Selecting low-cost sensors for air quality monitoring

Sustainable Communities and Waste

National Environmental Science Program

Guidance for researchers

About this fact sheet

Low-cost sensors (LCS) for air quality monitoring are undergoing a rapid but uneven evolution. Dozens of models are now available to the Australian market from a wide variety of developers, from traditional sensor instrument companies to large IT companies and crowd-funded start-ups.

LCS devices vary widely in their design and in the certainty of their data quality. Selecting a model suitable for your research project can be time-consuming. This fact sheet aims to assist researchers by providing guidance on key attributes and concerns they may wish to consider when choosing LCS devices.

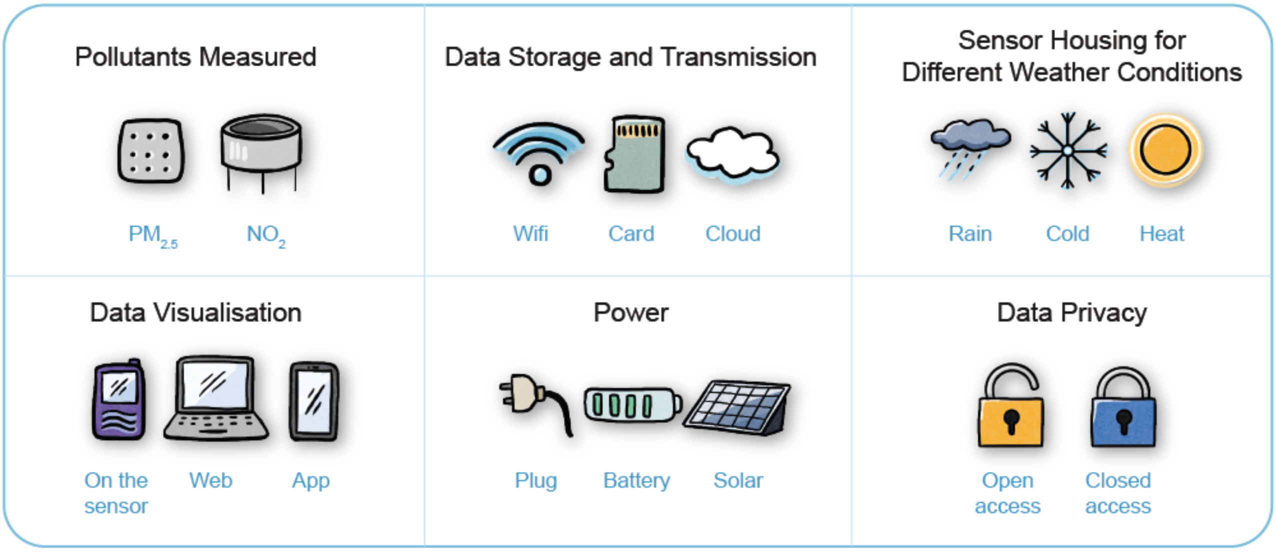
This guidance complements our online LCS selection tool: monitors.cleanairstars.com.

Matching choice of model with research goals

Research that makes use of LCS devices is rapidly expanding. The goals are many and varied and include a broad spectrum of air quality applications:

- citizen science / participatory science
- indoor and outdoor air quality monitoring and intervention studies
- LCS performance testing and evaluation studies
- studies on the use of LCS data to change behaviour.

It's critical to choose an LCS device that aligns with your research design and goals. For example, will the LCS device perform with high enough accuracy or precision to provide robust and useful data? Will you need to field calibrate the device's sensors against reference instruments? Attributes related to data analysis and control may also be critical, for example, access to raw data or other data formats you require.

