Smarter Suffolk Project

Air Quality Sensors: Final Report

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Contents

1 Executive Summary

Air pollution comes from a diverse range of sources, including industry, transport, burning solid fuels and others. DEFRA describe air pollution as posing the single greatest environmental risk to human health. Short term exposure to elevated levels of air pollution can cause a range of health effects, in particular to vulnerable groups such as those with health issues, elderly and very young. Long term exposure has the potential to shorten all lifespans. In particular, particulate matter is a focus for the recent Environment Bill 2020.

This report investigates the potential to install air quality sensors on street lights across the county, to provide the local authorities with additional information on air quality in Suffolk. The sensors investigated are considered "low cost" sensors, compared with reference monitors that are significantly more expensive. Four suppliers provided air quality sensors to the project. The report details and investigates the data returned from the sensors, particularly with reference to particulate matter, and makes conclusions and recommendations based on the data analysis.

It pulls together this information in a financial and business case assessment, and makes recommendations for use of "low cost" air quality monitoring in Suffolk.

Throughout the course of the project, interviews and reviews of air quality parameters of interest have been undertaken. Based on conversations with district and borough council environment officers, four analytes were selected for monitoring in this project:

- Nitrogen dioxide
- Ozone
- Particulate matter sized less than 2.5 µm ($PM_{2.5}$)
- Particulate matter sized less than 10 µm (PM_{10})

During the course of the project, the Environment Bill 2020 was read, introducing a greater focus on monitoring and reducing $PM_{2.5}$ concentrations. This introduced a focus on sensors on particulate matter as an analyte of interest.

Within Suffolk, the district and borough councils have responsibility under the Environment Act 1995 to review and report air quality in their areas. Current reporting, as Annual Air Quality Status Reports, focuses on NO_2, though exploratory preparation is underway to undertake $PM_{2.5}$ monitoring too. At present, district and borough councils monitor for NO_2 in locations of concern; no other air quality monitoring is consistently undertaken. Suffolk County Council have a number of responsibilities and activities in air quality management and monitoring, which are carried out across relevant functions.

Exploration with interviews and through analysis of the data gathered within this project highlighted the importance of appropriate calibration, and clear understanding of the standards to which the measurements are made. "Low cost" analysers are typically provided as 'factory calibrated' with limited or no ongoing maintenance or calibration requirements. They are more affordable, easier to deploy and run, and can provide indicative or comparative values. However, they do not provide reference-grade values, and their limitations should be considered when deciding which device and how to deploy it.

Sensors communicated data in near-real time using different network technologies. Across the air quality devices in this project two network solutions were used, each supplied by two of the four suppliers. The two solutions were:

- Connection via mobile data with a SIM card in each device; this connection technology was found to be generally reliable;
- Connection via Zigbee protocol to a street lighting supplier's own Zigbee network; this connection was found to rely on very close proximity to an active street lighting network with multiple street lighting nodes.

Sensors were provided by four suppliers, with two suppliers providing the same model of sensor, but with different mounting hardware:

- Aeroqual AQY1 sensor, mounted in a protective housing on the lighting column;
- Aeroqual AQY1 sensor, mounted on brackets on the lighting column;
- Libelium Smart City Pro sensor, mounted on brackets on the lighting column;
- Liveable Cities' Alphasense OPC-Rx sensor, fitted into the street light NEMA connection on the lantern: this sensor measured particulates only.

All sensors could be powered via the lighting column. The Libelium Smart City Pro was supplied powered by solar panel, and was not connected to the mains power.
The low cost air quality sensor market is busy and active, with many other sensors available, which should form part of any decision of sensors to install. This report discusses a few alternatives, but not all. During the period of the project, the Aeroqual AQY1 sensor was discontinued by the manufacturer, who offer alternative models. The mounting housing provided by one supplier is considered likely to affect air flow to the inlets, and therefore air quality measurements.

Data was acquired for assessment from the suppliers' dashboards or by email from the suppliers. Over 12 million data points were acquired for assessment, from four sources.

Sensor reliability was assessed as continuity of data. All sensor providers had a number of sensors that ceased to be operational during the trial, and gaps in data gathered of various lengths up to several months. Sensor unreliability was attributed to several factors, including communications networks, issues with devices and power connections, accidental damage or removal of sensors, expiry of licencing, and potentially other factors.

Particulate matter measuring in these sensors is by optical particle counting which uses light scattering inside the device to detect the particles and measure sizes. This measurement process is potentially impacted by water vapour in the atmosphere, which condenses on the particles increasing their apparent number and size. This can lead to elevated PM measurements at times of elevated humidity. Assessment of data discovered that this was a factor in elevated measurements with differing impacts on differing sensors. Some sensors have approaches to account for this impact, but most do not.

Calibration of sensors was found to be variable. To assess calibration, PM results were compared with DEFRA modelled values. Some sensors provided PM measurements that were higher than modelled, and some results that were lower. Two sensors were co-located for a period of time, and indicated significant discrepancy in measured PM values. In conclusion, while the variation in air quality analytes from these sensors can be seen as indicative, the absolute values are not considered reliable.

The business case for the use of air quality sensors has been examined. At present, Suffolk County Council does not routinely make air quality measurements. With increased importance of understanding variation in $PM_{2.5}$ across the county, the significant health impacts, and the potential for in-place measurements to inform action and awareness campaigns, Suffolk County Council may wish to consider providing particulate matter monitoring. Low cost sensors can provide indicative values, but the impact of calibration, humidity artefacts, and location of installation should be considered. It is anticipated that PM monitoring will be introduced as a requirement of the forthcoming Environment Act (currently Environment Bill 2020).

Not all the sensors in this project are currently available, concerns were raised regarding the values provided by the other models, and many available models have not been assessed in detail within this project. Therefore, no specific sensor model can be recommended.

It is concluded that selection of sensor, maintenance and calibration, and management of reliability and continuity of data, should be carefully assessed prior to wider deployment. Monitoring of particulate matter concentrations in Suffolk, in particular $PM_{2.5}$, is expected to become an important part of environmental management in the near future.

2 Introduction

2.1 Introduction

This report discusses a selection of air quality sensors for monitoring air quality for Suffolk County Council, and the use of and data from these sensors.

The first section of this report describes our understanding of the uses of air quality information within the local authorities, and the relevance of those uses to the type of monitoring that is appropriate.

The second section describes and reviews selected commercially available remote sensors that can be used for air quality monitoring. A wide range of air quality sensors are available; this report discusses a selection based on those:

- Supplied or proposed by project suppliers;
- Suggested as of specific interest by project stakeholders;
- Encountered during wider research as being relevant for similar use cases.

These sensors are offered by different companies, using Internet-of-Things communication technologies to report air quality in real-time. This report examines the function of these sensors, and the data they provide. Some of these sensors are currently under evaluation at BT's Adastral Park research and development campus near Ipswich, Suffolk; these and selected others have also been installed on public highways across Suffolk.

The third section compares these sensors. Preliminary evaluation is made based on initial observations. This section includes how the data the sensors provide could potentially inform air quality knowledge and associated decision-making, and an initial consideration of their potential for incorporation into decision models.

The fourth section analyses data from the sensors, making comparisons between different models, and drawing recommendations and conclusions based on identified issues.

The fifth section assesses the financial, social and business case inputs for the air quality sensors across Suffolk.

The sixth section provides overall conclusions and recommendations.

2.2 Air Quality analysis

2.2.1 Analytes

Environment Officers say that the following are the parameters of key interest:

- Nitrogen dioxide NO_2 (sometimes referred to as nitrogen oxides NOx)
- Particulates as $PM_{2.5}$
- Particulates as PM_{10}
- Ozone due to its relationship with nitric oxide (NO) and NO_2

These and other potential parameters of interest are discussed in the following subsections. National Air Quality Objectives are provided by Defra online (see section 2.3) (DEFRA, 2004).

2.2.2 Nitrogen dioxide / nitrogen oxides

Nitrogen oxides are produced by fuel combustion, both from atmospheric oxygen and nitrogen combining in flames, and from oxidation of nitrogen compounds in fuel. The main contribution to nitrogen oxides in the UK is motor vehicles, with power stations and other domestic and industrial combustion processes also being significant. Improvements in road vehicles have led to significant fall in nitrogen oxide pollution over the last thirty years (National Atmospheric Emissions Inventory, no date).

Due to the reporting of nitrogen oxides both as nitrogen dioxide (NO_2) and nitrogen oxides, a brief description of the interrelation between nitric oxide, nitrogen dioxide, nitrates and ozone is given here: Nitrogen oxides (NOx) are mostly emitted as nitric oxide (NO) which is oxidised by ozone in the atmosphere to nitrogen dioxide within tens of minutes (Air Pollution Information System, 2016c).

Nitrogen oxides are removed slowly. Because nitrogen oxides can travel hundreds of kilometers in the atmosphere, much of the nitrogen oxides produced in the UK eventually leave the UK. During the day, nitric oxide, nitrogen dioxide and ozone are present in a form of equilibrium depending on the amount of sunlight. Ultimately, nitrogen dioxide is oxidised to nitric acid (as HNO_3 vapour) which is either absorbed into the ground, converted into nitrate-containing particles or dissolved into cloud droplets. During the night without the presence of sunlight, different oxidation processes convert nitrogen dioxide into nitrates.

National air quality objectives for NO_2 concentrations:

- Annual mean objective of 40µg/m^3 NO_2
- 1-hour mean of 200 µg/m^3 NO_2 not to be exceeded more than 18 times a year

2.2.3 Particulate Matter as $PM_{2.5}$ and PM_{10}

Particulate Matter, sometimes referred to as particulates or dust particles, refers to solid particles suspended in the atmosphere. It is present in the atmosphere from a range of different sources and with different histories, leading to a range of size, shape and structure, and chemical composition. Particles of intermediate size (0.1 to 2.0µm) can be transported globally in the atmosphere, while finer and larger particles deposit closer to their source.

Particulate Matter is usually divided into particles with a diameter less than 10µm, referred to as PM_{10}, and particles with a diameter less than 2.5µm, referred to as $PM_{2.5}$. In humid conditions, water vapour condenses around these particles, which can increase their apparent size as measured by these sensors.

The three main sources of particulate matter are (Air Pollution Information System, 2016b):

1. Chemical reactions of gases in the atmosphere, forming solid particles (of less than 0.001µm). These include sulphate, nitrate and ammonium salts, and sunlight-driven oxidation of non-methane volatile organic compounds.
2. Industrial and transport combustion emits fine particles (mostly 0.1 to 2.5 µm), either carbon-based or on heavy metals.
3. Several mechanical processes (friction such as tyre and break wear; erosion and distribution from soils, construction, factories and volcanoes; sea salt from the ocean surface) create larger (2.5 to 20µm) particles. Within days these can have accumulated other chemical salts on their surfaces.

Particulate matter has significant human health impacts, including premature mortality, allergic reactions and cardiovascular diseases, both from the physical impact of the solid particles and from their chemical composition. It also impacts negatively on plants and animals. The impact of particulate matter in light scattering can cause problems, but also attenuates global warming.

Reducing emissions of $PM_{2.5}$ is a particular target for local authorities, delivered by district and unitary authorities. This includes a target to reduce pollution from domestic burning, which is considered to have contributed 38% of $PM_{2.5}$ emissions in 2019 (DEFRA, 2019, 2021b).

National air quality objectives (which should not be exceeded) for particulate matter concentrations:

- Annual mean objective of 40μg/m^3 PM_{10}
- 1-hour mean of 50 μg/m^3 PM_{10} not to be exceeded more than 35 times a year
- Annual mean objective of 25 μg/m^3 $PM_{2.5}$

2.2.4 Ozone

Ozone is present throughout the atmosphere, but has problematic or beneficial impacts at different heights above the earth. Ozone in the higher stratosphere is positive, which is why the "ozone hole" is problematic. Ozone at closer to ground level is a toxic pollutant and greenhouse gas, with a problematic impact on human health (especially for people with asthma) and vegetation.

Ozone at ground level is formed by sunlight-driven reactions with other pollutants: nitrogen oxides and volatile organic compounds. These reactions can be slow, and so ozone concentrations can be driven by emissions of other pollutants hundreds or thousands of miles upwind. Highest ozone concentrations can be created where there are local emissions of those pollutants, with a warm and slow-moving atmosphere creating and trapping the ozone. A background level of ozone at ground level is also produced by atmospheric mixing from natural ozone in the higher stratosphere. The distances travelled mean that ozone reduction needs to be addressed internationally.

The quasi equilibrium reactions between ozone, nitric oxide and nitrogen dioxide has been described in section 2.2.2 above; one impact of this is that reduction of concentrations of nitrogen oxides can have the side effect of increasing ozone concentrations, as there is less NO to react with the ozone converting it into NO_2.

National air quality objectives for ozone concentrations:

- 8-hour mean of 100 μg/m^3 not to be exceeded more than 10 times a year

2.2.5 Ammonia

Ammonia is considered likely to be produced, particularly in rural areas where it is produced by manures, slurries and fertilizers applied in agriculture, although there are other sources. Across the UK, concentrations of ammonia range from 0.1 μg/m^3 in north west Scotland to 10 μg/m^3 associated with intensive cattle farming (Air Pollution Information System, 2016a). However, it is highly reactive, and present only relatively briefly before reacting with other pollutants in the atmosphere to form ammonium salts which remain present as particulate matter, which could contribute to the PM measurements. It is therefore considered by district

council environment officers that direct measurement of ammonia is not sufficiently worthwhile for the local authorities.
A national air quality objective for ammonia is not given.

2.2.6 Other pollutants

Other atmospheric pollutants include volatile organic compounds (VOCs), sulphur dioxide, heavy metals and methane. These were not considered by Suffolk County Council as priority pollutants for assessing options for sensing within this trial.

2.2.7 Physical atmospheric parameters

Some air quality sensors also measure humidity, temperature and dew point.
Relative humidity is important for correction of measurements of particulate matter and is used in the measurement algorithm by some sensors.

2.3 Defra UK Air Information Resource

The UK Air Information Resource (UK-AIR) is hosted and maintained by an environmental consulting company called Ricardo for The Department for Environment, Food and Rural Affairs (Defra), and contains a range of air quality measurements, modelling, advice and information for the UK. It can be found at https://uk-air.defra.gov.uk. A selection of key information available on this website is described in this section.

The Daily Air Quality Index (DAQI) is provided for the UK, and provides information on levels of air pollution, and recommended actions and health advice. It is based on running means of concentrations of ozone, nitrogen dioxide, sulphur dioxide, $PM_{2.5}$ particulates and PM_{10} particulates, with concentrations averaged over different time periods for different pollutants. The concentration bands for the index points for each pollutant may provide guidelines for relative low, moderate and high concentrations of these pollutants, and are given in Table 1.

Pollutant	Period of running mean	"Low" µg/m^3	"Moderate" µg/m^3	"High" µg/m^3
Ozone	8 hours	0 – 100	101 – 160	160 +
Nitrogen Dioxide	1 hour	0 - 200	201 - 400	401 +
Sulphur Dioxide*	15 minute	0 - 266	267 - 532	533 +
$PM_{2.5}$	24 hour	0 - 35	36 - 53	54 +
PM_{10}	24 hour	0 - 50	51 - 75	76 +

Table 1: DAQI description boundaries
from https://uk-air.defra.gov.uk/air-pollution/daqi?view=more-info accessed 10 Jan 2021
** Sulphur dioxide included for completeness, but not covered by the sensors trialled in the Smarter Suffolk project*

The DAQI is applied to the Defra air quality five-day forecasts which are based on emissions, and atmospheric processes which cause transport, reaction and removal. Defra also apply the DAQI to measured air quality. Map views of measurements and forecasts are presented at https://uk-air.defra.gov.uk on a UK map, and searchable by location.

The UK-AIR website also links to UK and EU Air Quality Limits at https://uk-air.defra.gov.uk/assets/documents/Air_Quality_Objectives_Update.pdf which include air quality standards, which are considered to indicate what is acceptable concentrations over a period of time. Limit values are also given, which are concentrations (averaged over a given period of time) with a specified number of allowed exceedances per year.

The Environment Agency manage for Defra 300 air quality monitoring sites across the UK, and Defra also access data from another 1500. This data is available from the UK AIR website. One site is shown located in Suffolk, at Sibton, and the information available indicates that the only pollutant measured here currently is ozone (https://uk-air.defra.gov.uk/networks/site-info?uka_id=UKA00012).

The UK AIR website also includes links to documents, research and local AQMAs.

2.4 Suffolk local authority uses of air quality monitoring

Air quality sensing is used in a range of ways within the local authorities, with a range of requirements associated with the potential use of the data. To understand the potential uses of air quality data, key members of county and district council teams have been interviewed; their valuable contribution is gratefully acknowledged. This section summarises their input, and they are named in Section 7.

2.4.1 District and borough councils: statutory responsibilities and monitoring

Part IV of the Environment Act 1995 places a requirement on district and unitary authorities to review air quality in their area. In Suffolk, this duty is discharged by:

- Babergh and Mid Suffolk District Councils
- East Suffolk Council
- Ipswich Borough Council
- West Suffolk Council

Defra Policy Guidance 16, published 2016, shifted the focus of the council's work to increase the emphasis on local action to improve air quality, particularly $PM_{2.5}$, with less emphasis on monitoring.

Within these district councils, interest in air quality is used within the Environmental Health or Environmental Protection teams to inform their Local Air Quality Management Plan and inform actions in Air Quality Action plans such as awareness campaigns. Planning Department also have interest in air quality data for local plans and strategies, and to inform future planning policies, for both human health and ecology purposes. Existing published data is accessed by consultants working on local projects. On occasion, data is requested by councillors or the public. Key reasons for air quality monitoring are statutory duties under the Environment Act 1995, and public interest. Monitoring is undertaken to fulfil statutory duties, work towards achieving National Air Quality Objectives and monitor progress towards these objectives, and can also be directed to address residents' concerns relating to traffic volume. Monitoring information is also used in the planning and development process, if there are concerns relating to impacts of air quality from a particular development. Existing data can be used in public campaigns and outreach activities.

