NPL National Physical Laboratory

NPL REPORT ENV 54

FUTURE TRENDS IN AIR QUALITY MEASUREMENT

FREYA CLEASBY

YING ZHANG

MAY 2024

Future Trends in Air Quality Measurement – Public Version

Dr Freya Cleasby

Dr Ying Zhang

Environment Team, Partnerships Directorate

ABSTRACT

This document explores future trends in air quality measurement out to 2050, taking a holistic view across science and research, government priorities, societal changes, industrial progress, and the international landscape, and identifies the related future measurement challenges.

After initial research, topics were grouped into seven future trend themes. These themes are Pollutants, Technology, Health, Data and Modelling, Wider Impacts, Biosphere, and Indoor Air Quality. Further literature research on each theme was carried out. UK Air Quality experts' views were sought through interviews. Combining NPL knowledge and expertise, all inputs were synthesised. Each theme is discussed in detail in respective chapters. In conclusion, the measurement challenges pertaining to each theme are set out.

ISSN: 2059-6030

DOI: https://doi.org/10.47120/npl.ENV54

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Richard Barker, Head of Environment

CONTENTS

1. BACKGROUND

Despite significant improvements in air quality, air pollution remains one of the biggest environmental risks to human health. In 2019, Global Air Quality was responsible for 7 million premature deaths, as well as contributing to extensive crop loss and biodiversity decline across Europe, North America and East Asia.[1] In the UK, this is estimated to be between 29,000-43,000 deaths annually, as well as other long term health issues. This is expected to cost the NHS and social care services at least £1.6 billion between 2017-2025.[2]

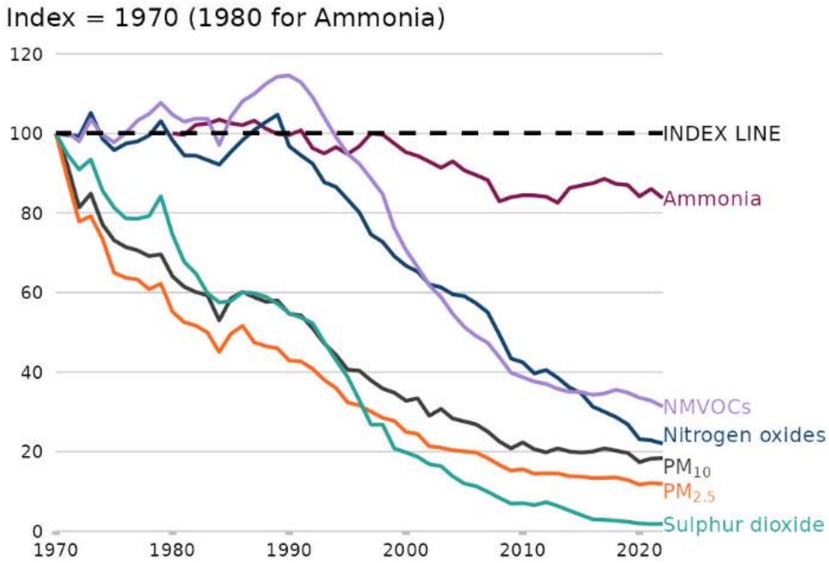

Figure 1. Trends in annual emissions of particulate matter (PM10 and PM2.5), nitrogen oxides, ammonia, non-methane volatile organic compounds, and sulphur dioxide, 1970-2020 (1980-2020 for ammonia).[3] Image licensed under the Open Government Licence.

Since 1970 air pollutant emissions have been improving overall (Figure 1), this is due to the combination of UK and international air quality legislation. Changes in technology, urban planning and broader behavioural changes have all contributed to this improvement. This decline in air pollution levels brings its own challenges, as technological innovations must happen in order to continue monitoring these lower levels. While air pollution levels have been improving, WHO estimated that over 90% of the global population were exposed to air quality breaching WHO guidelines (using 2016 data).[4] There is no safe lower limit for health when it comes to air pollution, meaning it will remain a priority for monitoring even at low levels. The public also have little control over the quality of the air they breathe, meaning governments are obliged to keep pollution reduction a priority.

Air quality isn't an isolated issue, there are other factors that will inadvertently contribute to air quality, both positively and negatively. Climate change and associated policies (primarily Net Zero) will have significantly impact air quality. If the right considerations are made, this can be in a positive way, however the impact could be adverse.[5] In addition to climate, health and public awareness, and new air quality guidelines will be important drivers for how air quality will change in the future.

1.1. AIR QUALITY IN THE UK

Currently, the UK has legally binding emission reduction commitments for fine particulate matter ($PM_{2.5}$), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs).[6] In 2019, the Department for Environment, Food and Rural Affairs (DEFRA) outlined a new Clean Air Strategy, in order to tackle air quality.[7] This strategy recognised that, as major sources of emissions have decreased, smaller and more diffuse sources of air pollution, such as burning of solid fuels and spreading manure on farms, need addressing. With the publication of this strategy comes more ambitious pollutant reduction targets, which present a new set of challenges.

The UK has an expansive series of air quality networks that are already measuring levels of the five pollutants outlined above, as well as heavy metals, ozone, polycyclic aromatic hydrocarbons, and more.[8] NPL is responsible for operation of the Heavy Metals, Black Carbon and the Particle Concentrations and Numbers Networks. These networks are key for monitoring Air Quality and understanding how mitigation policies and actions are working.

Departments within the UK Government publish and regularly refresh their Areas of Research Interest (ARIs). These documents are a key resource to understand where departmental research and scientific policy priorities lie. In 2021, the DEFRA ARIs had a focus section on Environmental Quality, including ambitions to better understand ecosystem responses to air quality, understand toxicity of particulates, develop methods to assess personal exposure, and develop monitoring and modelling approaches. Other departmental ARIs (DfT and DLUHC) include increasing evidence of the health impacts of poor indoor air quality, understanding the impact of road schemes and real-world pollutant emissions of vehicles, and understanding the interdependencies between addressing different environmental impacts. Additionally, the Chief Medical Officer's report for 2022 was focussed on air quality, the health impacts, solutions, and monitoring and forecasting.[9] Finally, two reports were published by the Parliamentary Office of Science and Technology (POST) in 2023 on both indoor and outdoor air quality.[2,10] This shows that poor air quality is high on the agenda for a number of departments and is a topic the UK government is committed to tackling.

1.2. PURPOSE AND STRUCTURE OF THIS REPORT

This report analyses the future trends in air quality measurement, developing a picture of the future landscape of air quality and air quality measurement in the UK to 2050. It identifies and prioritises the measurement challenges that may occur as a result of these trends. This report serves as a thought leadership piece, adding a perspective to the areas of scientific work required to advance air quality measurement in order to improve air quality in the UK.

Chapter 2 sets out the future trends in air quality in detail, and discusses potential measurement needs and challenges that will arise. Chapter 3 sets out these trends in a roadmap of air quality measurement to 2050 and sets out a comprehensive table covering challenges from each theme. Chapter 4 concludes the report with summary of the key challenges.

The conclusions in this report are synthesised from a range of Foresighting exercises, including a review of the literature, in-depth discussions with NPL air quality scientists and an external consultation from experts across the sector.

2. FUTURE TRENDS IN AIR QUALITY MEASUREMENT

This document explores future trends in air quality measurement out to 2050, taking a holistic view across science and research, government priorities, societal changes, industrial progress, and the international landscape, and identifies the related future measurement challenges.

After initial research, topics were grouped into seven future trend themes. These were reviewed periodically to ensure they effectively encompassed all the future trends discovered throughout the project. These themes are Pollutants, Technology, Health, Data and Modelling, Wider Impacts, Biosphere, and Indoor Air Quality. Each theme is discussed in detail in this chapter, and the measurement challenges pertaining to each are set out.

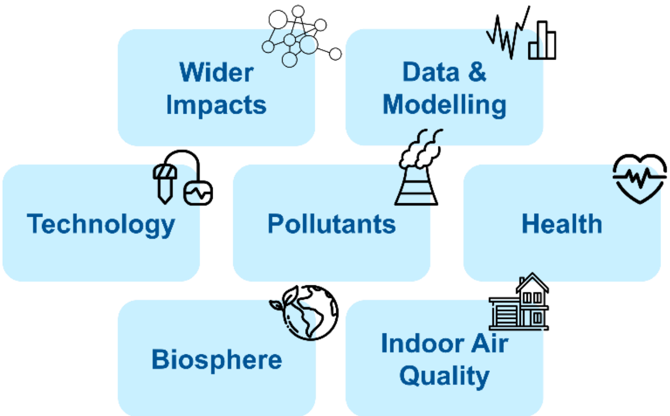

Figure 2. Infographic showing the seven themes for the future trends in air quality measurement.

2.1. EVOLVING POLLUTANTS

How air pollutants change will be a significant factor in the future of air quality measurement. Changes in pollutants could be as the result of a range of factors, including new industrial processes and societal behaviour emitting new pollutants, changes to secondary pollutants and new regulations. Some of the causes of pollutant change are addressed in other themes, however the pollutants themselves will independently bring their own challenges to the air quality measurement field.

