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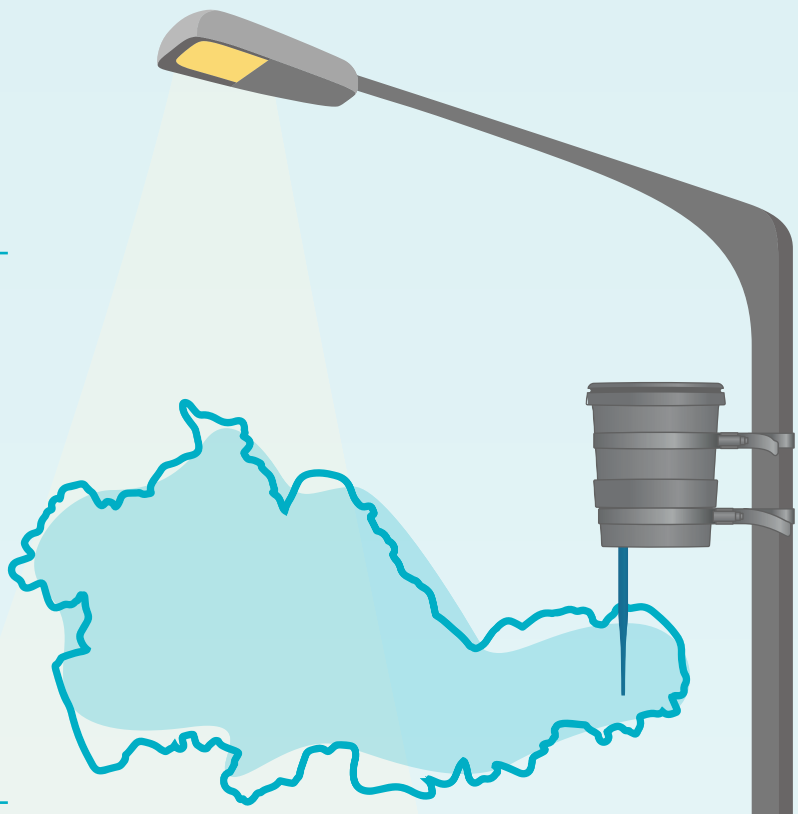

WM-AIR

PROCURING AND DEPLOYING LOW-COST SENSOR NETWORKS:

Guidance and questions for low-cost and commercial AQ sensing networks

Low-cost sensors provide a novel opportunity to monitor air quality at unprecedented spatial resolution. Devices are available at capital costs which are significantly lower than traditional monitoring methods. Whilst such devices allow for greater spatial resolution of air quality data there are a number of important things to consider during the procurement and deployment of low-cost sensor networks. This briefing document identifies some key considerations for using low-cost sensor networks based on experiences drawn from the NERC and EPSRC funded WM-Air & Birmingham Urban Observatory projects.

Whilst we cannot provide advice on which companies or particular sensors to work with, below we outline some guidance which we hope will help you with deciding on whether small form-factor sensors are a viable option for your application(s), and if so, what you should consider when choosing what sensors to purchase or which company to work with. NB: here we refer to low-cost sensors as options that are an order of magnitude cheaper than traditional monitoring methods (for example, £100-1000's per unit rather than £10,000-£100,000's).

1. Are low-cost sensors the best approach for me? Are indicative values enough for my application?

Low-cost sensors provide inherently different insights into air quality than their traditional counterparts. Fundamentally they do not offer the same accuracy, selectivity or sensitivity. However, this doesn't mean they cannot provide meaningful AQ data. Low-cost sensing offers the opportunity for sensors to be deployed in larger numbers to gain a better sense of spatial variations and are often more agile than reference instruments making it easier to monitor in areas previously unattainable.

Before procuring low-cost AQ sensors it is best practice to consider the purpose and goals of the network. Consider:

- Is this a long-term or a short-term network?
- Is the project aiming to capture a specific AQ intervention or source?
- Could the network act as an alternative method of screening for exceedances of AQ objectives? Whilst a low-cost network may not confidently report a level difference of 20 to 21, it could report at coarser resolutions and for example give an idea if an area has a concentration of 20μgm^{-3} or 100μgm^{-3}.
- What locations are available to install the sensors? For example, what street furniture is accessible? And are special permissions necessary to install with the local Council?
- Do these locations have power (if required by the sensor)?
- Will specialist equipment such as cherry pickers be required or can the installations be done safely by ladder?
- Is the installer fully insured for public liability?
- Will the installer be able to provide full risk assessments and seek necessary permissions from Local Authority Highways if footpath closures are required?
- How vulnerable are locations to tampering from the public? Higher install heights can reduce this risk but can then make installations more challenging and reduce relevance to public exposure.
- Does this project provide opportunity for education and community engagement resources?