Each of these councils produce an Annual Air Quality Status Report, monitor for nitrogen dioxide, and declare Air Quality Management Areas (AQMA) where nitrogen dioxide emissions are of concern. These locations are addressed by a number of measures aimed to reduce NO_2 concentrations, and when shown successful by ongoing monitoring the AQMA declaration is revoked. These reports detailing monitoring results are available on the relevant council's webpage.

This section is closely informed by the 2020 Annual Air Quality Status Report from East Suffolk (East Suffolk Council, 2020). The other three district and unitary councils in Suffolk also produce reports following the same format and with similar content.

Nitrogen dioxide measurements are made by diffusion tubes (passive monitoring) and automatic nitrogen dioxide analysers (using chemiluminescent technology), largely located in the AQMAs. This monitoring provides mean concentrations of NO_2 over each calendar month. Monitoring is in compliance with DEFRA Policy Guidance 16 (DEFRA, 2016) and Technical Guidance 16 (DEFRA, 2018) which provide monitoring criteria and location guidance.

Operational and calibration standards for these nitrogen dioxide analysers are stringent, and are detailed in the councils' Annual Reports. These standards are not met by the air quality analysers in the Smarter Suffolk trial. Environment Officers from the district and borough councils advise that the air quality sensors trialled within the Smarter Suffolk project would not meet their statutory requirements. For these sensors to be useful to the district and borough council environment officers, they would need to be ratified with a Defra verified monitor: this would be of most interest for PM measurements.

Environment Officers from the councils are also involved with planning applications, pro-active awareness raising campaigns and air quality related input into council actions. They also collaborate with a range of relevant organisations. Their annual reports welcome local involvement, and stress that a key source of air pollution in their districts is road traffic, so prioritise "active travel".

Currently only NO_2 is monitored, and there is significant interest in obtaining PM monitoring, on hourly, daily or yearly basis. It is considered likely that future legislation may introduce legally-structured objectives for $PM_{2.5}$. Real-time or near real-time data can be useful if influencing behaviour or responding to incidents, and automated alerts at certain criteria would be useful. For statutory reporting purposes, DEFRA-approved standards are required, but for public engagement activities, device accuracy relative to each other is more important. Monitoring at roadside and industrial locations and background locations is of interest, and monitoring covering a wider geographical area, beyond the specific and limited urban locations covered by existing NO_2 monitoring. An interest is in analysers that are possible to relocate as required, to enable monitoring for shorter time periods at locations and times of interest. Measurements averaging over 15 minute, half-hour or hourly periods would be of interest.

Local authorities are currently required to work towards reducing emissions of $PM_{2.5}$, as detailed in Policy Guidance LAQM.PG(16) (Chapter 7). In Suffolk, this is being addressed by a partnership approach, in which the Suffolk Air Quality Group, including the district and unitary councils, has engaged with Suffolk County Council Public Health. Key activities are likely to include promotion of active travel and other vehicle reduction schemes, and assessment of planning applications and local plans to consider air quality.

2.4.2 Suffolk County Council

As regulatory air quality management is seated in the district and borough councils, Suffolk County Council (SCC) does not have a specific function relating to air quality monitoring or management. It does have responsibilities and activities in air quality in a number of themes.

- Suffolk County Council is the planning authority for specific planning applications (minerals, waste and county council developments). SCC does assess these applications in relation to their potential impact on air quality, as do the district and borough councils.
- SCC manages plans to enable and encourage active travel (cycling and walking) which have a range of benefits, including to air quality via the reduction of vehicle movements.
- SCC manages road and transport planning, which includes consideration of AQMAs declared by the district and borough councils in lorry route and other network planning.
- Environment-positive initiatives from SCC including “Creating the Greenest County” and SCC’s “Climate Emergency Declaration” have air quality benefits.
- Work has been done associated with Public Health England’s research review on air quality around schools. PHE are finalising publications on air quality around schools part I, literature review (Osborne *et al.*, 2021a) and part II, mapping $PM_{2.5}$ and exploring inequality metrics (Osborne *et al.*, 2021b). Understanding air quality in the vicinity of schools also raises the challenge of who would be responsible for any actions required.
- SCC have employed Ricardo to provide a comprehensive picture of current status of air quality in Suffolk, and understand the potential air quality benefits from the Climate Emergency Plan actions. This work is ongoing.

In discussion with the transport planning team at Suffolk County Council, they state that they currently access air quality data from the district and borough council’s annual air quality status reports. These provide NO_2 monitoring data in monthly totals. There is an interest to increase direct measurement in the following ways:

- The team use the monthly NO_2 measurements reported by the district and borough environment officers.
- The team are not clear what analytes would be of most interest. Measurement of $PM_{2.5}$ is considered the top priority.
- Potential to measure PM_1 or $PM_{0.1}$ may be of increased interest in the future.
- Flexibility to move air quality analyser locations with changing need; locations may be used for a period of a few months to build a background picture or monitor changes.
- Tracking air quality before, during and after changes and trialled changes would enable justification of the actions taken.
- Can monitoring be used to observe carbon reduction as part of the zero-carbon climate emergency pledge?
- Air quality analysis does not need to be verified to the Defra-required standards that statutory monitoring requires, but needs to be sufficiently robust to be presented and defended in planning appeals and other negotiations and challenges.
- Increasing understanding of the impact of weather conditions and geography on air quality distribution.
- Could air quality measurements be used to control traffic movement to impact on exceedences? Evidence would be required to install and apply dynamic traffic route planning.
- Existing locations are based on DEFRA modelling, but do not necessarily correspond to locations relevant to enquiries from the public.

2.4.3 Public Health England

The Environmental Hazards and Emergencies Department within Public Health England typically uses air quality monitoring data for public health risk assessment (Dunne, 2021). This is typically in the context of a specific incident, such as a smoke plume from a fire, or if contacted by the local authority or Environment Agency regarding complaints such as emissions from a regulated process. Their purpose is the assessment and protection of public health. They are primarily interested in locations where there is potential for residential or other public exposure.

In that context, they would look to use any locally available monitoring data that is relevant to the specific incident situation. Real-time or near real-time information is useful during an acute incident, and longer time period information reviewed daily or weekly is useful for chronic and longer-term situations.

Whilst PHE would prefer to have data to standards equivalent to those for DEFRA's Automatic Urban and Rural Network (AURN) data, when not available they wish to see details of limitations, corrections or constraints.

2.4.4 Calibration of measurements

As discussed in preceding sections, different uses of air quality data have different calibration standards requirements. Whilst statutory monitoring needs to meet specified standards, monitoring for other purposes needs to be fit for purpose. Suppliers of air quality monitors should be clear on how they calibrate their devices, and how users can justify use of the data obtained. Air quality devices require regular maintenance to maintain consistency of reported data.

This can be attained by co-location quality control with a pre-existing reference station, a process that can be undertaken commercially, at a cost.

2.4.5 Clean Air Strategy

The Environment Bill is described as delivering key aspects of the UK's Clean Air Strategy, aimed at improving health benefits and associated with the UK's clear air strategy (DEFRA, 2019, 2021b). The Clean Air Strategy describes the range of sources of air pollution as both distant and local, and has an aim to half the harm to human health (DEFRA, 2019). Air quality is described as the largest environmental health risk in the UK, with $PM_{2.5}$ as a key concern. Chapters deal with reducing emissions from transport, farming, industry and at home. The strategy quotes the figure of domestic burning contributing 38% of UK's primary emissions of $PM_{2.5}$, (based on DEFRA analysis of the 2016 National Atmospheric Emissions Inventory) as well as other pollutants, and lists a range of measures to reduce emissions from domestic burning.

3 Specific sensors

3.1 Introduction

Air quality sensors trialled within this project are considered in this report and are detailed below. This includes discussion of how the sensors function, how the suppliers provide information, and how they operate. A brief discussion is included of a few additional air quality sensors that have been encountered during the project, but not trialled.

3.1.1 Communications networks

The sensors communicate with online dashboards via Internet-of-Things type technologies. The sensors assessed use different communications technologies, which include:

- 3GPP mobile services, enabling access where mobile network coverage is available;
- Zigbee protocol communication utilising mesh networks created for street lighting.

Networks for connected places and smart city communication across the Smarter Suffolk Project have been discussed in detail in Steventon, 2021. The accessibility of a communication network is integral to the appropriate selection of air quality sensor hardware.

3.2 Aeroqual AQY1 sensor

3.2.1 Introduction

Aeroqual are a manufacturer of a range of air quality sensors, and in conversations with a range of users appear to be a relatively well known and respected supplier in this field. This project was supplied with Aeroqual AQY1 sensor by third parties Telensa and CIMCON. This is Aeroqual's smallest product for outdoor air quality monitoring. Details have been obtained from Aeroqual's website (Aeroqual, 2020a) in the form of their online information, and downloadable user guide (Aeroqual, 2020b) and specification sheet . In March 2021 Aeroqual announced that they are ceasing production of AQY1 until further notice (Aeroqual, 2021).

3.2.2 Analytes and analysis

The Aeroqual AQY1 sensor measures:

- Ozone (O_3)
- Particulate Matter as $PM_{2.5}$ (PM_{10} also reported but not specified)
- Nitrogen Dioxide (NO_2)
- Temperature, relative humidity and dew point

Details for the measurements of these are as follows (Aeroqual, 2020b):

- Ozone is measured using Aeroqual's own Gas Sensitive Semiconductor (GSS) ozone sensor https://www.aeroqual.com/company/our-technology/gss-technology.
- NO_2 measurement are adjusted using the ozone sensor to correct for ozone interference on the electrochemical NO_2 sensor. Aeroqual claim that this makes their ozone measurement "*real*" rather than "*an approximation as delivered by other devices that use an electrochemical NO_2 sensor*". Electrochemical sensors for NO_2 and O_3 are cross-sensitive to the other analyte. Aeroqual state that as their GSS ozone sensor is selective to ozone it can be used to correct the NO_2 sensor. They run this correction as a device-embedded algorithm in real time. Other commentators are concerned by this indirect measurement approach, which does not directly analyse the parameter.
- $PM_{2.5}$ is measured by optical particle counting using light scattering to size and count particles before converting to a mass fraction. High humidity can lead to over-reporting of particulate levels due to moisture on particle surfaces leading to an over-measurement of the particle diameter, so humidity measurements are used to correct for this.

The lifetimes of the sensors depend on the air quality of the environment in which they are placed, with up to 10-14 months in a city such as London with PM_{10} less than 50 µg/m^3.

3.2.3 Calibration and maintenance

The AQY1 is described as factory calibrated. Calibration against a reference station is required for higher data quality, using co-location calibration applying linear regression to provide calibration parameters which can be input into the AQY1 via the Aeroqual Cloud or

Connect. This enables interoperability with regulatory monitoring data, and could be performed before and after deployment, or at intervals. Instructions for co-location calibration are provided with the User Guide; co-location should occur for at least three days, with readings at least hourly intervals. Calibration calculations for ozone and particulates are straightforward to provide gain and offset; calculations for nitrogen dioxide need to take into account the readings on the ozone sensor as well as the nitrogen dioxide sensor. Calibration validation, if desired, would take another three days of co-location. There is no suitable reference station in Suffolk.

Annual maintenance includes replacement of the three analytical sensors. Instructions in the User Guide present this as a relatively straightforward swp of the internal sensors. Calibration parameters need to be reset following sensor replacement.

Given sensing specifications are:

PARTICLE SENSING	SIZES	RANGE	ACCURACY	LOWER DETECTABLE LIMIT (2 σ)
Laser scattering	$PM_{2.5}$	0 to 1000 µg/m³	±(10 µg/m³ + 5 % of reading)	1 µg/m³

GAS SENSING	RANGE	RESOLUTION	NOISE	LOWER DETECTION LIMIT	PRECISION	LINEARITY (% OF FS)	DRIFT 24 HOUR
			ZERO; SPAN % OF READING				ZERO; SPAN % OF FS
Ozone (O_3)	0-200 ppb	0.1 Ppb	1 ppb; 2 %	1 ppb	4 % of reading or 4 ppb	3 %	2 ppb; 1 %
Nitrogen Dioxide (NO_2)	0-500 ppb	0.1 ppb	2 ppb; 4 %	2 ppb	8 % of reading or 8 ppb	6 %	< 4 ppb; 1 %

Table 2: Sensing specification from AQY1 User Guide

Range for physical environmental sensing are given as:

- Temperature: -40°C to 125°C
- Relative Humidity: 0 to 100%
- Dew Point: -30°C to 50°C

3.2.4 Sensor hardware

The sensor dimensions are 215 x 170 x 125mm, including solar shield and mounting brackets, and weighs less than 1kg. It has an operating range of -10°C to 40°C. It is shown in Figure 1.

Figure 1: Aeroqual AQY1 Micro Air Quality Monitoring Station (Aeroqual, 2020a)

PM sampling is via a 4cm anti-static inlet, and gas sampling via a Teflon and stainless steel inlet, both with 5V dc fan.

The sensor is mounted with a wall or pole mounting bracket supplied. Mounting location should have good airflow and be away from specific point sources such as external venting from buildings.

The sensor is powered via a 12 V DC, 24W power supply, via a power connection on the unit. Solar power is claimed to be usable if the supply output delivers 12V DC, 24W, 2A.

The sensor claims to have a life expectancy of 5 yrs, with annual sensor replacement and maintenance (more frequent if located with higher particulate levels than typically observed in the UK), and calibration as required for the use case.

3.2.5 Sensor communication

The AQY 1 sensor communicates via 3G or 4G networks or via WiFi.

In this project, communication is directly from the Aeroqual unit via 3G or 4G networks for Telensa. For CIMCON, WiFi transmissions from the Aeroqual AQY1 unit are received by CIMCON's NearSky platform, which uses a streetlight-mounted data processor to enable onwards data communications.

3.2.6 Approvals, standards and compliance

The AQY1 is IP33 rated, described by Aeroqual as weatherproof with solar shield.

3.2.7 Sensor software, dashboard and data

For the Smarter Suffolk project, data is provided by Telensa as CSV files via email and SFTP. CIMCON provides dashboard visualisations of the data, and RESTful API to enable data export and integration to other systems.

Aeroqual run two software products with this sensor: Aeroqual Connect is their instrument operating system. Aeroqual Cloud is their cloud-based monitoring, management and technical support system, accessed via web browser. These have not been accessed directly in this project.

3.3 Libelium Plug and Sense Smart City Pro sensor

3.3.1 Introduction

Libelium design and manufacture a wide range of Internet of Things sensors. These are generally based on one of a selection of base units with optional probes. Libelium was provided to the Smarter Suffolk project by SSE Enterprise, as part of their Smart Cities offering.

One of the Libelium platforms is the Plug and Sense platform, which is described in this section. The base station has sockets to add sensors from a wide selection, and offers a selection of options with pre-determined sensor selections. Two of these are focused on air quality sensing: their Smart Environment Pro, and Smart Cities Pro. This project worked with the Smart City Pro sensor, which is described here.

Details have been obtained from Libelium's website (Libelium, no date b, no date a). Their Waspmote Plug and Sense Sensor guide, supplied by SEE, is included in the digital archive for this report.

3.3.2 Analytes and analysis

The Libelium Smart Cities Pro offers the following sensors, of which six can be selected for attachment to the base unit at any one time, with limitations on sensor permutations.

- Noise
- Particle Matter as PM_1, $PM_{2.5}$ and PM_{10}
- Carbon monoxide
- Carbon dioxide
- Oxygen (O_2)
- Ozone (O_3)
- Nitric Oxide (NO)
- Nitrogen Dioxide (NO_2)
- Sulphur Dioxide (SO_2)
- Ammonia (NH_3)
- Methane (CH_4) "*and other combustible gases*"
- Hydrogen Sulphide (H_2S)
- Temperature, humidity, atmospheric pressure
- Luminosity in Lux
- Ultrasound for distance

Details for the measurements of ozone, nitrogen dioxide, nitric oxide, particulate matter and sulphur dioxide (the selected and provided chemical sensors) and temperature, humidity and pressure (the default physical parameters) are as follows (from Plug & Sense sensors guide):

- Ozone is measured using Libelium's OX-A431 electrochemical ozone sensor. Performance characteristics are listed in Table 3. Ozone is cross-sensitive to nitrogen dioxide, which is not corrected by the sensor.
- NO_2 is measured using Libelium's NO2-A43F sensor, described as a high accuracy gas sensor probe. Performance characteristics are listed in Table 3. Nitrogen dioxide is cross-sensitive to ozone, which is not corrected by the sensor.
- Nitric oxide is measured using Libelium's NO-A4 electrochemcial sensor, described as a gas sensor for low concentrations.
- Sulphur dioxide is measured using Libelium's SO2-A4 sensor, described as a high accuracy gas sensor probe. Performance characteristics are listed in Table 3.
- PM_1, $PM2_{.5}$, and PM_{10} are measured using Libelium's OPC-N3 laser probe with a low powered fan, operating at 280ml/min for a user-defined sampling period of up to 30 seconds. This measures particulates from 0.35 to 40 µm and categorises into 24 size bins, which are combined for the reporting intervals. Libelium claim their sensor can measure from clean room levels to 2,000 $\mu g/m^3$. The fan and laser have high current consumption, and should be turned off when not in use to save battery. The probe requires maintenance and cleaning for continued accurate operation, which is needed more frequently in environments with high levels of particulates, as they can accumulate in the sensor structure. The Libelium Sensors Guide warns that high humidity or foggy environments can increase the sensor measurements, as water droplets will be identified as particles. This is not corrected for.

3.3.3 Calibration and maintenance

Libelium comment that electrochemical sensors must be continuously powered on for optimum measurements and improved performance. This does mean continual power consumption, and must be applied during sleep modes without depowering the sensor. Libelium claim that electrochemical sensors have very low power consumption (less than 1mA). They also require up to several hours stabilisation time, and recommend to allow 24 hours prior to using readings.

Calibrated gas sensors are manufactured after order to ensure longevity of calibration. Manufacture and delivery takes 4 to 6 weeks and lifetime of the calibrated sensor is approximately 6 months for maximum accuracy. Sensor probes should then be replaced with new probes for continued accuracy and performance. Therefore these probes should be considered a disposable, consumable item. This is an intrinsic limitation of electro-chemical calibrated gas sensors, compared with professional gas stations.

