Operational Network of Air quality Impact Resources

A guide to developing technical requirements

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Overview

This *Guide to developing technical requirements* has been developed as a companion to OPENAIR *Technical Requirements Template*. It will help you to complete the template and develop a detailed technical requirements plan for your smart air quality sensing project.

How to use this template

This Guide has two main sections that correspond to sections of the *Technical Requirements Template*:

1. Sensing device requirements
2. Data architecture, platforms, and services requirements

Section 1: Sensing device requirements

The sensing device that is best for your program will depend on several factors. This section of the guide provides the relevant details to aid your thinking, and help you understand key components that will affect the device choice.

The factors include:

1. air quality concerns
2. data application area
3. sensor performance and technical requirements
4. communications technology
5. proprietary technology vs open technology
6. environmental factors and robustness
7. device lifetime
8. power supply: battery, solar, or mains power
9. size, form, and aesthetic
10. modularity.

1. Air quality concerns

The following section will help you to identify pollution sources and pollutants of concern. A well-focused and effective project should aim to focus on just two or three main pollutants associated with one or two pollution sources.

TIP: Key air pollutants
Remember, all emissions to air can be of concern if their associated pollutant concentrations exceed guideline values. The Australian National Environment Protection (Ambient Air Quality) Measure (Air NEPM) sets standards for six key air pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), lead (Pb), ozone (O_3), and particulate matter (PM)[1].

The pollutant sources and pollutants of concern covered in this section are:

- urban heat
- road traffic emissions
- diesel emissions associated with non-traffic sources
- aviation emissions near airports
- woodsmoke from wood burning heaters, stoves, and fireplaces
- smoke from bushfires or controlled landscape burning
- dust from construction, mining, and quarries
- coal dust from trains and mines
- industrial air pollution sources
- natural air pollution sources.

CO_2 EMISSION INDEX

Carbon dioxide (CO_2) is not usually considered to be a primary air pollutant, but measuring it alongside other pollution sources can significantly improve the ability to interpret data.

The ratio of CO_2 to a pollutant associated with vehicle emissions (nitric oxide [NO], NO_2, and particulates) can be used to estimate the 'CO₂ emission index,' and thus roughly characterise the types of vehicles causing emissions in a particular location. For example, a diesel truck will emit considerably more particulates and NO_2 relative to the CO_2 it produces, when compared to a car running off standard petroleum.

This approach has been used by the Breathe London program to analyse the impact of the new Ultra Low-Emission Zone (ULEZ) in Central London. An added benefit is the ability to map CO_2 emissions at high spatial resolution, with the potential to influence transport and planning policy based on carbon reduction commitments.

[1] PM (particulate matter) refers to airborne solids or liquids. Its size is measured in micrometres and is indicated by the subscript. E.g. PM_{10} has a diameter of 10 micrometres or less. (NSW Health, 2020)

<table>
<tr><th colspan="2">Urban heat</th></tr>
<tr><th>Pollutant source / pollutant of concern</th><th>Activities for impact</th></tr>
<tr><td>
Urban development and land use changes can contribute significantly to localised air quality. Urban microclimates can vary enormously in terms of ambient air temperature, as a result of localised variations of the built environment, vegetation cover, shading, transport, and topology. Changes to inner-city transport infrastructure often go hand in hand with highly localised changes to land use. Granular data on how these changes impact air quality can assist local authorities to develop policies mitigating these impacts.
Often, in cities, ground surfaces are hard and sealed, trapping heat and radiating it back into the atmosphere at night. Less vegetation or canopy cover can also contribute to the heating effect. The urban heat island (UHI) effect is also considered to be responsible for increasing heat-related effects of climate change in urban areas. Monitoring increases in temperature can allow local authorities to protect vulnerable communities from the effects of urban heat, and track its impact on the overall environment.
Pollutants of concern

Primary pollutants of interest: While not a pollutant, the primary aspects to measure the UHI effect in this instance could include Temperature and Relative Humidity (RH)
Additional pollutants to consider: NO, NO_2, SO_2, SO_3, PM, O_3 (as a secondary pollutant), NO_2

</td><td>
Local governments can play a crucial role in working closely with developers, planning authorities, and communities to design policies that can assist in reducing the UHI effect. Some strategies are illustrated below:
Reduce localised heat

Inclusion of green infrastructure in new developments through planning policy, and supporting green infrastructure investments through various incentive schemes.
Green infrastructure requires irrigation. Designing precincts that support smart water management options, particularly those that relate to water recycling, and rainwater or stormwater harvesting.
Introducing stringent policies around integrating green space in a dense urban setting to encourage developers, architects, and planners to consider green infrastructure as part of their built environment, right at the design stage.
Local environmental plans to encourage use of light-coloured or reflective materials for roofs, roads, and pavements, or design elements (like use of permeable materials on ground surfaces) that help absorb water in a similar way to natural landscapes.

Reduce exposure to heat

Encouraging planners and developers to design precincts that provide shade for built surfaces, or create shaded structures using canopy covers or clad walls and roofs with vegetation.

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Urban heat	
Pollutant source / pollutant of concern	**Activities for impact**
	• Improving accessibility to naturally and artificially cooled spaces. For example, improving access to air-conditioned libraries, or outdoor spaces that have sufficient shade.

Road traffic emissions	
Pollutant source / pollutant of concern	**Activities for impact**
Internal combustion engines create air pollution that can cause localised pollution hotspots, or can accumulate across larger urban areas to contribute to the production of 'smog'. Engine types vary by fuel use and design, with diesel engines producing the largest quantities of harmful pollutants. More modern engine and fuel technologies can reduce the pollution impact per vehicle. Traffic-related emissions remain a major air quality concern for local governments, particularly in more urban areas. *Pollutants of concern* Engines produce particulates associated with the combustion of hydrocarbons, as well as the noxious gases NO_2, SO_2, and CO (plus a cocktail of other trace chemicals). Sunlight splits NO_2 into nitric oxide and an oxygen atom, and the single oxygen atom then combines with oxygen molecules present in the atmosphere to produce O_3.	Local governments in Australia have jurisdiction over local roads, while state government manages larger arterial roads, as well as public transport. Where direct jurisdiction exists, direct interventions can be made. For issues under state government management, local government can take an advocacy role. Efforts to reduce the impact of air pollution associated with road traffic may be divided into two broad strategies: 1. Reduction of road traffic emissions at source, either through a reduction of polluting vehicles in the area of focus, or by reducing the emissions associated with each vehicle by changing the way that it moves through an area (e.g. speed, acceleration, braking, idling). 2. Reducing the impact of traffic emissions on people, either through the mitigation of emissions after they occur (e.g. with green infrastructure), or through redesign of the built environment to separate people from high-

Road traffic emissions	
Pollutant source / pollutant of concern	**Activities for impact**
In addition to exhaust fumes from fuel combustion, a significant and often overlooked source of particulate pollution from vehicles is abrasive action from braking and tyres, which generates PM_{10} and $PM_{2.5}$ pollution. This type of emission is also strongly associated with electric vehicles, highlighting that a shift away from internal combustion towards electric transportation in the coming years is not a complete answer to road traffic emissions. • Primary pollutants of interest: $PM_{2.5}$, NO_2 • Additional pollutants to consider: PM_{10}, O_3, CO, CO_2	emission hotspots (e.g. physical barriers to dispersion, moving service access locations). Strategies for directly reducing road traffic emissions at source: • Localised physical changes to the streetscape, designed to alter the flow, speed, or quantity of vehicles passing through a particular location. • Localised changes to road rules or 'settings' (e.g. altered speed limits, optimised traffic light settings, 'no idling' rules). These 'soft' interventions are also designed to alter the flow, speed, or quantity of vehicles passing through a particular location. • Widespread traffic policy that impacts a much larger defined area, such as a whole city centre (e.g. car-free pedestrian zones, low emission zones, or congestion charging). • Investment in public or active transport infrastructure and services, to provide more accessible and convenient alternatives to private car use. • Improved access to end-of-trip or 'last mile' transport options. • Changes to freight delivery times or rules. • Zoning changes to reduce density allowances in areas with high traffic congestion. • Electrification of public transport (e.g. buses). • Reduction of UHI (e.g. water-sensitive urban design; lighter-coloured concrete) to lower ozone creation around road surfaces during hot weather. Strategies for reducing the impact of traffic emissions on people:

Road traffic emissions	
Pollutant source / pollutant of concern	**Activities for impact**
	• Planting greener infrastructure (trees, green walls, and roofs), with attention paid to plant species, water management, health of plants, and associated operational responsibilities. • Physical barriers along roadsides (e.g. fences, embankments) • Design of streetscapes, with attention to the street canyon effect, and position of pedestrian and cycle paths relative to high-traffic zones. • Development approvals that separate vulnerable receptor sites (e.g. schools, aged care, or hospitals) from roads with high emissions.

Diesel emissions associated with non-traffic sources	
Pollutant source / pollutant of concern	**Activities for impact**
Diesel engines are used in many applications and in a range of sectors, including ports and shipping terminals, construction, generators, mining, forestry, and rail locomotives. Non-road diesel engines are a substantial source of emissions in Australia.	Depending on which sector the diesel emissions are associated with, local governments play a crucial role in either: a) developing robust strategies that can mitigate emissions in their jurisdiction, or; b) working in conjunction with state government or state government agencies in an advocacy role. For example, the Australian Government is responsible for regulating fuel used by cruise ships, but local governments can play an advocacy role relating to specific activities. Strategies to mitigate emissions from non-road diesel sources fit into two categories:

Pollutants of concern Diesel engines emit particulate matter (mainly $PM_{2.5}$), oxides of nitrogen, volatile organic compounds, and a range of air toxins. They continue to be a major threat to human health. For example, emissions from ships in port are an emerging area of concern, negatively impacting ambient air quality locally, as well as within the airshed. Higher sulphur content in the marine fuel used in ships results in higher emissions of fine particles and sulphur dioxide. Similarly, diesel backup generators emit pollutant gases like CO_2, NO, NO_2, and PM. Diesel emissions from machinery and equipment on construction sites are also of concern. • Primary pollutants of interest: $PM_{2.5}$, PM_{10} • Additional pollutants to consider: NO_2, SO_2	1. Complying with emission standards • purchasing engines that conform with highest US or EU emission standards • ensuring fuel used is compliant with national standards. 2. Managing compliance through procurement • developing procurement policies that encourage or allow purchase, lease, or contracting of compliant equipment only • auditing and reporting on compliance with low-emissions procurement policies. Other strategies could include education of drivers and equipment operators on the use and maintenance of equipment, and restricting unnecessary engine idling.

Aviation emissions near airports	
Pollutant source / pollutant of concern	**Activities for impact**
Aircraft produce emissions that react in the atmosphere to form pollutants that impact air quality. The size of particles (and emission levels) depend on the type of aircraft, engine conditions, and type of fuel. Pollutants from aircraft engines include NO, NO2, CO, unburned hydrocarbons (UHC), and smoke. In addition to aircraft, ground support vehicles and equipment also produce emissions. Traffic from shuttle buses and passenger vans also generate emissions in and around airports.	While there is a growing need to model and monitor airport emissions to accurately estimate exposures in the surrounding neighbourhood, further characterisation of both outdoor and indoor impacts of aviation emissions is also needed to better mitigate emissions. Many interventions are also underway to improve the jet fuel used, which will have the effect of reducing emissions. Regulating emissions from airports is generally the responsibility of state and federal governments. Local governments can play an advocacy role in specific

Aviation emissions near airports	
Pollutant source / pollutant of concern	**Activities for impact**
Other common emissions sources at the airport include auxiliary power units (APU) providing electricity and air conditioning to aircraft parked at airport terminal gates, stationary airport power sources, and construction equipment operating at the airport. *Pollutants of concern* • Primary pollutants of interest: $PM_{2.5}$, NO_2 • Additional pollutants to consider: O_3, PM_{10}, CH_4, CO	areas, including non-road equipment storage, fuel use, and by providing support to monitor emissions around the airport premises. Strategies include: 1. Regulating sulphur content in the fuel used for non-road equipment 2. Stringent restrictions on procuring fuel-efficient non-road equipment 3. Characterisation of outdoor and indoor airport emissions to better understand monitoring needs 4. Managing public transport trips to reduce emissions, or providing low-carbon or electric vehicles for airport travel 5. Undertaking research on development and deployment of alternative fuels to improve environmental benefits.

Woodsmoke from wood burning heaters, stoves, and fireplaces	
Pollutant source / pollutant of concern	**Activities for impact**
Communities in towns where cold winter climates are predominant have traditionally used wood burning stoves and fires for residential heating. Smoke from household chimneys can have health and amenity impacts for communities. Dispersion patterns of smoke from its source is often determined by the topology of the town or ambient temperatures. In some areas, topological characteristics	Local governments are the responsible authority for regulating woodsmoke emissions from residential properties. Transition from traditional practices of woodfired burning to use of electricity can be a long-term, complex process, and must be well-managed. Local temperature and air quality data may have a role to play in the development of an energy demand management solution.

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<tr><td>do not allow the smoke to disperse, instead causing it to gather in a particular location. Likewise, temperature inversions can hold smoke on ground for an extended period. Longer exposure to smoke, especially in winter, has proved to be a cause of public health concern in these areas.

Potential solutions to drive reduced use of wood burning heating options include wood heater rebate and replacement programs; education programs on wood heater use and chimney maintenance; improved thermal efficiency in buildings; better insulation; and bans on wood heater installations in new developments.

Pollutants of concern

• Primary pollutants of interest: $PM_{2.5}$, PM_{10}, NO_2
• Additional pollutants to consider: CO, CO_2</td><td>The following strategies can be adopted to mitigate emissions from woodfired burning.

Regulatory interventions

• Local governments in NSW can issue smoke abatement notices under the Protection of the Environment Operations Act 1997, which requires residents to ensure that excessive smoke is not emitted from chimneys, and to take action on the notice within 21 days of issue.

Other interventions

• Multifaceted campaigns to raise awareness around impacts of woodfired burning, based on solid data.
• Provision of information on the health impacts of smoke (with reference to topography and climate) to aid stakeholder understanding.
• Improved energy efficiency in buildings, through building by-laws to encourage effective demand management.
• Strategic use of woodsmoke information developed for local governments by state government.
• Participation in wood heater rebate and replacement campaigns, when run by state government or other organisations.</td></tr>
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Smoke from bushfires or controlled landscape burning	
Pollutant source / pollutant of concern	**Activities for impact**
Smoke from bushfires and controlled burning/hazard-reduction burning (also called landscape fires) causes a range of health impacts that can particularly affect vulnerable people, and those with pre-existing illness. Smoke from landscape fires contains large numbers of contaminants (including $PM_{2.5}$ and PM_{10}, and toxic gases like carbon monoxide and oxides of nitrogen). These pollutants have lasting health impacts, including respiratory complications, irritation of eyes, and long-term or concentrated exposures may also result in asthma and severe heart conditions. Although controlled burning is considered to be one of the strategic responses to bushfires, it can result in a level of criticism from local communities due to poor communication around controlled burning events, and lack of understanding of the issue. *Pollutants of concern* • Primary pollutants of interest: $PM_{2.5}$, PM_{10}, NO_2 • Additional pollutants to consider: CO, CO_2	Planned mitigation activities can allow local governments to reduce the impacts on communities of smoke from bushfires or controlled burning. Strategies can include: • Monitoring real-time air quality data for locations adjacent to controlled burning sites, to support responses to smoke hazards associated with year-round bushfire management activities. • Community awareness campaigns targeting controlled burning, to allow local government to design more inclusive response strategies. • Planning of activities related to controlled burning, to reduce the smoke impact on communities. • Issuing timely smoke alerts to communities on bushfires or controlled burning, to help restore community confidence in local government and controlled burning activities. • Providing regular updates on the levels of particulate matter as a result of either bushfires or controlled burning, supplemented with health advice to reduce smoke impacts on vulnerable populations and communities.