2.1.1. Known pollutants

While the number of known pollutants is vast, this section focusses on those that possess the biggest concern for the future. Particulate matter (PM) is expected to be a continued concern, with over 50% of expert interviewees highlighting issues around $PM_{2.5}$. Two sources of increasing importance are domestic burning (wood, coal, and smokeless fuels) and non-exhaust emissions (tyre and brake wear). Domestic burning is now responsible for 27% of

$PM_{2.5}$ emissions.[3] Non-exhaust emissions are becoming more prevalent as tailpipe emissions reduce - both through catalytic converter technology in petrol/diesel cars, and the electrification of the fleet, rolling out heavier vehicles.[11,12]

Ultrafine particles (UFPs) are also expected to be subject to increased attention in the near term. This includes black carbon, a component of UFPs, which has significant climate and biosphere implications. Currently, there are only legal limits for $PM_{2.5}$ and PM_{10}. UFPs currently do not have defined upper and lower limits, and no specific legal regulations. With research suggesting UFPs are significantly more harmful to health than other types of PM, these limits will need to be defined, as well as standardisation of the measurement of UFPs.[13,14] Questions around whether current PM measurement methods accurately reflect the UFP content need addressing. Additionally, with the UK Clean Air Strategy and Air Quality Strategy heavily targeting PM reductions, more information about composition, toxicity and source apportionment of PM will be required going forward.

Other ambient air pollutants that are expected to be key in the next 10-15 years include ammonia, and volatile organic compounds (VOCs). While ammonia is part of the UK's emission reduction commitments, the levels of ammonia have not been decreasing at the same rate as other pollutants. Ammonia reacts with nitrogen oxides and sulphur dioxide to form secondary particulate matter which significantly impacts on human health. The agriculture sector accounts for 88% of ammonia emissions in the UK.[15]

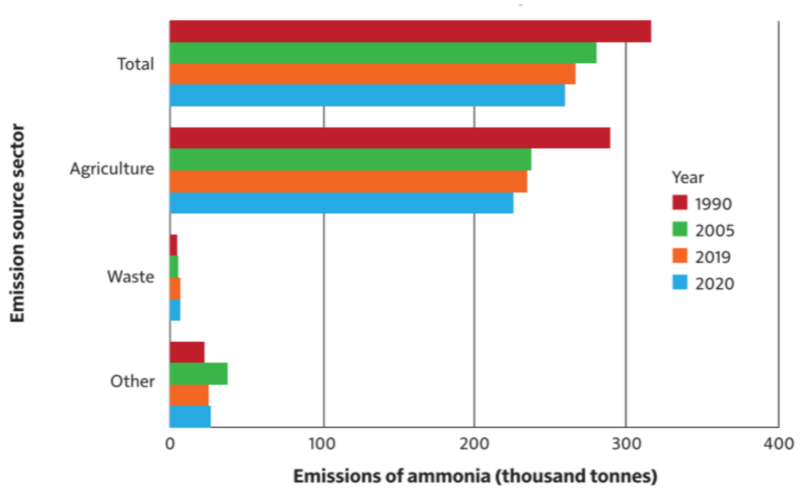

Figure 3. UK annual emissions of ammonia by major emission sources in 1990, 2005, 2019 and 2020.[9] Image licensed under the Open Government Licence.

This is largely due to emissions during storage and spreading of manure and slurries and from fertiliser application.[7] DEFRA have committed to both improving the evidence base around ammonia pollution and reducing the emissions. Diffusive samplers and active samplers have the sensitivity to detect low level and background ammonia, unfortunately these techniques have 4-week sampling times. Currently there are no low-cost powered sensors with the required sensitivity for background ammonia measurements, however this is one of the ways being explored to improve accessibility and temporal resolution to ammonia monitoring in the agricultural sector.[16]

While there are legal limits and guidance around VOCs, there are questions as to whether these are targeting the most appropriate VOC pollutants. The number of compounds that fall into the VOC category is vast, and ensuring the most important compounds are well understood and measurements are standardised, is a challenge that will only increase as the list of concerning VOCs grows.[17] While VOCs are a concern in ambient air, discussions with experts showed that it is of even greater concern in the indoor environment and will be discussed further in Section 2.7.

Lastly, as the composition of pollutants in the air changes, the amount of ozone in ambient air will change. As a secondary pollutant, it is more difficult to predict how ozone will respond to the reductions in other pollutants.[2] Ozone formation is heavily dependent on weather, with build-up common on hot summer days – something that will be increasingly concerning with the warming climate. Ozone has long residence time in the air, and hence can be transported substantial distances, meaning transboundary ozone pollution adds further uncertainty for future concentrations.[18]

2.1.2. Emergence of new pollutants

While it is difficult to discuss pollutants not yet identified in detail, it is worth being mindful of the challenges that new pollutants will bring. As new industries are established for future technologies, such as battery production, hydrogen and future fuels, new pollutants will need measuring. With Net Zero, societal and behavioural changes will bring new emission sources and new pollutants. Additionally, new, and better measurement techniques will also identify as yet unknown pollutants. Agility will be key to responding to the challenge of new pollutants, supporting the expansion of air quality regulations, and establishing robust monitoring systems in short time scales.

2.1.3. Pollutant measurement challenges and needs

Below are broad examples of key measurement challenge areas that will need solving in order to understand key pollutants and how to then mitigate against them. More specific examples of measurement challenges can be found in section 3.2.

Improvements to PM measurement methods and understanding of PM composition. Developing improved methods of measuring UFPs to understand their ambient air concentration. Validation and comparison of measurement methods for composition, toxicity, and source apportionment of PM.

Validation of new ammonia measurement methods to improve the evidence base and enable accessible measurements to the agriculture industry.

Development of standardised, **updated monitoring systems for VOCs** prevalent in the ambient air.

Validation of source apportionment, pollutant transport and pollutant persistency methods to understand the global transport of ozone pollution.

Agile development of new measurement techniques to respond to emerging pollutants. Validation of new methods, development of new standards and reference materials in support of new legislation and regulations.

2.2. ADVANCES IN TECHNOLOGY

Technology and instrumentation play a huge part in the measurement and monitoring of Air Quality. Joint with the health theme, technology was the most highly ranked by interviewees in terms of priority, more specifically the intrinsic metrological need that comes with technological advancement. This theme covers new technology in the field, improvements to existing measurement techniques and air quality networks. As air quality changes over time, using technology to understand the composition and movement of pollution will become key for policy making decisions.

2.2.1. New technology and networks

As with all technology, air quality measurement instrumentation is always developing and improving. Looking at current trends in technology, a large trend will be towards miniaturisation of devices. We are seeing this play out today in the development of low-cost sensors.[19] Currently low-cost sensors have significant limitations in terms of reliability and accuracy, there are also challenges around calibration and longevity.[19,20] As the accuracy and reliability of low-cost sensors improves, their use in air quality monitoring and networks will increase. Driving the guidance and validation of these low-cost sensors gives NPL the opportunity to be a leader in the field and to set the direction for instrument innovation.

Other areas of technological advancement will include increased mobile monitoring, whereby measurements can be taken at areas of interest and hotspots, rather than fixed locations. This will allow flexibility, more equal dispersion of expertise and the ability to measure point source emissions in an agile way. Mobile monitoring could take the traditional form of instrumentation in vans or could utilise new technology such as instrumented unmanned aerial vehicles (UAVs).[21] The use of UAVs could enable measurements to be recorded in remote or inaccessible locations. While mobile monitoring using vans is a trend that could increase in the near term, it is more likely to be longer term before the technological readiness level of instrumented UAVs is sufficient. Satellite monitoring is an area that has also been receiving attention recently, with the potential to be used for air quality monitoring becoming more realised.[22]

Presently NPL manage three Air Quality Networks on behalf of DEFRA. These are the Particle Number and Concentrations, the Heavy Metals, and the Black Carbon Networks.[23] As the availability of different air quality instrumentation expands, different types of sensors will contribute to dense hybrid networks. Hierarchies of instruments providing differing levels of accuracy in measurement will complement each other in the overall monitoring of air quality. The biggest challenge in developing these hybrid networks will be the integration of the different instrumentation into a cohesive system. Ensuring the instruments and the resultant data are compatible will be key.

Another challenge that arises from the continued deployment of more sensors and expansion of networks is calibration of instruments. Calibration is key to assuring data quality and without it, instrument measurements can drift unknowingly. Manual calibration is resource heavy, and unlikely to be feasible in a future with significantly more sensors. Innovations need to be made to ensure calibration is accessible and cost effective in the future, this could be automating calibration, transferring calibration online or devising a centralised calibration system.

2.2.2. Improving measurements

As air quality improves and interventions become more targeted, there will be two key changes to air quality measurement: sensitivity in measurements and information from measurements. Information from measurements includes spatial and temporal resolution, and speciation.

