Review of Next Generation Air Monitors for Air Pollution

Report to:

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1.0 Introduction

Historically, air pollution management initiatives have focused on urban and regional air quality relying mainly on traditional air pollution monitoring networks. These networks provide the foundation of our understanding of pollution trends and their associated health effects, inform compliance with standards, and are the basis of studies on the impacts of regulatory changes and air quality management programs. With increasing awareness of spatial variability in air pollution concentrations within cities and the importance of pollution gradients from traffic and neighborhood sources, such as residential wood combustion, (1,2) there is an increasing need to also evaluate air pollution variability at local or neighborhood scales.

Improved understanding of spatial gradients in air pollution has informed the understanding of air pollution health impacts. For example, numerous studies have reported relationships between a key component of urban air pollution—traffic-related air pollution (TRAP)— with a wide array of health effects including birth outcomes, (3,4) childhood and adult respiratory disease, (5–13) and cardiovascular effects (14–17). In Canada, approximately 10 million individuals, an estimated 32% of the population, are prone to TRAP exposure because they reside within 100 m of a major roadway or 500 m of a highway. (1) Of these 10 million people, 2 million live within a 50 m of a major road. (1) Furthermore, an estimated 16% to 36% of Canadian elementary schools within the 10 largest cities are located in high traffic zones (within 75 or 200 m of major roads, respectively). (18) Taken together, the magnitude of TRAP exposure and the evidence of health impacts in Canada, suggests TRAP is one of the most important air quality issues facing the country.

Residential wood combustion (RWC) is another major contributor to localized hotspots in air pollution. Mobile monitoring campaigns have studied RWC (19,20) and linked it to a number of adverse health impacts. (9,10)

A meta-analysis by Zhou and Levy (21) estimated the spatial extent of various air pollutants from their source based on four categories: reactive pollutants formed in the atmosphere (350 m), reactive pollutants removed from the atmosphere (175 m), inert pollutants with low background (140 m) and inert pollutants with high background (1000 m or more). (21) Another systematic review by Karner et al. (22) confirmed similar results showing edge-normalized TRAP pollutants require distances between 115 m to 570 m to decay to background levels. Pollutants displayed either no trend with distance (e.g. particle mass concentrations), a consistent decay with distance (e.g. nitrogen dioxide (NO_2), benzene) or a rapid initial decay of at least 50% by 150 m, followed by gradual decay (e.g. carbon monoxide (CO) and some particle number concentrations). (22) Besides proximity to pollutant sources, other variables such as meteorological conditions (e.g. wind speed and direction, solar radiation, precipitation, inversion conditions), (23–26) topography (e.g. valleys), (27) and landscape and infrastructure (e,g. highways, tunnels, (28,29) street canyons, (30–34) vegetative or structural barriers (1)) can all influence spatial air pollution patterns.

As spatial monitoring improves, pollution sources, hotspots, dispersion patterns and health effects can all be better addressed while reducing the reliance on predictive models. Thus, there is a need to supplement conventional spatially dispersed air quality monitoring networks with alternative approaches that capture this fine level of variability. Passive sampling arrays, mobile monitoring, and emerging sensor technologies are all approaches that have been used to address spatial coverage.

The sensor market has flourished in recent years resulting in economic, low power, miniaturized, autonomous (and typically wireless) air quality monitoring units. Although these units may be less precise when first marketed, later generations will likely demonstrate improved reliability and rigor. The merits of these instruments include the collection of real-time, location-specific, open-access data. Outputs may be utilized by the public as an educational tool in promoting air quality awareness while assisting individuals in time-activity pattern modifications to reduce harmful exposures to air contaminants. Included among the new technologies are smartphone applications, real-time data from solar-powered systems—such as the Village Green Project, remote and passive fence-line monitors, wearable sensors and wireless sensors. (35) This revolution in sensors and related applications may afford sustainable solutions for applications in personal monitoring, education, hotspot screening, community-based monitoring, air monitoring network supplementation, ambient air monitoring networks or even compliance assessment. (35)

In this report, we review new air quality sensor technologies and discuss their use in the context of conventional monitoring, mobile monitoring, passive air quality measurement and new applications. We summarize information on sensor performance and provide recommendations regarding future applications.