Dust from construction, mining, and quarries	
Pollutant source / pollutant of concern	**Activities for impact**
Construction site dust (arising from demolition activity, earth moving, heavy vehicle movements on unsealed site roads, and cutting of concrete) can result in wide dispersion of dust, significantly affecting nearby communities. Dispersion of dust is often dependent on a combination of factors, including weather conditions, on-site activities, and mitigation measures. In addition to construction sites, activities in mines and quarries that involve heavy vehicle activity, earth moving, or rock blasting also create significant additional dust sources, affecting nearby regions. While weather conditions like wind and dry weather trigger the dispersion of dust, rain can have a cleansing effect, allowing dust to settle on-site and preventing dispersion. *Pollutants of concern* • Primary pollutants of interest: $PM_{2.5}$ • Additional pollutants to consider: PM_{10}, PM_1	Local governments can introduce stringent measures by working in close collaboration with developers and construction site workers, to reduce dispersion of dust arising from construction activities in mines and development sites. Strategies to reduce dust dispersion can include: • Mandating dust mitigation plans during the lifetime of the construction phase, including spraying unsealed roads with water to reduce the amount of dust becoming airborne. • Planning of activities with reference to weather conditions. For example, informed planning of activities that are known to generate dust, to avoid them coinciding with weather conditions most associated with dust generation and dispersal. • Installing on-site weather monitoring stations to monitor levels of particulate matter.

Coal dust from trains and mines	
Pollutant source / pollutant of concern	**Activities for impact**
The majority of the dust generated in mines or mining activities arises from activities like rock blasting, ore extraction, bulldozing, or movement of vehicles	The NSW Environment Protection Authority is responsible for managing air quality (PM levels) around mining sites. Coal dust from rail is primarily

on-site. Weather conditions like winds and dry weather also trigger dispersion of dust around the site. The contribution of fine particles from vehicle exhaust and mobile equipment on mine sites is also an issue. Furthermore, there are growing concerns in the community regarding fugitive emissions arising from coal dust (during coal loading, unloading, and transport by train). *Pollutants of concern* • Primary pollutants of interest: PM_{10}, $PM_{2.5}$ • Additional pollutants to consider: PM_1	administered under the Protection of the Environment (Operations) Act 1997 (POEO Act). However, there are no regulatory requirements in NSW for the management of coal dust from rail activities. The POEO Act and its subordinate legislation clearly articulate the obligations of those who occupy premises, and encourage them to manage activities in a manner that either prevents or minimises air pollution. Local governments can play an advocacy role in the development of policies, or contribute to/circulate discussion papers released by the EPA. Strategies where local governments can play an advocacy role, and assist in co-development of activities or policies: • Encouraging planned dust control activities around mining sites. • Conducting regular surveys with the communities around these sites to monitor health impacts. • Providing health advice or alerts in advance to communities when the dust from activities in a mine or quarry site is expected to be higher than normal (due to planned activities or weather conditions). • Working with the EPA and local landowners (owning rail corridors in a local government area) to develop policies or activities targeted towards mitigating the impact of coal dust.

Industrial air pollution sources	
Pollutant source / pollutant of concern	**Activities for impact**
Industrial processes can emit pollutants into the air, including CO, SO_2, SO_3, hydrocarbons, and particulates. Direct emissions produced inside industrial	Monitoring and regulating emissions from industrial sources is the responsibility of state and federal authorities. However, monitoring data at a local level (in and

facilities, as well as indirect emissions produced off-site, can emit pollutants at various stages of production. Burning fuels for power or heat, leaks, and use of fuels in production processes are among the sources of pollution. Similarly, coal-fired power stations can emit sulphur dioxide, oxides of nitrogen, and particulate matter ($PM_{2.5}$). Measurement of industrial pollutants is generally required and undertaken under state and federal legislation, to ensure compliance with regulatory benchmarks. Monitoring these pollutants can also improve the ability of state authorities to design measures to mitigate health-related impacts (both for industry workers, as well as people living in neighbouring regions). *Pollutants of concern* • Primary pollutants of interest: $PM_{2.5}$, NO_2 • Additional pollutants to consider: PM_{10}, SO_2, VOC	around these facilities) can assist local governments in issuing health alerts to individuals or suburbs. Local-level monitoring activities may include: • Setting up local weather or smart low-cost monitoring networks to capture granular-level sensing data. These networks can be managed and/or owned by local government. • Working closely with state health authorities and industry owners to generate health advice, and issue spatially accurate alerts to communities. • Managing health impacts of direct emissions on workers inside facilities, by establishing on-site monitoring networks near high-impact activities. This may lead to data-informed site activity planning, to avoid potentially polluting activities coinciding with windier or dry weather conditions (and to reduce negative health impacts on workers). • Using air quality data collected near to vulnerable community receptors like hospitals or childcare centres to develop new policies or protocols to improve air quality in and around these places.

Natural air pollution sources	
Pollutant source / pollutant of concern	**Activities for impact**
In addition to human-made sources of pollution, natural sources can also contribute to regional and localised air pollution. Windblown dust (or dust arising from dust storms) can contribute to the increased concentration of particulate matter in the air (PM_{10} and $PM_{2.5}$). Particles can settle down at the source of wind, or can travel across areas far from the original source. Dust can be a major source of ambient air pollution, and its impact on human health and respiratory	Air pollution control is regulated by state authorities. However, local governments can assist with research by undertaking local studies to determine changes in local air pollution levels. Increased levels of natural air pollutants can result in increases in particulate matter and gases (e.g. a dust event, or a sea spray event, can contribute to local air pollution). Similarly, some types of native

<table>
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<tr><td>functioning deserves more attention. Dust can also be an impediment to the process of air quality monitoring, as it interferes with sensing data.

Another source of pollution that can affect air quality are biogenic emissions, often originating from vegetation and soils. Other relevant geogenic and biogenic sources include volcanic emissions, lightning, sea salt, and volatile organic compounds (VOC) released by vegetation and pollen.

While of lesser concern, sea salt (from particles blown into the air from the breaking of ocean waves) often reacts with existing pollutants in the air, contributing to local air pollution. In this way, sea salt can contribute to the exceedance of already existing PM_{10} levels, and may trigger an increase in local air pollution levels.

Pollutants of concern

• Primary pollutants of interest: PM_{10}, O_3, VOCs
• Additional pollutants to consider: $PM_{2.5}$</td><td>vegetation, including eucalypts, can release volatile organic compounds into the atmosphere, which can contribute to ground-level ozone formation on hot days.

Strategies to mitigate the air pollution impacts from natural sources can be categorised in two ways:

Action-based:
• Sharing improved health alerts (based on spatial modelling and natural events) to protect local communities and vulnerable groups from potential health impacts likely to arise from natural events.
• Selecting trees with air quality enhancement characteristics, and reduced pollen-releasing characteristics.

Research and monitoring:
• Using spatial analysis to determine areas of impact (e.g. meteorological satellite measurements and modelling).
• Improved frequency of monitoring/reporting of local natural events (like dust storms or sea spray events). This is especially relevant for coastal local government areas, to allow improved understanding of the correlation between increased particulate matter levels, and local natural events.
• Monitoring particulate matter levels in areas close to beaches, areas with frequent dust storms, or near thick vegetation patches, to improve health alerts for the community (including for schools, childcare centres, and other local businesses).</td></tr>
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2. Data application area

Smart low-cost air quality sensing devices range in price from a couple of hundred dollars to several thousand dollars. Even the most expensive of these devices are still classed as 'low-cost' relative to regulatory air quality monitoring equipment, which can cost tens or even hundreds of thousands of dollars.

TIP: Find a balance between device performance and cost

In general, more costly devices will produce higher-quality data than lower-cost devices. However, obtaining the highest-quality data is not always the aim, depending on your project. You should clearly define the minimum data quality that will support your chosen *application area*, and seek a balance between device performance and cost. Spend what you need to get the job done well, but avoid overinvesting to achieve a data quality that exceeds your requirements.

The OPENAIR Framework for Categorising Air Quality Sensing Devices

The OPENAIR Framework for Categorising Air Quality Sensing Devices consists of four tiers that characterise different air quality sensing devices and associated data applications according to the data accuracy they provide or require. This has been adapted from the US Environmental Protection Agency (US EPA)'s five-tier framework[2]. The following section of this OPENAIR supplementary resource provides an overview of these tiers. It will be helpful for you to determine which tier best describes your own monitoring project. For more information on this, please see the OPENAIR supplementary resource *A framework for categorising air quality sensing devices.*

Note: Local government air quality monitoring projects should align with Tier 1, 2 or 3. Tier 4 sits beyond the technical expertise, capacity, and data use requirements of most local authorities, and tends to be the domain of central government agencies.

[3] Sampling rate refers to the frequency that a device takes a measurement of a given parameter. For example, a gas sensor reading might be taken every two seconds for a 60-second period, producing 30 readings that are combined to produce an output expressed as a mean or median. High sampling rate can be useful for 'smoothing out' highly localised and time-bound pollution concentrations in locations such as busy roadsides, providing a more representative figure for that location over a period.

Tier 1: Education and engagement	Tier 2: Hotspot identification and characterisation
Low-accuracy data from 'ultra-low-cost' devices can be used for educational and engagement purposes in schools, or as part of participatory community programs. Simplicity, usability, robustness, and ease of set-up are critical attributes for Tier 1 devices. Data accuracy is less important, so long as a device responds in a predictable and expected way to changing conditions. **Tier 1 data collection can:** • Engage and educate people about air quality and environmental science • build community understanding of technology (e.g. sensing, communications, the Internet of Things, data management and interpretation) • empower grassroots advocacy for impact creation • leverage/support initiatives that aim for behaviour change (e.g. reducing car usage for local trips, or reducing/eliminating wood burning for home heating).	**Low- to medium-accuracy data from low-cost devices can be used to identify 'hotspot' locations with air pollution concentrations significantly higher than the ambient background.** Tier 2 devices are used to investigate the concentrations, temporal trends, and dispersal patterns of air pollution from known sources. Device deployments generally target 'hotspots' (where pollution levels are suspected to be higher than the surrounding area), though may also include vulnerable receptor sites such as schools and aged care facilities (where pollution levels may or may not be elevated to levels of concern). Devices tend to be deployed for a limited period in a specific target location (e.g. near known pollution sources, such as highways, construction sites, or industrial facilities). A degree of data inaccuracy is allowable for hotspot identification. What matters is that the error/accuracy of data produced by the device is less than the size of the pollution elevation that is being investigated. Hotspot monitoring should be considered 'indicative'. It can initially confirm (or disprove) a hypothesis and may be useful for securing funding and resources to explore a localised air quality issue more deeply. Depending on the aim of the project, it may be necessary to validate the findings from hotspot monitoring using higher-tier sensing equipment. **Tier 2 data collection can:** • support improved understanding of air pollution hotspots and local microclimates, including how and why they form • help to inform political, planning, or urban design decisions

Tier 3: Supplementary monitoring	Tier 4: Regulatory monitoring
Medium- to high-accuracy data from low-cost devices can be used to supplement data from regulatory monitoring networks (Tier 4). Supplemental monitoring involves the use of higher-performance low-cost air quality sensing devices to provide data of an appropriate quality for supplementing data from a regulatory air quality monitoring network. Devices are deployed over a long period of time to establish local pollution baselines and provide general monitoring and trend evaluation. Tier 3 data can supplement an existing regulatory network in two ways: 1. By filling in spatial gaps (e.g. supplementary sensing devices can provide data for locations positioned between regulatory stations, supporting more accurate spatial interpolation of regulatory data) 2. By filling in temporal gaps (e.g. a shorter reporting interval is often available from low-cost sensing devices, providing higher temporal definition around short-term pollution events). **Tier 3 data collection can:** • support the development of insights that affect policy and planning decisions at a systemic level (at local government scale or higher). This may have implications for areas of impact as diverse as public health, public infrastructure and services, utilities, community services, urban development and design, industrial development, and climate mitigation and resilience.	**High-grade monitoring devices provide scientific measurements of air quality in the local region.** In Australia, regulatory monitoring refers to highly accurate monitoring systems that are compliant with the National Ambient Air Quality (NAAQ) standards and are operated by state and territory governments. Sensing devices are calibrated to a reference instrument on a regular basis. Necessary security, power, and IT infrastructure are in place to ensure continuous operation and minimal loss of data points. **Example scenario:** A regional network of high-performance ambient air quality monitoring stations is managed by a regulatory authority. Data collection aligns with established national standards. Data is used to support state and national policy, and is also the primary source of trusted real-time information for public authorities (e.g. health, transport, and emergency services), as well as for the general public.

3. Sensor and sensing device performance and technical requirements

The performance of a sensor or sensing device relates to the quality and attributes of the data it produces. There are standardised key performance indicators or 'data quality parameters' that provide a universal reference. These can be found on sensor/sensing device specification sheets.

DEFINITIONS

Sensor: A specialist component, designed to capture empirical data about a directly observed phenomenon. A sensor is a component within a device that is generally sold to device manufacturers. A sensor cannot function separately to a supporting device.

Sensing device: A complete device, sold as a commercial product to end users. A sensing device will typically consist of the following components: device housing; a microprocessor; a sensor board; one or more sensors; a power supply; a communications module; and data storage.

This next section will explore the most important data quality parameters, and help you to rank/prioritise them according to your planned data application area.

Understanding data quality parameters

Data quality parameters	Description	Effect on project outcome	Where to find this information
1. Precision, bias, and accuracy	**Accuracy** is a percentage value of how much the device's value aligns with the reference value, or the actual amount of the pollutant present. **Bias** is the positive or negative offset of the measured value, compared to the reference. It is systemic in nature (inherent to the design of the sensor) and repeatable. Usually quoted as a value with the relevant units E.g. parts per million (ppm) for a gas sensor.	Accuracy, bias, and precision will determine which sensing devices are appropriate for your application. If your planned data application area requires high performance in these areas, then best practice is to characterise and understand these factors in each purchased device *prior* to field deployment (as they are likely	Bias and precision are commonly found in sensor data sheets (best case scenario), as well as the air quality sensing device data sheet. Accuracy of a sensor changes with humidity and temperature, and will be specified in more detail in application notes for sensors, and in third-party evaluation test reports.