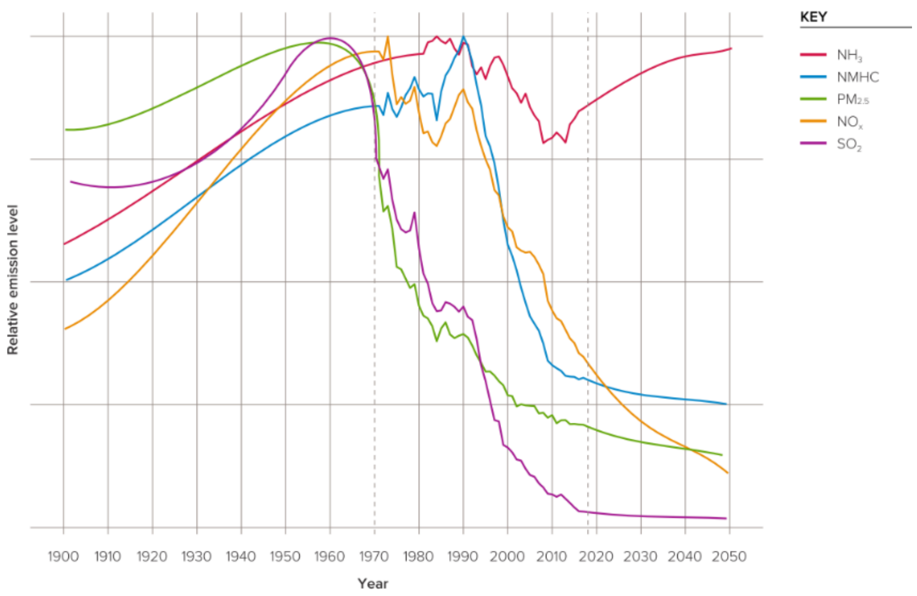

Figure 4. Illustrative relative trends in emissions of different air pollutants scaled from zero to maximum value.[5] Image licensed under the Creative Commons Attribution 4.0 International Licence.

Decreases in pollution levels will demand instrumentation able to make measurements with lower limit of detection, having lower cross-sensitivity, and reduced instrument noise. There will also be new requirements for cheaper and more real-time reference materials. Through the lens of information from measurements, technology will need to deliver easily accessible speciation and source apportionment measurements as evidential backing for targeted policy interventions. In addition to speciation and source apportionment, the future landscape of dense monitoring networks will enable further advancements in higher temporal and spatial resolutions, which in turn will allow a more rapid monitoring feedback loop. This will enable air quality responses to policy interventions and mitigation actions to be understood on a more granular level.

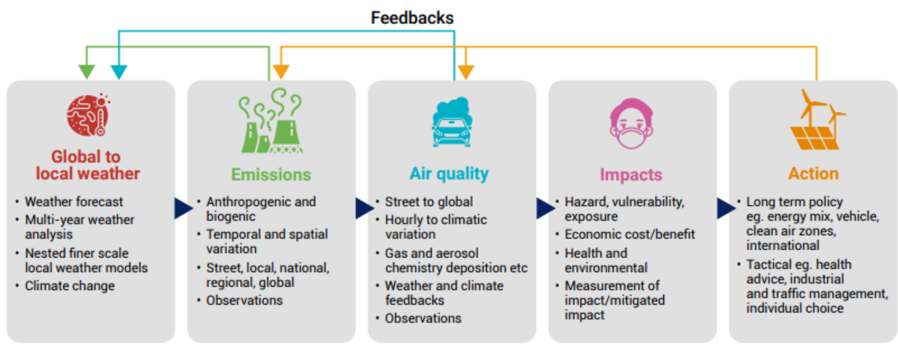

Figure 5. Schematic illustrating how monitoring feedback loops can be integrated into the wider system.[24] Image reproduced with permission.

While more spatially and temporally resolute, and more accurate measurements will form part of the future landscape of air quality measurement, there will also be an emphasis on fit for purpose measurements. As public interest in air quality grows, measurements informing air quality of public spaces such as train stations, hospitals and schools will become more commonplace. Measurements of this kind may not need to be of the highest accuracy and smallest uncertainty but will be fit for the purpose they are serving. These “fit for purpose” measurements will still require metrological infrastructure and support, of a different level. Being at the forefront of the development of this metrology infrastructure is an area NPL can show leadership and add real value.

With both technological advances, and changes in pollutants, improvements to emissions inventories will be a key change that will come with advancing air quality measurement in the future.

2.2.3. Measurement needs and challenges for air quality technology

Below are broad examples of key measurement challenges that will need solving to support the progress of air quality technology. More specific examples of measurement challenges can be found in section 3.2.

Developing best practice for dense, hybrid networks. Integrating a variety of types of measurement techniques and ensuring data compatibility across systems. Validation of the reliability and accuracy of low-cost sensors, mobile monitoring, and other new measurement techniques.

Improving calibration methods. Developing and validating new calibration techniques that are widely accessible and cost-effective.

Improving information available from air quality monitoring. Developing and validating new measurement methods for source apportionment and speciation. Improving sensitivity of measurements, through noise reduction in instruments, targeted measurements, and lower limits of detection.

Developing the metrology infrastructure and support mechanisms for different levels of measurement.

2.3. INCREASING EMPHASIS ON HEALTH IMPACTS

The impact to human health is the biggest driver for monitoring and improving air quality. Linking air quality measurements to the health impacts is crucial, ever evolving with new pollutants and will involve multidisciplinary working. Cross-disciplinary scientists, toxicologists, geneticists, epidemiologists, data scientists and more will all have to come together to solve the problems of how air quality is affecting human health.

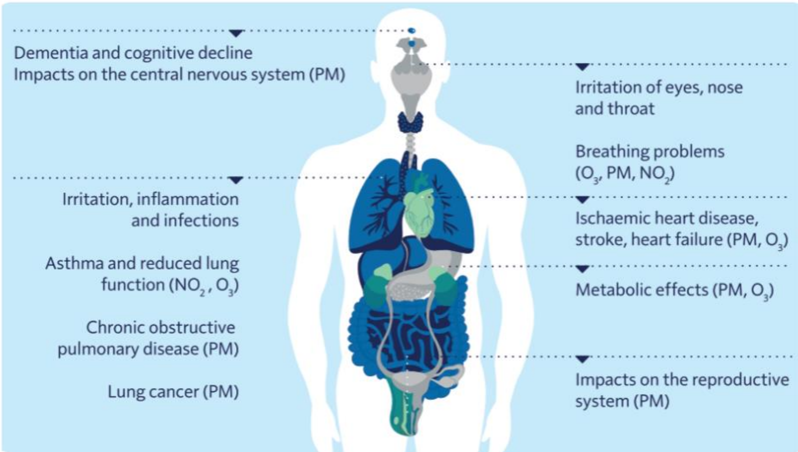

Figure 6. Health effects from air pollutants.[9] Image licensed under the Open Government Licence.

This theme covers both how we understand the health implications of poor air quality and how technological advances will enable better understanding of personal exposure.

2.3.1. Health studies

As time goes on and public awareness around air quality grows, understanding of the health impacts of pollutants will be more important than ever. Long-term exposure to pollutants can be harmful to the neurological, reproductive, and respiratory systems and causes cancer and even, death. For this reason, long-term studies of air pollution exposure are crucial to understanding the health impacts.[25]

Toxicology of individual pollutants needs to be better understood in order to target the reduction of the most harmful compounds. Part of this challenge relates to particle morphology, understanding how morphology effects toxicity will be key to designing effective toxicity measurements. Standardised approaches to determining pollutant toxicity should be developed in order to rapidly identify the health implications of current, new pollutants and pollutant mixtures. An example of advancements in this area are the methods of determining oxidative potential of PM being developed as a proxy for toxicity.[26] Research into oxidative potential is still in early stages, however it has the potential to identify if individual components of PM affect health differently. This could inform policies on how different PM emission sources should be controlled.

Coupled with toxicology, epidemiology will be key to understanding how best to improve air quality and public exposure. By combining high confidence sustained data capture from air quality networks with health data, epidemiology can establish causal associations between air pollution and health outcomes. While this is very complex, it can quantify risk related to exposure to air pollution.[27,28]

Genomic and even one step further, multi-omic (a holistic approach to studying genomics, transcriptomics, proteomics, and metabolomics) technologies will be required to improve understanding of individual risk and impact of pollutant exposure.[29] Data collected by the UK BioBank will be essential for epidemiological and multi-omic studies to better link health outcomes and air quality.[9] The widespread use of multi-omic technologies is a longer term trend expected to be in 2050 or beyond.

2.3.2. Personal exposure monitoring

As the population ages and lives longer, the impact of poor air quality on health will become more prevalent. This will raise the profile of air quality as the public become more aware of how pollution affects their health. This rise in awareness will be coupled with a demand for more information about personal exposure to poor air quality.[9]

The challenge for greater understanding of personal exposure to air pollutants will progress in two stages. In the near term, more accurate models of personal exposure will be developed. Currently, personal exposure is mostly determined by air quality models for ambient air. However, as we spend significantly more time indoors, it raises the question of whether this is an accurate representation of the average person's exposure. Advances in current models based on average public exposure will be followed by models that can accurately show personal exposure as users move from environment to environment, utilising data from the future dense, hybrid networks discussed in section 2.2.1.

Beyond personal exposure models, as technology is continually miniaturised, we can expect sensors to reduce to a size that is portable. Once sensor technology is small enough, wearable personal monitoring devices can be developed, and users can accurately track pollution exposure during their daily lives. While this technology is currently on the market, it will be 2050 or beyond before the technology is accurate and reliable enough to contribute scientifically to policy problems.

2.3.3. Air quality measurement needs and challenges for health

Below are broad examples of key measurement challenges that relate to understanding the health impacts of air quality. More specific examples of measurement challenges can be found in section 3.2.

Improving toxicity measurement techniques, including well-characterised particles for controlled toxicology studies and understandings of the effect of particle morphology on toxicology.

Understanding uncertainty in health studies. Understanding the uncertainty propagation in epidemiological and with multi-omics data.

Developing best practice for personal exposure modelling. Validating personal exposure models with network measurement data.