Given sensing specifications are:

	Particulate Matter	Ozone	Nitrogen Dioxide
Method	Laser based light scattering	Electrochemical sensor	
Measurement range	0 – 1000 particles / second	0 – 18 ppm	0 – 20 ppm
Maximum overload		50 ppm	50 ppm
Expected life	Recommend 6 months probe replacement	Recommend 6 months probe replacement	Recommend 6 months probe replacement
Sensitivity drift	Not given	-20 to -40% per year	-20 to -40% per year Zero drift <20ppb/yr
Response time		≤ 45 seconds	≤ 60 seconds
Calibration	As provided	As provided	As provided
Resolution	Not specified	Not specified	Not specified
Accuracy	Not given	± 0.2ppm in ideal conditions NB may need to correct for NO_2 due to cross-sensitivity	± 0.2ppm in ideal conditions NB may need to correct for O_3 due to cross-sensitivity
Temp range	-10 to +50 °C	-20 to +40 °C	-30 to +40 °C
Humidity range	0 – 99% non-condensing	15 – 85% non-condensing	15 – 85% non-condensing

Table 3: Sensor specifications taken from Smart Cities Pro sensor guide (Libelium, no date b)

Given accuracies are described as a theoretical figure calculated as an optimum case. Measurement error may be bigger in real conditions.

3.3.4 Sensor hardware

The main unit body plus aerial has dimensions of 164 x 410 x 85mm, which does not include sensor probes. It weighs approximately 800g, excluding probes. It has an operating range of -30°C to 70°C. It is shown in Figure 2.

Figure 2: Libelium base unit, and Libelium Smart City (showing different sensors to those selected for this project) Images (Libelium, no date a)

3.3.5 Sensor communication

For the sensor installation for the Smarter Suffolk project, the supplier (SSE) operates their streetlighting network on a Zigbee mesh network, which is created by their lighting management system, with submaster gateways distributed across the area served. This Zigbee network is accessed by the Libelium sensors provided, for communications from these sensors.

The Libelium sensors can operate on a range of communications networks. These are described here as the list includes some that are less widely known.

- 802.15.4: the IEEE-maintained technical standard used by a selection of low-rate personal area networks, describing the physical layer and media access control. This standard is used by Zigbee.
- Zigbee: specifies high-level communications protocols for personal area networks based on IEEE 802.15.4. It has a range of up to around 100m line-of-sight to access a gateway or mesh network.
- 868 MHz: part of the licence-free radio spectrum in the EU, used in low power, wide area networks including LoRaWAN.
- 900MHz: part of the radio spectrum typically used by a range of industrial and scientific equipment.
- WiFi: standards-based wireless network protocol used for local area networks.
- 4G: broadband cellular network technology.
- Sigfox: an operator that provides low power wide area networks. They install and operate their own network, and claim wide coverage across England and Northern Ireland (less in Wales and Scotland).
- LoRaWAN: low power wide area network operating using the LoRa modulation in the licence-free spectrum (868MHz in the EU), with access provided by many different operators.

3.3.6 Approvals, standards and compliance

The Libelium sensors are CE compliant.
The main Plug and Sense unit is IP65 rated, with IK08 impact resistance.
Information on other certifications and standards has not been identified.

3.3.7 Sensor software, dashboard and data

For the Smarter Suffolk project, data was accessed from SSE's Smart City dashboard, which provides visualisations and from which the data could be downloaded as CSV files.

3.4 Liveable Cities

3.4.1 Introduction

Liveable Cities are a division of LED Roadway Lighting, and have developed particulate matter sensors that are fitted onto streetlighting NEMA sockets, making them very easy to install.

3.4.2 Analytes and analysis

The sensor measures:

- Particulate Matter as $PM_{2.5}$
- Particulate Matter as PM_{10}

$PM_{2.5}$ and PM_{10} is measured using AlphaSense OPC-Rx sensor (Alphasense, 2019; Liveable Cities, 2021). This uses laser-scattering technology, and applies humidity measurements to correct for the impact of moisture increasing apparent particle diameter.

The lifetime of the sensor is not stated.

3.4.3 Calibration and maintenance

Liveable Cities do not provide information on calibration.

Alphasense suggest that calibration should be checked on receipt, at 30 days and at intervals thereafter.

3.4.4 Sensor hardware

The sensor dimensions are 89mm diameter x 202mm, weighs around 160g. It has an operating range of -40°C to 60°C. It is shown in Figure 3.

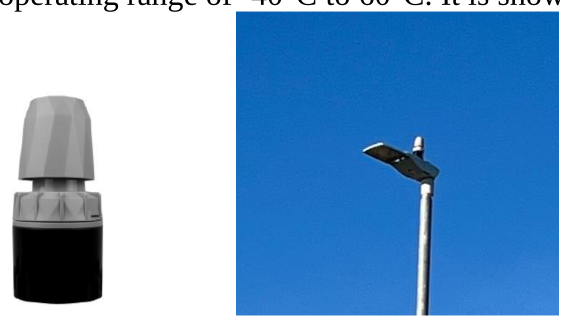


Figure 3: Liveable Cities Particulate Matter Sensor.
Image on left supplied by Liveable Cities. Image on right showing on-site installation (H.Steventon)

The sensor is mounted on the top of the street lights, plugged into their NEMA socket. This places it relatively high above the highway, but makes for easy installation. The sensor is powered via the standard NEMA control socket present on streetlights, which makes it very easy for street lighting contractors to install, power and change.

3.4.5 Sensor communication

The particulate matter sensor communicates directly via LTE-M or cellular LTE networks. 3G or 4G networks or via WiFi. LTE-M is not available in Suffolk, so the sensors in the Smarter Suffolk project operate on the cellular network.

3.4.6 Approvals, standards and compliance

The sensor is CE rated, and does not state an IP rating.

3.4.7 Sensor software, dashboard and data

Liveable Cities supports TALQ2 Smart City Protocol, has an API for data extraction and a useable dashboard with extensive visualisations and downloadable data.

3.5 Alternative Air Quality Sensors not provided to the project

During this project, several other air quality sensors have been encountered. These are discussed briefly in the following subsections.

3.5.1 E-Mote and iPM from Envirowatch

SCC commissioned CUPhosco to design a lighting column with integrated air quality meter. This was aimed to address the issues that externally mounted air quality meters can be prone to interference, vandalism or inadvertent damage, and are mounted at heights above that of human exposure. The aim was to have air quality meter at pedestrian height fitted inside the lighting column. Within that project, they worked with Envirowatch for AQ meters who were reported to have a more robust and lower maintenance solution, with better accuracy than many of the IoT AQ meters available. Envirowatch work closely with BT for installation of air quality monitors in BT’s street cabinets. The air quality sensors from Envirowatch have a smaller diameter than other products, enabling potential incorporation into adapted street lighting columns.

Envirowatch offer two air quality sensors (Envirowatch, 2020, 2021), the e-mote, which measures CO, NO and NO_2, and their newer iPM for PM_1, $PM_{2.5}$ and PM_{10}. They describe their iPM as using a temperature controlled inlet to maintain constant relative humidity rather than constant temperature.

They communicate using GPRS, NB-IoT, WiFi or ZigBee. The iPM requires power, and the E-Mote can be solar powered.

3.5.2 AQMesh

AQMesh is a small air quality sensor, that is well regarded by a number of experts including from air quality consultancy Ricardo (AQMesh, no date).

AQMesh can measure up to six gases from a selection of twelve, plus noise, wind speed and direction, relative humidity, temperature and pressure. Most gases, including NO_2 and O_3, are measured by electrochemical sensors, and particulates are measured by light-scattering optical particle counter. It can adjust PM readings to account for humidity, if configured.

It is usually solar powered, and can be mains powered if required. Its dimensions are 250mm x 220mm x 170mm.

AQMesh uses LTE communication, such as 5G, or NB-IoT.

It has a range of data access options, including near-real time API access.

3.5.3 Vaisala

Vaisala is a global company that produces products and services in environmental and industrial measurement. These products include two small air quality sensors, AQT410 and AQT420 (Vaisala, no date). These were considered well regarded by air quality consultancy Ricardo.

The AQT410 measures four gases selected from nitrogen dioxide (NO_2), Nitrogen monoxide, sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3) and hydrogen sulphide. The AQT420 also includes PM2.5 and PM10.

Vaisala claim to be applying *"Intelligent algorithms that compensate for aging and environmental conditions"* with a maintenance and calibration interval of two to three years.

The unit is approximately cylindrical, with dimensions of 128mm x 132mm (for AQT410) or 208mm x 132 mm (for AQT420).

Communication and power are via a physical connection with a separate gateway.

Data can be available via a web-based database.

3.5.4 Zephyr from EarthSense

EarthSense are a UK based company who provide an air quality sensor and an air pollution map. Their sensor is used by Mid Suffolk and Babergh District Council on a moveable basis, and is installed by BT at Adastral Park.

Zephyr (Zephyr, no date) can measure a range of pollutants, including nitric oxide and nitrogen dioxide, ozone, carbon monoxide, sulphur dioxide and hydrogen sulphide, and PM_1, $PM_{2.5}$ and PM_{10}.

A subscription service includes calibration and cartridge replacements.

The Zephyr unit measures 235mm x 160mm x 114mm.
It can be powered via mains power or solar power, and connects via GSM using WiFi, Bluetooth, 2G, 4G, 5G, NB-IoT and LTE Cat-M1.

Including cartridges, it is IP63 rated.

Data is transferred to an online database from which it can be downloaded by a range of methods including API access.

3.5.5 Synetica EnLink AirX sensor

Synetica are a UK based company designing and manufacturing energy, environment and asset monitoring sensors. Their sensors all use LoRaWAN technology to communicate. The air quality sensor is the EnLink Air, with the EnLink Air X being the model of the sensor suitable for external use. Details have been obtained from Synetica's website in the form of their online information, and downloadable datasheet (Synetica, no date).

They measure temperature, humidity, light, pressure, sound, VOCs, CO_2, O_2, $PM_{2.5}$ – PM_{10} and an optional selection of up to four other sensors. The EnLink Air and Air-X are described as factory calibrated for particulate matter, physical parameters and some other chemical parameters. Calibration sheets are provided for most analytes, including NO_2 and ozone.

Synetica say that all sensors have a micro USB connection for setup and direct monitoring. They also describe internet based visualisation and analysis using their IoT platform; this has not been accessed or demonstrated during the project.

3.5.6 Airscan

UK-based tracking company Iknaia tracks assets and environmental data. They produce the Airscan AQM, which was identified by Richard Webster. Iknaia (Iknaia, no date) uses data from passing Bluetooth and WiFi devices on highways to analyse journey time. Their Airscan AQM combines this with air quality monitoring.

The sensor can measure four gases selected from CO, SO_2, O_3, NO, NO_2, H_2S, particulate matter, and temperature, humidity and pressure.

The sensor is factory calibrated, and requires a 24 hour stabilisation period. It has a two year expected life.

The sensor is 195mmx 160mm x third dimension not given (appears to be around 100mm) and weighs 750g.

Communication is via 3G, 4G or 5G, WiFi or Ethernet.

It is IP66 rated.

Data is available via an online dashboard and open API.

3.5.7 NowWireless and XanLabs

Now Wireless is a smart city infrastructure supplier that offers XanLabs Pollution Monitors, identified by Richard Webster.

Their MultiSensor (Now Wireless, no date) includes electro-chemical gas sensors for nitrogen dioxide, carbon monoxide, and nitrous oxide (N_20), and an optical sensor for $PM_{2.5}$ and PM_{10}.

Calibration and maintenance requirements are not detailed online, but are described as "networked auto-calibration".

The sensor dimensions are not given.

It communicates via 3G, 4G, WiFi, BlueTooth, LoRa, and Zigbee.

3.5.8 Envirowatch and Vortex

BT Internet of Things researchers suggested sensors already hosted at Adastral Park as part of other projects. These included Vortex (Vortex, no date). The Vortex SilaxAir sensor measures nitrogen dioxide, ozone, $PM_{2.5}$ and PM_{10}. Calibration and maintenance requirements are not detailed online. The sensor dimensions are not given. Communications is via a Zigbee mesh, and an API is available for data access.

3.6 Comparison of sensors

Details from selected sensors described in the preceding section are summarised in Table 4. This features sensors installed in this project, as well as AQMesh for comparison. The table includes parameters measured, size of the hardware, its IP rating, network requirements and data representation.
Analytes and accuracy are restricted to NO_2, O_3, and particulate matter, as the key selected analytes.

	Aeroqual AQY1	Liveable Cities	Libelium Smart City Pro	AQMesh
NO_2	Electrochemical Corrects for O_3 0 - 0.500 ppm precision 8% or 8ppb	n/a	0 - 20ppm Drift <40% per yr Accuracy ± 0.2ppm	Electrochemical 0 – 20 ppm Precision >0.85 Accuracy 4ppb
O_3	Gas sensitive semiconductor 0 – 0.2 ppm Precision 4% or 4ppb	n/a	Electrochemical 0 - 18ppm Drift <40% per yr Accuracy ± 0.2ppm	Electrochemical 0 – 20 ppm Precision > 0.9 Accuracy 5ppb
PM	Light scattering Humidity correction 0-1000 µg/m^3 Accuracy ±10ug/m3 + 5%	Light scattering Humidity correction	Light scattering 0-2000 µg/m^3	Light scattering 0-350,000 µg/m^3 Precision >0.85 Accuracy 5 µg/m^3
Physical parameters	T, RH, DP	RH measured but not reported	T, H, P Others available	T, RH, P, noise, wind
Size (mm)	215 x 170 x 125	89 diameter x 202	164 x 410 x 85 Plus sensor probes	250 x 220 x 170
Weight	<1kg	160g	800g for main unit	2 – 2.7kg
IP rating	IP33	Not stated	IP65 for main unit, sensor probes differ	IP65
Network	3G or 4G or WiFi	Cellular	Zigbee Others available	4G, 5G LTE or NB-IoT
Data access	Supplier dependent	Supplier dashboard and API	Supplier dependent	Web dashboard and API
Power	12V DC	Streetlight NEMA socket	Can be solar powered	Solar powered or mains powered
Lifespan and maintenance	Environment dependent 10-14 months in city 5yr with annual sensor replacement	Not stated	Calibration for 6mo	2 – 5 years depending on analyte

Table 4: Comparative Summary of air quality sensor hardware

3.6.1 Hardware: Ingress Protection Ratings, dimensions

The range of IP ratings represents the challenges of waterproofing gas sensors. These could all be anticipated to be suitable for exterior use in urban situations.

Dimensions of these sensors are very approximately similar.

A couple offer solar power options, which could significantly increase their usable locations.

3.6.2 Measurement scope

Whilst Aeroqual AQY1 sensor has a significantly lower maximum concentration than the other sensors for the analytes of interest, this maximum is anticipated to be within the ranges encountered for this project. Observations during the project will explore this.
The Aeroqual AQY1 sensor claims that it does not report PM_{10}. The PM_{10} measurements identified on data from this sensor may or may not be reliable.

Some sensors provide additional measurements of physical atmospheric parameters. These parameters may be a useful addition.

3.6.3 Communications

Sensors accessing mobile data services (ie GPRS/3G/4G or NB-IoT) would need to be installed in a location with adequate mobile coverage, but this would not be expected to provide a significant geographical constraint in most areas.
Sensors requiring LoRaWAN are dependent on the provision and maintenance of the LoRa gateways and network, which may be provided by local authority, sensor provider or a third party.
Sensors requiring SigFox connection (not used in this project) would require SigFox network coverage, which is currently good across most of Suffolk, with some areas not yet covered.
Sensors relying on local area networking, such as Zigbee, are reliant on the very close proximity of the mesh network. Suppliers using these technologies anticipate that network to be provided by streetlighting.

A separate, non-thematic report has been provided to discuss infrastructure communications options in more detail (Steventon, 2021).

4 Assessment of Data

4.1 Introduction

Data from the installed sensors has been analysed, and is discussed in this section. Timeseries presentations of the data are included in Appendix A, with key conclusions made in the following sections.

Data used in the analysis was obtained from the following sources:

- CIMCON data was downloaded from the CIMCON dashboard
- SSE data was downloaded from the SSE dashboard
- Telensa data was emailed as csv files throughout the project; Telensa data was also available from the BT Data Exchange
- Liveable Cities data was downloaded from the Liveable Cities dashboard

Data was assessed using the Python programming language in interface Jupyter Notebooks, using two key libraries: pandas to structure dataframes and matplotlib for graphical presentations. Data was assessed for continuity of operation, which is presented in Section 4.2. An assessment of analyte concentration is presented in Section 4.3. This includes summary descriptive statistics, and visual presentation of concentration ranges as boxplots. A boxplot is a visualisation of key statistical parameters, and illustrates the interquartile range (from the 25 percentile to the 75 percentile) as a box, with a line indicating the median; whiskers illustrate a statistical range of data beyond the interquartile range, and outliers are indicated as individual points beyond that (Bruce, Bruce and Gedeck, 2020). Note that the summary statistics include the mean of the values, and the 50 percentile, which is equivalent to the median. It may be significantly different to the mean, depending on the range of values.

4.2 Continuity of operation

4.2.1 Introduction

To assess reliability of the sensors, data has been analysed for continuity. For all suppliers, periods of non-reporting have been encountered, and some sensors have ceased to operate. Across the project and suppliers, the following have been encountered as causes of permanent and temporary operational failure.

- Removal of sensors by contractors undertaking other works to streetlights
- Lack of reliability of data connection networks
- Lack of reliability of power connection to devices

Suffolk County Council worked hard at requests from suppliers to move and reboot sensors, with many sensors receiving multiple operational visits. However, ongoing and frequent site visits was not possible given other works commitments. It would be expected that deployed equipment should be reliable over the projected lifetime of the equipment.

Suppliers were not all proactive in identifying non-operational equipment, and did not contribute to maintaining continued operation.

The following sections (Sections 4.2.2 to 4.2.5) analyse the frequency and length of non-operational periods for equipment from each of the four suppliers, by analysing number and length of gaps in acquired data.