Data quality parameters	Description	Effect on project outcome	Where to find this information
	Precision is the ability to output the same measurement with the same pollutant value present. High precision means the range of error about the measurement point is small; low precision means there is high range of error about the measurement point. Usually quoted as a percentage of a reading, or the span of the range.	to vary between devices, and will determine your data processing activities during their use). *See the correlation section for more detail.*	
2. Range and error	The concentration range that a device can measure. The error is often quoted as a percentage of the entire range, or of the measurement made.	Ensure that your target pollution concentration and error requirements are within the device's capability, or your results may not be valid.	Commonly stated in air quality device data sheets, and sensor data sheets. Actual reportable range may be less than that stated, and can be investigated through lab test results by third parties.
3. Correlation (R^2)	The correlation coefficient (R^2 value) is a measure of the relationship between the device's readings, compared to a reference instrument's readings. A sensor or device may over-report or under-report values, compared to a trusted reference. A value of 1 indicates a perfect linear scaling of values between the reference instrument and the sensor (i.e. they match). An R^2 value less than 1 indicates a deviation from the reference. The lower the value (i.e. the closer it is to 0), the greater the deviation. A high R^2 value (e.g. 0.9) indicates a more accurate sensor than a low R^2 value (e.g. 0.4).	Correlation is a significant metric determined through co-location of a sensor/device with trusted reference equipment. It will determine if your sensor/device is appropriate for your project, while providing calibration coefficients to be applied to each sensor's dataset, once deployed to the field.	R-squared (R^2) values can be found on device specification sheets, in third-party evaluation reports (such as from the USA based AQ-SPEC), or in research literature. However, many of the lesser-known sensors do not have R^2 values calculated. The US EPA recommends co-location testing as a minimum requirement, so that you can determine these values yourself.

Data quality parameters	Description	Effect on project outcome	Where to find this information
4. Sensitivity and ageing	A metric mostly applied to gas sensing devices, indicating how much the reading is subject to change when another variable changes (such as temperature, humidity, and other interfering gases). Sensitivity drift is also quoted as a percentage of change per year for a specific operating environment.	Useful when deploying devices in environments where high or low humidity or temperature values will have a significant effect on the readings. These metrics should be scrutinised if high accuracy is required for gas sensing, or if high humidity is suspected to impact particulate value readings.	These metrics apply to particulate sensors as well, but are not quoted, and need to be determined experimentally (if required). Gas sensors will have these metrics on their data sheets, and described in more detail in application notes. Drift over time can also be experimentally measured, however this will require two instances of co-location for a total period of 60 days, as well as lab testing (as per US EPA protocol).

IS IT BENCHMARKED?

An additional consideration relating to data quality is whether you can verify the performance claims of the device or sensor manufacturer through independent evaluation. Most data sheets report performance metrics that are correct under ideal conditions. Actual performance in the field may differ. Some devices are independently benchmarked against reference equipment, either in a lab, or in an outdoor co-location with regulatory sensors. For these devices, a much clearer understanding of their data quality output during ‘normal’ operation is available, allowing you to further assess their suitability for your use case. Note that many commercially available devices have not been independently benchmarked, or there is no independent information available about benchmarking that may have been done. The data quality from these devices is therefore more uncertain.

4. Communications technology

Any sensing device with live data connectivity must have inbuilt communications technology. There are several common communications options in commercial devices, and the following section will help you to determine which option is best for your project.

Choosing an appropriate communications technology option

Option	Location of devices	Number of devices	Cost and pricing model	Community participation	Reliability	Device functionality constraints
Wi-Fi	Generally requires devices to be deployed on properties with reliable Wi-Fi (e.g. schools), ruling out public space. Local government-managed public Wi-Fi may expand your options.	The number of devices you deploy is limited by the number of locations you can secure access to, that have reliable Wi-Fi coverage.	Essentially free, from the perspective of your project, as you will be reliant upon existing Wi-Fi networks.	Wi-Fi can be a good option to support community-hosted devices. However, you are advised to consider the practicalities and ethics of relying upon private internet connections to run your project. In particular, note that lower socio-economic groups may have difficulty maintaining continuous connectivity throughout the whole period of your project, and that this might cause disruption to your data collection. For this reason, local government-run	Relying on private Wi-Fi (or even public-access Wi-Fi through town centres) can be high risk, because networks can shut down unexpectedly, and you will have no control over this. If it is important to you that your data sets are largely continuous and uninterrupted, then it may be best to avoid Wi-Fi.	Mains power is required (due to high power demand of Wi-Fi). Wi-Fi supports high bandwidth data transfer, meaning it will support very high reporting rates (e.g. every 30 seconds), as well as more sophisticated edge computing associated with certain high-performance device options (generally outside of the 'low-cost' definition). Most non-technical use cases will not require these functions.

Option	Location of devices	Number of devices	Cost and pricing model	Community participation	Reliability	Device functionality constraints
				public Wi-Fi may be a better solution.		
Open LoRaWAN (The Things Network)	Coverage in a 1-5km radius of a gateway (dependent upon topology and built environment). It tends to be best for one or two focused areas (e.g. a suburb or town centre) that can be serviced by one or two gateways. Investment is most cost-effective when it supports multiple activities and business models (not just environmental sensing). In this scenario, you may find that your organisation has invested in a broader	There is no meaningful limit on device numbers when you use The Things Network (TTN). A basic service package can accommodate thousands of devices, and there is zero marginal cost per device. There is no limit to device types, providing they can be configured for TTN.	There is an upfront cost for gateways and their installation, plus recurring operations costs payable to a service provider. There are no ‘per device’ costs. As such, the majority of costs are ‘capex’, with more set/predictable ‘opex’. Cost-effectiveness is reliant upon a critical mass of devices (generally 20+ at a minimum).	Excellent for community participation. The Things Network (TTN) is an open-access, global grassroots community that has been developed specifically to empower community engagement with IoT. Anyone can create a TTN account, and start adding and managing their own devices.	No Service Level Agreement (SLA) available.	Signal is often attenuated by poor weather, and periodic device dropouts are not uncommon. However, being open-access, other gateways in the vicinity (owned by other people) can provide backup connectivity, and help to reduce the risk of dropouts for any given device. LoRaWAN (of any variety) allows for two-way communications, and more complex functionality.
Private proprietary LoRaWAN		Private commercial LoRaWAN and Sigfox both tend to	A per-device subscription model tends to replace	Neither option is conducive to community	No Service Level Agreements (SLAs) possible.	

Option	Location of devices	Number of devices	Cost and pricing model	Community participation	Reliability	Device functionality constraints
Sigfox	network, giving you more widespread coverage, and more options for deploying devices in multiple locations.	charge for each device connected, which may place a budgetary limit on the number you choose to deploy. Otherwise, there are no technical constraints on device numbers or types.	gateway procurement and operation charges. Commercial packages vary. Your upfront 'capex' may be lower, however ongoing operational costs for proprietary LPWAN may increase as you expand your use of the service.	participation. The per-device connection fee is a barrier to DIY community involvement. Furthermore, access to the services is not generally designed for open public access.		Sigfox only allows one-way communications, meaning that it is not possible to control devices over the air.
3G/4G (LTE)	Highest flexibility with location, as the signal is carried through existing cellular infrastructure. Good option for covering large areas, such as distribution of a smaller number of devices across a whole LGA.	The main restriction on the number of 3G/4G or NBIoT devices is a per-device cost. There are no technical limits to the number of devices you run.	A per-device, fixed, recurring fee is calculated according to data use. No investment required in additional infrastructure (e.g. gateways).	Not conducive to DIY participation, due to the fees associated with connection. However, due to the widespread and reliable coverage, it can be a good option where a community stakeholder is hosting a device, and local government	Very reliable. Multiple SLAs possible, of increasing strength.	3G devices are still on the market, however 3G technology is due to be completely decommissioned soon, which will render 3G devices obsolete.
NBIoT						NBIoT will have a useful life of about 10

Option	Location of devices	Number of devices	Cost and pricing model	Community participation	Reliability	Device functionality constraints
				retains management responsibility.		years. Today, the services offered by the major telcos can be expensive per device, but prices will probably come down over time. Negotiation may be possible if there is a promise of future service usage growth.

5. Proprietary technology vs open technology

Sensing strategy reference tool: proprietary vs open device technology options

How to use this table: Consider each factor in the following table and check the 'your position' box that best aligns with your situation. The right-hand column should help you to make this choice. After going through this process for each factor, your responses should provide you with a better idea of which technology option would best support your situation.

Factor	Your position	Proprietary or open technology?
The planned scale of your future sensing device network	☐ You expect to grow an air quality monitoring network over the coming years, both in terms of coverage and sophistication.	More open technology options may be advisable, as they are a flexible choice for expanding and evolving your air quality monitoring activities into the future. Proprietary options can reduce future flexibility, and may restrict your options if you plan to expand and evolve your approach. Open technology involves more upfront investment of time, effort, and resources because you do more of the heavy lifting yourself.
	OR ☐ You are looking to keep things simple and contained, and do not expect to expand much beyond the scope of the current planned initiative.	More proprietary technology options may be a cost-effective and simple approach. Good proprietary options can reduce the hard work required upfront, and give you quick wins. You might forfeit flexibility in the medium term.
Smart city development aspirations	☐ Your organisation has a well-developed position on smart cities, and you aspire to develop your smart city strategy and activities further in the coming years.	Open technology options are advisable. They tend to align with emerging smart city best practice, because they prioritise transparency, accessibility, and interoperability. Open technology can enable you to better understand how your air quality data is being interpreted and abstracted, support more customised data management approaches, and integrate with other smart city systems and platforms (e.g. an emerging enterprise architecture). This is generally the foundation required for developing more sophisticated data use

Factor	Your position	Proprietary or open technology?
		cases (e.g. data-driven models, such as near-term forecasting of local air quality, or real-time multifactor analysis, alerts, and automation).
	OR ☐ Your organisation does not have a strong position on smart cities, and you do not expect this to be a strategic focus in the short to medium term.	More proprietary technology options may be a cost-effective and simple approach if you are not overly concerned with smart city strategy development, and you do not have ambitious plans for how you will use your air quality data.
Your technology and data integration intentions	☐ Your organisation is concerned about a proliferation of parallel smart technology systems, and the development of data siloes. You are keen to develop a more centralised and integrated solution that brings together data streams from multiple activities, and supports more complex data use cases.	Open technology options are advisable. They are built for interoperability, and can support sophisticated integration with your existing internal systems, allowing you to pull air quality data into a more centralised system and extract additional value from it, in the context of other data streams. Such sophistication may take a reasonable amount of time and effort to establish.
	OR ☐ You are not interested in developing complex, real-time use cases for your air quality data, and your organisation does not have any existing concerns about data siloes.	Proprietary technology may be suitable. It *can* restrict your options for integrating technology and data with other platforms and systems, and can therefore limit the ways in which you make sense of (and respond to) live data. However, this may not be a problem if you want to keep your response to data quite simple. For example, if you wish to gather some basic data for a year or two, manually analyse it, and produce a report, a basic, stand-alone proprietary solution may be the most sensible approach.
Transparency of data processing	☐ Your organisation needs to understand precisely what has been done to air quality data, and who has accessed it. This is critical to your ability to interpret and share data, and support a maturing data policy.	Open technology options are advisable. They should provide full transparency around the way that air quality data is being interpreted and managed.

Factor	Your position	Proprietary or open technology?
	OR ☐ Your organisation is not overly concerned with the fine details of data processing, and you are happy to place face-value trust in the outputs of your chosen technology provider. You also lack a well-developed data policy that might apply to smart city data management and sharing.	Proprietary technology may be suitable, however you are advised to have a really clear idea of how you intend to share and make use of data, or respond to public questions. A lack of transparency around data interpretation means that it may not stand up to deeper scrutiny.
Position on vendor lock-in	☐ Your organisation has recognised a problem relating to technology procurement and vendor lock-in, and may even have established a formal position on the issue.	By choosing more open technology, you are choosing more flexible commercial options, and a more modular system. This gives you the freedom to swap out specific commercial providers or equipment in favour of alternatives, without stranding your entire technology stack.
	OR ☐ Your organisation is not overly concerned with vendor lock-in, or the issue has otherwise not been identified or discussed.	Proprietary technology poses an unavoidable risk of vendor lock-in. Once invested in physical devices, there is no option to take those assets and connect them into someone else's system. The hardware might be owned by the customer, but it can only ever be made to work through the proprietary support platforms of the manufacturer. This may be agreeable, as the trade-off can be simplicity, and total outsourcing of technical management. However, it is important that a contract with a proprietary vendor is entered into with an awareness of the lock-in risk. If you believe that your needs are likely to evolve in the short to medium term, you are going to want flexibility, and the terms of your initial contract (or what the vendor can offer you in an amended contract) may be quite limiting.

Factor	Your position	Proprietary or open technology?
In-house technical knowledge and resourcing capacity	☐ Your organisation has *some* in-house technical knowledge and expertise relating to IoT and smart cities, and has the resourcing capacity to support the set-up and operation of more open device technologies.	Open device technology ideally requires a basic in-house knowledge of IoT and smart cities, to support an informed selection of hardware and supporting services. The technical work of setting up, integrating, commissioning, and operating devices can be outsourced, but it is still advisable that at least one individual within your organisation is competent enough to be able to negotiate strongly with contractors.
	OR ☐ Your organisation does not have much in-house knowledge of IoT or smart city technology, or else lacks capacity to support adequate in-house resourcing of technical delivery.	Proprietary devices tend to come as part of a complete service package, with little to no effort or expertise required of the customer. This may be the only option for organisations that lack sufficient in-house technical knowledge or resourcing capacity. However, it should be noted that many non-proprietary services exist that can take on the setting up, integrating, commissioning, and operating of sensing devices.
Your digital asset management needs	☐ Your organisation is amassing a growing collection of digital assets, across a diversity of smart city initiatives. You wish to register and manage all these assets within a central asset management platform.	Open device options, working through open IoT platforms, can easily be integrated with an existing asset management platform, alongside multiple other assets.
	OR ☐ Your organisation does not have many digital assets, and you do not expect this to change in the short to medium term. You are happy for your devices to be managed through a third-party platform, separate to any central asset management system.	It is difficult or sometimes impossible to integrate proprietary devices with a separate asset management platform.