Metrology infrastructure to support personal monitoring devices. Guidance, accessible calibration techniques, standards, and validation of personal monitors.

2.4. INCREASED USE OF DATA AND MODELLING

Data and modelling are intrinsic in measurement science, and a balance between investment in both will be important in the future. Often measurands are unable to be directly measured, meaning proxies and models are required. How data are processed and assured is also a key part of the measurement process, as without it, there can be no confidence in the results.

This theme covers both data and modelling for measurands, as well as looking out to the future of forecasting air quality for the public.

2.4.1. Data

As we become more reliant on data, informing policy decisions, meeting regulations, providing understanding of our pollution, data metrology and quality of data becomes more important.[30] Priorities for air quality data include reducing measurement uncertainty (especially at low concentrations), increasing temporal and spatial coverage, and increasing data capture. Without good quality data, the information that is extracted from that data becomes less and less realistic as a picture of the state of play. Ensuring that measurements are accurate, and data are of high quality is a key measurement challenge that affects all areas of air quality science.

Metrology can provide confidence that data are of the expected quality for the output. Data assurance for instruments over time can provide confidence that performance is consistent, and data are at the expected accuracy. As networks expand and the number of instruments in the field grows, conducting data assurance services must be innovative. A centralised data assurance system, online, whereby experts do not have to travel around the country conducting assurance assessments would all resource to be more efficiently deployed.

The expansion of networks, especially to a more hybrid system will be in combining data from different types of devices. As discussed in section 2.2.1, integrating and combining the data from different scales will be challenging but will have powerful results.

Additionally, the expansion of networks will result in an increase volume of data collected. Machine learning and AI tool interactions with large network data hubs will enable more information to be pulled out of collected data and give a greater understanding of air quality trends. AI and machine learning could also be utilised to improve calibration and assurance techniques, removing a huge part of the resource intensive nature of calibration. “Virtual sensors” can also be used to digitally enhance network density through AI and machine learning.

2.4.2. Modelling

Models and forecasting tools are becoming more complex and sophisticated to incorporate the myriad of factors that impact air quality.[4,31] In the future, this will require better embedded use of machine learning and AI in models.[32,33] Transparency within models and understanding of the principles of operation of the models are vital for validation and ensuring the right data are used for policy decisions. Understanding the input needs of modellers will be crucial in order to support the development of effective models. In the future, models and forecasts for air quality will be accessed by a wider user base, as the public interest in personal exposure increases. We could see air quality forecasts alongside the weather forecast, with the public using it to plan their activities. In order for these to be accurate, trusted sources of data, the models need to be challenged, and the data needs to be good quality.

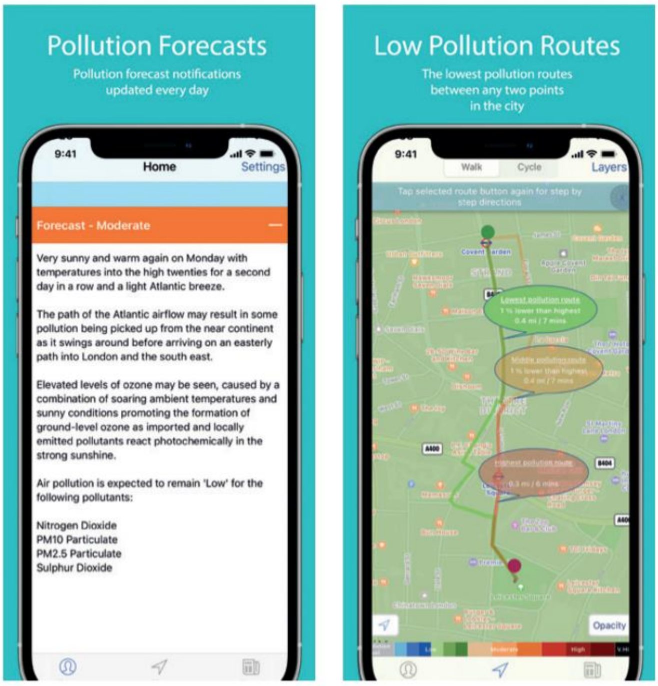

Figure 7. Example of air quality forecasting for public use.[9] Image licensed under the Open Government Licence.

The other important factor to modelling is the uncertainty associated with the measurements and results. Once measurements are fed through models to give the measurand, or the forecast, the uncertainty must be propagated through the calculations. Knowing the final uncertainty associated with the data is key to fully understanding what the result means. As more policy and personal decisions are based on air quality data, understanding the associated uncertainty is as important as ever before. With lower limits in regulations, the uncertainty in measurements have a larger impact on whether the regulations have been breached. To better convey the uncertainty in models, uncertainty maps could be presented alongside the air quality maps.

2.4.3. Air quality data and modelling measurement needs and challenges

Below are broad examples of key measurement challenges that relate to data and modelling in air quality. More specific examples of measurement challenges can be found in section 3.2.

Validating and assuring **data quality** to provide confidence in instrument measurements.

Developing best practice for the use of **machine learning and AI** tools in air quality networks.

Ensuring **transparency in models and forecasts**. Ensuring the validation and uncertainty of new models and forecasting tools.

2.5. UNDERSTANDING WIDER IMPACTS ON AIR QUALITY

As the UK Government's Net Zero Strategy is implemented, changes such as increased use of active travel, electric vehicles, changes in agricultural practices, improved energy efficiency in homes and adoption of alternative fuels will start to come into effect.[34] All of these interdependent factors and other behavioural and societal changes will impact the state of air quality in the UK between the present day and 2050.

Many of the air quality measurement challenges in this theme cross over and relate to other themes, however it is important to acknowledge that the drivers are different. When it comes to these interdependent factors, air quality might not be at the top of the agenda, so ensuring proper monitoring and feedback of impacts are communicated to decision makers is key.

2.5.1. Climate and Net Zero

As discussed in depth in the Air Quality Expert Group report on Net Zero impacts, the biggest transition we will see in the future is related to climate change.[35] Whether this is changes from rising temperatures or mitigation actions and policies, it will impact daily lives hugely. Some of the main impacts of climate change (ignoring impacts of Net Zero policies) will include more frequent and intense heat waves causing more frequent and more severe episodes of elevated ozone and PM. Changes in temperature, humidity and precipitation will alter the emissions, formation, processing, and removal of PM, affecting its composition and distribution. Emissions of NH_3, VOCs and soil NO_x are expected to increase with global temperature rises, which will have implications to ozone and PM as these are precursors. Increased wildfires will lead to increases in black carbon and ozone; however, ozone increases will be offset by greater ozone destruction in air from the Atlantic, a consequence of a warmer, more humid atmosphere.[5,36]

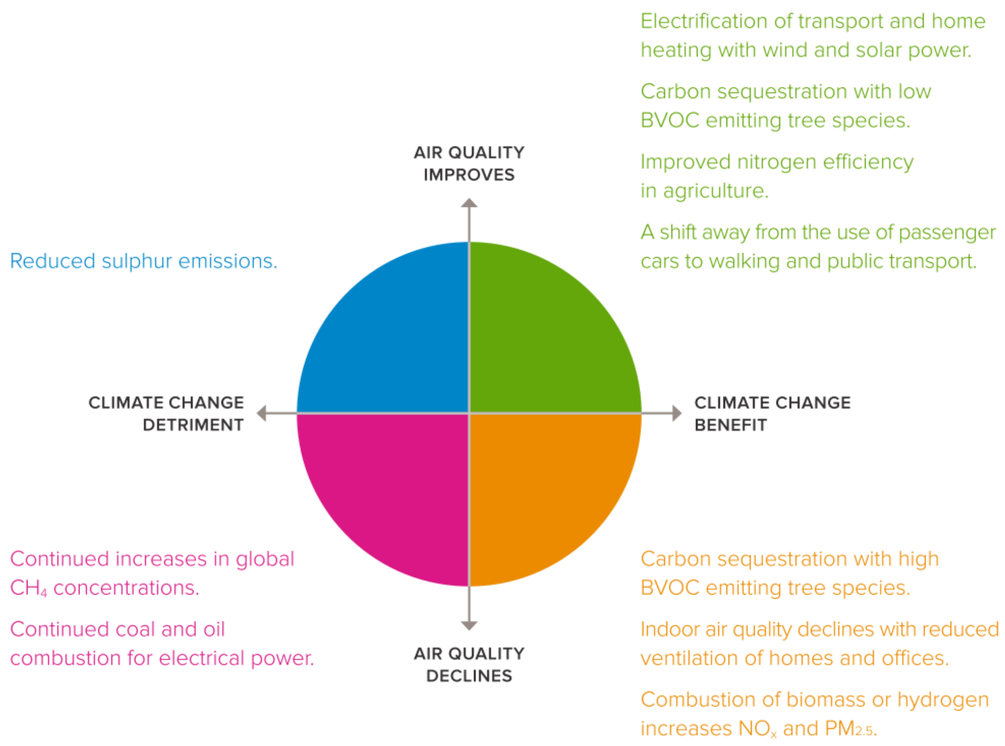

Figure 8. Examples of different responses of air quality and climate change to net-zero measures.[5] Image licensed under the Creative Commons Attribution 4.0 International Licence.