4.2.2 CIMCON

Five Aeroqual AQY1 sensors were provided by CIMCON. These reported the following analytes at the following frequencies:

- $PM_{2.5}$ at 15 minute intervals
- NO_2 at 60 minute intervals
- O_3 at 60 minute intervals
- Dew Point at 60 minute intervals
- Relative Humidity at 60 minute intervals
- Temperature (reported in Fahrenheit) at 60 minute intervals

Data from the five air quality sensors supplied by CIMCON indicate intermittent periods of operation, with periods during which they were non-operational (see Figure 12 to Figure 16 in Section 10). Times and dates for latest data received are tabulated in Table 5. For four of the sensors, the periods of operation and non-operation were the same for all analytes. For one sensor (Denmark Road) data for one analyte (PM2.5) has been received during periods when data from other analytes have not. This report analyses data from installation up to the end of September 2021.

Location	Last date of received data
St Johns Road	Operational at end of September
London Road	23:00 on 17 April 2021(23:45 for $PM_{2.5}$)
Riverside	12:00 on 27 May 2021 (12:45 for $PM_{2.5}$)
Denmark Road	04:00 on 13 July 2021 (04:45 for $PM_{2.5}$) (Operational at end of September for O_3 only)
Royal Plain	09:00 on 25 June 2021 (09:45 for $PM_{2.5}$)

Table 5: Final date of operation of CIMCON-supplied air quality sensors

Analysis of length of gap during the operational period has been undertaken, which indicates the following:

Location	No of gaps in $PM_{2.5}$	No of gaps in other parameters	No of gaps >2 hrs	Longest gap in data
St Johns Road	291	291	163	69 days, 14:00:00
London Road	28	25	3	61 days, 7:00:00
Riverside	82	82	18	13 days, 15:00:00
Denmark Road	60	55	11*	56 days, 10:30:00
Royal Plain	186	178	45	20 days, 0:00:00

* 24 gaps in O_3, which was operational over a longer period than other analytes

Table 6: Gaps in data prior to final date of operation of CIMCON-supplied air quality sensors

CIMCON have not yet provided an explanation for these non-operational periods, nor why the devices started returning data again at times.
They have informed the project that vendor licencing expiry has resulted in cessation of data provision at time of report preparation.

4.2.3 SSE

Five sensors were provided by SSE. These reported the following parameters at 60 minute frequencies:

- Nitric Oxide (ppm)
- Ozone (ppm)
- PM1 (ppm)
- PM10 (µg/m^3)
- PM2.5 (µg/m^3)
- Ambient Pressure (kPa)
- Ambient Temperature (°C)
- Battery (%)
- Humidity

Air quality analytes are reported in units of ppm. Whilst it is possible to convert chemical parameters from ppm to µg/m^3, this is not straightforward for particulate matter (PM), as the density of the particulates is unknown and variable. This means that the PM concentrations cannot be compared with objectives, or with measurements from other sensors.

They were installed and began to be operational between 9 June and 22 August 2021. Data has been obtained from SSE's online dashboard up to 31 October 2021 for analysis in this report, a period of at least ten weeks.

Data from the five air quality sensors supplied by SSE indicate generally intermittent operation; with gaps greater than 2 hours (Table 12). Times and dates for latest data received are tabulated in Table 11. This report analyses data from installation to the end of October 2021, a period of ten weeks.

Location	Last date of received data
Adastral Park	Operational at end of October 2021
Ashburnham Way	00:00 on 08 September 2021
Bloodmoor Road	18:00 on 17 August 2021
Lorne Park Road	Operational at end of October 2021
Old Farm Road	Operational at end of October 2021

Table 7: Final date of operation of SSE-supplied air quality sensors

Analysis of length of gap (greater than 2 hours, as 1 hour is the analysis frequency) prior during the operational period has been undertaken, which indicates the following:

Location	No of gaps > 2 hrs	Longest gap in data
Adastral Park	117	1 day, 12:00
Ashburnham Way	22	2 days, 19:00
Bloodmoor Road	0*	*operated for 8 measurements on 17/08/21 only
Lorne Park Road	23	13:00
Old Farm Road	50	1 day, 1:00

**Sensor at Bloodmoor Road not included in analysis: only 8 measurements acquired, insufficient for statistical analysis.*
Table 8: Gaps in data prior to final date of operation of SSE-supplied air quality sensors

SSE explain (Allen, 2021) that operational failure of the two devices that have ceased operation is considered to be due to poor Zigbee communications connection. A site visit on 16/08/2021 relocated all devices, for improved Zigbee connections. However, devices at Bloodmoore Road and Ashburnham Way did not continue to operate following relocation.

4.2.4 Telensa

Data from thirteen sensors provided by Telensa have been analysed. These reported the following analytes at 1 minute frequencies:

- $PM_{2.5}$
- PM_{10}
- Ozone in ppb
- Nitrogen Dioxide in ppb

They were installed and operational during 2020. Data has been analysed from October 2020 to September 2021 for analysis in this report, a twelve month period.

Data from the air quality sensors supplied by Telensa indicate generally continual operation, with gaps greater than 15 minutes in all sensors and a few sensors with many gaps greater than 2 hours (Table 10). Times and dates for latest data received are tabulated in Table 9.

Location	Last date of received data
AQY BC-1037	2021-06-27 02:50:00
AQY BC-1039	Operational at end September 2021
AQY BC-1043	2021-06-23 09:57:00
AQY BC-1047	2021-09-12 08:58:00
AQY BC-1050	Operational at end September 2021
AQY BC-1051	2021-07-21 09:58:00
AQY BC-1048	Operational at end September 2021
AQY BC-1052	2021-06-25 10:24:00
AQY BC-1053	2021-09-02 05:29:00
AQY BE-1231	2021-08-23 16:18:00
AQY-BA-467A	2021-07-30 11:26:00
AQY BC-1054	2021-08-23 01:57:00
AQY BC-1040	Operational at end September 2021

Table 9: Final date of received data of Telensa-supplied air quality sensors

Analysis of length of gap (greater than 15 minutes) prior during the operational period has been undertaken, which indicates the following:

Location	No of gaps	No of gaps > 2 hrs	Longest gap in data
AQY BC-1037	22	5	2 days 04:34:00
AQY BC-1039	11	2	176 days 08:03:00
AQY BC-1043	43	4	0 days 05:03:00
AQY BC-1047	15	3	232 days 21:52:00
AQY BC-1050	1008	12	84 days 19:07:00
AQY BC-1051	4111	9	1 days 02:03:00
AQY BC-1048	94	56	78 days 07:57:00
AQY BC-1052	96	43	170 days 12:27:00
AQY BC-1053	122	25	137 days 05:24:00
AQY BE-1231	1820	213	28 days 07:07:00
AQY-BA-467A	2895	619	22 days 06:45:00
AQY BC-1054	1040	46	51 days 17:21:00
AQY BC-1040	206	3	1 days 00:02:00

Table 10: Gaps in data prior to final date of operation of Telensa-supplied air quality sensors

4.2.5 Liveable Cities

Five sensors were provided by Liveable Cities. These reported the following analytes at the following frequencies:

- $PM_{2.5}$ at 5 minute intervals
- PM_{10} at 5 minute intervals

They were installed and operational from 25 September 2021. Data has been obtained up to 31 October 2021 for analysis in this report, a five week (36 day) period.

Data from the five air quality sensors supplied by Liveable Cities indicate generally continual operation, with some gaps greater than 15 minutes and few gaps greater than 2 hours (Table 12). Times and dates for latest data received are tabulated in Table 11. This report analyses data from installation to the end of October 2021, a period of five weeks (36 days).

Location	Last date of received data
Allwin Road	15:30 on 4 October 2021
Appledown Dr	Operational at end of October 2021
Ortewell Road	07:52 on 21 October 2021
Rougham Tower Av	Operational at end of October 2021
The Daubentons	08:37 on 28 October 2021

Table 11: Final date of operation of Liveable Cities-supplied air quality sensors

Analysis of length of gap (greater than 15 minutes) prior during the operational period has been undertaken, which indicates the following:

Location	No of gaps	No of gaps > 2 hrs	Longest gap in data
Allwin Road	46	3	3 days, 20:02:16
Appledown Dr	63	3	3 days, 22:00:25
Ortewell Road	53	3	3 days, 23:45:25
Rougham Tower Av	51	4	3 days, 23:30:25
The Daubentons	120	3	4 days, 0:15:24

Table 12: Gaps in data prior to final date of operation of Liveable Cities-supplied air quality sensors

One non-operational sensor is being replaced and returned to Liveable Cities for assessment. No information has been provided yet on why it failed.

4.3 Concentration Data

4.3.1 CIMCON, Lowestoft

4.3.1.1 Particulate Matter 2.5

Results for $PM_{2.5}$ concentrations from the sensors supplied by CIMCON is in Table 13 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 200 µg/m^3 for each boxplot.

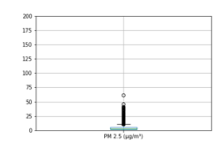
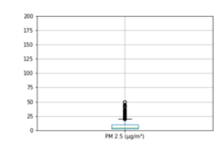
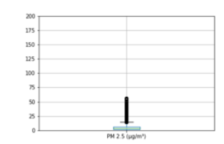
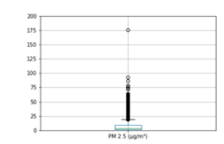
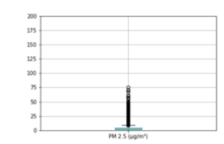
PM 2.5 (µg/m³)	Denmark Road	London Road	Royal Plain	Riverside	St John's Road
count	5049.0	2729.0	10384.0	8330.0	6198.0
mean	4.4	7.4	5.4	7.1	4.3
std	4.6	6.7	6.1	8.4	5.4
min	0.1	0.1	0.1	0.2	0.2
25%	1.7	2.9	1.7	2.0	1.5
50%	2.7	4.8	3.4	4.1	2.6
75%	5.3	9.7	6.8	8.8	4.7
max	61.3	49.6	56.1	175.5	75.8
					

Table 13: Summary statistics of measured $PM_{2.5}$ concentrations, CIMCON-supplied sensors, Lowestoft

The means for this nine month period of data do not exceed the annual mean objective for $PM_{2.5}$ of 25 µg/m^3 $PM_{2.5}$ (Section 2.2.3). It is not meaningful to compare individual values to the annual mean objective from a regulatory perspective, but as a guideline, between 0.55% and 3.36% of individual values were above 25 µg/m^3 $PM_{2.5}$, with the greatest numbers of those higher values at Riverside, London Road and Royal Plain. These three locations also had a higher mean than the other two locations, and a higher 75%ile.

Whilst there are significant caveats on the data examined due to the nature of this project, the observations from these sensors do not indicate exceedances in $PM_{2.5}$ concentrations. These observations are of interest to Suffolk County Council and East Suffolk District Council.

4.3.1.2 Particulate Matter 10

The sensors provided by CIMCON did not report PM_{10}.

4.3.1.3 Nitrogen Dioxide (NO_2)

Results for NO_2 concentrations from the sensors supplied by CIMCON is in Table 14 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 50 µg/m^3 for each boxplot.

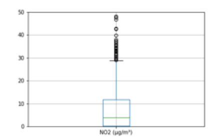
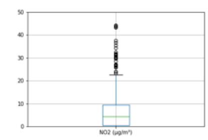
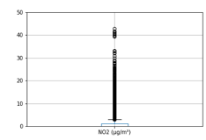
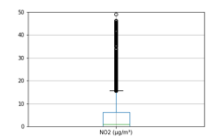
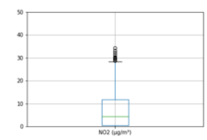
	Denmark Road	London Road	Royal Plain	Riverside	St John's Road
	NO2 (µg/m³)	NO2 (µg/m³)	NO2 (µg/m³)	NO2 (µg/m³)	NO2 (µg/m³)
count	1278.0	692.0	2627.0	2119.0	1561.0
mean	7.2	6.6	2.1	5.8	7.2
std	8.7	7.8	5.2	10.0	7.7
min	0.0	0.0	0.0	0.0	0.0
25%	0.2	0.4	0.0	0.0	0.4
50%	3.9	4.3	0.0	1.0	4.4
75%	11.6	9.4	1.2	6.2	11.6
max	48.0	44.2	42.8	49.0	34.2
					

Table 14: Summary statistics of measured nitrogen dioxide concentrations, CIMCON-supplied sensors, Lowestoft

Comparing these to annual mean objectives for NO_2 of 40µg/m^3 (Section 2.2.2), indicates that for these sensors, the mean of the measurements acquired during the nine months of operation, indicates the annual mean objective value was not exceeded. High values were also compared with the UK objective of 200 µg/m^3 as an hourly mean, which is not to be exceeded more than 18 times per year: during the nine months of observations, this value has not been exceeded once.

Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in NO_2 concentrations. These observations are of interest and use to Suffolk County Council and East Suffolk District Council.

4.3.1.4 Ozone (O_3)

Results for O_3 concentrations from the sensors supplied by CIMCON is in Table 15 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 100 µg/m^3 for each boxplot.

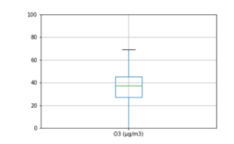
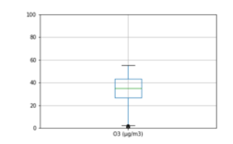
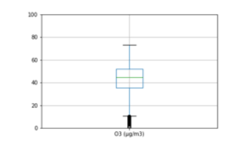
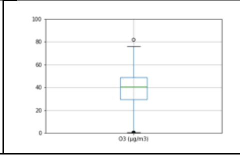
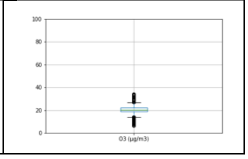
	Denmark Road	London Road	Royal Plain	Riverside	St John's Road
	O3 (μg/m3)	O3 (μg/m3)	O3 (μg/m3)	O3 (μg/m3)	O3 (μg/m3)
count	2220.0	692.0	2627.0	2119.0	1561.0
mean	36.1	33.9	42.4	37.9	20.2
std	12.3	11.7	12.3	14.8	3.2
min	0.0	0.1	0.5	0.0	6.6
25%	26.9	26.6	35.2	29.4	18.7
50%	37.4	35.0	44.6	40.6	20.3
75%	45.2	43.0	51.9	48.7	22.0
max	69.2	55.2	73.2	82.0	34.1
					

Table 15: Summary statistics of measured ozone concentrations, CIMCON-supplied sensors, Lowestoft

Comparing these to 8-hour mean objectives for O_3 of 100µg/m^3 (not to be exceeded more than ten times in a year (Section 2.2.4), indicates that for these sensors, during the nine months of operation, the 8-hour mean objective value was never exceeded.

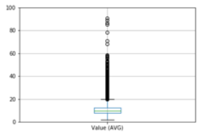
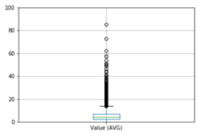
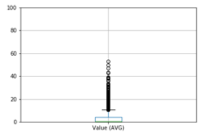
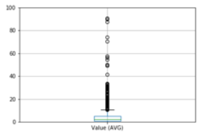
Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in NO_2 concentrations. These observations are of interest and use to Suffolk County Council and East Suffolk District Council.

4.3.2 SSE, Lowestoft

Particulate matter concentrations reported by SSE have units of µg/m^3, and other air quality analytes are reported with units of ppm. For chemical air quality parameters, these can be converted to concentrations using a standard adjustment, using recommended assumptions (DEFRA, 2014).

4.3.2.1 Particulate Matter <1

Sensors supplied by SSE were the only sensors to report PM_1, the concentration of particulates below 1 µm diameter. Summary statistics for PM_1 concentrations from the sensors supplied by SSE is in Table 16 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 100 µg/m^3 for each boxplot.

	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	Value (AVG)	*	Value (AVG)	Value (AVG)
count	2715.0	1637.0		1729.0	1506.0
mean	11.8	6.4		3.2	4.3
std	8.4	7.8		6.0	7.4
min	1.8	0.2		0.0	0.0
25%	7.8	2.2		0.0	0.9
50%	9.4	3.9		0.5	2.2
75%	12.5	6.9		4.2	4.9
max	90.6	85.0		52.9	90.8
			*		

**Sensor at Bloodmoor Road not included in analysis: only 8 measurements acquired, insufficient for statistical analysis.*

Table 16: Summary statistics of measured particulate matter concentrations, SSE-supplied sensors, Lowestoft, values in µg/m³

There are no national objectives for PM_1 to which these concentrations can be compared. It can be seen from these data that lowest concentrations of PM_1 are present at Lorne Park Road.

4.3.2.2 Particulate Matter 2.5

Results for $PM_{2.5}$ concentrations from the sensors supplied by SSE is in Table 17 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 650 µg/m^3 for each boxplot.

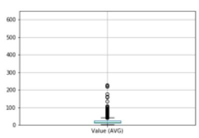
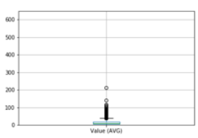
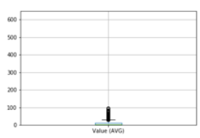
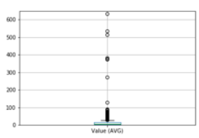
	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	Value (AVG)	Not calculated due to limited data	Value (AVG)	Value (AVG)
count	2733.0	1637.0		1729.0	1506.0
mean	20.4	14.0		7.8	12.4
std	16.8	15.1		12.1	32.3
min	3.1	0.3		0.0	0.0
25%	11.2	5.1		0.0	3.6
50%	15.5	9.0		2.1	7.0
75%	23.1	18.1		12.3	13.5
max	226.6	211.6		95.2	634.4
					

Table 17: Summary statistics of measured particulate matter 2.5 concentrations, SSE-supplied sensors, Lowestoft

Comparing these to annual mean objectives for $PM_{2.5}$ of 25 µg/m^3 (Section 2.2.3), indicates that for these sensors, the means of the measurements acquired during the five weeks of operation do not exceed the annual mean objective value. It is not meaningful to compare individual values to the annual mean objective from a regulatory perspective, but as a guideline, between 7.75% and 21.44% of individual values were above 25 µg/m^3 $PM_{2.5}$, with the greatest numbers of those higher values at Adastral Park, and highest values observed at Old Farm Road.

It can be seen from these data that highest concentrations of $PM_{2.5}$ are present at Old Farm Road, and lowest at Lorne Park Road (which also had lowest PM_1 concentrations).