2.0 Air Quality Measurement

2.1 Traditional Monitoring Networks

Traditional air quality monitoring networks are the foundation for air quality management, policy and regulations, population exposure assessments and health effects research. In Canada, two federal air pollution monitoring networks gather air quality data—the National Air Pollution Surveillance (NAPS) network (with 289 sites across 216 communities) and the Canadian Air and Precipitation Monitoring Network (CAPMoN) with 30 rural stations. (36) NAPS monitors long-term ambient air quality indicators (carbon monoxide: CO, nitrogen dioxide: NO_2, sulfur dioxide: SO_2, ozone: O_3 and particulate matter less than 25 microns: $PM_{2.5}$) using nation-wide uniform standards assuring measurement accuracy, precision, comparability and representativeness. (36,37) These networks are characterized by a limited number of monitoring sites (e.g. 1-30 sites within an urban area), which operate continuously to provide quality information used in the characterization of contaminants at high temporal resolutions.

A shortcoming of these fixed-site monitoring networks is the limited capture of significant spatial patterns in common air pollutants; this is a threefold problem. Firstly, these monitoring sites are stationary and their arrangement is governed by restrictive siting criteria, which consequently limits the number of suitable locations. (38) Siting considerations include the availability of electrical power, accessibility, local emissions sources, pollution transport, security, installation and shelter specifications, and land use characteristics. (39,40) Secondly, because of the high cost and maintenance requirements (i.e. electrically powered temperature-controlled facilities requiring security) for these stations, (41) the networks cannot be set up with adequate density or distribution to capture fine spatial variability. For instance, Vancouver has a monitor density of approximately one station per 160,000 individuals, or 5 monitoring sites per 1,000 square kilometers. (42) Rather, these parsimonious fixed-sites are operated to generate data informing on urban background concentrations, regional air quality or intercity differences, with a strong focus on larger urban centers. Thirdly, NAPS locations have traditionally been chosen to avoid local pollution sources. (1) For example, Hystad et al., (38) applied the NAPS data to derive national air pollution models for $PM_{2.5}$, NO_2, benzene, ethylbenzene and 1,3-butadiene, but revealed in the process, the scarce availability of NAPS monitors near major roads (35 monitors within 500 m) and industrial emission sources (7 monitors within 500 m).

The diverse functions of NAPS include: supporting municipal planners in performing environmental assessments, serving researchers examining ambient air pollution and human health, and providing the public with information on air quality and health risks (e.g. Air Quality Health Index, AQHI). (37) Traditional networks are fundamental and irreplaceable; nevertheless, provisions are being made to expand these networks to include additional near-road sites for TRAP and to improve spatial resolution. (1) Although this network expansion will provide valuable new information, additional strategies are also worthy of consideration.

2.2 Passive Samplers

Passive or diffusive sampling has been employed in urban and rural ambient monitoring since the 1970s to measure gaseous pollutants. (43) Diffusive samplers can be distributed at numerous locations (including remote regions) because they are unobtrusive, relatively inexpensive (excluding lab charges), lightweight, small, practical, and not burdened by power requirements. (43,44) The versatility of these monitors is demonstrated in their ability to provide information on both coarse-resolution temporal changes (typically 0.5 or more days) if used in succession, and spatial patterns (if deployed simultaneously). (45) Passive samplers are able to quantify cumulative air pollutant exposures (i.e. total or average levels) with low detection limits given a sufficiently long sampling period. (44) With their low cost, large numbers of samplers can be deployed within an area of interest to give a snapshot of the air quality over a particular time period.

Despite these strengths, passive samplers are inherently limited in providing information on short-term (less than a few hours) pollutant concentrations and are inadequate for accurately addressing regulatory compliance. Other concerns that need to be tackled before using samplers include: the linearity in response to increasing concentrations, pollutant specificity and chemical interference (e.g. O_3, sulfur oxides (SO_x) and nitrogen oxides (NO_x)), air turbulence effects on sample collection, suboptimal functioning with atmospheric changes (e.g. wind velocity, temperature, humidity, radiation) and the necessity for subsequent laboratory analysis which adds to logistical complexity and delays in providing results. Typically, these samplers are co-located with continuous monitoring methods to establish comparisons. (43,44)