In terms of Net Zero policy impacts, there will be some with clear co-benefits and others where impact to air quality needs to be considered with implementation. Some examples of clear co-benefit opportunities include decarbonisation of the electricity grid will lead to reductions in NO_x and SO_2, with knock-on reductions to $PM_{2.5}$ and ozone. Increases in active travel (walking, cycling and public transport use) will reduce emissions and will have further health benefits beyond improving air quality.

Changes to agricultural practices such as improved management of nitrogen would reduce NO_x emissions and have a regional knock-on reduction in $PM_{2.5}$. Agriculture is also the biggest contributor to ammonia emissions.[15] Developing accessible air quality monitoring systems for the agricultural industry would allow farmers to better understand the impact of their systems and adapt their practices accordingly.[16] However currently, the ammonia monitoring technology is too expensive and not developed for the industry to adopt.

Alternatively, there are some areas of Net Zero that are already emerging as disadvantages when it comes to air quality. The transition to battery electric vehicles is increasing the $PM_{2.5}$ emitted from non-exhaust sources, such as tyre and brake wear, due to electric vehicles being heavier. As urban NO_x reduces, the chemical suppression of ozone in the atmosphere is reduced, which will lead to some ozone increases.

Understanding the effect of these and future net zero policies will require a monitoring feedback loop that will be able to rapidly inform policy makers of the impact of actions. This brings the discussion back to the need for dense networks with high spatial and temporal resolution measurements (section 2.2.1). Embedding air quality measurement into a wider systems approach would allow this monitoring to become integral to decision making. This could be incorporating air quality measurement into smart city designs, adding sensors to public transport, lamp posts or in public spaces.

The other consideration when it comes to climate change is the resilience of instruments. Will the air quality monitoring networks and systems perform at the same accuracy at increased temperatures or extreme weather events. Understanding the climate resilience of air quality monitoring instruments is a key challenge that needs to be solved as our environment changes.

2.5.2. Nuclear

The government pledged the deployment of three times more civil nuclear energy production in 2050 than now, which will represent up to 25% of our projected electricity demand.[37] There must be further consideration of what this means for air quality. While the reduction in combustion of carbon-based fuels will have a positive impact on air quality, there will be pollution generated in the construction of nuclear power plants and potential new unknown pollutants from future nuclear fuel processes.[5] An example of this could be monitoring long-lived radionuclides that could have long-term cumulative effects. Monitoring the effect of increasing the contribution of civil nuclear energy on air quality will again be crucial to informing decision makers.

2.5.3. Transboundary effects

Pollution does not respect national boundaries, and thus air quality is a global problem. This was recognised in 1979 with the signing of the Convention on Long-Range Transboundary Air Pollution.[38] Because of the transboundary nature of pollution, an international effort is required to fully improve air quality.[39] The ability to track air pollution across international boundaries and understand the source apportionment of pollution is vital to implementing mitigations in the most effective locations.[28,40] Setting up international networks to collaboratively work to improve air quality is an approach that would require significant metrological infrastructure, especially in countries without the same level of expertise in air quality measurement.[41]

2.5.4. Measurement needs and challenges associated with wider impacts

Below are broad examples of key measurement challenges related to wider impacts on air quality. More specific examples of measurement challenges can be found in section 3.2.

Developing a spatially and temporally dense monitoring network to **understand policy impacts.**

Improvement in agricultural air quality monitoring. Development of low-cost ammonia sensors and metrology infrastructure to support the agriculture industry.

Standardisation of transboundary pollution measurements.

Understanding of instrument climate resilience.

2.6. IMPACT ON THE BIOSPHERE

While health is the main driver for understanding and improving air quality, the impacts of pollution on our ecosystems is also an important consideration. This will involve monitoring changes in the biosphere and integrating that with air quality measurements to understand causation. While this theme is mostly out of scope for the environmental monitoring strategy at NPL, it is important to consider the measurement challenge areas, where solutions align with other planned activities and opportunities for growth.

2.6.1. Plant and animal life

Understanding how air pollution deposits and accumulates within the biosphere is one of the key ways to understand how air pollution affects plant life.[42] There are multiple methods of monitoring pollution impact on the ecosystem, including measurement of heavy metal accumulation in trees, uptake of pollutants in moss and the measurement of environmental DNA (eDNA) to study the biodiversity of plants and animals [42–45] These eDNA samples can be collected on filters during monitoring for other pollutants.

Conversely, understanding the emissions of trees and other plant life is important as there is a push for more green spaces and rewilding, especially in the urban environment. An emissions inventory of tree emissions would be a useful tool for urban planners when designing green spaces. Additionally, there is further understanding how emissions from trees and plants will change with the changing climate and increasing extreme weather events.[46]

2.6.2. Bioaerosols

Another area within the biosphere of concern, is the rise of bioaerosols. This can extend to any biological particle suspended in the air, including bacteria, fungi, viruses and pollen.[47] Fungi such as mould is of particular concern, especially in the indoor environment, due to the significant risk to health.[9] There are links between climate change and increases in pollen and mould pollution, an effect that should be monitored as climate related policies are implemented.[48] Pollen is one of the key bioaerosols that is already being monitored in networks in other countries. In the UK, pollen is monitored at some research stations, however this could increase to a more expansive network in the future.

There is also an increased risk of cross-species viral transmission, which can cause epidemics and pandemics like COVID-19 as biodiversity declines.[49] This has two-fold implications for air quality measurement. Firstly, monitoring biodiversity impacts from poor air quality and informing mitigation actions will help prevent further pandemic events. Secondly, if another virus with airborne transmission were to outbreak, using air quality measurement principles and metrology would be key to understanding how to limit infection.

2.6.3. Air quality measurement needs and challenges for the biosphere

Below are broad examples of key measurement challenges related to air quality impact on the biosphere. More specific examples of measurement challenges can be found in section 3.2.

Development of an emissions inventory for tree emissions, with validated modelling for different scenarios – urban, rural, future temperature changes etc.

Development and standardisation of pollen measurement methods.

Standardisation of eDNA measurements.

2.7. INCREASED EMPHASIS ON INDOOR AIR QUALITY

Indoor air quality is a large, complicated theme with relatively little research compared to ambient air quality. This section touches on some of the key issues and measurement challenges, however a more in-depth Foresighting exercise is needed to fully appreciate the future of indoor air quality measurement and how NPL can be positioned to meet future need.

As measures to improve outdoor air quality evolve, indoor air pollution is becoming a bigger proportion of the air quality problem. With people spending up to 90% of their time indoors, such as in the home, schools, workplaces, public places and when using cars and public transport, understanding indoor air quality is more important than ever.[10] Additionally, if we are to truly understand personal exposure, more monitoring of indoor air quality is needed. There are key questions that need to be solved in order for indoor air quality monitoring to be widely used; what indoor air pollutants need to be measured, where to measure indoor air, how best to measure indoor air and what do acceptable indoor air quality limits look like?

2.7.1. Pollutants

In the indoor environment there is a more complex and varied set of pollutants and sources compared to ambient air. Sources include VOCs from building materials, cleaning products, furniture, cookers, paints, and personal care products. In recent years wood burning has increased in popularity, bringing with it significant increased PM emissions in the home. The use of dry, seasoned wood can reduce the PM emissions, however more education for users is required.[50,51] Transport is another significant source of PM, while this is more traditionally seen as an ambient air pollution issue, it still has implications for indoor air. This is specifically an issue inside cars and at train and tube stations.

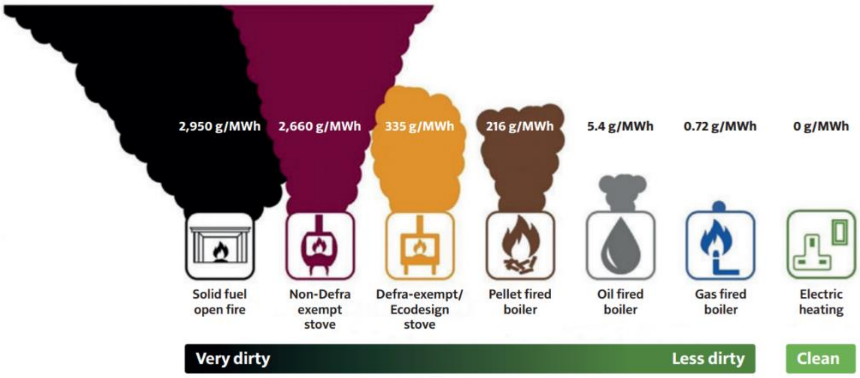

Figure 9. The relative PM2.5 emissions from use of domestic heating methods (excluding emissions from source generation).[9] Image licensed under the Open Government Licence.

There has also been a recent rise in vaping, as an alternative to smoking cigarettes, often used indoors. The pollution emitted from vapes and e-cigarettes is not well understood yet, however it is expected that at least PM ($PM_{2.5}$ and UFPs) and some other toxic substances, such as aldehydes and heavy metals are being emitted by the devices.[52]

Bioaerosols are also an important consideration in the indoor environment, pollen, fungal spores, pet allergens, bacteria, and mould. The number of homes estimated to have damp and mould in the UK is up to 27%.[53] The severe respiratory effect of mould means this has received significant attention in recent years and will continue to be a priority indoor pollutant in the future.