4.3.2.3 Particulate Matter 10

Results for PM_{10} concentrations from the sensors supplied by SSE is in Table 18 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 1500 µg/m^3 for each boxplot.

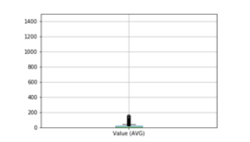
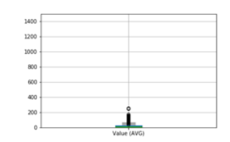
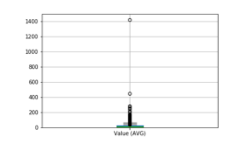
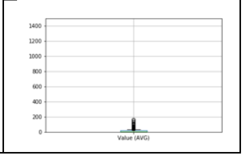
	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	**Value (AVG)**	Not calculated due to limited data	**Value (AVG)**	**Value (AVG)**
count	2733.0	1637.0		1729.0	1506.0
mean	13.3	21.2		14.1	13.0
std	14.9	22.0		42.1	14.7
min	1.0	0.6		0.0	0.0
25%	3.8	7.2		0.0	3.8
50%	7.9	15.0		4.8	7.5
75%	17.5	27.8		16.5	17.4
max	149.0	252.0		1418.0	166.0
					

Table 18: Summary statistics of measured particulate matter 10 concentrations, SSE-supplied sensors, Lowestoft

Comparing these to annual mean objectives for PM_{10} of 40 µg/m^3 PM_{10} (Section 2.2.3), indicates that for these sensors, the means of the measurements acquired during the five weeks of operation do not exceed the annual mean objective value. It is not meaningful to compare individual values to the 24-hr mean objective from a regulatory perspective, but as a guideline, between 2.26% and 8.06% of individual values were above 50 µg/m^3 PM_{10}, with the greatest numbers and highest values observed at Rougham Tower Avenue.

It can be seen from these data that highest mean and 75%ile concentrations of PM_{10} are present at Ashburnham Way, with a highest peak value at Lorne Park Road.

4.3.2.4 Nitric Oxide (NO)

Unlike other providers, SSE sensors reported nitric oxide (NO) concentrations rather than NO_2 concentrations. The Libelium Sensors supplied have options for fitting either NO or NO_2 sensors, and it is likely that an error was made in specifying the requested sensor units.

Results for NO concentrations from the sensors supplied by SSE is in Table 19 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 30 ppm for each boxplot.

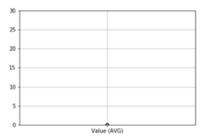
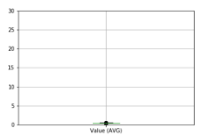
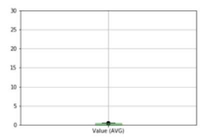
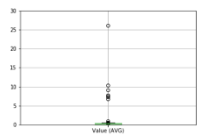
	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	Value (AVG)	Not calculated due to limited data	Value (AVG)	Value (AVG)
count	2715.0	1637.0		1729.0	1506.0
mean	0.0	0.4		0.2	0.1
std	0.0	0.0		0.0	0.9
min	0.0	0.3		0.0	0.0
25%	0.0	0.4		0.1	0.0
50%	0.0	0.5		0.2	0.0
75%	0.0	0.5		0.2	0.0
max	0.0	0.6		0.2	26.1
					

Table 19: Summary statistics of measured nitric oxide concentrations, SSE-supplied sensors, Lowestoft

There is no objective for NO (Section 2.2.2) for comparison. It is noted that with one exception, values at each sensor are close to, or at, not detected (0.0 ppm), as would be expected given the ephemeral nature of NO, which is rapidly oxidised to NO_2 (Section 2.2.2). At Old Farm Road, eight measurements of NO exceeded 1 ppm, which account for 0.5% of the total NO measurements at that location.

4.3.2.5 Ozone (O_3)

Summary statistics for O_3 concentrations from the sensors supplied by SSE is in

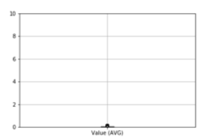
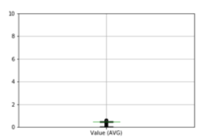
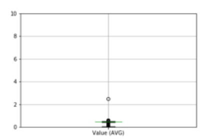
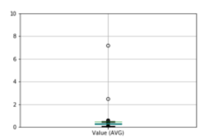
	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	Value (AVG)	Not calculated due to limited data	Value (AVG)	Value (AVG)
count	3468.000	1760.000		1841.000	1818.000
mean	0.013	0.460		0.013	0.241
std	0.017	0.034		0.069	0.202
min	0.000	0.247		0.000	0.000
25%	0.000	0.449		0.000	0.222
50%	0.006	0.466		0.000	0.296
75%	0.020	0.480		0.000	0.313
max	0.151	0.599		2.471	7.166
					

Table 20 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 10 ppm for each boxplot.

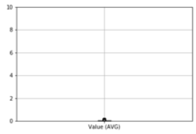
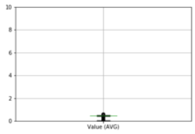
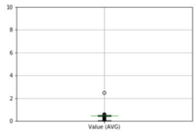
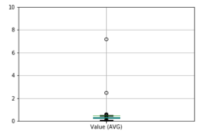
	Adastral Park	Ashburnham W	Bloodmoor Rd	Lorne Park Rd	Old Farm Road
	Value (AVG)	Value (AVG)	Not calculated due to limited data	Value (AVG)	Value (AVG)
count	3468.000	1760.000		1841.000	1818.000
mean	0.013	0.460		0.013	0.241
std	0.017	0.034		0.069	0.202
min	0.000	0.247		0.000	0.000
25%	0.000	0.449		0.000	0.222
50%	0.006	0.466		0.000	0.296
75%	0.020	0.480		0.000	0.313
max	0.151	0.599		2.471	7.166
					

Table 20: Summary statistics of measured ozone concentrations, SSE-supplied sensors, Lowestoft

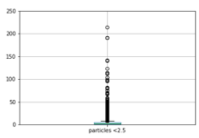
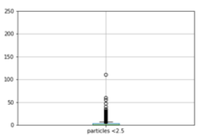
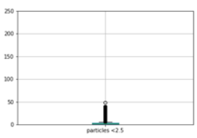
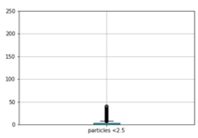
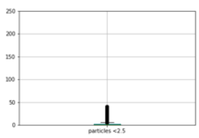
The UK objectives for O_3 of 100µg/m^3 as an 8-hr mean, not to be exceeded more than ten times in a year (Section 2.2.4), is equivalent to 0.051ppm (DEFRA, 2014). This indicates that for these sensors, during the period of operation, the 8-hour mean objective value appears to be exceeded on individual occasions at Ashburnham Way and Old Farm Road. An 8-hour mean has not been calculated. In comparison with the ranges of data from sensors supplied by CIMCON installed in Lowestoft, it is considered that these sensors are not calibrated accurately, and further investigation is required.

Whilst there are significant caveats on the data examined due to the nature of this project, it is considered that the observations from these sensors may indicate exceedances in O_3 concentrations. These observations are of interest and use to Suffolk County Council and East Suffolk District Council.

4.3.3 Telensa

4.3.3.1 Particulate Matter 2.5

Results for $PM_{2.5}$ concentrations from the sensors supplied by Telensa is in

	AQY BC-1051	AQY BC-1048	AQY BC-1052	AQY BC-1053	AQY BE-1231
	particles <2.5	particles <2.5	particles <2.5	particles <2.5	particles <2.5
count	283463.0	322694.0	112115.0	137574.0	82199.0
mean	3.6	2.6	3.2	3.0	2.3
std	4.6	2.9	4.7	2.9	3.3
min	0.0	0.0	0.0	0.0	0.0
25%	1.1	0.9	1.1	1.1	0.5
50%	2.0	1.6	1.9	2.0	1.0
75%	4.1	3.3	3.2	3.7	2.4
max	213.5	110.7	48.6	40.8	40.1
					

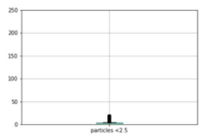
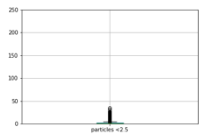
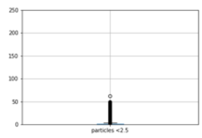
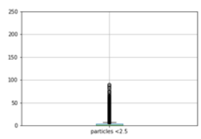
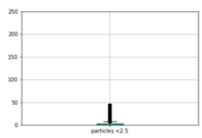
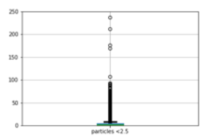
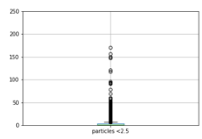
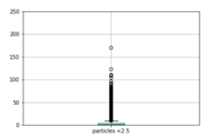
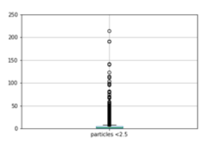
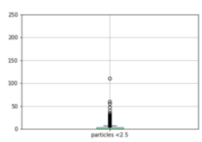
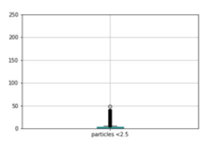
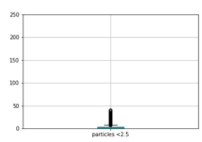
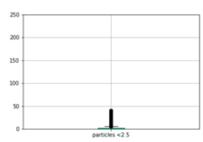
	AQY-BA-467A	AQY BC-1054	AQY BC-1040		
	particles <2.5	particles <2.5	particles <2.5		
count	80212.0	240590.0	229570.0		
mean	2.8	1.9	1.2		
std	1.5	2.4	2.9		
min	0.0	0.0	0.0		
25%	1.9	0.7	0.2		
50%	2.4	1.2	0.5		
75%	3.2	2.3	1.3		
max	18.8	34.6	62.2		
					

Table 21 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 250 µg/m^3 for each boxplot.

	AQY BC-1037	AQY BC-1039	AQY BC-1043	AQY BC-1047	AQY BC-1050
	particles <2.5	particles <2.5	particles <2.5	particles <2.5	particles <2.5
count	369206.0	261848.0	368060.0	156652.0	342490.0
mean	2.7	3.2	3.5	2.4	4.3
std	3.3	4.0	4.1	3.3	5.5
min	0.0	0.0	0.0	0.0	0.0
25%	0.8	1.1	1.1	0.7	1.5
50%	1.4	2.0	2.0	1.2	2.5
75%	3.1	3.7	4.3	3.0	4.8
max	89.6	44.2	237.2	170.3	170.0
					

	AQY BC-1051	AQY BC-1048	AQY BC-1052	AQY BC-1053	AQY BE-1231
	particles <2.5	particles <2.5	particles <2.5	particles <2.5	particles <2.5
count	283463.0	322694.0	112115.0	137574.0	82199.0
mean	3.6	2.6	3.2	3.0	2.3
std	4.6	2.9	4.7	2.9	3.3
min	0.0	0.0	0.0	0.0	0.0
25%	1.1	0.9	1.1	1.1	0.5
50%	2.0	1.6	1.9	2.0	1.0
75%	4.1	3.3	3.2	3.7	2.4
max	213.5	110.7	48.6	40.8	40.1
					

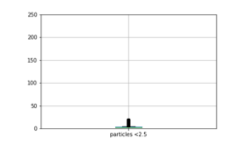
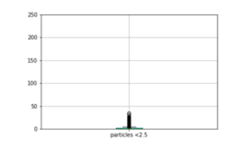
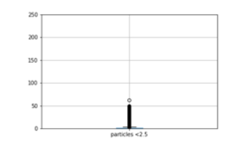
	AQY-BA-467A	AQY BC-1054	AQY BC-1040		
	particles <2.5	particles <2.5	particles <2.5		
count	80212.0	240590.0	229570.0		
mean	2.8	1.9	1.2		
std	1.5	2.4	2.9		
min	0.0	0.0	0.0		
25%	1.9	0.7	0.2		
50%	2.4	1.2	0.5		
75%	3.2	2.3	1.3		
max	18.8	34.6	62.2		
					

Table 21: Summary statistics of measured particulate matter concentrations, Telensa-supplied sensors, Ipswich

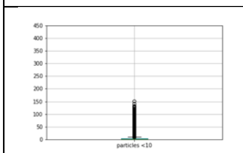
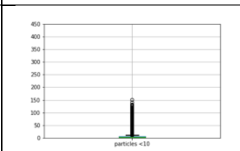
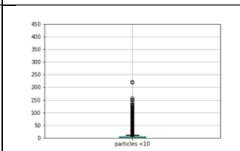
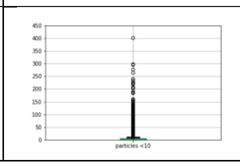
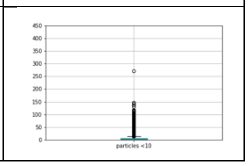
Comparing these to annual mean objectives for $PM_{2.5}$ of 25 µg/m^3 $PM_{2.5}$ (Section 2.2.3), indicates that for these sensors, over the measurements acquired during the year analysed, the annual mean objective value was not exceeded as a mean. It is not meaningful to compare individual values to the annual mean objective from a regulatory perspective, but as a guideline, between 0% and 1.7% of individual values were above 25 µg/m^3 $PM_{2.5}$, with the greatest numbers of those higher values at sensors AQY BC-1050 and AQY BC-1052.

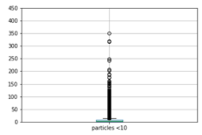
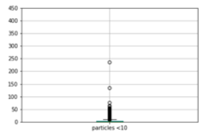
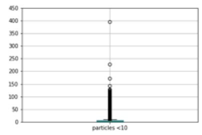
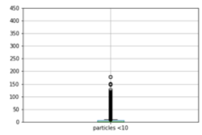
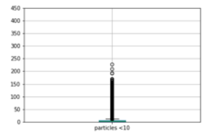
Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in $PM_{2.5}$ concentrations. These observations are of interest and use to Suffolk County Council and Ipswich Borough Council.

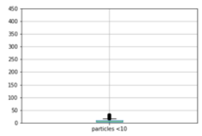
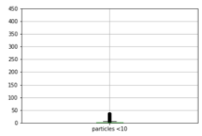
4.3.3.2 Particulate Matter 10

*Results for PM_{10} concentrations from the sensors supplied by Telensa is in *Sensor AQY BC-1040 had over 58% of reported PM_{10} values = 0; it is therefore removed from analysis*

Table 22 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 450 µg/m^3 for each boxplot.

	AQY BC-1037	AQY BC-1039	AQY BC-1043	AQY BC-1047	AQY BC-1050
	particles <10	particles <10	particles <10	particles <10	particles <10
count	369206.0	261848.0	368060.0	156652.0	342490.0
mean	4.4	4.8	4.2	3.7	5.5
std	7.5	5.8	5.5	5.8	6.3
min	0.0	0.0	0.0	0.0	0.0
25%	1.2	1.7	1.2	1.0	2.0
50%	2.4	3.2	2.6	2.2	3.9
75%	4.5	6.0	5.0	4.2	6.7
max	151.0	76.9	221.2	401.9	270.1
					

particles <10	AQY BC-1051	AQY BC-1048	AQY BC-1052	AQY BC-1053	AQY BE-1231
count	283463.0	322694.0	112115.0	137574.0	82199.0
mean	6.9	3.6	5.2	4.2	6.4
std	8.1	3.8	6.6	5.2	9.3
min	0.0	0.0	0.0	0.0	0.0
25%	2.9	1.3	2.3	1.4	2.5
50%	4.8	2.6	3.6	2.9	4.2
75%	7.7	4.7	5.7	5.2	6.7
max	349.6	235.6	395.7	177.7	228.5
					

particles <10	AQY-BA-467A	AQY BC-1054	AQY BC-1040		
count	80212.0	240590.0	See note at * below		
mean	7.9	2.3			
std	4.2	3.3			
min	0.0	0.0			
25%	5.0	0.4			
50%	7.0	1.3			
75%	10.0	2.8			
max	31.0	36.0			
					

**Sensor AQY BC-1040 had over 58% of reported PM_{10} values = 0; it is therefore removed from analysis*

Table 22: Summary statistics of measured particulate matter 10 concentrations, Telensa-supplied sensors, Ipswich

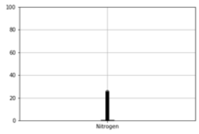
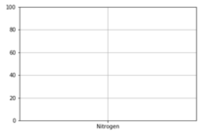
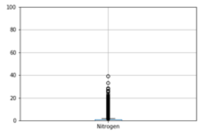
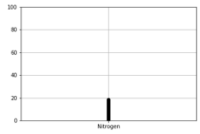
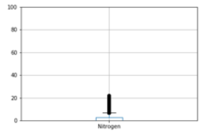
Comparing these to annual mean objectives for PM_{10} of 40 µg/m^3 PM_{10} (Section 2.2.3), indicates that for these sensors, over the measurements acquired during period of operation analysed, the means of the observed data do not exceed the annual mean objective value. It is not meaningful to compare individual values to the 24-hr mean objective from a regulatory perspective, but as a guideline, between 0% and 1% of individual values were above 50 µg/m^3 PM_{10}, with the greatest numbers and highest values observed at sensor AQY BE-1231.

Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in PM_{10} concentrations. These observations are of interest and use to Suffolk County Council and Ipswich Borough Council.

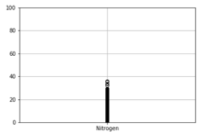
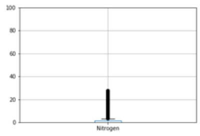
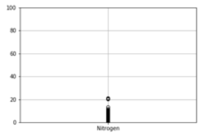
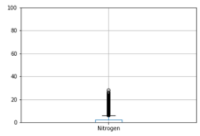
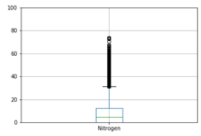
4.3.3.3 Nitrogen Dioxide (NO_2)

Results for NO_2 concentrations from the sensors supplied by Telensa is in Table 23 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 100 µg/m^3 for each boxplot.