Factor	Your position	Proprietary or open technology?
Your data ownership and management needs	☐ Your organisation requires full ownership of sensor data, and the ability to manage it in accordance with a clearly defined data policy.	Open technology is advisable, as all data collected is owned by you. Many proprietary sensing device options operate on a data-as-a-service subscription model. Devices remain the property of the supplier, and the data they produce is sold to you. In some cases, you may not even own the data, but rather you pay for the right to access and use it. This can severely restrict your options for managing access, privacy, and ethical considerations associated with data sharing.
	OR ☐ Your organisation is happy to receive data-as-a-service, and is not overly concerned with ownership or management details.	A proprietary data-as-a-service model may be suitable for you. It offers a simple data provision option, with no need for in-house knowledge or operational resourcing. Some of the data-as-a-service models can work out to be more affordable (or you get more devices and coverage for your expenditure) than if you buy devices outright. This might outweigh the benefits of owning your own data. IoT technologies are rapidly evolving and improving. There is an argument that a service-based agreement decouples your organisation from a specific technology, and the risks associated with it becoming obsolete in the near future. If you are simply purchasing data, the supplier takes on the 'how' of its collection. New (and presumably better-performing) hardware and software can be swapped in as it emerges, at no cost to the consumer. Meanwhile, the consumer avoids stranded assets. The trade-off here is that you lose the ability to manage data on your own terms, which may have repercussions for how you are able to use or share it.

Factor	Your position	Proprietary or open technology?
Your data sharing needs	☐ You would like to share data widely, both within your organisation, and with a variety of external stakeholders (including, but not limited to, the public).	Open technology provides more flexible options for managing data access and sharing data with a variety of users, both within your organisation, and with external stakeholders. For example, you will generally have the option of a customised 'application programming interface' (API), which provides a real-time data stream from your devices to a third party. Some proprietary platforms will offer an API, but only open platforms will allow you to customise an API in accordance with a defined data use case, or with your organisation's data policy.
	OR ☐ Your organisation has modest data sharing needs. You anticipate little interest in the data beyond your immediate team. Public access to data via a dashboard may be of interest, however you do not intend to share more broadly (e.g. inter-organisational sharing).	Most proprietary sensing devices will be tied to a platform that has the option of a public dashboard. There may be some customisation available, but this may be somewhat limited. While an API option may exist for streaming data to a third party, it is unlikely to be customisable.

6. Environmental factors and robustness

Regional climate, and the specific microclimate of a location where you intend to deploy a device, will determine the conditions that the device will be exposed to, supporting a requirement for a certain level of device robustness and functionality. Extremes of temperature, direct weather exposure, high humidity, and high salt aerosols can take their toll on devices (and their mountings) across their functional lifetime.

These high-level questions can help you to consider the environmental robustness requirements of your devices:

- Are your devices likely to experience temperature extremes (+35/-0°C)?
- Are your devices likely to experience high salt content in the air?
- Are your devices likely to experience high humidity? Note that mist/fog/cloud counts in this regard, and may be present at lower temperatures. Humidity interference can be corrected for, but if you anticipate this challenge, then you need to check that the service provider can offer this correction as part of a data provision service.

The following section of this guide will explore key considerations related to device robustness: **IP rating; solar radiation shields; and materials used**.

IP rating

An IP (ingress protection) rating is a standardised rating system that certifies commercial products for two core attributes: their ability to withstand water ingress; and their ability to withstand dust ingress. An IP rating is expressed as two numbers. The first can be 0-6 and relates to dust ingress, where 6 is the highest possible protection. The second number can be 0-9 and relates to water ingress, where 9 is the highest possible protection.

A water ingress protection of 7 equates to ‘protection against full immersion for up to 30 minutes at depths between 15cm and 1m (Wikipedia, n.d.). Higher water protection ratings relate to ingress protection at depth, under pressure.

The highest IP rating relevant for electronic devices deployed outdoors in unsubmerged contexts is IP67, which is the gold standard for smart sensors.

However, an IP rating of 64 is also common with low-cost devices. A water ingress protection of 4 equates to ‘protection against splashing water from any direction, tested for a minimum of 10 minutes with an oscillating spray’. For many device types, this will be ample protection for the location where you are planning to deploy, and in theory, an IP64 device should be fully protected from even the most torrential and prolonged rain.

A higher IP rating may add to the overall cost of a device, though this is not always true.

TIP: Pay attention to the IP rating when procuring your devices

When making a procurement decision, pay attention to the IP rating. Firstly, avoid any products that do not have any IP rating at all. Secondly, it is inadvisable to procure devices intended for outdoor deployment that have an IP rating of less than 64. Finally, if you have two similar choices, but one has a higher IP rating, consider choosing it over the other option.

Solar radiation shield

A temperature sensing device fitted with a solar radiation shield. Image source: UTS

A solar radiation shield (shown in the image to the left), or Stevenson screen, is a special kind of housing designed for meteorological sensors. It prevents direct thermal radiation from the sun from heating up the sensor or surrounding components, while enabling the highest possible airflow around the sensor, from all directions. A shield should be white or light in colour, maximising reflectivity of infrared. It should also be lightweight, and devoid of thermal mass. Traditional shields are rectangular in profile, but a lot of smart sensing devices employ a cylindrical design.

A radiation shield can make a difference of a few degrees to a temperature reading. Importantly, chemical gas sensors are very susceptible to temperature, so they can give erroneous readings if they are not kept at the true ambient temperature for the location.

Many commercial sensing devices come with solar radiation shields, and many others do not. A common issue for devices that lack a solar radiation shield is to build up thermal energy inside the housing, due to poor ventilation, and poor layout of components. Sometimes, a choice might be made on the grounds of aesthetics or compactness to forego a shield (this can be a legitimate approach in some contexts).

Some rules of thumb:

- If your focus is on urban heat monitoring, and you care about temperature difference of a degree or two (as required for the study of the Urban Heat Island effect), then it is advisable to use a device with a radiation shield.
- If you are studying noxious gases (such as NO_2 or CO), you are advised to use a device with a radiation shield.

Materials to resist corrosion by salt aerosols

Certain environments can corrode the materials used for fixing a device (as shown in the image to the right). Most commonly, coastal settings close to the ocean that are subject to salt aerosols can cause the rusting of steel components. Certain plants (such as mangroves) can also excrete salt into the air, creating high-corrosion microclimates in their vicinity. There is even a risk of salt exposure in cold or alpine climates, where salt is used to keep roads free from ice, and can be splashed into the air by passing traffic.

If you know that your device will be subject to such conditions, choose materials that are resistant to salt corrosion. This consideration must extent to all mounting brackets, components, and fixings.

A temperature and humidity sensing device deployed on an ocean pier, suffering from rust corrosion. Image source: UTS

Marine-grade stainless steel	Standard stainless steel is not resistant to salt water or salt aerosols for any prolonged period of time. Marine-grade stainless steel (typically “316” grade) is a product designed for marine applications, and contains molybdenum (which allows the alloy to resist sodium chloride). It is more expensive than standard stainless steel, but should be considered for any deployments that are likely to see salt exposure. It is the highest-cost option, but also the most effective.
Galvanised steel	Galvanised steel uses a thin layer of zinc to protect the steel beneath from corrosion by water. It will provide some salt protection, however it is important to note that zinc also oxidises in contact with salt. Over time, oxidised zinc washes away, until the protective galvanic layer is broken, and the steel beneath it is exposed. Galvanised steel can be lower-cost than marine-grade stainless steel, and can be a more cost-effective alternative for salt environments. The thicker the galvanising, the longer it will provide protection. Galvanised steel, combined with rust-resistant paint, can be an easier option to work with, if you want to develop custom mounting solutions for your devices, or weld them to fixed infrastructure.

UV-resistant plastic	Certain plastics provide a corrosion-resistant alternative for device housings and mounting equipment. It is important that the plastic used is resistant to degradation by UV light. In Australia, UV levels are, on average, higher than in many other parts of the world.

A NOTE REGARDING ALUMINIUM
Contrary to what you may think, aluminium is not resistant to salt water. Although aluminium does not rust like steel, its outer surface corrodes into a white, chalky aluminium oxide, which can run in streaks from any mounting brackets or fittings, creating an aesthetic concern. It is possible to coat aluminium to prevent this oxidation, however custom fittings for products with limited distribution may not have had such treatment.

Quality of build

The quality of engineering and fabrication in a device is something that is very hard to define or assess prior to procurement. Nevertheless, it is a factor that can vary greatly, and is a consideration for the robustness and overall performance of a device as a piece of physical hardware.

There are a few factors associated with high- or low-quality of build and general performance that you can bear in mind to aid your procurement decision-making:

- **Track record of the device**. If the device in question has been used successfully in past projects, it is a strong indication of its quality (and even more so if it was used by your own organisation).
- **Profile of the manufacturer.** A new device from a well-established and trusted manufacturer is likely to be of high quality.
- **Profile of the device and word of mouth**. Some devices build a reputation as being a high-quality option. If there is a device that you are interested in, find out if it has been used by other organisations whose assessment you trust, and reach out to see what they thought of it.
- **Independent benchmarking.** Most independent benchmarking of commercial sensing devices focuses on data quality. However, some studies that include outdoor deployment also assess robustness, and other general performance considerations. It is always worth searching for such reports.

7. Device lifetime

Your chosen use case will determine your requirements for device lifetime. Different commercial device options will afford different functional lifetimes. The functional lifetime of a sensing device relates to a complex mix of factors. Some of these may be considered during procurement, to help ensure that you choose an option that meets your needs.

Understand a device's functional lifetime, and how to procure the right device to meet your project's needs

Attribute of a device that affects its functional lifetime	Explanation	Procurement advice
The complexity of a device	The more complex a device is, the more there is that can go wrong. More complex devices might have more moving parts, more individual components, and more potential failure points. Sometimes, more sophisticated functionality can translate into a higher risk of failure.	*Avoid unnecessary complexity* It makes sense to choose a device that is as simple and elegant as possible while still meeting your needs. In other words, know precisely what you need, and take a lean approach. Some common additional complexities to be aware of: • Heated air intake for particulate monitors. Useful in high humidity environments if high data quality is required. • Additional onboard processing. Certain use cases may call for this, though always compare this to cloud-based processing options. More onboard processing may equate to more complex electronic hardware and more complex firmware, either of which can go wrong.
The quality of a device	Some devices are made to a higher standard than others. A high-quality, well-engineered design is most likely to operate reliably for its full projected functional lifetime.	*Balance quality against needs/budget* Purchase as high a quality device as you can manage or justify, relative to your project's sensing needs, particularly if a long lifetime is a priority. Beware of a false economy: a cheaper upfront option

Attribute of a device that affects its functional lifetime	Explanation	Procurement advice
		may result in more overall cost if it fails early, or requires more maintenance. A limiting factor is the total number of devices you plan to deploy. If you want a large network, higher-cost device options may be off the table. Consider what your budget can stretch to, in light of your planned network size.
The lifetime of chemical sensors	The lifetime of chemical sensors is largely a product of the levels of pollution to which that sensor is exposed. A gas sensor incorporates a chemical agent that reacts with a target gas and slowly degrades. Over time, its accuracy will drift, until it reaches a point where readings are no longer reliable. If pollution levels are very high, this process will occur faster.	*Consider drift correction functionality* Consider the location where you plan to deploy your device. Do you anticipate very high gas pollution levels throughout the operational lifetime of the device (e.g. an inner-city street canyon; an enclosed bus depot)? It is possible to correct for gas sensor calibration drift. If you expect to be dealing with high levels of gas pollution, then you should check that a device includes drift correction functionality, either onboard, or as cloud-based processing.
The lifetime of particulate sensors	The lifetime of particulate sensors is a product of moving parts (fan failure is not uncommon), and particle deposition on components and receptors over time. The latter constraint was shown in a study to be a limiting factor for sensors deployed during a summer of exceptionally heavy bushfire smoke (Australia's 2019/2020 'Black Summer').	*Be aware of the limits imposed by high-pollution environments* Consider the location where you plan to deploy your device. Do you anticipate very high particulate pollution levels throughout the operational lifetime of the device (e.g. high dust associated with a construction site)? Low-cost particulate sensors use a laser light-scattering technology called a nephelometer. Particle deposition challenges are difficult to address with this technology, because such sensors cannot be cleaned as part of any maintenance routine. High-precision

Attribute of a device that affects its functional lifetime	Explanation	Procurement advice
		particulate sensors have replaceable filters that get around this issue; however, these fall well outside any reasonable definition of 'low-cost', and are not a procurement consideration. Therefore, the best procurement advice is to be aware of this as a potentially limiting factor, and to accept it as part of your business model. If you need to use sensors in a high-particulate environment, plan for a shorter operational lifetime.
Battery life	Battery life is a product of: **Battery type** (generally: lead acid, alkaline, Lithium-Ion). L-Ion batteries deliver the highest long-term performance and lifetime, but are more expensive. **Battery size** (which often equates to the size of the device itself). If you want a very compact option, then you are likely going to have a smaller battery, and a shorter battery life. **Power cycling** (the number of times a battery is drained of power and recharged). Deeper discharge cycles can have a greater impact on battery life. **Discharge of a battery below a critical threshold**, which can arise where power demand exceeds daily solar recharge capacity, and can cause permanent damage. For devices reliant upon a single battery for their deployed lifetime (with no mains or solar recharge capacity), some additional factors come into play:	*Lithium-Ion with charge protection* Choose Lithium-ion batteries where budget allows (for battery-only and battery-solar set-ups). If using solar, check that the device has built-in protection to prevent battery charge running too low, and damaging recharge capacity. *Adequate solar panel size for your planned location* Ensure that the solar panel is large enough to meet demand in the planned deployment location, because consistent undercharging can damage the operational lifetime of the battery. Also consider the need to periodically inspect and clean panels, to maintain optimal functionality. *Understand your specific place-based data requirements* If you plan to focus air quality monitoring in a very specific and relatively confined locality (such as a single transport hub), and your aim is to understand highly localised pollution sources and dispersal patterns, then higher sampling rate and reporting interval may help.

Attribute of a device that affects its functional lifetime	Explanation	Procurement advice
	Sampling rate[3] and reporting interval[4]. If you want these to be high (generally more important for very focused, place-based inquiry), then battery power gets used up more quickly. **Communications coverage and strength**. For LPWAN technologies (which tend to be the only type compatible with battery-only power supply), higher power demand is associated with a higher 'spreading factor' (which can be thought of as 'how hard the device tries to be heard when it transmits its data'). A higher spreading factor is often necessary in locations with weaker signal coverage or strength (e.g. further from a gateway). The result: if you are deploying somewhere with weak communications coverage, your battery will not last as long. **Onboard processing capacity**. More sophisticated devices might deliver higher data quality through more advanced onboard processing, but you may pay for this with shorter battery life. The alternative is greater reliance upon cloud-based processing, which is increasingly a viable option that can support more power-optimised devices.	If this is a consideration, consider mains power or solar if the lifetime of the device is also a concern. *Dynamic spreading factor* If you are using battery-only devices on a LPWAN network, and you think you may be deploying in locations with more marginal signal coverage, you can discuss options for using a *dynamic spreading factor* with the device supplier. This is a configurable setting that allows a device to adjust its spreading factor according to need, optimising the use of power for each device in your network. In turn, this helps to maximise battery life for each device.