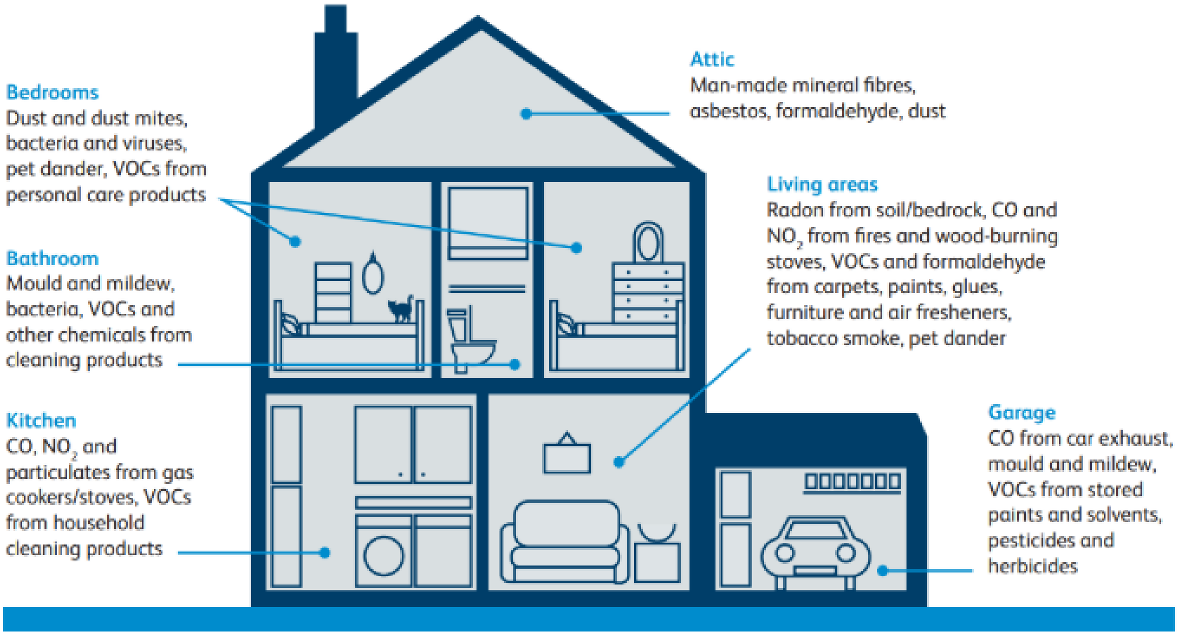

Figure 10. Examples of sources of indoor pollution in a home.[10] Image licensed under the Open Parliament Licence.

Considerations of the indoor-outdoor boundary also need to be made, as both environments affect each other.[54] Monitoring and understanding how pollutants transition from the indoor to the outdoor environment and vice versa is important when understanding indoor air quality, and how it impacts ambient air. This will also feed into strategies to best improve indoor air quality.

2.7.2. Standardisation and regulations

Currently there are no legislative regulations for indoor air quality, however it is likely that this will change in the near future for public spaces. For regulations to be implemented, a number of standardised methods of measuring indoor air quality must be developed. In the next 5-10 years it is expected that there will be published standards for indoor air quality monitoring, the development of which will involve substantial metrology input. In order to develop standards a number of questions need addressing. What pollutants need to be measured, and what are the acceptable limits of these pollutants? It is likely there will be overlap with ambient air quality standards, however there will be differences. Where and how to measure indoors? Placing instruments in every room is not feasible, so the positioning of sensors needs to be optimised.

It is also expected that in the near term, indoor air quality monitoring of public spaces will become commonplace. This includes spaces where individuals cannot control the air quality, such as train stations, hospitals, and schools. As discussed in section 2.2.2, these measurements will necessarily be reference instrument levels of accuracy but will be fit for purpose. Ensuring there is metrological infrastructure to support this level of measurement in public spaces will be key for the user.

2.7.3. Buildings

Transitioning to more energy efficient buildings will impact indoor air quality. 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.[5] It is likely that high energy efficient buildings will have reduced ventilation, in order to keep heat in, this will trap air pollution inside. Developing a system of good energy efficiency while maintaining good ventilation for air quality will be a challenge in the future, this will require a good understanding of indoor air quality measurement to fully quantify the affects.[55]

As public awareness of air quality increases, we could see a rise in air filters in homes. Measurement to ensure these are still performing to their standards will be a key part of the ongoing support for these products. Developing standards for these measurements and identifying the performance limits will be a measurement need in this area.

2.7.4. Indoor air quality measurement needs and challenges

Below are broad examples of key measurement challenges related to indoor air quality. More specific examples of measurement challenges can be found in section 3.2.

Understanding the most prevalent indoor air pollutants and their emission sources.

Developing indoor air quality measurement standards.

Metrology infrastructure and support systems for public space indoor air quality monitoring.

Understanding the impact of energy efficiency practices on indoor air quality.

3. OVERVIEW OF FUTURE TRENDS AND MEASUREMENT CHALLENGES

3.1. OVERVIEW OF FUTURE TRENDS

An overview of the biggest changes and most impactful future trends has been captured in Figure 11 below. Included are direct measurement trends, and future issues that will require significant measurement support and innovation. This serves as the start of the discussion of the landscape of air quality measurement future trends and will evolve as political, economic, societal, technological, and environmental factors play out.

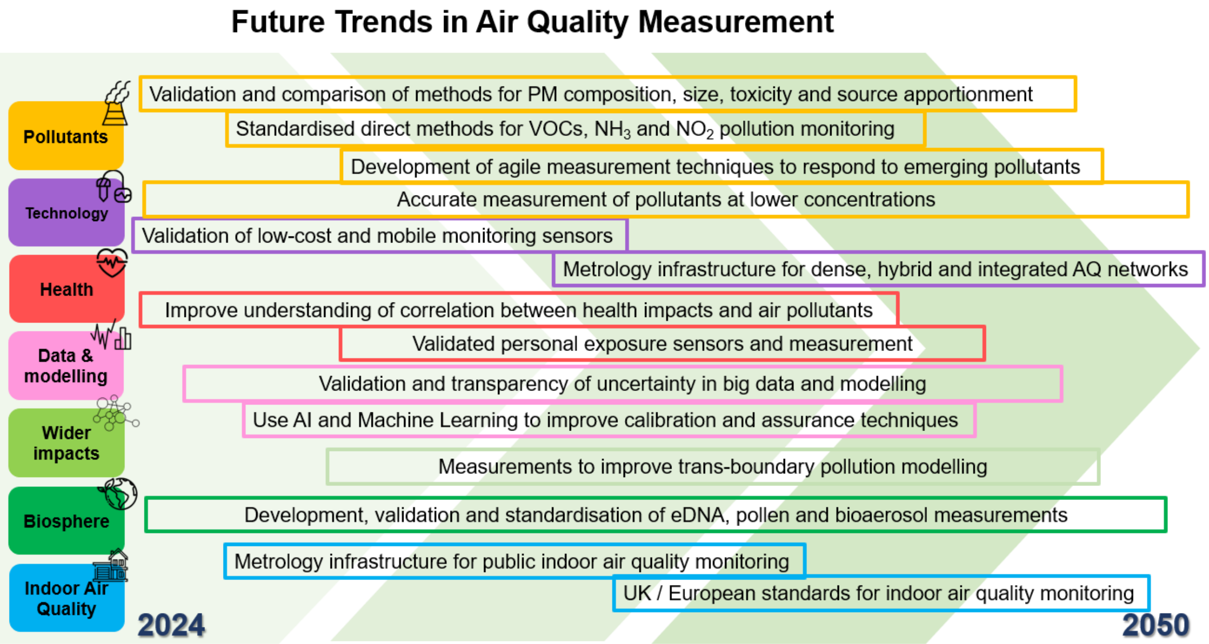

Figure 11. Overview of future trends in air quality measurement

3.2. MEASUREMENT CHALLENGES

Measurement challenges have been identified for each of the 7 future trend themes. A significant number of challenges will fit into multiple themes, in this case the theme where the primary impact will be made has been chosen. This list is representative of issues and challenges identified through desk-based research, discussions with air quality experts within NPL and external interviews with air quality experts from academia, government, and industry. This list is not exhaustive and includes challenges that will be out of scope for NPL. Challenges have been assigned one of three colours: green – this is within the scope of activities NPL already carries out; amber – a challenge NPL should be strategically positioned to meet in the future; red – a challenge out of scope for NPL, but where awareness is useful and collaboration with other organisations is welcome.