Nitrogen	AQY BC-1037	AQY BC-1039	AQY BC-1043	AQY BC-1047	AQY BC-1050
count	369206.0	261848.0	368060.0	156652.0	342490.0
mean	1.4	0.0	1.2	1.3	1.8
std	3.0	0.0	2.6	2.9	3.1
min	0.0	0.0	0.0	0.0	0.0
25%	0.0	0.0	0.0	0.0	0.0
50%	0.0	0.0	0.0	0.0	0.0
75%	0.2	0.0	0.7	0.1	2.8
max	25.1	0.0	39.2	18.2	22.0

Nitrogen	AQY BC-1051	AQY BC-1048	AQY BC-1052	AQY BC-1053	AQY BE-1231
count	283463.0	322694.0	112115.0	137574.0	82199.0
mean	0.6	1.3	0.0	1.7	7.6
std	2.4	2.6	0.3	3.2	10.5
min	0.0	0.0	0.0	0.0	-23.1
25%	0.0	0.0	0.0	0.0	0.0
50%	0.0	0.0	0.0	0.0	4.8
75%	0.0	1.4	0.0	2.5	12.5
max	36.1	27.4	21.2	28.1	73.8

Nitrogen	AQY-BA-467A	AQY BC-1054	AQY BC-1040
count	80212.0	240590.0	229570.0
mean	-16.3	4.4	0.1
std	12.2	4.5	0.7
min	-34.0	0.0	0.0
25%	-26.8	0.0	0.0
50%	-21.7	3.3	0.0
75%	-3.0	8.1	0.0
max	57.6	36.9	18.3

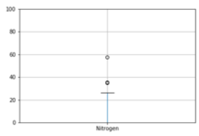
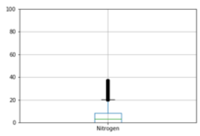
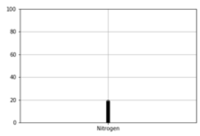




Table 23: Summary statistics of measured NO_2 concentrations, Telensa-supplied sensors, Ipswich
Note: 50%ile = median, not the same as the mean; many reported NO_2 values were zero.

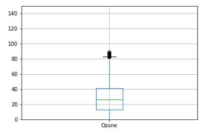
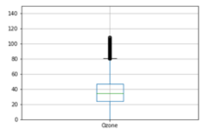
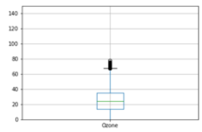
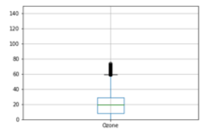
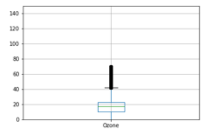
Comparing these to annual mean objectives for NO_2 of $40 \mu g/m^3$ (Section 2.2.2) which is equivalent to 20.9 ppb (converted applying DEFRA, 2014), indicates that for these sensors, the mean of the measurements acquired during the twelve months analysed, the annual mean

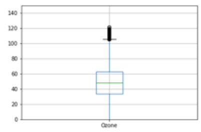
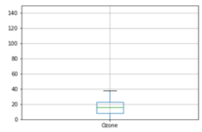
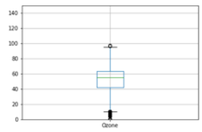
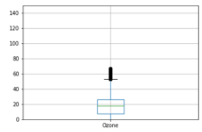
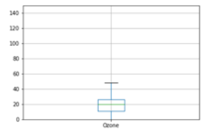
objective value was not exceeded. High values were also compared with the UK objective of 200 $\mu g/m^3$ (104.6 ppb) as an hourly mean, which is not to be exceeded more than 18 times per year: during the twelve months of observations, this value has not been exceeded.
Data from sensor BA-467A have provided unreliable results, with negative values. Negative values have not been observed from other sensors.

Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in NO_2 concentrations. These observations are of interest and use to Suffolk County Council and Ipswich Borough District Council.

4.3.3.4 Ozone (O_3)

Results for O_3 concentrations from the sensors supplied by Telensa are in Table 24 below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 150 ppb for each boxplot.

Ozone	AQY BC-1037	AQY BC-1039	AQY BC-1043	AQY BC-1047	AQY BC-1050
count	369206.0	261848.0	368060.0	156652.0	342490.0
mean	27.2	34.5	24.9	19.5	16.9
std	17.8	18.3	14.3	13.7	10.0
min	0.0	-4.7	0.0	0.0	0.0
25%	13.3	23.9	14.0	8.2	10.4
50%	26.4	34.8	24.2	19.6	17.4
75%	41.1	46.7	35.5	28.7	23.0
max	89.0	108.5	77.8	73.7	69.6
					

Ozone	AQY BC-1051	AQY BC-1048	AQY BC-1052	AQY BC-1053	AQY BE-1231
count	283463.0	322694.0	112115.0	137574.0	82199.0
mean	47.8	15.4	51.8	17.4	18.3
std	20.3	9.6	15.8	11.7	9.8
min	0.0	0.0	0.0	0.0	0.0
25%	34.1	8.3	42.3	7.8	11.0
50%	48.4	15.6	55.1	17.6	19.9
75%	62.6	22.7	63.7	25.9	26.1
max	121.3	37.7	97.5	66.9	48.6
					

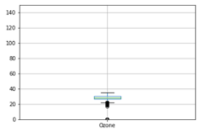
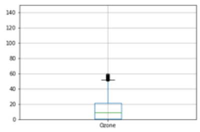
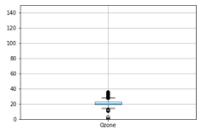
AQY-BA-467A	AQY BC-1054	AQY BC-1040		
Ozone	Ozone	Ozone		
count 80212.0	count 240590.0	count 229570.0		
mean 28.2	mean 12.5	mean 21.4		
std 2.4	std 12.6	std 3.0		
min 0.0	min 0.0	min 0.0		
25% 26.8	25% 0.6	25% 19.3		
50% 28.3	50% 9.2	50% 20.8		
75% 30.1	75% 21.2	75% 22.8		
max 35.0	max 57.8	max 35.7		
				

Table 24: Summary statistics of measured ozone concentrations, Telensa-supplied sensors, Ipswich

The UK objectives for O_3 of 100µg/m^3 as an 8-hr mean, not to be exceeded more than ten times in a year (Section 2.2.4), is equivalent to 51ppb (conversion using DEFRA, 2014). However, in only two cases did the 75%ile exceed the objective. Comparing individual values to 8-hour mean objectives for O_3 of 51ppb indicates that for these sensors, during the twelve months analysed, the 8-hour mean objective value was exceeded by individual values at most locations, with most exceedances at sensors AQY BC-1052 and AQY BC-1051. These have not been assessed as eight-hour means.

Whilst there are significant caveats on the data examined due to the nature of this project, it is not considered that the observations from these sensors indicate exceedances in O_3 concentrations. These observations are of interest and use to Suffolk County Council and Ipswich Borough Council.

4.3.3.5 Mean values for all analytes

Mean values gathered across the year for each analyte for each sensor are included in Table 25.

Sensor	Latitude	Longitude	PM2.5	PM10	NO2	O3
1037	52.08124	1.1247121	2.7	4.4	1.4	27.2
1039	52.0533368	1.1450536	3.2	4.8	0	34.5
1043	52.061512	1.1436098	3.5	4.2	1.2	24.9
1047	52.070328	1.1339986	2.4	3.7	1.3	19.5
1050	52.059998	1.1475604	4.3	5.5	1.8	16.9
1051	52.057896	1.278854	3.6	6.9	0.6	47.8
1048	52.05298	1.1622314	2.6	3.6	1.3	15.4
1052	52.056995	1.27893	3.2	5.2	0	51.8
1053	52.05777	1.1632092	3	4.2	1.7	17.4
1231	52.0542	1.1434	2.3	6.4	7.6	18.3
467A	52.0542	1.1434	2.8	7.9	-16.3	28.2
1054	52.059617	1.1541932	1.9	2.3	4.4	12.5
1040	52.058537	1.1584599	1.2	1	0.1	21.4

Table 25: Mean values for each analyte, Telensa-supplied sensors in Ipswich

4.3.3.6 Protective Housing

Aeroqual AQY1 units supplied by Telensa were provided mounted in a protective housing as shown in Figure 4 which compares the same device as supplied by Telensa with that as supplied by CIMCON (photos reproduced from Figure 10 and Figure 8).

Figure 4: Aeroqual AQY1 units, as supplied by Telensa (left) with additional housing and CIMCON (right) mounted directly.

These sensors were installed in different places so a direct comparison of measured values cannot be made. However, the locations of installation were similar, and modelled values from DEFRA background mapping data are comparable (Ipswich: range 9.2 – 11.1 µg/m^3; Waveney which includes Lowestoft: range 7.9 – 11.8 µg/m^3 (DEFRA, 2021a)), which would indicate that similar mean values would be expected. However, comparing mean values of PM2.5 between these two sensors reveals lower values measured in sensors in Ipswich supplied by Telensa (mean values between 1.2 and 4.3 µg/m^3) compared with those supplied by CIMCON (mean values between 4.3 and 7.4 µg/m^3). This may be due to a number of reasons, one of which may be restriction in air flow created by the additional housing. It is recommended that units are installed in accordance with manufacturers' design expectations.

4.3.4 Liveable Cities, Bury St Edmunds

4.3.4.1 PM2.5

Summary statistics for $PM_{2.5}$ concentrations from the sensors supplied by Liveable Cities between 25 September 2021 and 31 October 2021 is below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 200 µg/m^3 for each boxplot. Eight measurements at Rougham Tower Avenue exceeded 200 µg/m^3 with a maximum of 526.7 µg/m^3, and are not shown in these boxplots.

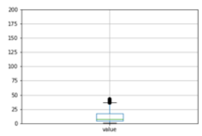
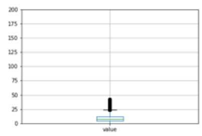
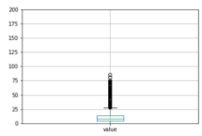
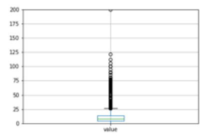
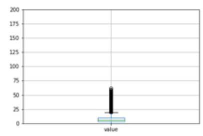
	Allwin Road	Appledown Drive	Ortewell Road	Rougham Tower	The Daubentons
	value	value	value	value	value
count	756.0	4038.0	2256.0	3053.0	2693.0
mean	11.9	9.1	10.6	11.8	8.2
std	10.5	6.2	10.6	19.4	7.5
min	0.5	0.0	0.0	0.1	0.3
25%	4.4	4.6	4.2	4.7	3.9
50%	7.5	7.6	8.5	8.4	6.3
75%	17.3	12.3	13.7	13.6	10.1
max	42.9	42.5	85.4	526.7	61.9
					

Table 26: Summary statistics of measured $PM_{2.5}$ concentrations, Liveable Cities-supplied sensors, Bury St Edmunds

Comparing these to annual mean objectives for $PM_{2.5}$ of 25 µg/m^3 $PM_{2.5}$ (Section 2.2.3), indicates that for these sensors, over the measurements acquired during the five weeks of operation analysed, the means of the observed data do not exceed the annual mean objective value. It is not meaningful to compare individual values to the annual mean objective from a regulatory perspective, but as a guideline, between 1.8% and 15.3% of individual values were above 25 µg/m^3 $PM_{2.5}$, with the greatest numbers of those higher values at Allwin Road, and highest values observed at Rougham Tower Avenue.

Whilst there are significant caveats on the data examined due to the nature of this project, it is considered that the observations from these sensors may indicate potential exceedances in $PM_{2.5}$ concentrations. These observations are of interest to Suffolk County Council and West Suffolk District Council, and have been discussed with West Suffolk District Council.

4.3.4.2 PM10

Summary statistics for PM_{10} concentrations from the sensors supplied by Liveable Cities is in below, presented as summary statistics tables, and visually as boxplots. For easy comparison, the boxplot range has been set to a maximum of 500 µg/m^3 for each boxplot. Twenty seven measurements at Rougham Tower Avenue, twelve at Orttewell Road and one at The Daubentons exceeded 500 µg/m^3, with a maximum of 5312.8 µg/m^3, and are not shown in these boxplots.

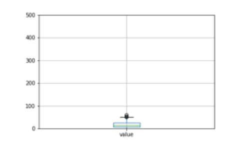
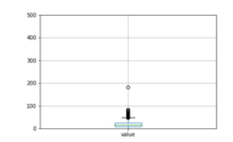
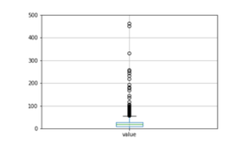
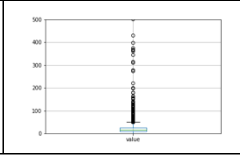
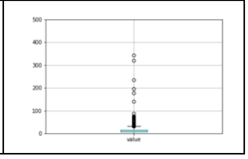
	Allwin Road	Appledown Drive	Orttewell Road	Rougham Tower	The Daubentons
	value	value	value	value	value
count	756.0	4039.0	2257.0	3053.0	2693.0
mean	17.6	18.6	25.6	34.9	13.9
std	12.5	13.0	62.0	193.6	17.9
min	0.6	0.0	0.0	0.1	0.3
25%	7.9	9.4	9.6	9.5	6.9
50%	14.0	15.1	17.4	15.7	11.1
75%	25.1	25.2	28.4	25.8	17.0
max	59.0	181.9	1205.9	5312.8	542.0
					

Table 27: Summary statistics of measured PM_{10} concentrations, Liveable Cities-supplied sensors, Bury St Edmunds

Comparing these to annual mean objectives for PM_{10} of 40 μg/m^3 PM_{10} (Section 2.2.3), indicates that for these sensors, over the measurements acquired during the five weeks of operation analysed, the means of the observed data do not exceed the annual mean objective value. It is not meaningful to compare individual values to the 24-hr mean objective from a regulatory perspective, but as a guideline, between 0.53% and 6.16% of individual values were above 40 μg/m^3 PM_{10}, with the greatest numbers and highest values observed at Rougham Tower Avenue.

Elevated PM_{10} values were identified occurring on 8 October 2021. An initial peak was observed at Rougham Tower Avenue and Orttewell Road commencing at 02:07 and peaking at 02:22 or 02:37, with peak concentrations of 1421.5 μg/m^3 and 853.2 μg/m^3. At Orttewell Road this had reduced to baseline by 03:57, and at Rougham Tower Avenue by 04:37. Concentrations increased again at 05:52 (Orttewell Road) and 06:22 (Rougham Tower Avenue) to reach maximums of 256.9 μg/m^3 at 06:37 at Orttewell Road and 5312.8 μg/m^3 at 09:08 at Rougham Tower Avenue. These reduced to around baseline at 11:37am. Elevated concentrations were seen again the following morning, between 01:37am and 09:22am at Orttewell Road with a maximum of 791.8 μg/m^3, and 12:37am and 10:07am at Rougham Tower Avenue with a maximum of 2215.2 μg/m^3.

A source of these elevated PM_{10} concentrations on 8 and 9 October was explored. They were discussed with Matt Axton (Environment Officer, West Suffolk Council) and with Liveable Cities, the supplier. Whilst there is some local industry and construction that may have the potential to cause elevated air quality parameters, but no source can be confidently identified with the current information. Following discussion with Matt Axton (West Suffolk Council) and the supplier (Liveable Cities and their sensor supplier), it is considered likely that high relative humidity associated with observed fog on these occasions may be elevating apparent particle matter concentrations, as detailed in Section 2.2.3. Persistent fog was reported on 8 and 9 October 2021 (Time and Date, 2021). This is being further explored by the supplier.

During this period, the sensors were not reporting relative humidity (RH) measurements made at the sensor. In an attempt to identify whether these elevated PM_{10} values co-occur with elevated RH, measured relative humidity values were obtained from the closest SCC-access weather station (A14 Haughley New Street). This provided RH values of up to 96%, with values over 94% on eighteen occasions during the month, and therefore was not considered useful to identify elevated RH at the sensor location.

Sensor configuration has now been adjusted to record RH values in order to identify whether these apparent PM_{10} peaks correlate with elevated RH, but data has not been gathered in time for inclusion in this report. The supplier and manufacturer are undecided how to manage this potential interference. It is recommended that comparison and investigation into the impact of RH on the PM values measured by this sensor continues. This is discussed further in Section 6.2.3.

The impact of elevated RH (above 85%) on other sensors from the same manufacturer (Alphasense) has been researched (Crilley *et al.*, 2018), and correction for ambient RH recommended.

Whilst there are significant caveats on the data examined due to the nature of this project, it is considered that the observations from these sensors may indicate potential exceedances in PM_{10} concentrations, though these may be an artefact caused by elevated relative humidity. These observations are of interest and use to Suffolk County Council and West Suffolk District Council, and have been discussed with West Suffolk District Council.

4.3.4.3 Nitrogen Dioxide (NO_2)
The sensors provided by Liveable Cities did not report NO_2.

4.3.4.4 Ozone (O_3)
The sensors provided by Liveable Cities did not report O_3.

4.3.5 Further data exploration
4.3.5.1 Comparison with published modelled air quality background mapping data
Further exploration of $PM_{2.5}$ concentrations has been undertaken.

There are no current particulate matter measurements made in Suffolk. DEFRA publish modelled air quality data in background mapping data, with values for specific locations presented as a single value for the year (DEFRA, 2021a). For 2021, modelled values of $PM_{2.5}$ in Ipswich range of modelled values from 9.3 µg/m^3 to 11.1 µg/m^3, with a mean of 10.2 µg/m^3.

This has revealed that measured values from sensors in this project are significantly lower than expected. Mean $PM_{2.5}$ measured across all the sensors is 2.9 µg/m^3. It was postulated that analysis of measured values may be impacted by values of zero that are artefacts rather than actual measurements, so this analysis was repeated with using only measurements greater than zero, in which case a mean measured $PM_{2.5}$ across all Telensa-provided sensors is calculated. It is considered likely that the measured values are inaccurate due to miscalibration of the sensors, though there may also be a difference between modelled values and actual values.

Additionally, mean $PM_{2.5}$ values were calculated for each month analysed, for one sensor (BC-1050). This indicates a range in values, but not a significant decrease during the period analysed.