[3] Sampling rate refers to the frequency that a device takes a measurement of a given parameter. For example, a gas sensor reading might be taken every two seconds for a 60-second period, producing 30 readings that are combined to produce an output expressed as a mean or median. High sampling rate can be useful for 'smoothing out' highly localised and time-bound pollution concentrations in locations such as busy roadsides, providing a more representative figure for that location over a period.

[4] Reporting interval refers to the frequency that a device sends live data packets over a communications network. Each time a packet is sent, power is used. A device that reports once an hour will use a quarter of the power for communications that a device reporting once every 15 minutes would use.

Attribute of a device that affects its functional lifetime	Explanation	Procurement advice
Modularity	A modular device has the potential to be reconfigured or updated over its functional lifetime. This can help to extend device lifetime in two ways: Components such as gas sensors or batteries can sometimes be replaced, which can significantly extend the lifetime of the device. However, the cost/benefit of recall, refurbishment, and redeployment is a factor to consider. Some devices reach the end of their functional lifetime prior to any sort of component failure, due to being redundant in terms of their functionality, relative to the aims of the organisation. A more modular design gives flexibility to repurpose a device to a new project or use case, extending its functional lifetime.	*A degree of modularity might help* Consider a modular device if lifetime is a big factor for your project. A replaceable battery is the most important feature in this instance. Replaceable gas sensors are also worth considering. Confirm all costs and timeframes associated with component replacement with the device supplier, as part of initial procurement negotiations. Note that modular devices may compromise on compactness.

8. Power supply: battery, solar, or mains power

When you procure a sensing device, you must decide on a power supply option that supports your chosen use case, and works within the practical constraints of your project.

The power supply option for a sensing device can be either battery-only, solar plus battery, or mains supply. The particular combination of device attributes will determine the best power supply option, and may rule out some options entirely. A great deal of added complexity comes with a consideration of deployment context and operations. This next section will help you to make an informed power supply decision.

8.1. The implications of fixed device attributes for power demand

Device attributes		Battery-only	Solar + battery	Mains
Type of sensors	Temperature and Humidity only	Adequate for devices that use low-power communications (LoRaWAN, Sigfox, NBIoT).	Good for all options. Only *necessary* for devices that use high-power communications (3G/4G, Wi-Fi), or for very high sampling rates or reporting intervals (uncommon).	
	Gas sensors	Generally not suitable.	One of these power options is required, in most cases.	
	Particulate sensor			
Communications technology	Wi-Fi	Generally not suitable.	Adequate for all communications options (providing other power demand is minimised).	Adequate for all device communications options. No limitations.
	3G/4G			
	LPWAN (LoRaWAN/Sigfox)	Generally suitable (providing other power demand is minimised).		

Device attributes		Battery-only	Solar + battery	Mains
	NBIoT	Possible (providing other power demand is minimised).		
Onboard processing	Low onboard processing (power-optimised)	Adequate for devices that run Temperature/Humidity sensors only.	Adequate for all devices (providing other power demand is minimised).	Adequate for all devices. No limitations.
	High onboard processing	Not possible.	May be impractical, as it requires a very large panel and battery.	

8.2. Deployment and operational factors that might impact your preferred power supply option

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
Locations with marginal communications signal strength	Battery-only	Marginal signal strength may be a problem for devices that rely upon LPWAN communications technologies (LoRaWAN and Sigfox). This is generally the result of: • A long distance to gateways • Limited number of gateways	One approach to dealing with marginal signal strength is to increase the 'spreading factor' of a device. This may be thought of as how hard a device tries to be heard by nearby gateways. If it tries harder, it uses up more power. Thus, you can account for a deployment location with

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		• Undulating terrain • Tall buildings in the way • Dense vegetation in the way.	marginal signal, but the trade-off is reduced battery life. For battery-only devices, this can cut their operational lifetime by as much as half. If you are using LPWAN communications, and you think that marginal signal strength may be an issue for some locations (but you plan to deploy battery-only devices), make sure you speak to the prospective supplier about spreading factor, and make sure this is something they can customise for you. Such custom configuration is not always possible. In some cases, a 'dynamic spreading factor' can be implemented. Here, the device is smart enough that it adapts its spreading factor automatically, in response to the signal strength that it detects. It will settle on a spreading factor that is optimised to the location you deploy it in.
Reporting interval	Battery-only; Solar + battery	Near-real-time data reporting is where a device periodically transmits a packet of data. The reporting interval is the period that elapses between each transmission, and it can be	To help optimise the power use of a device that relies upon batteries or solar power, it is advisable to have a clear understanding of the reporting interval required to support your data

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		customised to meet the needs of a particular data use case. Typical reporting intervals tend to vary between 10 and 60 minutes. Each time a device transmits data it uses power, so a shorter reporting interval means a greater power demand.	use case. Do you need data every ten minutes, or will hourly reports do? Once you understand your needs, you can avoid an overinvestment of power in unnecessarily short reporting intervals.
Locations with low solar exposure	Solar power	Devices with solar power can be deployed anywhere with at least 120 degrees of clear sky within the 180-degree northern aspect. This gives access to a broad range of locations where it would be impossible to access mains power. Solar exposure can vary significantly as a result of deployment location and time: • Buildings and trees can cause alternating periods of direct sun and full shade throughout a day • Trees can provide shade in summer, but not in winter	If you plan to use solar, and you think that solar exposure may be a concern, consider using a larger solar panel to compensate. However, it is noted that public locations tend to demand low-profile equipment and low pole clutter, which can exclude the use of large panels. Large panels can also require more robust mountings to deal with higher wind loading, which can significantly increase installation costs across multiple devices. The other option tends to be to switch to mains power for devices in more shaded locations. This is common for use cases like street canyon monitoring, where there tends to be good access to mains power.

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		• Prolonged periods of poor weather may reduce total daily solar exposure below a critical threshold. Winter sunlight is less intense, and days are shorter. This may reduce total daily solar exposure below a critical threshold.	You should also consider how much risk of device drop-out (and corresponding gaps in the data) due to solar failure is acceptable for your chosen use case.
The availability of locations with accessible mains power	Mains power	Devices reliant upon mains power are limited to locations where power is available. Approval for connection is not always achievable. Approval, where it is possible, is also likely to be more complex and prolonged.	If you intend to make use of mains power, it is advisable that you mount devices on assets that belong to your organisation (e.g. street poles, building facades).
Intermittent mains power	Mains power	Mains power can be intermittent. For example, street light circuits often switch off during the day.	Add a battery to your device that recharges from mains power at night, and provides power back to the device throughout the day.
Cost of installing mains power	Mains power	Connection of a device to mains power requires a licensed electrician. Often, power needs to be extended from a nearby source, and converted	Consider the ‘hidden costs’ of mains power connection, which may be much higher than the cost of installing solar-powered devices.

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		through a transformer to the appropriate voltage. If you are deploying on street poles, the installer will need a 'working at heights' licence, and may also need high voltage (HV) certification if they are working close to overhead HV cables. They may require the use of a telelift, or cherry picker. The installation itself will take longer than a solar install. All of this can amount to installation costs far higher than any associated with the installation of solar or battery-only devices.	Obtain a schematic for complete installation from your device supplier, and send this to electrical contractors to obtain a quote as early as you can, to give you a clear idea of what these costs will be.
Time for installation approvals	Mains power	Installation of a smart device on any asset requires detailed proposals, and an approval process. The complexity of a proposal, and the time taken for it to be assessed and approved, tends to be much higher for mains-powered installations than it is for solar or battery-only installations. In cases where the mounting asset and/or power supply is not owned or managed by your organisation, this process will be even longer. There can often be multiple	If you are planning mains-powered installations, and you are delivering a project within a defined timeframe, then you need to allow enough time to approve the installations. It is entirely possible that deployments can be delayed by months. Get the ball rolling early. At the procurement stage, obtain as much information as you can from your device supplier about the specific installation requirements, and make early

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		departments or organisations that need to approve your plan.	inquiries to relevant authorities. You may be able to conduct most of the approval process before you even receive the physical hardware.
Operational costs	Solar power Mains power	All three power supply options have ongoing operational costs. Battery-only devices may have the lowest operational costs, particularly if battery replacement is not planned within the lifetime of the project (some low-power devices can operate for seven years or more off an original set of batteries). If you do plan to change batteries, then the cost of doing so can be quite high. Solar-powered devices can suffer faults and power dropouts, particularly in instances where panel and battery size are kept to a minimum and power usage is optimised, which allows for less resilience to adverse conditions. A combination of restricted solar exposure (e.g. nearby buildings or trees), shallow mid-winter solar aspect, and prolonged poor weather can	If you plan to use battery-only devices, you should consider from the outset whether they can function for the entire lifetime of the project off the original batteries. If a battery replacement is required, you should factor in the operational cost of this, which can be quite high (particularly if devices need to be returned to base for the switch). Solar-powered devices need to be constantly checked, to confirm that solar voltage input and battery voltage are stable and above a minimum threshold. If a power failure occurs, it is necessary to have someone who can rapidly undertake a visual inspection and, if necessary, clean the panel. Ideally, this is someone on your own staff. The alternative is to have a standing maintenance contract with a third party.

Deployment and operational factors that might impact your preferred power supply option	Power supply options impacted	Explanation of the issue	Procurement advice
		put a device on the edge of power failure. If a panel is then fouled (e.g. by dust, bird droppings, or leaves), the device can easily suffer a power outage. Mains-powered devices consume power that might incur a recurring fee (particularly if you are accessing a third-party power supply). This will require associated administration which, together with the fee itself, represents an ongoing operational cost.	The ongoing operational cost of mains power is likely to be low, and will not be time-constrained or experience variation throughout the year, or across the lifetime of the device. The cost is likely to be less than that of battery replacement or solar maintenance, but greater than a battery-only network where no battery replacement is planned.

9. Size, form, and aesthetic

The size, form, and general aesthetic of devices can matter a great deal if they are to be deployed in public places. It may often be the case that more compact, aesthetically designed products have a higher price tag. You should have a clear idea of your aesthetic requirements, and make sure that you procure a device that meets them.

The following table explores some common aesthetic considerations, and will help you to determine procurement options that are suited to your project plan.

Aesthetic consideration	Explanation	Procurement advice
Pole clutter minimisation	The concept of 'pole clutter' relates to the proliferation of smart city hardware on street poles, which can lead to an unsightly mess that spoils the look and feel of a public space.	*Option 1: Choose a compact, all-in-one design* Air quality monitoring devices come in a variety of shapes, sizes, and aesthetic presentations. Some are contained within a single compact housing. Others consist of multiple, separate components that are mounted in a cluster (e.g. sensor and radiation shield; main device; battery and power management; solar panel). Some have clearly been designed to have aesthetic attributes, while others can look like escaped laboratory experiments. The best option for pole clutter minimisation is to choose a compact, all-in-one design. *Option 2: Consider combining multiple sensing needs in one device* You should consider whether your organisation has broader needs for environmental sensing, because it is often possible to combine multiple sensing functions in one device. An example might be the inclusion of noise sensors in an air quality sensing device, where noise data might be used for a completely unrelated initiative. By taking this approach, you can have one device on a pole, where you otherwise might have had two.

Aesthetic consideration	Explanation	Procurement advice
		Option 3: Mount the device inside a smart pole While this results in the most visually unobtrusive option, caution is advised. Firstly, a pole may not afford suitable airflow to a sensor, resulting in an inaccurate air quality reading. Secondly, a pole may be a source of thermal radiation, which skews ambient temperature readings and gas readings. There is a preference to hold sensors out away from poles on extension arms to avoid these issues, so internal mounting should be approached very cautiously.
Size of solar panel	Solar panels may vary in size. Often, a manufacturer will aim to minimise panel size and optimise power use of a device, to support a low profile for public space deployment. Smaller panels are also subject to lower wind loading and may be easier to approve. While a smaller panel might support an aesthetic outcome, you should weigh it up against the risk of power failure. In locations with low sun exposure, smaller solar panels result in little contingency for poor weather and winter sun. A small panel is also more susceptible to failure due to fouling, such as from wet leaves or bird droppings.	If you are challenged by the possibility of marginal solar exposure, there are three options open to you: *Option 1: Use a larger solar panel for problem locations* It is always possible to use a larger solar panel to counteract power failure risk. However, a larger panel may become an aesthetic challenge. It may also require additional engineering, and a more complex approval process as a result of higher wind loading. *Option 2: Use mains power for problem locations* Most solar + battery devices have the option for a mains power connection – a choice that can be taken for certain locations with low sun exposure. This means that you can avoid the need for a larger solar panel, which may have an unacceptable aesthetic profile. However, it should be noted that connection of a battery-optimised device to a mains power source often requires an additional transformer, which will not

Aesthetic consideration	Explanation	Procurement advice
		be incorporated into the device as standard, and will take the form of a separate enclosure that needs to be co-located on the pole.
Mounting solutions	Air quality monitoring devices generally need to be held out from a mounting surface (e.g. a street pole) on a bracket, to avoid thermal interference, and ensure good airflow (two factors that can cause significant data inaccuracies). The mounting solutions available may be restricted by the device option that you choose, and the mounting hardware itself can vary in aesthetic appeal and robustness.	Develop a clear idea of your preferred mounting infrastructure (e.g. type of street pole) as early as possible, and understand your fastening options (e.g. steel bands; screws; etc.). When reviewing device options during the procurement stage of your project, make sure that you investigate the mounting hardware options that come with each device. Ask the supplier for installation schematics and photographs, and consider the aesthetic implications. You might find that the standard mounting solution supplied with your chosen device is unacceptable, aesthetically or practically, in which case: *Option 3: Develop a custom mounting solution* This approach can make good sense, especially if you plan to use a repeating piece of infrastructure to mount your devices (e.g. a specific brand of street poles owned by local government). It means you can create a solution that connects simply and elegantly with that infrastructure, and matches a broader design pattern. You might also choose to upgrade materials (e.g. use marine-grade stainless steel), to provide extra protection from corrosion and UV degradation.

10. Modularity

Some commercially available sensing devices are designed as modular systems that allow different sorts of sensors to be added or removed. There are two benefits of modularity:

- **Flexible sensing to support evolving data needs.** You might start out with a focus on particulates and NO_2, but in a year's time you could decide that you also want to monitor CO_2. Rather than installing separate devices, having the option to add a CO_2 sensor to your existing devices can be both cost-effective and operationally efficient. This ability to expand the functionality of your devices extends beyond air quality monitoring, and may connect with other local government priorities (e.g. noise monitoring).
    - **The ability to replace sensors and extend the operational lifetime of a device.** Gas sensors degrade chemically over time, and particulate sensors can become fouled through deposition. These processes place limits on the lifetime of sensors. If sensors can be replaced, then the overall lifetime of a device might be significantly extended. The cost of the service, which might include device retrieval, shipping, and reinstallation, should be considered.