Theme	Measurement Challenge	Specific examples	Scope
Pollutants	Improving measurement of regulated pollutants	Validation of improved measurement methods for composition, toxicity, and source apportionment of PM	
		Validation of new ammonia measurement methods to support accessible measurements in agriculture	
		Standardisation of new VOC measurements to reflect VOCs currently prevalent	
		Validation of direct NO and direct NO_2 measurement methods	
		Development of source apportionment, pollutant transport and pollutant persistency measurements to understand global pollution transport	
	Monitoring pollutants	Scalability and calibration of monitoring networks for new pollutants	
		Introduction of new measurements within existing networks	
	Measurements of unregulated and new pollutants	Agile development of new measurement techniques and standards to respond to emerging pollutants.	
		Developing improved methods of measuring UFPs to accurately understand UFP concentration in the ambient air	
		Validation of new methods and reference materials in support of new legislation and regulations.	
		Traceability for black carbon measurements	
		Validation of methods and production of reference materials to underpin PFAS environmental compartmentalization and lifecycle modelling	
Technology	Monitoring Networks	Developing best practice for dense, hybrid networks, including sensor positioning, calibration and data confidence	
		Integration of a variety of types of measurement techniques and ensuring data compatibility across systems	
	New Instrumentation	Improvement and validation of the reliability and accuracy of low-cost sensors, mobile monitoring, and other new measurement techniques	
		Development of sustainable measurement methods	
		Supporting innovation in developing new measurement technology	
	Improved measurements	Confidence in measurements of low concentrations to support lower limits of detection	
		Developing methods to reduce or remove noise from measurements	

		Validation of measurements with high spatial and temporal resolution	
		Developing and validating new measurement methods for source apportionment and speciation	
		Developing methods to reduce the impact of temperature and humidity changes on instrumentation	
	Metrology infrastructure	Developing the metrology infrastructure for different levels of measurement	
		Developing accessible, cost-effective calibration methods, potentially automated or online	
		Supporting Local Authorities with new air quality monitoring instrumentation	
Health	Health impacts	Improving and standardising toxicity measurement techniques for known pollutants	
		Standardisation of oxidative potential measurements	
		Standardisation of lung-deposited surface area measurements	
		Production of standard characterised particles for toxicity studies	
		Development of new toxicity measurement methods for emerging pollutants	
		Supporting epidemiological studies with air quality data and uncertainty propagation	
	Human studies	Developing a multi-omics approach to understand genetic factors in air pollution health impacts	
		Best practice for long term human studies	
		Validation and uncertainty of human studies	
	Personal exposure	Developing best practice for accurate personal exposure modelling	
		Validating personal exposure models with network measurement data	
		Metrology infrastructure to support the expansion of personal monitoring device use - guidance, accessible calibration techniques, standards, and validation	
	Airborne diseases	Developing methods of understanding exposure and transport pathways for future airborne diseases	
Data & Modelling	Data	Confidence in the data quality for air quality measurements	
		Validate data processing methods	
		Producing and validating data for emissions inventories	
	Modelling/Forecasting	Validation of new models and parameters inputting into models	
		Showing uncertainty propagation in modelled air quality maps	

		Challenge to processing within models and forecasts	
		Uncertainty of air quality forecasts	
	Machine learning/AI	Best practice for the use of machine learning and AI in air quality networks	
		Ensuring transparency of operation when machine learning and AI is applied to data	
		Best practice for utilising machine learning and AI to develop automated calibration	
Wider impacts	Net Zero and Climate Change	Monitoring the impact of Net Zero policy decisions	
		Integrating air quality measurement into a wider systems approach for monitoring – e.g. smart cities	
		Developing measurement methods for new pollution sources due to net zero interventions – e.g. non-exhaust emissions	
		Modelling the impact of increasing temperatures and extreme weather on air quality	
		Monitoring agricultural practice change impact on air quality	
		Providing confidence in air quality impact predictions for future fuel options, including nuclear	
		Validating the climate resilience of instruments in changing temperatures, humidity etc	
	Transboundary pollution	Uncertainty in the composition of transboundary pollution	
		Accuracy in source apportionment in transboundary pollution	
		Standardisation of transboundary pollution modelling	
Biosphere	Ecosystem	Development of an emissions inventory for tree emissions, with validated modelling for different scenarios – urban, rural, future temperature changes etc.	
		Measuring pollutant deposition rates and impacts on plant life	
		Development and standardisation of eDNA measurements	
		Validation of models assessing air quality impacts on biodiversity	
	Bioaerosols	Development, standardisation, and validation of pollen pollution measurement techniques	
		Measurement techniques for mould, spores and other bioaerosols in the ambient environment	
Indoor Air Quality	Measurement indoors	Developing best practice and standards for indoor air quality measurement	
		Metrology infrastructure and support for public space indoor air quality monitoring	
		Understanding the indoor-outdoor transition of pollutants and how this can be measured or modelled	

		Understanding and modelling the effect of indoor air quality mitigations – e.g. window opening, air extraction	
	Indoor pollutants	Understanding the most prevalent indoor air pollutants and their emission sources	
		Understanding the impact of energy efficiency measures on indoor air quality	
		Developing indoor air pollution guidance	

4. CONCLUSIONS

There is increasing awareness of impact of poor air quality, especially the significant health implications and consequential cost to society. Due to this there is increasing drive from UK government and world organisations to reduce air pollution. This coupled with the difficulty with air quality often being “invisible” pollution amplifies the need to understand air pollution and measure air quality.

Looking to the future of air quality measurement, we can summarise the expected key challenges that require development across the seven themes. Starting with pollutants, broadly none of the current pollutants are expected to completely disappear and will continue to require monitoring, at lower concentrations, which provides technological challenges such as the requirement for lower limits of detection in instruments. The other main trend with pollutants is the emergence of new pollutants with the introduction of new industrial process and behavioural changes that are needed to address other societal challenges such as climate change and resource security. Solutions to these societal challenges will develop and change through the interplay of politics, economics, technology, and other environmental goals. Agile responses to resultant emerging pollutants and involvement in underpinning measurements well in advance of legislation will be key.

Technological trends that have emerged in this work mainly focus on the development of dense, hybrid air quality monitoring networks and the ability to monitor more measurands such as speciation and source apportionment. Building dense, hybrid networks will give higher spatial and temporal resolution, however significant challenge will arise from instrument and data integration and best practice for accessible calibration. Additionally, practical factors like cost and maintenance could limit the success of these systems. Reaching an optimal balance of competing factors will be a further challenge. Use of low-cost sensors will be an important trend in the future, with improvement in their accuracy, they could change the landscape of air quality monitoring.

For the health theme, the main future trend revolves around an increased public awareness of, and political pressure to address the health implications of poor air quality. Air quality health implications are individual, based on personal exposure and medical history, driving the need for better personal exposure understanding. Initially through more representative models of personal exposure and eventually with the use of accurate and reliable wearable personal monitors. There are still significant unknowns related to air quality and health, and there needs to be more research into the links between air quality, genomics, and health implications.

In the data and modelling theme, forecasting will be an important future trend. Increased use of forecasting and accuracy in forecasts will allow better planning around air quality, which in turn reduce cost and mitigate health impacts. Forecasting, and other data and modelling tools are likely to be significantly impacted by the increased use of machine learning and AI. An example of which could be using AI to better position sensors or develop a deeper understanding of trends in the data. An important challenge will be to ensure transparency in the operation of these tools, this is crucial to validate and give confidence to resultant data.

Climate change and Net Zero will be the most important wider impact to air quality and is likely to be the biggest societal change we will see in the next 30 years. For example, increasing global temperatures and extreme weather events risk increased air pollution. Monitoring the impact of Net Zero related policies in the air quality space should be integral to Net Zero interventions. If air quality is not embedded within the policies and monitoring systems, such as smart cities, it is at risk of being left behind, or made worse.

For the biosphere, improving shortcomings in measurement methods for mould and pollen are the two biggest concerns. Mould has received significant attention with recent mortality evidence, and increasing global temperatures will increase pollen levels, with its own health implications.

Finally, we come to indoor air quality, a theme very much on the rise as an overall future trend. The public is spending a significantly higher proportion of time indoors; however, this is not currently reflected in investment in understanding indoor air quality. Understanding how to monitor indoor air quality will be an important challenge going forwards and needs to be prioritised if we are going to seriously address the issue of poor air quality as a whole. It is expected that this will start with monitoring in public spaces in places like trains stations, schools, and hospitals, and then progress on to regulations.

NPL in its role as UK's National Metrology Institute will continue to lead the development and drive innovation of metrology in air quality measurement. Furthermore, we welcome engagement and collaboration with government, industrial partners and academics particularly across these seven themes. Perspectives on the future challenges in air quality and air quality measurement will continue to develop and evolve. NPL strive to continue meeting those challenges and remaining a leader in the air quality field through research and development in air quality measurement science.

5. ANNEX - CONTRIBUTORS

NPL:

Freya Cleasby

Ying Zhang

Nick Martin

Andrew Brown

Richard Brown

Richard Barker

Valerio Ferracci

Craig Barnfield

David Worton

Panayot Petrov

Emma Braysher

Jordan Tompkins

Krzysztof Ciupek

Tom Gardiner

External contributors:

Alastair Lewis, University of York

Roderic L. Jones, University of Cambridge

James Allan, University of Manchester/NCAS

Roy Harrison, University of Birmingham

Hugh Coe, University of Manchester

Richard Maggs, Bureau Veritas

Paul Willis, Ricardo

Tony Clark, DEFRA/JAQU

Rob Kinnersley, Environment Agency

Sani Dimitroulopoulou, UKHSA

Rohit Chakraborty, UKHSA

Zhe Bi, NIM China

Tom Townend, AQ MESH

Douglas Booker, National AQ Testing Service

Iq Mead, Imperial College

Carol Lee, LB Richmond, Merton & Wandsworth

6. REFERENCES

1. Fowler, D., Pyle, J. A., Sutton, M. A. & Williams, M. L. Global Air Quality, past present and future: an introduction: introduction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* vol. 378 https://doi.org/10.1098/rsta.2019.0323 (2020).

2. Blake, E. & Wentworth, J. *POSTnote 691 Urban Outdoor Air Quality*. (2023).

3. DEFRA. Emissions of air pollutants in the UK - Summary. https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-summary (2023).

