Aftertreatment technology
Equipment to reduce harmful exhaust emissions from for example combustion processes, such as particle filters or catalytic converters on vehicles or flue gas scrubbers in industrial plant.

Bioenergy with carbon capture and storage (BECCS)
BECCS involves the generation of energy through the burning of biomass (wood and agricultural products, solid waste, landfill gas and biogas or ethanol and biodiesel) coupled with the capture and storage of the resulting CO_2 in geological or other long-term reservoirs.

Biofuels
Biofuels refer to any fuel that is derived from recent biomass – organic material including plant materials and animal waste, ie not fossil derived.

Carbon dioxide equivalent (CO_2e)
As each GHG differs in its contributions to warming, GHG emissions are commonly expressed as the CO_2 equivalent – the amount of CO_2 which would need to be emitted to have the same warming effect.

Decarbonisation
Decarbonisation refers to the process of removing or reducing the CO_2 output of the economy – removing carbon from the production of energy and supply chains. While the term strictly refers to the reduction of CO_2 emissions, it is commonly used to describe efforts to reduce all GHGs.

Differential toxicity of PM
Particulate matter in the atmosphere consists of a wide range of elements and compounds, some in liquid form while others are solids and within a size range from a few nm to 20 µm. While the effect of the PM size classes PM_{10} and $PM_{2.5}$ on human health are known, differences in contribution to human health effects from each of the chemical components remains unknown.

Dry deposition
Dry deposition refers to processes through which gases and aerosols are deposited on surfaces in the absence of precipitation. Common mechanisms include uptake by soil, vegetation, water surfaces, and gravitational settling.

Greenhouse gas (GHG) emissions
GHGs are gases which absorb the outgoing long wave (thermal) radiation and thus trap heat in the atmosphere. The primary GHGs emitted through human activities include carbon dioxide, methane, nitrous oxide, and fluorinated gases.

Net-zero emissions
The terms carbon neutrality and net-zero emissions reflect the same ambition: neutralising the impact of human activity on the climate system from greenhouse gas emissions. The IPCC consider net-zero emissions to be achieved when anthropogenic emissions of GHGs are balanced by anthropogenic removals over a specified period. Where multiple GHGs are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases.

Nitrogen oxides (NO_x), NO and NO_2

NO_x compounds (NO and NO_2) are produced in combustion processes, partly from nitrogen compounds in the fuel, but mostly by direct combination of atmospheric oxygen and nitrogen in flames. NO_x are also produced naturally by lightning, and by microbial processes in soils. NO_x significantly contribute to a number of environmental effects such as acid rain and eutrophication as well as ozone formation. NO_2, which is one of the NO_x compounds, is associated with adverse effects on human health. NO_x gases also contribute to climate change, through O_3 formation and aerosol effects.

North Atlantic Oscillation (NAO)

NAO refers to changes in the atmospheric pressure gradient over the North Atlantic, which influences weather in Europe and North America. It is driven by atmospheric pressure differentials between the Azores, which have high atmospheric pressure and Iceland, which has low pressure. When there is a greater-than-usual pressure difference between the regions (a positive NAO phase), Europe typically experiences warmer, windier, and rainier conditions than usual. When the difference is weaker (a negative NAO phase), Europe will experience cooler, calmer, and drier-than-usual conditions.

Methane (CH_4)

CH_4 is the main constituent of natural gas. It is the second most important GHG after CO_2, and it also leads to the formation of O_3 – another GHG. O_3 has harmful effects on people, ecosystems and agricultural productivity. CH_4 is a so-called “short-lived climate forcer”, with an atmospheric lifetime of about 10 years, compared with century timescales for CO_2 and N_2O.

Ozone (O_3)

O_3 is formed from dioxygen by the action of ultraviolet light and electrical discharges within the Earth’s atmosphere. It is also formed in the troposphere by photochemical reactions between NO_x and VOC compounds. It is present in very low concentrations in the troposphere, with its highest concentration in the O_3 layer of the stratosphere. O_3 is a powerful oxidant and causes damage to mucous and respiratory tissues in animals and humans, and also tissues in plants. While this makes O_3 a potent respiratory hazard and pollutant near ground level, a higher concentration in the O_3 layer is beneficial, preventing damaging ultraviolet light from reaching the Earth’s surface.

Particulate matter (PM)

PM refers to airborne mixtures of small solid particles and liquid droplets. The composition of the PM mixture is variable. PM is often further categorised as $PM_{2.5}$ (particles with a diameter smaller than 2.5 µm) and PM_{10} (diameter smaller than 10 µm). Some particles are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires. Others form in the atmosphere as a result of complex reactions of chemicals such as SO_2 and NO_x, which are pollutants emitted from power plants, industries and automobiles. Smaller particles are able to travel deep into the lungs and some very small particles may even get into the bloodstream. Of these, particles less than 2.5 µm in diameter, pose the greatest risk to health.

Precursor emissions
Precursor emissions are those which can contribute to the formation of other gases in the atmosphere and to particulate matter. For example, nitrogen oxides and volatile organic compounds can react in the presence of sunlight to form ozone and can also form particulate nitrate and secondary organic particulate matter respectively.

Scavenging processes
Processes which remove gasses or particulate matter from the atmosphere. Rainfall is a common scavenging process, as is scavenging of water-soluble gases by cloud droplets. Dry deposition is the other main scavenging process and refers to the deposition of gases and particles to terrestrial and water surfaces.

Stratosphere
The stratosphere is the layer of the atmosphere directly above the troposphere, between 12 – 50km above the Earth's surface. It contains the ozone layer.

Sulphur dioxide
The largest anthropogenic source of SO_2 in the atmosphere is the burning of fossil fuels by power plants and other industrial facilities and in shipping. Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore and vehicles using sulphur containing fuels. Natural sources also contribute substantial quantities of SO_2 to the atmosphere, sometimes at high altitude. Short-term exposures to SO_2 can harm the human respiratory system and make breathing difficult. High concentrations of SO_2 in the air generally also lead to the formation of other SO_x which can react with other compounds in the atmosphere to form small particles and contribute to PM pollution.

Synoptic meteorological conditions
In this context, the word synoptic refers to a combination of the conditions determining the weather including the pressure pattern, fronts, wind direction and speed and temperature structure of the atmosphere – and is generally applied at a regional scale.

Troposphere
The troposphere is the lowest layer of the atmosphere, ranging from 0 – 12km above the Earth's surface. All weather occurs in the troposphere.

Volatile organic compounds (VOCs)
VOCs are organic chemicals that are volatile at room temperature. They are responsible for example for the odour of scents and perfumes as well as pollutants. Sources of VOCs can be anthropogenic or biogenic. Anthropogenic sources include fossil fuel use and production; solvents used in coatings, paints, and inks; and biomass combustion. Biogenic VOCs (BVOCs) encompass VOCs emitted by plants, animals, or microorganisms. Some VOCs are dangerous to human health or cause harm to the environment. Anthropogenic VOCs are regulated by law, especially indoors, where concentrations are the highest. Most VOCs are not acutely toxic, but may have long-term chronic health effects.

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