The following matrix is a tool to help you determine how important device modularity is in terms of your project's procurement criteria. The table asks you to consider how much future flexibility you require, relative to the desired lifetime of your devices.

Scenarios	Lifetime Scenario A: <1 year	Lifetime Scenario B: 1-3 years	Lifetime Scenario C: Several years / ongoing
Flexibility Scenario 1: Open-ended Air quality looks like it will be a growing concern in your LGA over the next few years. There are several known pollution sources and areas of concern. You are only just starting to explore them, but you expect to expand your engagement with the issue in future.	Modularity is not that important. You want a quick win. It probably makes best sense to try a 'simple, affordable, disposable' device option, and not worry too much about the future.	Modularity might be a cost-effective way to evolve your sensing strategy in the medium term. You don't know exactly what the future holds, so try to future-proof your procurement choices.	Modularity is an important procurement criterion that you should strongly consider. You desire flexible technology options that will accommodate evolving needs, over several years.

Scenarios	Lifetime Scenario A: <1 year	Lifetime Scenario B: 1-3 years	Lifetime Scenario C: Several years / ongoing
Flexibility Scenario 2: Still figuring it out You are not certain what you want to do yet, and your current knowledge of air pollution issues in your LGA is quite limited.			
Flexibility Scenario 3: Simple and bounded There are one or two major local air quality concerns of which you are aware, and you have a pretty clear idea which pollutants you need to monitor in order to better understand them. You plan to set up a sensing network in the near future, but you do not anticipate an evolving program. At most, you might add some more sensing devices (of the same type) in future.	Modularity is not that important.		Modularity might be a cost-effective way to extend device lifetime.

Section 2: Data architecture, platforms, and services requirements

When you purchase and deploy smart air quality monitoring devices, you will need to have several data services and platforms in place to support them. You can think of these as components that – together with some associated services – make up a complete data architecture (alternately referred to as a 'technology stack'). Regardless of the approach you take to procurement, you are going to need to account for all these components (see Figure 1).

Data users		
User interfaces (laptop, mobile, tablet, etc.)		
Application enablement	**Air quality data applications**	End user business and IoT applications: • data discovery and sharing (e.g. public dashboard; open data portal; custom API) • developer services.
Intelligence enablement	**Analytics and visualisation platform**	A user-facing dashboard that might incorporate maps, customisable graphs, and more advanced data analytics tools (e.g. GIS; digital twins; machine learning/AI).
	Data management and storage *[Data platform]*	Device telemetry (sensor readings) must be structured and stored in a way that is secure, searchable, and accessible. Storage options tend to be cloud-based third-party services (commonly Amazon or Microsoft) that are connected to data management systems, which structure data and manage user access.
Connection management	**Device hosting and management + basic data interpretation** *[IoT platform]*	You will need a contract with a service provider that hosts devices in a digital platform. Device management involves the onboarding and commissioning of new devices and their subsequent management, with alerts in place for failures and errors. Be aware of your basic data interpretation requirements (like humidity interference correction for particulate data, and calibration and drift correction for gas data), and communicate these before proceeding.
Connectivity + edge gateway	**Communications**	You will need a contract with a communications provider that supports the transmission of live data from devices to a central online management location. Your chosen communications solution might involve local government-owned infrastructure (gateways), or you might engage a telecommunications provider and make use of their existing infrastructure.
IoT end point	**Devices** (IoT end point)	Physical digital hardware that produces and transmits data.
The physical world		

Figure 1. Basic components of data architecture for a sensing network

1. Define your needs for each component of the data architecture

The following tables are designed to help you determine procurement actions with respect to your existing data services and platforms. Where new solutions are required, there may be more than one procurement action worth considering.

The procurement actions recommended in the following tables should be considered further in terms of your appetite for a modular architecture, which is explored below.

Devices				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise, and capacity requirement**	**Further advice**
An existing solution is suitable	You DO have existing sensing devices installed, ready to install, or able to be relocated, that will support your data needs.	☐ No new devices are required	Low - medium	If you must install or relocate devices, some reasonable level of in-house knowledge, expertise, and capacity is advisable to support good outcomes, particularly if the devices are more open technologies. Lower in-house knowledge, expertise, and capacity may be necessary if you have an existing commercial relationship with a technology provider who is able to directly assist you.
OR **A new solution is required**	You DO NOT have all of the sensing devices that you need, and will therefore need to procure	☐ **Scenario 1:** More of the same Procure more devices of the same type	Low	This may be the simplest option, requiring the least additional expertise. However, it is advisable to carefully consider your aims and data needs, and be

Devices				
	Your situation	Your procurement action	In-house technical knowledge, expertise, and capacity requirement	Further advice
	additional devices to support this project. *Select one of the two scenarios for your procurement action.*			certain that they can be covered by the existing device type that you use.
		☐ **Scenario 2:** New device type(s) Procure new type(s) of device to meet your needs	Low – high	The amount of in-house knowledge, expertise, and capacity varies considerably, according to the device option selected. More open technology options tend to require a more hands-on approach. You may need to procure more than one type of device to support your project, which can significantly complicate matters (requiring higher levels of in-house capacity).
OR	☐ Not sure – *more research required*			

Communications				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise, and capacity requirement**	**Further advice**
An existing solution is suitable	You have access to an existing communications network that will provide the coverage required to support your planned new air quality monitoring project.	☐ None required	Low – medium	Your specific communications technology requirements will be defined by the device selection criteria that you defined in Section 1 (above). Speak to your communications contractor to run them through your use case and check your assumptions, as early as possible.
OR **New solution required**	You currently lack access to a communications network capable of providing the coverage required to support your planned new air quality monitoring project. You need to research and establish one. *Select one of the two options as your procurement action.*	**Option 1** ☐ Set up a local communications network to support your new devices (e.g. public Wi-Fi; LoRaWAN gateways; etc.)	Low – medium	There are pros and cons of different communications solutions that are explored in the *Data Communications Procurement* Best Practise Guide chapter. It is recommended that you refer to that guidance to assist with your decision here.
		Option 2 ☐ Engage a telecommunications provider to establish a new access plan for existing infrastructure that will support your new devices (e.g. start an NBIoT plan with Telstra).	Low	

Communications				
	Your situation	Your procurement action	In-house technical knowledge, expertise, and capacity requirement	Further advice
OR	☐ Not sure - *more research required*			

Device hosting, management, and basic data interpretation				
	Your situation	Your procurement action	In-house technical knowledge, expertise, and capacity requirement	Further advice
An existing solution is suitable	☐ You currently use a platform that can host and manage devices, and you intend to make use of it. It is already in use, supporting other smart city sensing activities, and you are confident that it can be expanded to serve your air quality sensing needs. You can confirm that: • it can handle live data streams from new device types	☐ None required	High	*Note:* *This option requires integration of independent technologies, and would require a combination of advanced in-house technical knowledge/expertise/capacity, advanced in-house air quality knowledge/expertise/capacity, and considerable close collaboration with the device supplier. As such, it is generally not a viable option for most local governments.*

Device hosting, management, and basic data interpretation				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise, and capacity requirement**	**Further advice**
	• your chosen air quality sensing devices can be integrated and managed through this platform • interpretation of raw sensor data can be reliably hosted and managed here.			
OR **A new solution is required**	☐ You DO NOT currently use a platform that can host and manage devices. (Or you otherwise deem that integration with an existing platform would be overly complex).	Engage a new commercial solution for device hosting and management: ☐ Through your chosen device supplier OR ☐ Through a third-party platform provider that is familiar with your preferred device option(s)	Medium	Proprietary device options tend to be tied to a specific back-end platform that supports device hosting, management, and basic data interpretation (i.e. you have no say in these decisions). Open technology device options generally provide more choice when it comes to choosing a hosting platform. If you intend to develop a hybrid network that makes use of two or more device types, or if you wish to include other third-party data streams (e.g. state government air quality data), then open third-party platforms are likely to be necessary.

Device hosting, management, and basic data interpretation				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise, and capacity requirement**	**Further advice**
OR	☐ Not sure – *more research required*			

Data management and storage				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise and capacity requirement**	**Further advice**
An existing stand-alone solution is suitable	☐ You DO currently use a data management and storage solution that can accommodate the needs of this project, and you intend to make use of it. You can confirm that:	☐ None required	High	Storage solutions fall into two categories: cloud-based; and local. Either option is likely to be configured and managed by a technical staff member within your organisation. Find out who this person is, run them through your use case, and check all your assumptions, as early as possible. Even if you do rely upon external contractors for management of an existing storage solution, you will likely

Data management and storage				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise and capacity requirement**	**Further advice**
	• either the current set-up is configured for live data streams • it can be adapted to be.			still require a fairly high degree of in-house expertise to support integration with your new project.
OR **A new <u>stand-alone</u> solution is required**	☐ You DO NOT currently use a data management and storage solution that can meet your needs, and you plan to establish a new stand-alone solution with an independent provider, and integrate it into your project.	☐ **Option 1:** Cloud Investigate and set up a new <u>cloud-based</u> data management and storage solution to meet your needs.	Medium	There are several options associated with data management and storage that you should consider when you procure a new solution. Considerations range from varying commercial packages and services, to differences in how data is structured and accessed.
		☐ **Option 2:** On-premises Investigate and set up a new <u>on-premises</u> data management and storage solution to meet your needs.	High	

Data management and storage				
	Your situation	Your procurement action	In-house technical knowledge, expertise and capacity requirement	Further advice
OR **A new <u>integrated</u> data management and storage solution is required**	☐ You DO NOT currently use a data management and storage solution that can meet your needs, and you plan to procure a new service to support your project.	☐ **Option 1:** Proprietary devices with storage included Proprietary device options are tied to an IoT and data platform that tends to incorporate data storage as part of a basic package.	Low	While 'all-in-one' proprietary data services make things easy for you in the short term, they also limit your ability to evolve your engagement with technology and data in the future. If you decide to start measuring other variables, and wish to bring all your data together in one place, a proprietary solution that is associated with a single device type may be something of a dead end.
		☐ **Option 2:** IoT platform with storage included Many stand-alone IoT platforms (device hosting and management) will also include an integrated data management and storage service.	Low	This option distances you from the complexity of direct data management, by having it integrated into a commercial package for device hosting and management. A stand-alone IoT platform will also support multiple device types and data streams. Being more open in design, it is also more likely to integrate with your own internal systems or platforms further up the technology stack. However, there are likely to be limitations to this approach, relative to the customisation and flexibility that you would find within a larger, enterprise-scale data management platform (see option 3 below).

Data management and storage				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise and capacity requirement**	**Further advice**
		☐ **Option 3:** Hybrid approach Connect a stand-alone IoT/data management platform (with storage included) to an existing enterprise data platform that you already operate.	Medium – high	Many local governments already have an enterprise-scale data platform capable of storing and managing real-time data. For this option, you would integrate a new stand-alone IoT and data management platform with that existing enterprise platform. This option may be the best of both worlds. You will have raw sensor data stored as a backup in the IoT/data management platform. You will have more centralised data storage and management on your enterprise platform, where you can bring together multiple other data streams, and manage far more complexity (in terms of data access, sharing, and hosting of custom analytics and visualisation). The integration task is likely to be quite complex, requiring the support of your in-house IT team.
OR	☐ Not sure – *more research required*			

Analytics and visualisation				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise and capacity requirement**	**Further advice**
An existing analytics and visualisation solution is suitable	☐ You DO currently use a platform that provides some (or all) the data analytics and visualisation capacity needed for your project, and you intend to make use of it. You can confirm that: • either the current solution is configured for live data streams • it can be adapted to be. The current solution can be integrated with a data platform that is technically appropriate for your project.	☐ None required *Existing analytics/visualisation solution is already integrated with an existing appropriate data platform*	High	You will still need to reconfigure your existing platform to accommodate your new data streams. New custom development of analytics/visualisation may still be required within the platform.
		OR ☐ Integrate your existing analytics/visualisation solution with the data platform you will use for the project.	Medium – high	Integration with a data platform can be done by a combination of your in-house IT team, and/or the service providers of the two platforms.

Analytics and visualisation				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise and capacity requirement**	**Further advice**
OR A new analytics and visualisation solution is required for some (or all) of your needs	☐ You DO NOT currently use a platform which provides for all your project's data analytics and visualisation needs. You therefore plan to procure access to a new commercial service to support your project.	☐ **Option 1:** Proprietary devices with analytics and visualisation included Proprietary device options are tied to a data platform that tends to incorporate basic analytics and visualisation as part of a basic package.	Low	Your functionality and customisation options are likely to be quite generic.
		☐ **Option 2:** An analytics/visualisation solution bundled into a new stand-alone IoT or data platform	Low	Your functionality and customisation options are likely to be quite generic, though perhaps less so than with a top-to-bottom proprietary service. Given that a stand-alone platform will be open, and able to host multiple device types, it is likely to be more able to support customised analytics and visualisation.

Analytics and visualisation				
	Your situation	Your procurement action	In-house technical knowledge, expertise and capacity requirement	Further advice
		☐ **Option 3:** A new stand-alone analytics/visualisation solution that integrates with your data platform	Medium – high	This option might include advanced data processing/modelling unique to your project, or a connection with a geospatial visualisation platform (such as a digital twin). It may make particular sense if you want quite complex data processing and outputs, and also intend to use your own enterprise-scale data platform for the project. This is also the approach to take if you want a custom user interface, such as a public data discovery dashboard.
OR	☐ Not sure - *more research required*			

ADVANCED DATA ANALYTICS

A brief overview of the most common advanced functionalities that you may wish to consider

Automated data quality control

Raw data from sensors can have any number of things wrong with it. It is possible to verify data from one sensor against data from other sensors, and against expected behaviour based on past trends. One common option is to compare real-time air quality data from smart low-cost devices with data from a nearby regulatory monitoring station, and check that it aligns (within a pre-defined error margin). Automated analytics capability can be established to flag and remove erroneous data, or in some cases correct data based on additional contextual information.

Heterogenous data modelling

You may choose to run a network with multiple device types, perhaps with different data quality outputs. It is possible to use a network of such ‘heterogenous’ data sources as the input for a model, where the outputs are an abstraction of your raw data sets. From a user perspective, the output of specific sensors ceases to be your focus, because the model results will now provide you with a more accurate perspective of the phenomenon you are studying, based upon multiple sensor data streams.

Environmental modelling

Environmental conditions, such as localised air quality, are a result of many intersecting factors. An environmental model might bring together real-time data for wind, rain, solar radiation, temperature, humidity, and air quality, to provide a more in-depth perspective. This type of analysis is useful if you want to understand how phenomena like pollution hotspots occur, or dispersion patterns from known pollution sources. Such a model can also create a foundation for near-term forecasting.

Machine learning

Machine learning (ML) involves a computer model that improves over time, as more data accrues. In the context of environmental monitoring, machine learning can be used to support ‘smart’ automations, or predictive capabilities like near-term forecasting. An example might be an ML program that learns how air quality in a particular location is likely to behave under certain weather conditions, and predicts what it will be several hours ahead (using the meteorological forecast). Actual empirical air quality data from sensors can be constantly used to evaluate that predictive capacity, and fine-tune the approach of the model to make it more accurate. Over time, the air quality forecast should improve.