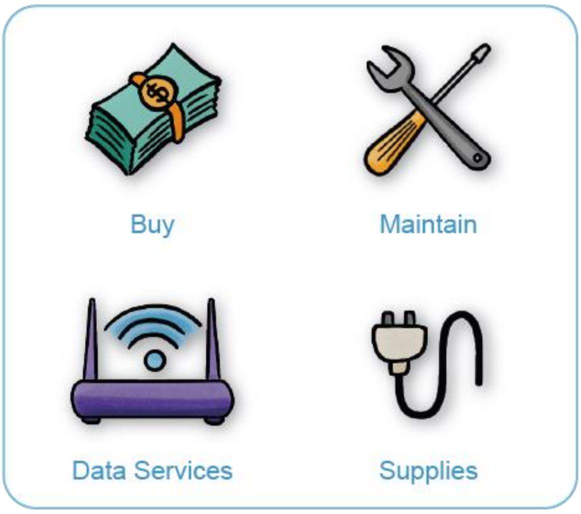


Key user concerns for LCS selection

Below are some key attributes or factors to consider when selecting an LCS device for your research project.

Purchase price and related costs

The purchase price of air quality sensor devices varies, but for the purposes of this fact sheet and associated online tool, LCS are defined as devices costing less than AUD$10,000. Device cost generally increases with the number of pollutants measured, and with the degree of sensor accuracy and sensitivity.



Most manufacturers offer units for a one-off purchase price, but some are also available on a subscriber basis. Manufacturers may offer discounts to buyers who purchase multiple units.

When costing LCS devices for your project, be sure to consider the total cost of ownership. This includes not only the purchase price or subscription fees for units, but also related ancillary and long-term operating costs, especially for more expensive models:

- mounting station (if required) and installation
- subscriber services for data transmission, storage or visualisation
- technical support
- maintenance, including repairing or replacing sensors
- calibration services
- power requirements.

Study duration can affect the cost of a monitoring project, especially when using LCS solutions with high maintenance requirements. ‘Plug and play’ type devices afford the option to easily replace modular sensors on the device, potentially an attractive feature for longer-term projects.

Some research-oriented LCS developers tailor aspects of their devices or networks to researchers' requirements. These developers may even seek out research partnerships.

Target pollutants

Many LCS products measure multiple pollutants. Check whether the device measures the specific pollutants of concern to your research project, and be aware that the type and number or target pollutants it measures can affect its cost.

In research projects using LCS, pollutants of interest can be classed into three main groups:

1. **Particulate matter (PM)** encompasses fine particles, with PM_1, $PM_{2.5}$, and coarser particles of PM_{10} or less being the main pollutants of interest in monitoring projects. Most LCS use optical particle counters to measure PM, with sensor lifetimes generally ranging from 1-4 years. These sensors generally measure $PM_{2.5}$ with reasonable accuracy, but typically do a poor job of measuring PM_{10}. (See '*Accuracy*'.)

2. **Gas-phase pollutants** can also be measured by some LCS devices. Nitrogen dioxide (NO_2) and ozone (O_3) are the main gas-phase pollutants of interest in air quality research.

   LCS typically use electrochemical sensors to measure gas-phase pollutants. Gas sensor lifetimes range from 6 months to 2 years.

   In general, LCS gas sensors are less accurate than the above PM sensors. Low gas concentrations are often difficult for these sensors to measure and they generally perform best when placed near the pollution source. Nevertheless, it is possible, though generally more costly, to purchase LCS devices that achieve accurate gas measurements.

   Some LCS models measure additional gases, including carbon monoxide (CO), nitric oxide (NO), sulphur dioxide (SO_2), ammonia (NH_3) and hydrogen sulfide (H_2S). These devices tend to be more costly. There are few independent evaluations on LCS performance for these gases.

3. **Volatile organic compounds (VOCs)** are a class of pollutants spanning a wide range of chemicals including many produced by humans. Low-cost sensors typically measure VOCs using metal oxide semiconductors (MOS) or photoionization detector (PID) sensors. Both MOS and PID sensors are challenged to measure VOCs accurately and can be very costly. Furthermore, LCS do not measure all VOCs. Sensors are more sensitive to some chemicals than others and may also respond to confounding (interferent) gases.

Meteorological data

Be sure to check whether a device can provide meteorological data you require, such as temperature, humidity, barometric pressure or wind.