Oct 20	Nov 20	Dec 20	Jan 21	Feb 21	Mar 21	Apr 21	May 21	Jun 21	Jul 21	Aug 21	Sep 21
2.6	7.9	4.5	8.2	-	28.7	5.2	3.1	3.2	3.5	2.2	4.8

Table 28: Mean measured $PM_{2.5}$ values for sensor BC-1050 for each month

4.4 Adastral Park Comparison

Installation of air quality sensors from two suppliers very close to each other at Adastral Park has enabled comparison of values measured by these sensors. This comparison has focused on $PM_{2.5}$ and PM_{10} as the key analytes of interest. These sensors were:

- Aeroqual AQY1 sensors BC-1051 and BC-1052 installed by Telensa
- Libellium sensor 'Adastral Park' installed by SSE

Comparing dates for which data is available indicates that the period of concurrent operation is 9 June 2021 (when SSE sensors were installed) to 21 July 2021 (when Telensa sensors ceased operating).

Visual inspection of timeseries for this period reveals that measurements from the SSE-installed sensor were much higher than from the Telensa-installed sensors (Figure 5).

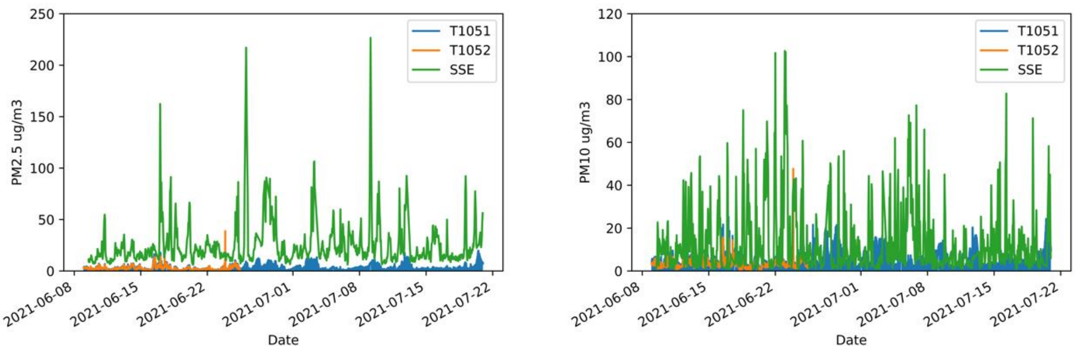


Figure 5: Measured $PM_{2.5}$ and PM_{10} at Adastral Park June – July 2021

However, comparison of data from this period including the longer period preceding in which only sensors from Telensa were operational indicates that the data from the Telensa sensors was lower during this period than previously. This could be because the sensors had become incorrectly calibrated over their longer period of operation, and require maintenance.

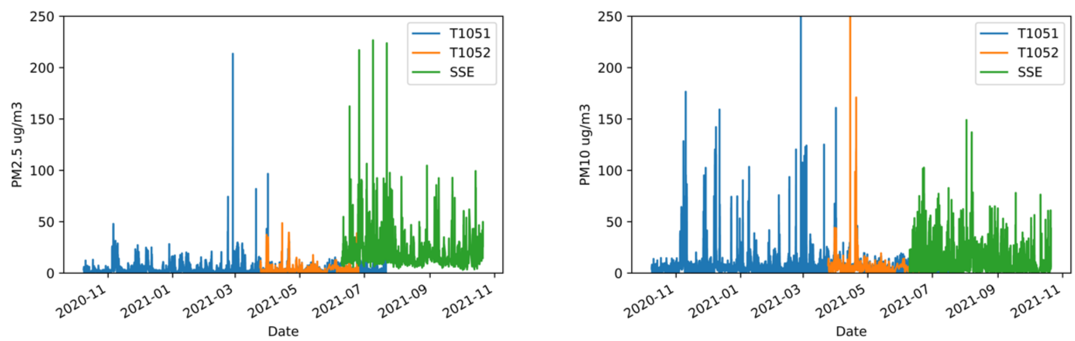


Figure 6: Measured $PM_{2.5}$ and PM_{10} at Adastral Park, October 2020 – October 2021

Descriptive statistics for the entire period of operation of these sensors are included in Figure 7. These indicate only approximately comparable results from the two sensors from Telensa, and significant differences to the measurements from the sensors from SSE.

This is attributed to calibration issues: the high average values measured from the SSE sensor far exceed the modelled particulate matter concentrations, and the low average values from the sensors supplied by Telensa during the period of comparison fall below the modelled particulate matter concentrations. Importance of calibration for absolute values is discussed further within the recommendations for this report.

BC-1051 $PM_{2.5}$

	particles <2.5
count	28187.0
mean	3.5
std	2.9
min	0.0
25%	1.6
50%	2.6
75%	4.4
max	20.8

BC-1052 $PM_{2.5}$

	particles <2.5
count	23092.0
mean	2.5
std	2.1
min	0.1
25%	1.2
50%	2.0
75%	3.1
max	38.8

SSE Adastral Park $PM_{2.5}$

	Value (AVG)
count	880.0
mean	24.6
std	21.1
min	6.0
25%	13.1
50%	18.0
75%	27.8
max	226.6

BC-1051 PM_{10}

	particles <10
count	28187.0
mean	5.1
std	3.7
min	0.0
25%	2.7
50%	4.1
75%	6.5
max	33.1

BC-1052 PM_{10}

	particles <10
count	23092.0
mean	3.6
std	2.3
min	0.1
25%	2.2
50%	3.2
75%	4.4
max	47.7

SSE Adastral Park PM_{10}

	Value (AVG)
count	880.0
mean	13.8
std	16.1
min	1.0
25%	3.7
50%	7.3
75%	17.0
max	102.6

Figure 7: Summary statistics of measured PM_{10} concentrations, Adastral Park

4.5 Inspection of installed units

A number of each installed units were visited in December 2021 for a visual inspection. As the units were installed high on lighting columns, close inspection was not possible. Photography was used to reveal visually resilience of the devices. Photographs and comments are included here.

4.5.1 CIMCON

Inspected units were installed in January 2021 and visited in December 2021, a period of eleven months. From ground level, no concerns were noted.

Figure 8: Aeroqual Air Quality Sensors supplied by CIMCON, after eleven months of operation (photo: H Steventon)

4.5.2 SSE

Inspected units were installed in June 2021, and visited in December 2021, a period of seven months. From ground level, no concerns were noted.

Figure 9: Libelium Air Quality Sensor supplied by SSE, after seven months of operation (photo: H Steventon)

4.5.3 Telensa

Units from Telensa had been installed for the longest period, with the inspected units installed in January 2020, nearly two years before inspection.

The Aeroqual AQY1 sensor was installed within an additional cage-like protective housing. The powder coating on the protective housing has not proved resilient to conditions and is visually degenerated (Figure 10). It is also considered that the structure of the housing may be restricting air flow to the unit and potentially impacting on the measured air quality parameters (Section 4.3.3.6).

Figure 10: Aeroqual AQY1 supplied by Telensa, after 23 months of operation (photos: H Steventon)

4.5.4 Liveable Cities

Inspected units were installed in September 2021 and visited in November 2021, a period of two months. As they are mounted on top of streetlight lanterns, they are not easily visible from ground level.

Figure 11: Node-mounted air quality sensor, supplied by Liveable Cities, after two months of operation (photos: H Steventon)

5 Financial Assessment / Business Case Inputs

Air quality monitoring for NO_2 is a regulatory requirement, and other air quality analytes are not currently measured in Suffolk. This economic analysis focuses on costs of service provision. Key benefits for increased air quality monitoring are environmental and health related, and the associated financial value of such benefits is not quantified in this report.

5.1 Current cost of service

Guideline costs for standard NO_2 diffusion tube analysis has been obtained from Suffolk's district and borough council environment officers, who provide the budget and resource for this work. Diffusion tubes cost approximately £3.00 to £3.30 each, and are operated for a month each. A year of diffusion tube analysis costs £36 to £40 in tubes and analysis, plus officer time to replace them, typically one person-day per council per month. There are approximately 300 diffusion tube sites in Suffolk. This corresponds to £11,000 pa plus £24,000 in officer time (assuming £500 per local authority per month), so £35,000 per year for 300 locations.

Diffusion tube monitoring is extremely cheap per location, and therefore heavily relied upon compared with other monitoring methods.

DEFRA approved monitoring stations are much more expensive, and therefore rarely installed. One is in central Ipswich. Recent indicative quotes for reference analysers are around £23,000-£30,000 capital cost and £10,000 per year operational cost for one location.

District and borough councils do not have additional budget for further air quality analysis.

Environment Officers state that they have very limited time for additional assessment of air quality data, and so any additional results must be really easy for them to identify exceedances and items of interest.

5.2 Indicative costs of sensor provision

Due to the variety of sources and funding mechanisms encountered during this trial, a range of indicative costs for additional real-time particulate matter monitoring are presented here.

- Costs of approximately £4000-£6000 per sensor have been encountered in this project, to which annual maintenance and calibration similar to those below should be added for ongoing maintenance (around £2000 per sensor per year).
- Recently quoted costs for easily-fitted NEMA-compatible air quality sensors are £720 per sensor, with £600 per year operational costs. Calibration would be additional to that. These sensors have been found to be really easily installed by street lighting operatives.
- Guideline costs provided to local environment officers for installation of similar sensors are: approximately £5000 capital costs per sensor to supply, calibrate and install, plus approximately £2000 per sensor per year for data management and reporting.

5.3 Financial comparison

There is currently no comparable local authority service, so the sensors trialled within this project cannot be compared with existing costs. They are significantly more expensive than diffusion tube monitoring, but offer analytes, time-granulated data, and real-time access to data that are not available from existing services, at a cost significantly lower than a reference analyser. However, further attention is required to ensure that calibration is fit for purpose.

It is possible that wider installation across Suffolk could provide an ongoing base of particulate matter data that could be useful for a range of purposes for environmental and human health benefits.

5.4 Environmental and social analysis

As described in Section 2.2 and 2.4 air quality monitoring is considered an essential part of environmental monitoring. Associated planning and campaigns encourage environmental benefits with positive consequences to human health.

Conversely, the provision of Internet of Things and "Smart City" sensors in general also has some environmental disbenefits (Alsamhi *et al.*, 2019; Yang *et al.*, 2021) including: the manufacture, delivery and installation of the sensors; the energy required for their ongoing operation; energy for their data communication, management, storage and access; and end-of-life disposal.

Use of air quality sensors could provide social and health benefits if decisions made based on the data received enable a reduction in air quality pollution, via planning decision making and / or public awareness behavioural campaigns.

5.5 Innovation Portfolio Builder

Proving Services have supplied an Innovation Portfolio Builder; air quality monitoring is not an identified option. Therefore, the potential impact for installing air quality sensors has not been assessed using this tool.

6 Conclusions and Recommendations

6.1 Conclusions

This report concludes that the provision of lower-cost air quality sensors measuring particulate matter as $PM_{2.5}$ and PM_{10} to inform Suffolk County Council and district and borough councils is beneficial:

- Quantifying and understanding air quality impacts across Suffolk would enable a more informed approach to air quality management decisions and public action campaigns. These could include transport, industry and burning as sources of air pollution, in addition to impacts from the sea and from long-scale transportation from beyond Suffolk.
- Air quality including particulate matter has a significant impact on public health and is of increasing concern; these health impacts also lead to (direct and indirect) economic impacts.
- Presence of particulate matter sensors could enable local regulatory bodies to identify times and sources of air quality analytes, and therefore respond to incidents and support action campaigns with greatest impact.

This research assessed the provision of sensors to measure NO_2. NO_2 measurements are made across the county for regulatory purposes. The sensors included in this project do not compete with existing sensors for regulatory measurements for two reasons:

- Sensors assessed in this project are not calibrated to required standards for LAQM reporting to DEFRA, which is key for regulatory NO_2 monitoring.

- Sensors assessed in this project are significantly more expensive than current monitoring solutions, and unlikely to become cost effective in the foreseeable future for this specific use.

This research also assessed the provision of sensors to measure O_3. It concludes that Ozone is not currently an analyte of ongoing interest, and not currently considered to be a key analyte for sensor deployment.

Analysis of the reliability and operational consistency of the sensors has revealed that a high level of intervention is required to maintain operation. This is not sustainable for deployed instrumentation. Reliability of sensor operation should be expected of suppliers.

Analysis of the data gathered from these sensors has required a very high level of data acquisition, management and manipulation. This should be managed either by suppliers themselves, or by a specialist consultancy working with the council or suppliers. This includes null and zero-value data heavily biasing results, lack of clarity on units of measurement, and of analytes. Data acquisition, management and manipulation has reduced the data analysis that could be undertaken within the project timescale.

6.2 Recommendations

Provision of "lower cost" / "affordable" air quality sensors reporting in real time remains a developing field. The multiple roles of county council, district and borough councils, public health and health bodies provide significant interest, with different needs and challenges. The wide ranging work undertaken during the project included interviews with users and suppliers and use of a range of equipment. Recommendations made by this report are covered in the following sections.

6.2.1 Analytes of interest

Analytes for inclusion in this project were selected in conjunction with local district and borough council environment officers as nitrogen dioxide, ozone and particulate matter categorised as less than 2.5µm diameter and less than 10µm diameter. These remain generically of interest to the environment officers. However, during the course of the project, interest from local authority environment officers and public health has focused on particulate matter.

During the course of this project The Environment Bill 2020 was passed, changing the landscape for air quality improvement. This will set targets for fine particulate matter $PM_{2.5}$, described by DEFRA as *"the most damaging pollutant to human health"* (DEFRA, 2021b). The impact of fine particulate matter on human health and the consequent legislative requirements have raised the profile of this pollutant. The bill introduces a legal-binding duty to introduce two air quality targets by October 2022 (DEFRA, 2021b):

- Reduction in annual average $PM_{2.5}$, for public health benefits
- Long-term (15 year) target to encourage investment, focused on reducing population exposure to $PM_{2.5}$, including locations that meet $PM_{2.5}$ standards, to recognise that there is no safe level of $PM_{2.5}$.

The specific targets for $PM_{2.5}$ will be developed with expert groups, with consultation commencing in Spring 2022.

It is therefore recommended that future air quality analysis that will be of most interest is for particulate matter as $PM_{2.5}$ and PM_{10}.

6.2.2 Sensors

Three different sensors have been trialled within this project, and wider options are available.

There remains considerable debate around “low cost” particulate matter sensors as assessed in this project. In general, low cost PM sensors use heated resistors with fans to move air to be analysed past their optical sensor. As such, they are sensitive to water vapour, with increased humidity leading to increased apparent sizes of particles, due to condensation on particles (Section 3). Some sensors also measure relative humidity, and apply a correction factor (such as Aeroqual AQY1, Section 3.2). The algorithms applied for this correction have not always appeared reliable, as seen in the very high PM measurements during fog events observed in sensors (Liveable Cities using Alphasense OPC-N3) in Bury St Edmunds.

In addition, particulate matter can deposit in the sensor chamber, interfering with accurate readings and requiring replacement on a frequency associated with the PM concentrations of the ambient air (more frequent replacement when PM concentrations are higher).

During the deployment phase of this project, anecdotal experience considered the Aeroqual AQY1 sensor to be well regarded. However, this sensor has been discontinued during the course of the project.

Some sensors assessed during this project are considering applying for MCERTS certification (DEFRA, no date), the Environment Agency’s scheme for monitoring equipment approval, promoting confidence in monitoring equipment. Consideration of reliability and calibration of the data, in the context of the use of the data, should be applied to selection of products (Section 6.2.4). Ongoing development of the specific sensors trialled, and other sensors in the comparable market, has meant that it is not appropriate to recommend any specific device.

6.2.3 Impact of Relative Humidity on PM

Artefact impact at high relative humidity on particulate matter measurements has been researched (Crilley *et al.*, 2018, and references therein) and discussions on how to correct for RH are instrument dependent and undergoing further development.

At times of high RH (taken as above 85% in Crilley *et al.*, 2018), the size and refractive index of hygroscopic particles increases (Di Antonio *et al.*, 2018), causing an exponential increase in apparent particulate matter concentrations as $\mu g/m^3$. Instrumental as well as ambient RH values could be used to correct for the impact of RH on apparent PM concentrations, and the correction would be instrument specific.

One of the instruments used in the trial (Aeroqual AQY1) claimed to make a correction for RH in reported PM concentrations. The other two measured RH but did not apply a correction. The impact of RH on PM measurements is considered to be instrument dependent. A range of correction approaches are discussed in the literature (such as by particle size distribution (Di Antonio *et al.*, 2018) or applying machine learning to previously installed sensors (Wang, Lung and Liu, 2020)). Commentary on the management of RH correction on measured PM values is beyond the scope of this report.

Heated particulate matter sensors that dry the incoming air stream prior to measurement may enable direct measurements to be made without correction for RH. None of the instruments trialled in this project have a heated inlet, although the Envirowatch iPM, which was part of the design project for installation in a lighting column does (Section 3.5.1).

6.2.4 Calibration

Recommendations are made for further use of air quality sensors and data. Discussions with district and borough air quality officers have been useful in further understanding requirements, and make the following recommendations.

- In order to give confidence in the datasets, it will be essential that any sensors used undergo suitable calibration (e.g. co-location of each unit against an AURN equivalent MCERTs reference monitoring station which has full UKAS QA/QC applied). The co-location measurements obtained could then be used to establish correction factors for each pollutant, for input to the quality control of the dataset management. Suitable data management, ratification and QA/QC processes will also need to be in place to ensure good data quality.
- 'Factory-calibrated' and 'supplier-calibrated' descriptions have not provided air quality sensors adequate for formal use.
- Calibration and data management (Section 6.2.5) processes from specialist air quality consultants are likely to add an indicative £2000 per sensor per year to capital and other operational costs.

Low cost 'pervasive' sensors offer data with limited configuration, maintenance and calibration, and can provide an increase in monitoring locations and frequency. The data from them should be considered as indicative, with variation and comparison of interest, and could be used for screening and assessment studies. Without calibration and maintenance formal use of the data values may be challenged, which limits the acceptability of this data within the local authority.

Data quality objectives from such pervasive sensors may continue to improve to a situation in which they are standardised or reach the same data quality from formal fixed-point sensors for compliance monitoring.

6.2.5 Data management

Presentation and management of data from different suppliers differed, and in some cases caused problems. The following recommendations are made.