DATA VISUALISATION

A brief overview of the most common advanced functionalities that you may wish to consider

Custom/complex graphing

Graphs are the simplest way for a user to view time-series data, and get a sense of temporal trends or the relationship between multiple data streams. Different platforms will have different levels of sophistication and customisation available for graphs. Some key functionalities that you may wish to consider include: plot multiple streams of the same parameter, from different sensors; double Y-axis, allowing comparison of two separate parameters; and custom time-period selection.

Heat maps

A heat map is a ‘spatial interpolation’ of data associated with specific points on a map. Using data from a network of sensors with fixed locations, we can assign a probability for what an environmental parameter *should* be for any other point on that map. Accurate calculation can require complex environmental geospatial modelling that incorporates factors such as meteorology, topology, built environment, and vegetation.

GIS integration

GIS are common data visualisation tools used by local governments, and may support strategic planning, asset management, and a variety of city operations. Integration of a smart city data platform with GIS is also common, allowing live sensor data to be viewed alongside a wide range of other fixed and real-time data streams. Enterprise-scale GIS often has a sophisticated suite of analytics and visualisation capabilities.

Digital twin integration

A digital twin is a virtual model of a physical location, and is essentially the synthesis of sensor data with GIS and advanced real-time data analytics. A digital twin can track multifactor interrelationships, and support complex live operational applications. It can also allow you to model ‘what if’ scenarios, and can be a powerful tool for planning and policy development. Digital twins are at the leading edge of smart city innovation, and can bring together all the most sophisticated analytics and visualisation functionalities (GIS, environmental modelling, ML) in a single, powerful application.

Data sharing				
	Your situation	**Your procurement action**	**In-house technical knowledge, expertise, and capacity requirement**	**Further advice**
An existing data sharing solution is suitable	☐ You DO currently use a data platform that provides some or all the data sharing capacity needed for your project, and you intend to make use of it. You can confirm that: • APIs are supported that will meet your data sharing needs • custom settings support your requirements for data sharing AND the needs of your chosen end users.	☐ None required *Existing data sharing capacity is already integrated with an existing appropriate data platform.*	Medium - high	This option will likely involve a fair amount of customisation within an existing data platform, to meet the specific data sharing needs of your new project. If you have in-house management of a data platform, technical capacity will need to be high. It can be lower if you can outsource customisation to a service provider. However, you will still need someone in-house to work through the details of what is needed.
OR **A new data sharing solution is required for**	☐ You DO NOT currently have access to data sharing functionality that can meet your needs, and you plan to procure a new service to support your project.	☐ Procure a new private stand-alone data discovery portal/service/platform. Common options include: • data discovery portal for archived	Medium	A stand-alone data sharing platform will need to be integrated with your chosen data platform, which *may* require a high degree of technical expertise (especially if closer attention is being paid to data labelling, formatting, and quality).

Data sharing				
	Your situation	Your procurement action	In-house technical knowledge, expertise, and capacity requirement	Further advice
some or all of your needs		and live stream data • public dashboard with ability to filter and download past data.		
	AND/OR ☐ You plan to share data via an online open data portal	☐ None required *Open data portals are free to use.*	Low - medium	There may be certain integration, labelling, or data quality requirements that you wish to meet. For example, Data.gov.au (the Australian Government's open data platform) ranks data sets according to the W3C *Linked Data Rating*. To achieve a high rating (which boosts usability and value), greater in-house technical knowledge, expertise, and capacity is required.
OR	☐ Not sure - *more research required*			

2. Platform quality requirements

When you consider procuring a platform or service, there are several quality attributes that you can assess to support your decision.

The following table provides a description of platform quality criteria, along with some key considerations. Use the table as a guide to help you complete the *Technical Requirements Template.*

	Criteria
Relatability How well the components of a system **relate and link** to each other.	Integration
	Interoperability
	Portability
Compatibility How well the components of a system are **compatible** with and **adaptable** to the needs of your operating **environment.**	Hosting
	Supportability
	Security
	Auditability
	Scalability
Functionality How well the system **functions** relative to your **needs**, once it is established or in operation.	Availability
	Reliability
	Performance
User experience How well the system **functions** meet your **user experience needs**, once it is established or in operation.	Usability
	Reporting
	User support
	Training

High priorities: essentially non-negotiable; without them, you would not be able to achieve your goals.

Before identifying something as a high priority, consider what a high level of service would look like for those criteria, and whether you would require it (given that there tends to be a concurrent additional cost). Would a mid-level service suffice?

Medium priorities: things that are strongly favoured, but can be worked around if need be; a slight compromise here would be reasonable.

This may translate into requiring a more modest level of service.

Low priorities: These are nice-to-haves.

You can afford to compromise on these criteria, particularly where costs are a big consideration, without jeopardising the quality of your project delivery.

Platform quality criteria reference table

Quality criteria	Description	Considerations and guidance
1. Integration	Integration refers to the ability of a platform or service to connect and work together with other platforms or services, to form a larger, complete, functional system that meets your needs. Interoperability (below) can be a critical factor that supports integration; however, integration can still be achieved with relatively low interoperability, through deep custom development (essentially, building a one-off piece of software that translates or bridges the gap between two quite different systems—something that tends to be costly and time-consuming).	Consider whether you wish to make use of existing internal or external platforms or services, and build a more modular data architecture. If so, you will need to choose new system components that are *integrable* (e.g. provide interfaces or APIs) with those existing systems.
2. Interoperability	Interoperability refers to the ability of a platform or service to exchange data and integrate functionality via common shared language and protocols. It is closely related to integration (above), but is more sophisticated, as it tends to be standards-based and can therefore be assessed in terms of compliance. Interoperable platforms should integrate with each other without the need for costly customisation. That is, they are similar enough that they speak to each other directly (and this is achieved through standards). Interoperability is the foundation of a maturing technology ecosystem. As the smart city sector matures, we can expect to see more interoperability standards emerge, and growing compliance from vendors.	Consider your aspirations to develop your project in the coming years, perhaps to meet an expanding set of data use cases, or to improve integration with local government systems. Perhaps you have a focus on developing an organisational smart city strategy. High interoperability will provide you with the greatest possible flexibility to meet future needs.

Quality criteria	Description	Considerations and guidance
3. Portability	Portability refers to the ability to migrate data or applications between two platforms or cloud service providers. Portability can include raw or abstracted sensor data, in-system data (such as user access records), or custom applications (such as data processing modules developed for specific devices). A given platform or storage location may be supportive of portability. *Note: The EU's General Data Protection Regulation (GDPR) enshrines a 'right to data portability' in law, which affects all platforms and services used in the EU.* Portability matters if: • you want to migrate some (or all) of your archived data into a new platform or database, due to a change of service provider • your organisation has a position on avoiding vendor lock-in.	Consider how long you plan to run your monitoring network, and the likelihood that you will expand or evolve it over multiple years. If this is the plan, you may want to ensure future flexibility. If you are planning a more modular data architecture, comprising multiple integrated components, you may have the option to swap in/out service providers in specific areas of your technology stack. This may be something forced by business necessity, or by changing data use requirements. In this scenario, portability will be highly important.
4. Hosting	Hosting refers to the ability of a platform or service to provide an environment that can host a diversity of sensing devices, or discreet software modules.	*For an IoT platform* Consider whether you will want to host multiple different device types, possibly from different manufacturers, each with its own data decoding and support requirements. Consider whether you need to host custom data interpretation modules for things like calibration drift correction, or temperature interference correction. Some platforms may come with these functionalities, but a majority will not (but may have varying capacity to support them).

Quality criteria	Description	Considerations and guidance
		For a data or analytics platform Consider whether you will need to implement custom data management, analytics, or visualisation functionality within your chosen platform, as it may require a new software package to be hosted within the main platform environment.
5. Supportability	The supportability of a platform or service relates to how well it can be configured and adapted to fit with the broader context of an organisation, and with the more specific context of a project or data use case. Supportability includes: • *Testability* – can you test it, to check if it meets your needs? • *Configurability and adaptability* – does the platform or service have existing settings/options that can easily be adjusted, to ensure that it fits into your specific context? • *Maintainability* – can the technical requirements of the new platform or service be maintained by the environment that you will be running it in (e.g. does it need certain data to function, and can you provide that data)? • How well does the platform or service fit within the broader policy or administrative environment of your organisation? Do you foresee potential hurdles to timely and effective set-up, integration, or operation?	Consider the extent to which you are planning a more modular data architecture, comprising multiple integrated components. A platform or service that forms part of a larger whole is more reliant upon the context of that whole, compared to a stand-alone, top-to-bottom solution. Consider the complexity of the functionality you desire. More complexity may translate into more configuration, and higher maintenance requirements.

Quality criteria	Description	Considerations and guidance
6. Security	Security refers to the ability of a system to detect and resist unwanted external interference or data access, and applies at all levels of a technology stack. Notable areas of focus for platforms and services include: • *User access management* – the ability of a platform or service to control who accesses a system, and to assign different permissions to different groups (custom access privileges). This can include access control functionality (e.g. password management; captcha; two-factor authentication). • *Data encryption* – the ability of a system to encrypt data where it is stored, or during transfer.	Consider the sensitivity of your data, your users, and your data use case, and assess the risk and repercussions of a data leak or data loss. Consider the number of users, and diversity of user groups, particularly if there is to be a public user base where people can create their own access accounts. Consider the number of access points in a system, particularly in more complex modular systems that comprise multiple integrated parts. The security of an integrated system may be as weak as its weakest component.
7. Auditability	Auditability refers to the ability of a platform or service to provide and maintain full traceability of user access and transactions. Each time a user accesses a platform and does something, it is possible to record who it was, what they did, and when they did it. 'Doing something' can be as simple as accessing data, or as intrusive as changing core settings or code (which should be admin users only). Additional auditability functionality includes the capacity for generating custom reports, based upon such records. This can be vital to best practice security management, data management, and data sharing. It can also support rollback of system settings.	Consider the relative sensitivity of your data, your system, your users, and your data use case, including ethical and legal obligations. Greater sensitivity tends to benefit from greater auditability. Consider the diversity and number of users who will be accessing your platform. Large numbers of users, particularly those outside of your organisation, will likely make auditability a high priority. A common circumstance is a project with multiple collaborating organisations, all with data users. Consider the relative complexity of the platform or service with respect to what admin users can change/configure. A more

<table>
<tr><th>Quality criteria</th><th>Description</th><th>Considerations and guidance</th></tr>
<tr><td></td><td></td><td>sophisticated system with a lot of admin options has a greater need for system changes to be accurately recorded and accessible.</td></tr>
<tr><td>8. Scalability</td><td>Scalability refers to the capacity of a platform or service to expand or contract its functional capacity, to meet changing needs. Scaling can include:
the addition of more devices to your network
an increase in the amount of data collected (which may result from more devices, more sensors per device, more metadata, shorter reporting intervals, etc.)
an increase in the number of data users accessing a platform or system
an increase in data sharing, to a greater number of external end points
a step up in the relative importance of a data use case, potentially to serve more critical business requirements.</td><td> Consider your aspirations, or the likelihood that you will want to scale your solution in one or more of the ways listed previously. Consider the extent to which your mid-to-long-term business case might rely upon the ability to rapidly scale (meaning that the ongoing sustainability of your system is tied to its scalability). Consider that scaling can often require components of a technology stack to be replaced by alternatives that are better suited to scaling, or to a changing strategy. If scalability is highly important to you, you should also prioritise flexibility in the design, to future-proof your system for changes and upgrades. </td></tr>
<tr><td>9. Availability</td><td> Availability refers to the amount of time that a platform or service is available to users, and able to perform its expected functions. It might be always available (near 100% or continuous availability) or much less available. This can be specified as average availability levels, or as ‘downtime per year’. </td><td> Consider <u>when exactly</u> your intended users will need to access/use the platform or service. Close to ‘all the time’ = priority high Specific scheduled times = priority medium No strong preference = priority low </td></tr>
</table>

Quality criteria	Description	Considerations and guidance
	Availability level *Downtime per year* 99.999% 5 minutes 99.99% 50 minutes 99.9% 8.76 hours 99% 3.65 days 95% 18.25 days 90% 36.5 days You also need to consider 'availability time window', such as the availability of the platform or service during business hours only, or beyond this time window. Your availability needs have repercussions for how routine maintenance of a platform or service is scheduled. Certain providers may have set policies that either meet or clash with your availability needs.	Consider the number of users reliant upon the system. If there is a significant public user base, are there PR concerns associated with service interruption? Are there contractual obligations that might be frustrated by platform or service outages? For example, a contractor responsible for operating the device network may be unable to perform day-to-day tasks if the IoT platform is not working. Consider the risk associated with interruption of your data use case. Is it mission critical? How much inconvenience will be caused? Will there be legal or ethical repercussions? Finally, consider the cost/benefit of high service levels, relative to business goals. A high availability will cost you more. Some platforms or services may not be able to offer high service level agreements at all. You need to determine whether the added cost is justified by the value generated from running the system.
10. Reliability	Reliability refers to the probability that the platform or service will do its job effectively, across a defined period. Or, put another way, reliability is a measure of the probability of system failure. It is often expressed as the 'mean time between failures'. Reliability is distinct from availability. A system might be available while also running suboptimally, and thus unable to fulfil the functions expected of it. One easy way to distinguish between the two is to think of availability as '<u>quantity</u> of service,' and reliability as '<u>quality</u> of service'.	*Considerations for reliability are the same as for availability. Both criteria relate to a loss of core function for a period, with associated repercussions for users and use cases.*

Quality criteria	Description	Considerations and guidance
11. Performance	Performance refers to the ability of a platform or service to support a series of context-specific needs. These are: • response times (application loading; browser refresh times) • processing times (functions; calculations; imports; exports) • query and reporting times (initial loads and subsequent loads; large-batch or real-time data movement).	Consider the number of users that you expect to be accessing a platform or service interface at the peak of its use. For example, many thousands of citizens simultaneously accessing a public dashboard during a bushfire smoke event may require high system performance. Comparatively, you may only expect a handful of internal staff ever to access the system. Consider the complexity of the data analytics that will be performed. Consider the quantity of data that you will be storing, processing, querying, importing, or exporting on a regular basis. This will likely relate to the number of sensing devices in your network, the amount of data that each one reports, the reporting interval of devices, the total period of operations, and the quantity of metadata you use. The more data you work with, the higher you will need your system performance to be.
12. Usability	Usability refers to how easy a platform or service is to use, including the overall look and feel of the interface, and the user experience (UX) design.	Consider who your end users will be, and what their needs are. What kind of technical skills/knowledge will they have? How familiar will they be with the concepts, language, and data? Consider whether the platform or service integrates with an existing interface that users are already familiar with; if it does, this can significantly improve usability. Consider how much of the set-up, configuration, and administration will be conducted internally (by your team), as opposed to by the vendor (as part of a service contract). If it will require hands-on work