Most, but not all base LCS models can measure temperature and humidity. It's a good idea to check independent evaluations, if available, or otherwise gauge the quality of LCS meteorological data. Some devices only measure internal temperature and humidity to improve their calibration models, making them unsuitable for measuring weather conditions.

If these meteorological datasets are crucial to your project, and accuracy is an issue with the model you select, you may opt to acquire a separate weather station.

LCS attributes that affect data quality

Depending on your research goals, sensor attributes including accuracy, precision, sampling rate, detection limits and calibration may be of critical concern.

Accuracy: Depending on your project's goals, accuracy can be a critical user concern. Accuracy varies greatly among different models of LCS devices, and even within models for the different pollutants they detect. For each pollutant you seek to measure, be sure the sensor meets your requirements for accuracy.

Technically speaking, accuracy refers to how well a sensor's pollution measurements agree, or correlate, with measurements of a reference instrument of known high accuracy, such as a regulatory monitor. Accuracy is often expressed as an R^2 value, a statistical term called the coefficient of determination. The closer the R^2 value to 1, the stronger the correlation and the greater the accuracy, with 1 being perfect correlation. Although there is no Australian standard for R^2 values in LCS, the US Environmental Protection Agency selects a target value of $R^2 \geq 0.70$ in its evaluations of $PM_{2.5}$ sensors.

R^2 values are generally higher for sensor data that's averaged over longer periods (for example, 24 hours versus 1 hour or 1 minute). This is because longer averaging periods reduce the 'noise' in sensor data caused by factors ranging from electrical interferences and sensor precision to rapid weather changes.

Reliable manufacturer information about accuracy is often lacking. This shortfall is a problem for potential LCS users for whom accuracy is critical. Accuracy and other performance information is available for some LCS models from independent evaluations and published literature (see 'Resources'.) Checking these evaluations before you buy can help gauge the suitability of a device. These independent evaluations may also help you understand how sensor readings vary with humidity or temperature.

Fewer independent evaluations are available for LCS performance on gas-phase pollutants and VOCs than for PM, but the number of evaluations is increasing. Be aware, however, that field test conditions of independent evaluators may not be analogous to your study area conditions. They can also provide biased statistics for both gases and particles due to fluctuations in pollutant concentrations and changing seasonal conditions.

Precision refers to how well a sensor reproduces a measurement under identical conditions, that is, the degree of agreement among repeat measurements. High sensor precision is particularly important for initiatives that seek to measure small variations in pollutant concentration.

Sampling rate (sampling interval or sampling frequency) refers to the rate or time interval at which a sensor can take measurements. This attribute may be important when monitoring projects must capture data about a pollutant plume that changes rapidly in concentration or is short-lived in time. Where air quality conditions are less variable, sampling rates on timescales of minutes or hours are likely adequate. Be aware that for some sensors, sampling frequency is reduced if the power source switches from mains to battery or solar.

Measurement range and detection limit: Make sure the device you choose can measure target pollutants across the full range of concern, from highest to lowest concentrations, anticipated in your study area. Check the manufacturer's technical specifications for the limit of detection, the lowest concentration of a pollutant the device can detect.

Calibration: Demonstrating measurement accuracy is important for some local government air quality monitoring projects. Some sensors are factory-calibrated prior to sale. Their settings are checked and adjusted, if necessary, to ensure sensor measurements compare well with a known and certified standard.

For some air quality monitoring projects, it may be necessary to field calibrate sensors, by co-locating the device with a reference instrument. These calibrations may be necessary to account for impacts that various air pollutants and weather (particularly humidity and temperature) can have on sensor accuracy. These weather effects may be substantial. Calibration allows users to address drift (wherein monitors deployed in the field gradually become less accurate).

Calibration models range from simple linear ones to complex multilinear models. Depending on your data analysis expertise and the complexity of calibration required, you may want to check whether the manufacturer provides calibration expertise. Some manufacturers offer customers the option to return a device to their factory to be recalibrated.

If calibration is important to your project, be sure to investigate further. Before buying, ask the manufacturer how to calibrate the instrument. Learn about any additional costs related to calibration, co-location and correction services, and factor in the extra time and planning required to carry out these activities.