- It is essential that units for analysis are accurate and clearly provided. It is beneficial for all units to be presented as $\mu g/m^3$, to enable comparison with other data, with air quality objectives and for reporting requirements to DEFRA under LAQM procedures. From two suppliers, units measured by the sensors and those reported were inconsistent, leading to potential errors in analysis. In particular, correct reporting of data as ppm, ppb or $\mu g/m^3$ as measured is essential for the data to be meaningful.
- Access to data to specified users is required including visualisation and running reports; for ease of access to users, and for ease of provision to this access, this should be configurable in the supplier dashboard or data access. Good dashboard management would ensure that users can access only agreed areas of data, and do not have the ability to make changes within the dashboard function where not appropriate. Access to users for specific data sources by sensor type or geographic area could be a

requirement from the county council. Such users could include district and borough council air quality officers. Alerts (via email) would enable fast response to identified peaks and unexpectedly large exceedances, which may enable identification of sources of increased air quality parameters.
- Calibration (Section 6.2.4) and data management processes from specialist air quality consultants are likely to add an indicative £2000 per sensor per year to capital and other operational costs.

6.2.6 Installation Heights and Locations

Installation on existing street furniture such as street lighting is convenient and can provide power as required.

Use of existing street lighting communications networks for return of data has appeared unreliable in this project, but remains an interesting solution to minimise operational costs. This report recommends that further development and field testing of street lighting communication networks by suppliers and testing by users is required prior to reliance for ongoing data capture.

Provision of monitors from one supplier in additional housing has the potential to affect air flow around the sensor inlets (Section 4.3.3.6). It is recommended that sensors are installed as anticipated by the manufacturer, and that the impact of additional hardware for installation as well as installation location is considered.

Geographical locations of installation vary depending on user interest (Section 2.4). Most users of air quality data are interested in data in locations:
- That are heavily used by people;
- That are considered likely to have air quality concerns, adjacent to sources such as industry, some agriculture and traffic;
- And, conversely, background locations away from likely sources, for comparison.

Domestic burning, in indoor and outdoor settings, continues to be a concern as a source of particulate matter concentrations in air. Locations of analysis may wish to reflect this. Environment Officers in Suffolk are keen to continue research to understand better the impact of domestic burning as a local source of particulate matter.

Heights of installation are important. Concentrations of analytes in air varies significantly within a few meters of the ground, with variation dependent on the location of sources, and on very local air flow patterns. It is not considered that there are currently suitable corrections for height, due to the range of influencing factors. Installation of air quality sensors on the top of lighting columns, therefore, may provide background / geographical spread information, but is not directly indicative of concentrations experienced at ground level. Installation at user height is more relevant for human impact. It is recommended that installation height be considered in future air quality deployment, for deployment to be at or close to human height.

6.2.7 Management and financial structure

Reliability of sensors was disappointing across the project. It is recommended that council service managers work closely with suppliers to require and achieve a higher level of reliability of data, and support in event of operational issues.

It has been proposed within the project, that a source of funding for sensor deployment could be incorporation of a strategically located air quality monitor within Section 38 agreement for new developments. Should this be pursued, the suitability of the sensors for their potential use, and operational costs including calibration and maintenance, should be considered.

6.3 Final Summary

The research within the Smarter Suffolk Live Labs project suggests that it is possible to install air quality sensors on lighting columns. The majority of the sensors trialled use power from the lighting column supply, with one supplier providing solar powered sensors. The impact of height of installation is relevant, and consideration should be given to installation at heights relevant to human health.

Wider use of air quality sensors requires a commitment to calibration and data management that has not been observed from suppliers. This needs to be achieved by the council, possibly working with a specialist consultancy.

Particulate matter measurements are and will continue to be of increasing priority, and are not currently made in Suffolk. It is likely that PM measurements will be of increasing importance in Suffolk. Access to real-time data with a useable dashboard and, if possible, alerts, would be welcome by council officers who use air quality data.

Business case assessment suggests that whilst the provision of air quality sensors will not lead to direct economic benefits, however the substantial public health benefits from increased measurement of particulate concentrations will support public health campaigns and awareness.

Recommendations are made for attention to capabilities and accuracy of air quality sensors, though this report remains supplier agnostic, and is not able to recommend specific models. In particular, measurement processes and the management of the apparent impact of relative humidity should be considered. Recommendation is made especially regarding calibration against MCERTs reference monitoring station, and QA/QC and data management. Installation in locations of interest is recommended, to include background monitoring away from suspected sources and areas of high particulate matter concentration. Heights of monitoring should be considered, with high level monitoring not providing direct human exposure concentrations.

Particulate matter, especially $PM_{2.5}$, will be of increasing interest across the UK, and Suffolk County Council are well placed to be a key participant in the increase of monitoring.

7 Discussions

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Sharon Payne, Behaviour Change Manager, Transport Strategy, Suffolk Council Council
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9 Document History

Date	**Version**	**Author**	**Notes**
07/03/2021	Draft	H Steventon	Interim Report Reviewed with Prof N Caldwell
09/03/2021	Issue 1.0	H Steventon	Interim Report Issued to Suffolk County Council
Dec 2021	Draft 2.0	H Steventon	Full Report Reviewed with Prof N Caldwell
Jan 2022	Issue 2.1	H Steventon	Full Report Issued to Suffolk County Council

10 Appendix A: Time series plots of measured data

10.1 Aeroqual AQY1 Sensors supplied by CIMCON

Measured data from January 2021 to October 2021, gaps indicating missing data.

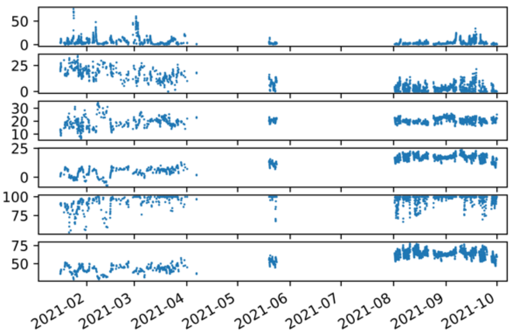

Figure 12: Air quality data, St Johns Road

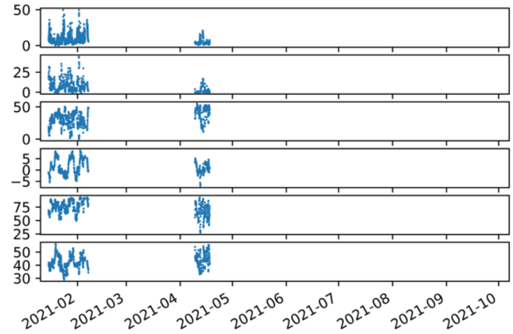

Figure 13: Air quality data, London Road

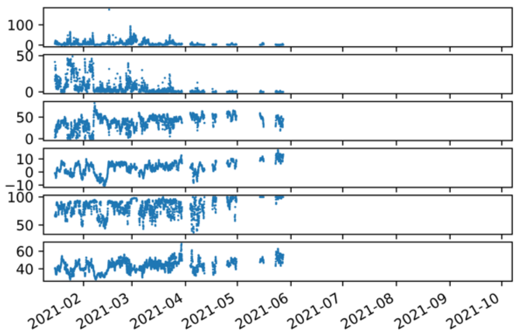

Figure 14: Air quality data, Riverside

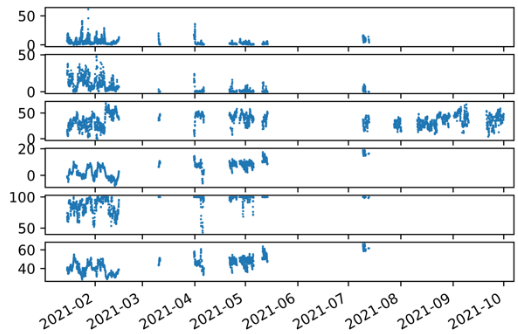

Figure 15: Air quality data, Denmark Road

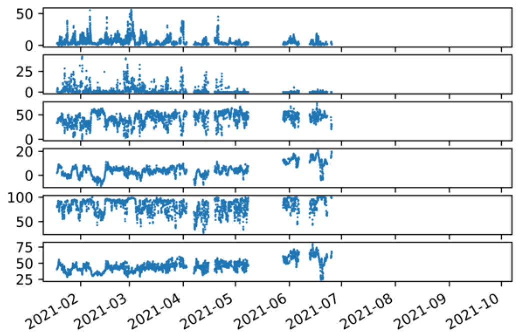

Figure 16: Air quality data, Royal Plain

10.2 Libelium Sensors supplied by SSE

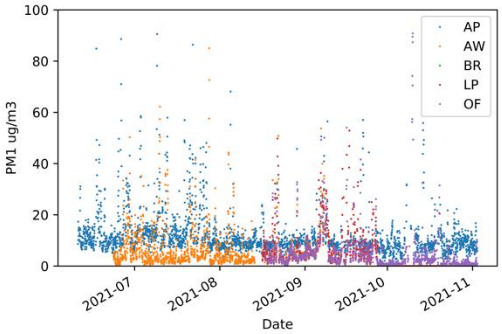

Figure 17: SSE-supplied sensors, PM_1

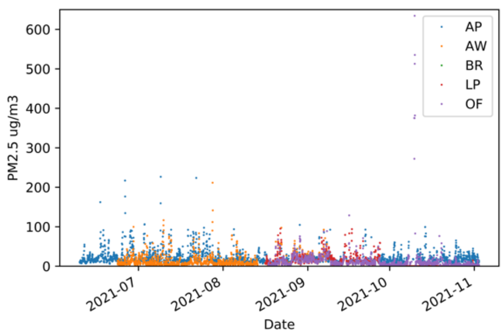

Figure 18: SSE-supplied sensors, $PM_{2.5}$

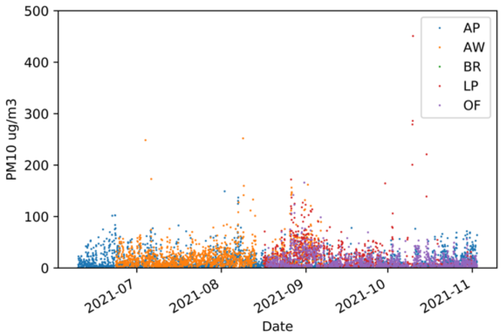

Figure 19: SSE-supplied sensors, PM_{10}

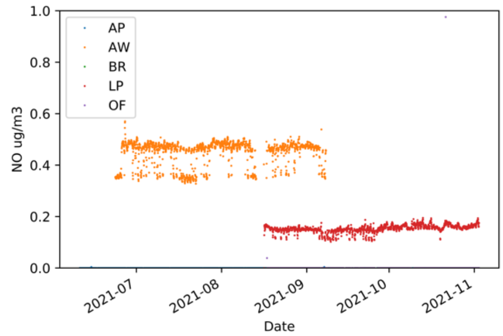

Figure 20: SSE-supplied sensors, NO

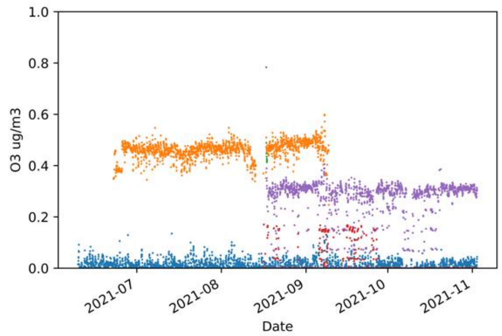

Figure 21: SSE-supplied sensors, O_3

10.3 Aeroqual AQY1 Sensors supplied by Telensa

Measured data from October 2020 to October 2021

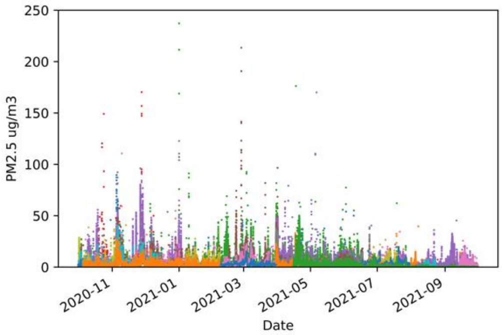

Figure 22: Telensa Sensors, $PM_{2.5}$

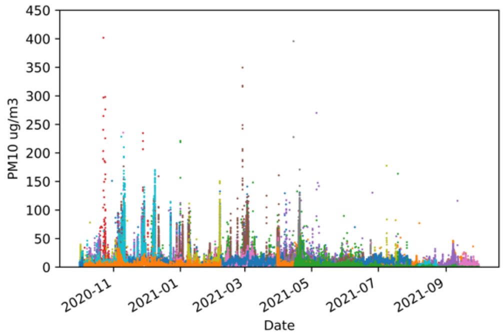

Figure 23: Telensa Sensors, PM_{10}

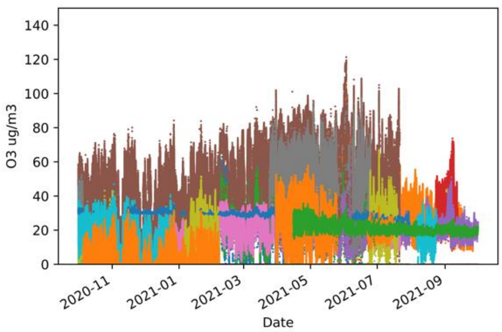

Figure 24: Telensa Sensors, O_3

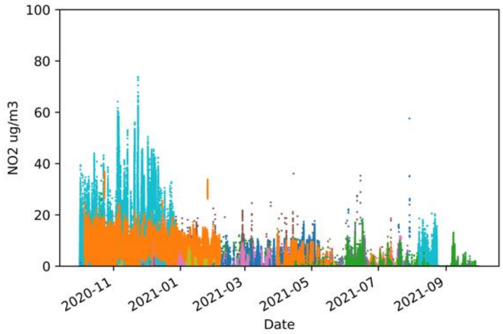

Figure 25: Telensa Sensors, NO_2

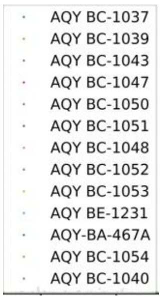

Figure 26: Legend for figures 10-13 above

10.4 Air Quality data from sensors supplied by Liveable Cities

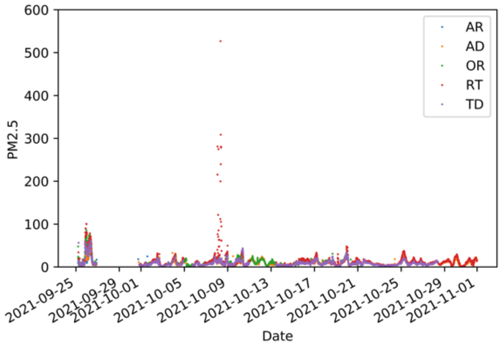

Figure 27: Liveable Cities Sensors $PM_{2.5}$

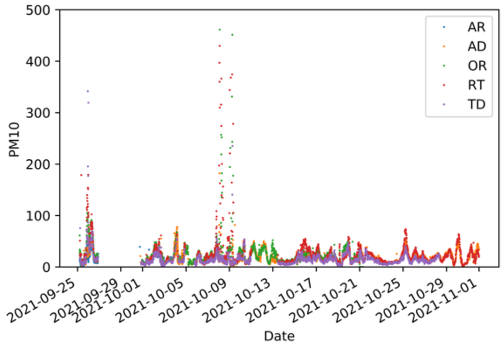

Figure 28: Liveable Cities Sensors PM_{10}

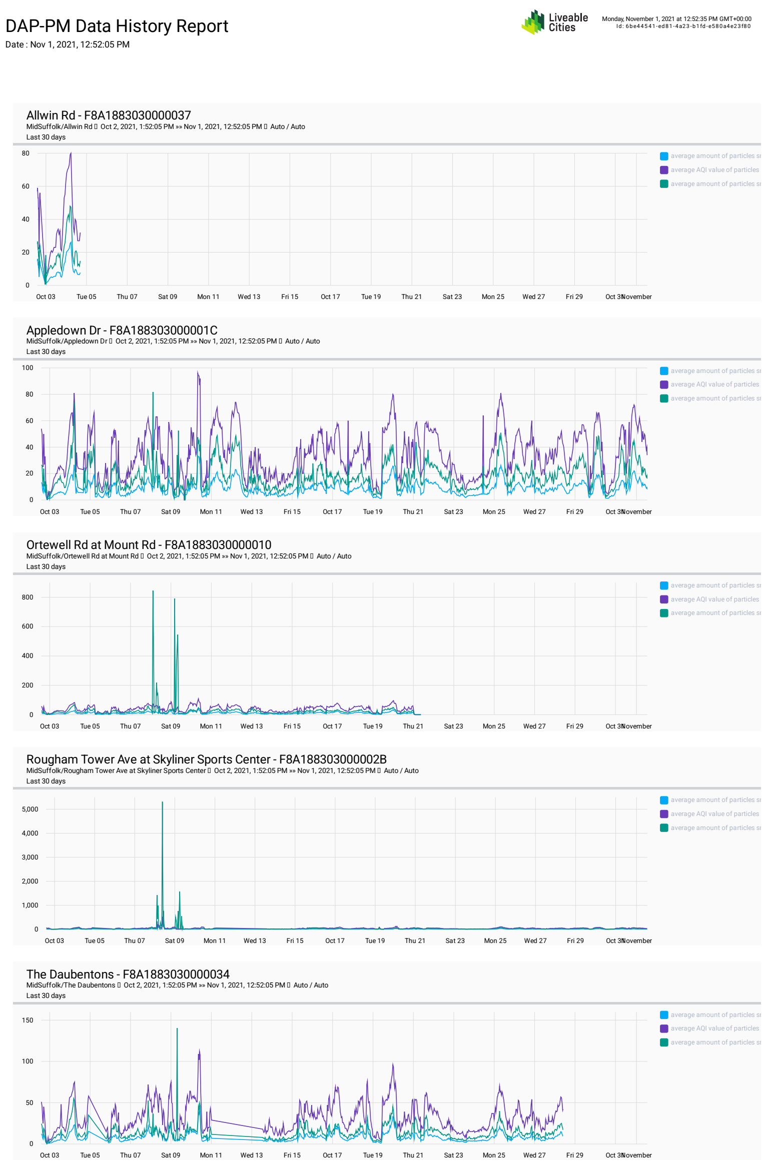

Figure 29: Liveable Cities Sensors: Report provided by supplier dashboard