- Would a % or ± error or limit of detection of a sensor impede on the sensors ability to deliver the project aim? (i.e. If a sensor has a limit of detection of 10µgm^{-3} and you are trying to detect concentrations below or close to the limit then the sensor is unlikely to be effective at getting the results required)

Once a clear purpose is defined, it is imperative to address logistical suitability of a device before progressing with procurement. The network plan should enable you to answer the following questions to help find the best sensor type for the work.

a. **Power:** Is mains power needed? This can be very difficult to achieve in the field. If not, would solar power be suitable (i.e. good sky-view at the site)? Bear in mind that solar insolation dramatically reduces in winter, especially in shaded urban areas. Alternatively, battery options are available but consider the battery life / maintenance requirements (i.e. frequency of changes) and suitability for the timescale of the project.

b. **Ownership:** Who owns the sensor? Who owns the data? If the project plans to keep data private, it may be best to choose an option where you have complete data ownership. In these instances, data security and encryption options may also be important. If contributing to open source data is important, some providers share data on public platforms.

c. **Size and weight:** Think of where the sensor is going to be installed. Are there weight restrictions for wind loadings/ health and safety? Do you need something small and inconspicuous for security?

d. **Data visualisation:** How do you see the data? Is it provided in a format suitable for purpose?

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2. Cost: Is the sensor *really* low-cost beyond the short term?

Whilst low-cost sensors capital costs are cheaper than regulatory monitoring stations, prices can still vary. Cheapest devices start from £10-100s, whereas some devices cost ~£5000 per unit. Remember, capital costs are just the start! Units may also incur additional operational costs in the form of maintenance, servicing and annual data subscriptions. Here are some key considerations in assessing the affordability of capital costs and operational costs.

What do you need to measure and how?

The number of pollutants of interest and methods of communication will affect price. Particulate matter (PM) sensors alone can fall in the low end of the cost spectrum, but multi-pollutant sensors tend to be more expensive. Consider what needs to be measured to meet the monitoring purpose. Comms can also increase price. Does the project require live data to be sent via WiFi/GSM/ LPWAN (see table below) to an online platform or is writing to local storage such as an SD card sufficient?

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Communication type	Description
WiFi	Use WiFi networks to communicate between modules and online servers. WiFi often provides fast and reliable data transfer. This can have higher power consumption and can limit placement location to where accessible WiFi is available.
GSM	GSM describes the standard network used by cellular devices (aka 4G, 5G). Whilst modern GSM connection is often reliable in urban centres and allows for large file transfers, this comes at increased power consumption. Costs can accumulate significantly when a monthly fee is incurred for a number of sites.
LPWAN	LPWAN stands for Low Power Wide Area Networks. These networks use reclaimed (old) cellular networks to communicate and are ideal for battery powered devices as they have limited power consumption. Examples of these networks are Sigfox, LoRa and NB-IoT. These networks are often relatively low-cost subscriptions for comms.

What is included in the price?

Whilst initial costs of a device may be within budget and appear low-cost, some sensors have ongoing costs associated with them including comms and data subscriptions and regular replacement and calibration of sensor components. These can be quite substantial. Consider:

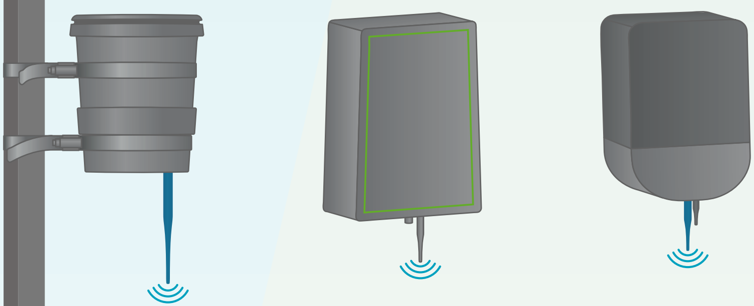
- Does the price include any maintenance?
- How frequently do parts need replacing and are these covered by a warranty?
- Is data storage and comms included in the cost?
- Is data storage and comms included in a one-off cost or is there an ongoing subscription to consider?
- Are the data available to download and keep – or is this dependent on the subscription service? What guarantees are available for data access longer term?