Quality criteria	Description	Considerations and guidance
		for your staff, the usability of advanced functions, or system back end, will be of higher importance.
13. Reporting	Reporting refers to the ability of a platform to produce a report or visualisation, based upon a custom user query. More developed reporting capabilities might include: • a customisable metadata schema (the ‘tags’ that you search by) • customisable search functionality (e.g. user-defined time periods, rather than pre-sets) • compound queries; and customisable visualisations. It includes the ability to download search or visualisation outputs in a variety of formats.	Consider the diversity of sensing device deployment contexts, device types, and telemetry streams within your monitoring network. More diversity generally translates into more filtering of data by users, to find the thing that they are focusing on. This, in turn, may require higher reporting functionality (more metadata customisation; more customisable search functions) than a relatively simple or uniform system. Consider user needs (and diversity of user needs). What are users likely to want to search for, and how will they do it? What will users do with reports once they have them?
14. User support	User support refers to the collection of user-focused resources that may accompany a platform or service. This can include documentation (such as user manuals and how-to guides); chat bots or self-explaining entry system; help and FAQ resources; user forums or knowledge exchanges; as well as more active support (such as a phone hotline or online help desk).	Consider all your users, which aspects of the system they will be using, and where they might need support. Are there materials appropriate for their needs and knowledge levels? Consider how much ‘active’ user support you might need, as opposed to more fixed documentation. As a general rule, lower end-user technical knowledge and expertise will require more active support from the service provider. Higher levels of end-user technical knowledge and expertise may mean that you can get by with less active support. More active support will likely come with a higher price tag. If this elevated level of support is important, then choose ‘high’ for this

Quality criteria	Description	Considerations and guidance
		criterion. Otherwise, the importance level may be tagged as ‘medium’.
15. Training	Training refers to the training materials (e.g. videos) and active support (e.g. training sessions, whether online or on-premises) provided to platform users. It tends to build upon user support materials.	Consider the complexity of the system, in terms of how a user might engage and make use of it. More complexity may require more in-depth training. Consider whether you might require a more formal training package co-ordinated through HR or your IT department, or a less formal, more ad hoc approach to training. Consider the diversity of users. You may need different training resources for different user groups, adding complexity to your training requirements (e.g. multiple languages; accessible to children; etc.)

3. Platform hosting considerations

A platform must be hosted on a server. You will need to make a choice between cloud-based hosting, and on-premises hosting. Which option is best for you?

TIP: There are pros and cons to both cloud-based or on-premises hosting

Most commercial services are now cloud-based. However, this does not rule out on-premises hosting as an option. Many local governments already run on-premises servers that can host the types of platforms required for running a smart sensing network. Some organisations officially favour the use of their own on-premises hosting capacity over cloud-based hosting. While there has been recent growth in the use of cloud-based solutions (which have improved greatly in functionality and reliability over the past decade), there are still pros and cons to both approaches that you should consider.

On-premises hosting

On-premises hosting involves running a platform and storing data on a local server, owned by your organisation and located on your own property. The server will be positioned behind your firewall. This is the basis of a 'private cloud', which connects multiple on-premises servers in a local network (see below), but in its most basic form, on-premises hosting involves just a single server, in a single location.

Most local governments tend to run some form of on-premises hosting infrastructure. This is often a legacy from when *all* hosting was on-premises, prior to the emergence of reliable commercial cloud-based hosting. Your IT department will likely have some sort of strategy in place for allocation of on-premises hosting capacity, and this may be tied to data management and IT security policy. You should speak with them about this, and find out if there is a preference or policy requirement that might affect the approach you take for hosting platforms and data in a smart sensing project.

Cloud-based hosting

Cloud-based hosting connects a collection of remote physical servers, in different locations, to run a virtual server 'in the cloud'. There are three main types: public; private; and hybrid.

1. Public clouds

Public clouds are available over the internet, and can be accessed by anyone who wants to use them. They run off multiple servers that are <u>not</u> owned by the end user (you). Common examples include Amazon Web Services (AWS), and Microsoft Azure. Cloud services like these are partitioned, with 'slices' of the overall processing power and storage sold off to paying tenants.

Advantages	Disadvantages
• **An economy of scale—**including a low start-up cost, relative to the high capital expenditure of setting up your own private servers. • **Elasticity**—the ability to scale elastically (expand/contract in real time, saving you money by never providing more than you need at that moment). • **Scalability**—almost no upper limit to scalability. • **Automation**—fully automated management (e.g. patches and updates). • **Reliability**—low risk of failure, due to being spread out over multiple data centres.	• **Security *can* be lower**—you can have less control over your data security. However, with growing sophistication of cloud services, this concern is reducing rapidly.

2. Private clouds

Private clouds operate entirely on physical infrastructure that is owned by the end user (you), and the total processing and storage capacity of the cloud is used by that single user. This is typically something unique to large organisations with multiple locations. It can extend to the use of privately leased servers by that same core user. It is not uncommon for governments to run private clouds, using multiple on-premises servers connected in a local network.

Advantages	Disadvantages
• **Highest possible data security**—due to all storage and hosting remaining behind your firewall. This may be particularly relevant for cases involving the storage of highly sensitive data. • **Greater control and customisation**—to meet the specific security and management needs of your project or organisation.	• **Higher costs**—particularly upfront costs for equipment. However, since most local government/smart city projects are too small to justify investment in new on-premises equipment, there is another more common set-up cost to consider. For new projects using existing on-premises infrastructure, you will need to cover the cost of significant in-house technical support, and possibly custom development, to establish your platform hosting. • **Responsibility**—you must operate everything, and cannot benefit from the automated support of a public server. • **Low flexibility**—your system is a fixed size, and will not scale up and down to meet your changing needs, meaning that your costs also stay fixed.

3. Hybrid clouds

A hybrid cloud is a mix of one or more public clouds, private clouds, and on-premises hosting. There are many combinations, and each will be unique. One approach that can make sense for local government (in a smart city context) is to use a public cloud for hosting the main service, with a testing environment and data backup stored and managed locally.

A hybrid cloud, designed well and tailored to the needs and resources of your project and organisation, can achieve the advantages of all the options, while minimising their disadvantages. It may be particularly well-suited if your organisation already has on-premises hosting capacity, and good in-house technical knowledge and capacity to support its use.

A critical consideration here is whether a given commercial platform provider can support that platform across a hybrid cloud, in the way described. Many will, but many others will not.

4. Data architecture modularity

A modular approach to data architecture involves keeping the various layers described above separate from – and independent of – each other. If you intend to make use of existing platforms and services, you are going to need to integrate them into a larger system, and this requires a more modular approach to data architecture. However, just because you have existing platforms that can support your needs, it does not necessarily make sense for you to use them. You should consider both the pros and cons to taking a modular approach, and the following tool is designed to help you do this.

Modular data architecture decision-making tool

	Pros	Cons
A modular services approach *A modular approach to data architecture involves keeping the various architectural components separate*	**a) Commercial flexibility.** One part of the system may be easily replaced with a different option that fulfils the same role. As a customer who engages commercial providers, this gives you flexibility, and helps to avoid vendor lock-in. **b) Customised solutions.** You can pick external platforms or service providers that meet your specific needs in one area (e.g. a data sharing portal), and combine them with others,	**a) Complexity and resourcing.** The downside to a modular architecture approach is that it is complex, and generally requires a relatively high baseline of technical knowledge, expertise, and capacity within your organisation. *It may be possible to engage a third-party expert (e.g. a university) to set up and manage a modular system, removing this responsibility from your organisation.*

	Pros	Cons
from – and independent of – each other.	to build a custom data architecture that is tailored to your use case at every level. c) **Local government system integration.** You can combine external platforms and services with local government systems, to create a hybrid architecture that (in theory) gives you the best of both worlds. d) **Data integration.** You can more easily combine data from multiple sources for more sophisticated insights and operational benefits, in line with emerging smart city best practice.	b) **Slower to get started.** 'Out-of-the-box', 'top-to-bottom' proprietary systems can see you collecting data very rapidly. Conversely, more modular systems can take a lot more time and effort to establish. If your project is time-critical, and you are less concerned with longer-term or big-picture strategy, customisation, flexibility, or data transparency, then a modular technology stack may not be the best option for you. c) **More unknown costs at the outset.** Modular architectures tend to feature multiple components, each with a range of commercial options. Each component will need to be integrated into a larger whole, and there is sometimes custom development required to optimise this, and achieve customised functionality. This complexity can translate into initial uncertainty about the total cost of establishment and operations. *However, there tends to be a degree of flexibility possible (in terms of options chosen), allowing deliveries to be tailored to fixed budgets as systems develop.*
An all-in-one services approach *The alternative to a modular approach is to engage a single service provider that combines all the architectural elements and functions*	a) **'Just get on with it'.** You do not need significant in-house knowledge, expertise, and staff capacity. You are essentially outsourcing this. If your organisation is just starting out on its smart city journey, this approach can allow you to 'just get on with it', without being hampered by a lack of in-house capacity. b) **Rapid set-up.** This approach is generally fast to set up; you are switching on a 'cookie cutter' approach that should be	a) **Vendor lock-in.** You are generally buying access to a complete proprietary top-to-bottom system that is tied to specific sensing devices. By investing in a complete proprietary solution, you become 'locked in' to a single vendor. You cannot integrate new sensors or data streams into your network, unless that vendor supplies and supports them. You cannot migrate your sensors to a new platform provider that better meets the needs of your

	Pros	Cons
described into an all-in-one commercial package. *This is a common feature when you purchase proprietary sensing devices, which tend to be tied to a specific platform. Providers may still be subcontracting elements to third parties (e.g. cloud storage), however this is not visible to you as the customer.*	ready to go. If speed is critical, and your aim is to start collecting air quality data by whatever means and within a constrained timeframe, an all-in-one approach can make good sense. **c) Focus on the data.** A lot can go wrong with technology. If you outsource responsibility for this, you can focus on what matters the most—data. It should be noted, however, that this is not always as straightforward as it may seem. If the data is what matters the most, then you should also keep in mind that an all-in-one service may restrict your understanding of that data, and the ways in which you are able to manage and share it (see cons).	community or organisation. You are stuck with that vendor and their commercial agenda, possibly for years. **b) Limited customisation and a lack of flexibility.** A non-modular data architecture means that you cannot pick and choose components that best meet your needs at the various levels of the technology stack. You must buy into a complete solution, and accept all its functions and limitations. There may be limited scope for customisation. As your project and thinking develops, you may wish to evolve your approach, for example by adding new sensor types, or new custom analytics capabilities. Modular architectures support this type of open-ended flexibility, but a proprietary system is less flexible. **c) Lack of transparency.** Many proprietary systems are 'black boxes', with little or no transparency in terms of how data is interpreted, abstracted, or managed. Air quality data requires several critical corrections and abstractions before it becomes usable, and it is vital to have *full* transparency on what these corrections and abstractions are. This is particularly important if there is an emphasis on sharing data with others, or if data is expected to come under any degree of scrutiny (e.g. it might be used to support a controversial policy position). **d) Data management limitations.** With the growth of smart cities, many local governments are developing increasingly mature data policies that address a growing diversity of live data stewardship considerations. The ability to customise and control data access and management may become a critical consideration for you

	Pros	Cons
		when procuring new platforms and services. Closed proprietary products tend to significantly limit your options in this regard. **e)** **Data sharing limitations.** Great value can be extracted from data by sharing it according to best practice protocols, and enabling it to flow to multiple complementary systems and users. Proprietary top-to-bottom systems tend to be designed as self-contained data siloes. While many might offer basic API connection to other local government platforms, often your options for customisation and complexity will be very limited. Open technologies, on the other hand, are designed with interoperability and data sharing as foundational concepts.
A hybrid approach *A well-designed hybrid solution might integrate a package of clustered services from an external contractor, with certain existing local government platforms (such as GIS visualisation, asset management, and open data sharing).* *This is still a modular architecture. However, it*	**For many, a hybrid approach may make the most sense.** As a rule, vendor service packages tend to cover the lower parts of the technology stack (communications, data ingestion, device management, interpretation, and storage). Local government integrations tend to be higher in the technology stack (GIS, data sharing portals). A hybrid approach has the potential to deliver the best of both worlds: **a)** Deeper technological expertise can be outsourced, protecting local governments from risk, and helping to keep internal operational resourcing at manageable levels. **b)** Rapid set-up is still possible. You can start capturing data quickly by leaning on a contractor to manage the lower part	**a)** **Reduced (but still existing) vendor lock-in.** Vendor lock-in is still a concern, though the effect is significantly reduced, particularly if you choose non-proprietary devices, and instead focus on combined service packages further up the stack. This helps you to avoid the most damaging vendor lock-in concern: physical sensing assets that can only be made to work through a single back end (operated by the device supplier). **b)** **Mild loss of customisation and flexibility.** This limitation is significantly less than that associated with complete top-to-bottom proprietary systems. It *can* relate to your options within a single-vendor service cluster, within your broader technology stack. However, given that these services tend to be designed to integrate with a wider data ecosystem, many of the limitations of closed proprietary systems are less evident. Make sure you

	Pros	Cons
accommodates the inclusion of more combined commercial packages forming larger blocks of the overall technology stack.	of the technology stack. Adding complexity through local government system integration can come later, but does not need to delay your project. **c)** Integration with local government systems affords greater flexibility than might otherwise be achieved in an entirely outsourced system. **d)** Data management and data sharing limitations are largely addressed through the integration of local government systems higher up in the architecture.	check customisation options (and associated commercials) with a new supplier during procurement. **c)** **Potential lack of transparency.** The 'black box' issue that arises with proprietary systems can apply to any smaller clusters of data platforms/services. Anywhere where interpretation and abstraction of environmental data is conducted should be transparent enough that anyone accessing that data can find out precisely what was done to it.

References

NSW Health. (2020). *Particulate matter (PM10 and PM2.5)*. NSW Government. https://www.health.nsw.gov.au/environment/air/Pages/particulate-matter.aspx

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Associated OPENAIR resources

Supplementary resources

Identify template

This template supports creation of a business plan and ‘data use action statement’ as strategic foundations for a smart low-cost sensing project.

A framework for categorising air quality sensing devices

This resource presents a new framework for categorising air quality sensing devices in an Australian context. It identifies four tiers of device types, separated in terms of functionality, and the quality and usability of their data output. It is designed to assist with the selection of devices that are appropriate to meeting the needs of a project and an intended data use case.

Further information

For more information about this project, please contact:

Peter Runcie

Project Lead, NSW Smart Sensing Network (NSSN)
Email: peter@natirar.com.au

This Best Practice Guide chapter is part of a suite of resources designed to support local government action on air quality through the use of smart low-cost sensing technologies. It is the first Australian project of its kind. Visit www.openair.org.au for more information.

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