Data transmission, storage and visualisation

Data transmission: Check whether the device's mode of data transmission is compatible with your research project.

Some models only offer Wi-Fi. This is a viable option in homes or other locations where those conducting the monitoring have control over Wi-Fi and sensor device settings. But in government buildings including schools, and in unsecured outdoors settings, reliable and adequately strong Wi-Fi transmission can be extremely difficult to acquire and sustain.

Fortunately, many LCS manufacturers offer models with a wide range of other transmission modes, including Bluetooth, satellite, 4G and low-power wide-area network (LoRaWAN). In some models, data can be stored on the device, for example, on an SD card, and retrieved manually.

Be sure to factor into your budget any additional costs for data retrieval or transmission, such as mobile subscription services.

Data storage, handling and access: For some monitoring projects, a device's capacity for on-board data storage may be important, for example, to safeguard against data loss in the event of transmission failure.

For models that only have local data storage, you'll need to manually access the device and upload the data to a website or computer. Other models store data on central servers or the cloud, where you can view or download it. Some models also offer the option to call up data through an Application Programming Interface (API).

Manufacturers convert raw sensor data into final reported pollution information using models or equations. If access to raw data (for example, for calibration purposes) or a specific data format is important to your project, check with the manufacturer. Access permission, ownership rights, privacy, data sharing and integrating with other sensor platforms may be other important data considerations for your project.

Display/visualisation: If you require a data display on the device itself, be aware this is not a feature of all models. More typically you'll also have the option (or be required) to visit a website or use an app to view the data. Some manufacturers offer advanced web-based data visualisation services, typically for a subscription fee. In models for which data is physically downloaded from the device, manufacturers may supply software for visualising the data on your computer.

Consider ease of use

Useability can be important in research projects using LCS devices. Before you buy, determine the expertise required to operate a device and its software. Find out if you'll need to purchase or make available additional tools, computers or software. Check whether it's easy to determine if sensors continue to operate properly and without interruption over time. Consider factors including device size and weight, especially for portable models.

Installation: Is the device easy to install? Does it have flexible options to ensure installation is compatible with your chosen location and does not become difficult or expensive? Models that reduce complexity and the technical expertise required for installation may be preferable. Also consider whether the device needs to be resistant to theft or vandalism.

Power options: A device must suit your needs in terms of power availability. Plug-in devices are the best option for stationary monitoring, but you'll need to ensure power is accessible. Some models have batteries or USB power supplies, useful for short-term or mobile data collection. Solar power is an option with some models, but requires attention paid to orientation and battery size.

Operation and maintenance: Ensure the device you choose is robust enough to perform well in its intended environment. Will it tolerate predictable wear and tear, such as shipping, or being dropped if it's a portable device? If outdoors, will it be durable enough to withstand expected extremes of heat, cold or moisture or dust? Some LCS models are rated according to the IP system, an international standard to indicate the degree of protection an enclosure provides against the ingress of dust, solid objects and moisture.

Determine whether special expertise is needed to perform the necessary maintenance on the device. Does it include a warranty and a good-quality manual and online support? Some manufacturers offer a fee-based technical support plan, and in some cases this support can even extend to assistance with design and implementation of air quality monitoring projects.

All air pollution monitors have limited lifespans and sensors typically become less accurate over time. Check manufacturer information to gauge how long you can expect your device's sensors to operate well before they require servicing and replacement.

Resources

Independent LCS evaluations

- Airlab
- AQ-SPEC Air Quality Sensor Performance Evaluation Center of California's South Coast Air Quality Management District (AQMD). Due to geo-blocking, you may need a VPN to access South Coast AQMD web pages.
- Evaluation of emerging sensor performance (US EPA)

Guidance on how to plan and run LCS projects

- Community in action: A comprehensive guide book on low-cost sensor (South Coast AQMD)
- The enhanced air sensor guidebook (US EPA)
- How to evaluate low-cost sensor by colocation with federal reference monitors (US EPA)
- Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors (US EPA)
- Forum Sensor.Community