What will be your staffing requirements for installing and maintaining the network?

The operational costs of low-cost sensing networks may require additional staffing. Consider:

- Will staff have to deploy and maintain the sensors, or will the supplier provide support?
- Who will manage the quality control of the data?
- Who will manage the data hosting?
- Is there an alert system monitored by the supplier to pick up on any malfunctions/errors? Or does this require manual monitoring by the user?
- What is the call-out cost and response time for any malfunctions?
- Does the supplier have engineers that can provide support in your area?

All of the above will alter the staffing hours that will need to be budgeted. Remember, the bigger the network the bigger the ongoing costs.

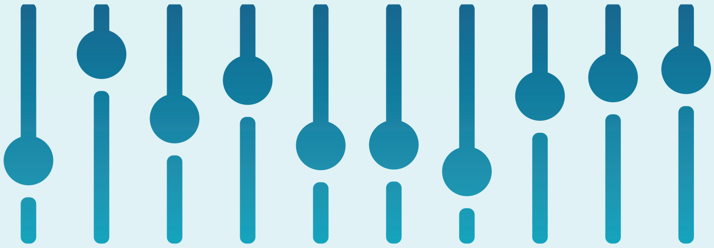


Are sensors available to purchase or to hire?

Some commercial sensors are available to hire rather than purchase outright. Consider the length of the deployment and whether a rental option may be more cost efficient than an outright purchase with upkeep.

3. How is the device hardware different from the others on the market?

The different options discussed in the previous section should provide some clues of the differences between available devices with power and comms tending to be the main difference between units in terms of hardware. When considering if a device offers value for money, it is worth asking what individual sensor 'heads' are contained within the device. The same underlying technology may be available at a range of prices! Some manufacturers design devices that utilise a cartridge system that houses the sensor heads allowing for replacement of individual sensor heads without replacing the entire device, which may be worth considering for extending a device lifetime. In many cases, the underlying hardware such as the sensor heads used within a device are the same across manufacturers and the main difference in cost may be 'sensing as a service' – i.e. what goes on in the server/cloud after the data has been collected (e.g. in terms of data quality control).



4. Data quality: How are the devices calibrated and how long does that calibration last?

One of the most frequent concerns surrounding low-cost sensors is data quality. As outlined above, these sensors do not have the same accuracy as regulatory instruments. Some sensors now have recognition of performance via certification, such as the Environment Agency's Monitoring Certification Scheme (MCERTS) and this may be something you wish to consider when looking to choose a sensor for environmental monitoring. Overall, with calibration, corrections and well considered QA/QC efforts low-cost sensors can provide useful data. The challenge comes from ensuring that the manufacturer and supplier are providing all the information needed to allow for appropriate confidence in the data. Whilst some manufacturers are very transparent in stating that they provide raw data and that corrections need to be carried out by the consumer, others will offer calibration and QA/QC checks as part of the service provided. If manufacturers do not provide the information needed, sometimes it is available online from other users or research. Projects will need to consider the skill set of personnel before deciding if they would rather manage these processes or leave it to the manufacturers to manage. Either way, the following questions will help provide insight into the sensors themselves and the required data quality processes.

a. **How are the sensors calibrated?** Calibration usually involves a period of co-location with a reference instrument of which a correction is developed. The best calibrations will also consider phenomena such as temperature and humidity which may affect sensor performance. It is also considered good practice to calibrate sensors in an environment similar to which they will be deployed in to ensure calibrations are applicable to the typical meteorology and sources associated with this environment. For this reason, seasonal calibrations may also be appropriate. Ask manufacturers for details about these processes. Different sources of particulates may also impact sensor accuracy as the geometry and chemistry of the particles can influence the sensor's response. For example, 10μgm^{-3} of $PM_{2.5}$ comprised of soot would scatter light differently from 10μgm^{-3} of $PM_{2.5}$ comprised from sea salt, which can affect the performance of the optical particle counting element within a sensor. Ask manufacturers about the impact of source type on sensor performance and check the literature as some peer reviewed research offer calibration models that vary by particulate composition for low-cost sensors. As sources of particulates vary by location, it is important to consider if the corrections applied by a manufacturer were developed to consider the environment type in the location that you will be sampling in. It may be appropriate to test sensors even after manufacturer calibrations with co-location at a reference site ahead of (and during) deployment to ensure data confidence.