4. Sokhi, R. S. *et al.* Advances in air quality research - current and emerging challenges. *Atmospheric Chemistry and Physics* vol. 22 4615–4703 https://doi.org/10.5194/acp-22-4615-2022 (2022).

5. Royal Society, T. *Effects of Net-Zero Policies and Climate Change on Air Quality*. (2021). https://royalsociety.org/news-resources/projects/air-quality-climate-change/

6. DEFRA. *Air Quality Strategy - Framework for Local Authority Delivery*. (2023). https://www.gov.uk/government/publications/the-air-quality-strategy-for-england/air-quality-strategy-framework-for-local-authority-delivery

7. DEFRA. *Clean Air Strategy*. (2019). https://www.gov.uk/government/publications/clean-air-strategy-2019

8. DEFRA. UK-Air Monitoring Networks. https://uk-air.defra.gov.uk/networks/.

9. DHSC. *Chief Medical Officer's Annual Report 2022 Air Pollution*. (2022). https://www.gov.uk/government/publications/chief-medical-officers-annual-report-2022-air-pollution

10. Duffield, G. & Bunn, S. *POSTbrief 54 Indoor Air Quality*. https://post.parliament.uk/research-briefings/post-pb-0054/ (2023) doi:10.58248/PB54.

11. Air Quality Expert Group. *Non-Exhaust Emissions from Road Traffic*. (2019). https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1907101151_20190709_Non_Exhaust_Emissions_typeset_Final.pdf

12. Mehlig, D., Woodward, H., Oxley, T., Holland, M. & Apsimon, H. Electrification of road transport and the impacts on air quality and health in the uk. *Atmosphere (Basel)* **12**, 1491 (2021).

13. Schraufnagel, D. E. The health effects of ultrafine particles. *Experimental and Molecular Medicine* vol. 52 311–317 https://doi.org/10.1038/s12276-020-0403-3 (2020).

14. Hong, G. & Jee, Y. K. Special issue on ultrafine particles: where are they from and how do they affect us? *Experimental and Molecular Medicine* vol. 52 309–310 https://doi.org/10.1038/s12276-020-0395-z (2020).

15. DEFRA. Emissions of air pollutants in the UK – Ammonia (NH3). https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-ammonia-nh3 (2023).

16. Janke, D. *et al.* A Low-Cost Wireless Sensor Network for Barn Climate and Emission Monitoring—Intermediate Results. *Atmosphere (Basel)* **14**, 1643 (2023).

17. Public Health England. *Indoor Air Quality Guidelines for Selected Volatile Organic Compounds (VOCs) in the UK*. (2019). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831319/VO__statement_Final_12092019_CS__1_.pdf#:~:text=In%20the%20UK%2C%20there%20are%20currently%20no%20indoor,the%20WHO%20%282010%29%20Indoor%20Air%20Quality%20%28IAQ%29%20guidelines.

18. Air Quality Expert Group. *Ozone in the UK-Recent Trends and Future Projections*. (2021). https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2112200932_Ozone_in_the_UK_Recent_Trends_and_Future_Projections.pdf

19. Brown, R. J. C. & Martin, N. A. How standardizing 'low-cost' air quality monitors will help measure pollution. *Nature Reviews Physics* vol. 5 139–140 https://doi.org/10.1038/s42254-023-00561-8 (2023).

20. Karagulian, F. *et al.* Review of the performance of low-cost sensors for air quality monitoring. *Atmosphere* vol. 10, 506 https://doi.org/10.3390/atmos10090506 (2019).

21. Olaguer, E. P. *et al.* The Michigan–Ontario Ozone Source Experiment (MOOSE): An Overview. *Atmosphere (Basel)* **14**, 1630 (2023).

22. NASA. NASA's Fleet of Earth Observing Satellites: Monitoring Our Planet's Health. https://airquality.gsfc.nasa.gov/ (2023).

23. NPL. NPL UK ambient air quality networks. https://www.npl.co.uk/air-quality-aerosol-metrology/ambient-quality-networks.

24. UKRI. *Clean Air Programme Science and Implementation Plan*. (2021).

25. Manisalidis, I., Stavropoulou, E., Stavropoulos, A. & Bezirtzoglou, E. Environmental and Health Impacts f Air Pollution: A Review *Atmosphere (Basel)* vol. 8 https://doi.org/10.3389/fpubh.2020.00014 (2020).

26. Daellenbach, K. R. *et al.* Sources of particulate-matter air pollution and its oxidative potential in Europe. *Nature* **587**, 414–419 (2020).

27. Klepeis, N. E. *et al.* The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Environ Epidemiol* **11**, 231–252 (2001).

28. Wolf, M. J. *et al.* New Insights for Tracking Global and Local Trends in Exposure to Air Pollutants. *Environ Sci Technol* **56**, 3984–3996 (2022).

29. Koh, E. J. & Hwang, S. Y. Multi-omics approaches for understanding environmental exposure and human health. *Molecular and Cellular Toxicology* vol. 15, 1-7 https://doi.org/10.1007/s13273-019-0001-4 (2019).

30. Cao, M., Xing, J., Sahu, S. K., Duan, L. & Li, J. Accurate prediction of air quality response to emissions for effective control policy design. *Journal of Environmental Sciences* **123**, 116–126 (2023).

31. Huang, W. *et al.* An overview of air quality analysis by big data techniques: Monitoring, forecasting, and traceability. *Information Fusion* **75**, 28–40 (2021).

32. Liao, H., Yuan, L., Wu, M. & Chen, H. Air quality prediction by integrating mechanism model and machine learning model. *Science of The Total Environment* **899**, 165646 (2023).

33. Méndez, M., Merayo, M. G. & Núñez, M. Machine learning algorithms to forecast air quality: a survey. *Artif Intell Rev* **56**, 10031–10066 (2023).

34. BEIS. *Net Zero Strategy: Build Back Greener*. (2021). https://assets.publishing.service.gov.uk/media/6194dfa4d3bf7f0555071b1b/net-zero-strategy-beis.pdf

35. Air Quality Expert Group. *Impacts of Net Zero Pathways on Future Air Quality in the UK*. https://www.gov.uk/government/policy-advisory-groups/air-quality-expert-group (2020).

36. Burke, M. *et al.* The contribution of wildfire to PM2.5 trends in the USA. *Nature* **622**, 761–766 (2023).

37. Government, H. *British Energy Security Strategy Secure, Clean and Affordable British Energy for the Long Term*. (2022).

38. Convention on long-range transboundary air pollution. (1979).

39. Abas, N., Saleem, M. S., Kalair, E. & Khan, N. Cooperative control of regional transboundary air pollutants. *Environmental Systems Research* **8**, 10 (2019).

40. Halkos, G. & Tsilika, K. Understanding transboundary air pollution network: Emissions, depositions and spatio-temporal distribution of pollution in European region. *Resour Conserv Recycl* **145**, 113–123 (2019).

41. EuraMet. EMN for pollution monitoring. https://www.euramet.org/european-metrology-networks/pollution-monitoring.

42. Nawaz, R. *et al.* Air Pollution Tolerance Index and Heavy Metals Accumulation of Tree Species for Sustainable Environmental Management in Megacity of Lahore. *Air* **1**, 55–68 (2022).

43. Świsłowski, P. & Rajfur, M. Assessment of the air quality in an industrial zone using active moss biomonitoring. *International Journal of Environmental Science and Technology* **21**, 4213–4222 (2024).

44. Ruppert, K. M., Kline, R. J. & Rahman, M. S. Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA. *Glob Ecol Conserv* **17**, e00547 (2019).

45. Clare, E. L. *et al.* Measuring biodiversity from DNA in the air. *Current Biology* **32**, 693-700.e5 (2022).

46. Gomez, J. *et al.* The projected future degradation in air quality is caused by more abundant natural aerosols in a warmer world. *Commun Earth Environ* **4**, 22 (2023).

47. Yao, M. Bioaerosol: A bridge and opportunity for many scientific research fields. *J Aerosol Sci* **115**, 108–112 (2018).

48. Paudel, B. *et al.* Increased duration of pollen and mold exposure are linked to climate change. *Sci Rep* **11**, 12816 (2021).

49. Carlson, C. J. *et al.* Climate change increases cross-species viral transmission risk. *Nature* **607**, 555–562 (2022).

50. Chakraborty, R., Heydon, J., Mayfield, M. & Mihaylova, L. Indoor Air Pollution from Residential Stoves: Examining the Flooding of Particulate Matter into Homes during Real-World Use. *Atmosphere (Basel)* **11**, 1326 (2020).

51. Vicente, E. D. *et al.* Impact of wood combustion on indoor air quality. *Science of The Total Environment* **705**, 135769 (2020).

52. Destaillats, H., Singer, B. & Salthammer, T. Does vaping affect indoor air quality? *Indoor Air* **30**, 793–794 (2020).

53. DLUHC, DHSC & UKHSA. Understanding and addressing the health risks of damp and mould in the home. https://www.gov.uk/government/publications/damp-and-mould-understanding-and-addressing-the-health-risks-for-rented-housing-providers/understanding-and-addressing-the-health-risks-of-damp-and-mould-in-the-home--2 (2023).

54. McDonald, B. C. *et al.* Volatile chemical products emerging as largest petrochemical source of urban organic emissions. *Science (1979)* **359**, 760–764 (2018).

55. Awbi, H. B. Ventilation for Good Indoor Air Quality and Energy Efficiency. *Energy Procedia* **112**, 277–286 (2017).