If the data are to be meaningfully used, then it is important to fully understand every element of the process from collection to final value.

b. **Who applies calibrations and how frequently are they updated?** Is there evidence of drift in sensors? Some manufacturers will automatically apply calibrations and weather corrections to the data before providing it to the consumers. Others may not do so, thus leaving consumers to correct data during processing. It is also important to question the role of drift on calibrations. Manufacturers may provide information on expected drift and some even buddy match or re-calibrate sensors using other online data and AI Algorithms. It is worth noting that many sensors have now been assessed in academic research which may inform of known issues with drift.

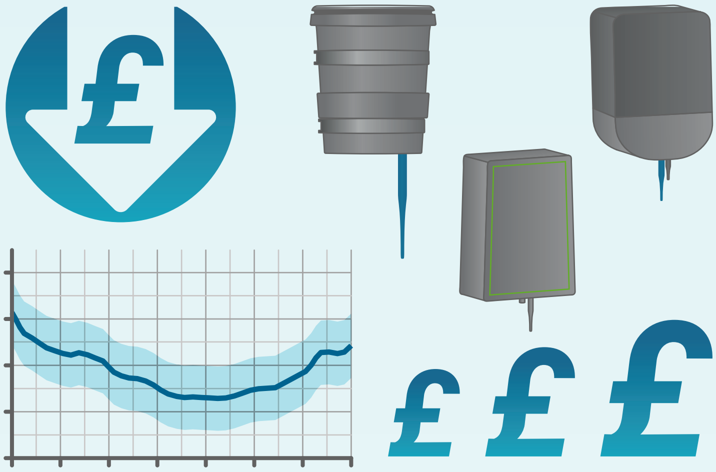
c. **How do sensors compare between themselves?** To be able to make confident distinctions between concentrations in different places, there needs to be confidence that sensors don't only correlate with reference instruments but also between themselves. Manufacturers may co-locate batches of sensors before shipping, but it is sensible to co-locate all the sensors that will be deployed as part of your network together for a period ahead of deployment to check for any potential outlying sensors. This can be repeated after a period of time to ensure sensors agree and may provide insight into issues around drift.

d. **How many sensors are needed for a reliable network?** Sensors networks can vary in size, they need to be designed to capture the variations in space and time required for the outline purpose. Some sensors may require rotation in and out of the field for calibration or maintenance/repair, thus it can be useful to allow some additional sensors to support this. Extra sensors deployed at regulatory stations as part of the sensor network may support data confidence by enabling ongoing data quality checks.

e. **What is the expected working lifespan of the sensors?** Whilst sensors may be able to be re-calibrated and batteries re-charged, all sensors will have an effective lifespan before parts or the entire device will have to be replaced. Finding out what happens then is always worth knowing!

f. **Can the sensor *really* measure PM_{10}?** Recent research[1] has raised questions around the ability of a PM sensing unit that is used in some commercial sensors to measure PM_{10}. This is due to the intersection of the laser scattering system with the particle path geometry leading to lower sampling efficiency for larger (typically heavier) particles with greater inertia within the instrument, compared to smaller particle sizes. Manufacturers may not always disclose which sensing unit is used inside their device. It is useful to research the components within a sensor to ensure they are effective for a network's needs.

It is also important to consider if you are providing open access data, that alongside the data itself, you clearly communicate the data quality and metadata outlined in the above questions, so users are informed before using the data.



5. How Transparent is all this?

Some manufacturers will be able to provide answers to some of these questions, whereas others may be more guarded about how the data is processed before you see it. **From a scientific perspective, if the data are to be meaningfully used, then it is important to fully understand every element of the process from collection to final value. From a regulatory perspective, understanding the device accuracy, selectivity and precision is key to applications ranging from public engagement to compliance assessment. If the process is not transparent, then it devalues the data and credibility of using it in an applied setting. It also allows you to decide whether the sensor is providing value for money. To this end, we also recommended using a range of sources including reports and research from existing sensor networks to ensure the latest good practice is being applied to sensor networks.**

Guidance briefing written by Nicole Cowell, Lee Chapman and William Bloss on behalf of the WM-Air and Birmingham Urban Observatory team and with contribution from Steve Dewar from WM-Air project partner, Coventry City Council in Autumn 2022. Further information and links to resources can be found on the WM-Air website at: **wm-air.org.uk/low-cost-sensors-for-air-quality-monitoring**

[1] https://blog.quant-aq.com/can-your-plantower-pms5003-based-air-quality-sensor-measure-pm10/?s=03