Passive samplers have been used in many contexts including monitoring of workplaces and indoor and ambient environments. (44) Their applications range from the monitoring of hotspots, (46,47) to obtaining personal long- or short-term samples, (43,48–52) to community-based assessment approaches. (53) A participant-based sampling strategy has successfully demonstrated that passive sampler kits mailed to participants can provide comparable measures to central monitoring stations. (53) Krupa et al. (44) contended that co-locating passive samplers may enable their use as calibration points for continuous monitors at discrete locations to assist air quality distribution mapping on variable spatiotemporal scales. Besides serving as calibration points for spatial mapping, the use of passive samplers has been influential in model development such as the multiple land use regression models developed for Canadian cities. For example, in the land-use regression model created for Windsor, Ontario a deployment of passive samplers (for 2 week durations in all seasons) was used to model and map concentrations of NO_2, SO_2 and volatile organic compounds (VOCs). (54)

A local-scale study of Vancouver Island cruise ship emissions provides an example of the use of Ogawa passive samplers to simultaneously measure nitrogen oxides (NO/NO_2) and SO_2 in long-term transect and paired sampling. (55) Distinct patterns of roadway concentration decay were seen and higher concentrations of nitrogen monoxide (NO) and NO_2 were observed on cruise ship days compared to non-cruise ship days. (55) The upcoming proposed New Brunswick Shale Gas Air Monitoring Study (a joint initiative from Health Canada and the New Brunswick Department of Environment and Local Government) will aim to understand air quality impacts from shale gas operation activities (e.g. new site development, gas plant discharges, and inactive well emissions) by using 7-day continuous passive badge samples for simple, heavy and air toxic VOCs. (56) Another example is the use of passive samplers to measure personal, indoor, and outdoor exposures to NO_2, SO_2, O_3, and VOCs in a study of Alberta's oil and gas industries and potential health effects in rural areas. (57)

While the above are examples of specific measurement initiatives, there are also examples in which passive samplers are part of routine monitoring programs. For instance, as part of the Italian National Integrated Program for Forest Ecosystem Monitoring Network, passive samplers for O_3 and NO_2 were used in remote monitoring of forest plots. (58) Similar applications have used passive samplers to assess summer-time air pollutant (O_3, NO_2 and nitric acid) distributions in national park forests (59) and O_3 exposures along river drainages. (60)

In addition to the use of passive samplers for common air contaminants, passive samplers have been used for gas phase sampling of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers in industrial Korea, (61,62) indoor and outdoor volatile organohalogens (63) and ambient VOCs in Japan, (64) pesticides in Luxembourg, (65) PAHs in Spain, (66) benzene in Sweden, (67) benzene, toluene, ethylbenzene and xylene (BTEX) in Eastern Asia, (68) polychlorinated naphthalenes in China, (69) and persistent organic pollutants in agricultural areas of India. (70) As shown in Table 1, passive sampling methods are available for a wide variety of inorganic and organic gaseous air pollutants. (71)

While diffusive samplers are, by definition, only applicable to gaseous or semivolatile pollutants, there are some examples in which particle sampling has been conducted passively. Guéguen et al. (72) used a network of passive coarse particulate matter (PM) samplers to determine chemical and isotopic signatures from ambient traffic and industrial pollution over a long collection period. Yamamoto and colleagues (73) created a passive personal aeroallergen sampler, based on principles of gravitational settling, using a gimbal-like structure to capture coarse particles (eg. pollens, pellets and spores). In another study, Wagner et al. (74) monitored the distance, and downwind and upwind effects of agricultural burns with passive PM monitors.

Passive samplers are a good option for networks because they are portable, low in cost and simple to operate. Therefore, even operators with limited experience (including citizen scientists and mailed survey participants) can employ these monitors to conduct spatial sampling campaigns for gaseous pollutants with few to no restrictions on location. Important caveats, however, are that these samplers will generally exhibit low precision compared to active monitoring approaches and their requirements for increased sampling durations of hours to days. (44)

Table 1. Passive Sampling for Gaseous Air Pollutants, Adapted from Górecki, 2002. (71)

Inorganic compounds	**Organic compounds**
Carbon monoxide, CO	Aliphatic hydrocarbons (C_5 - C_{12})
^{14}Carbon dioxide, $^{14}CO_2$	Aromatic hydrocarbons (benzene, toluene, xylenes, etc.)
Nitrogen oxides, N_xO_y	Non-methane organic compounds
Ammonia, NH_3	Chlorinated hydrocarbons (trichloroethylene, tetrachloroethylene, etc.)
Chlorine, Cl_2	Microbial volatile organic compounds (MVOCs)
Chlorine dioxide, ClO_2	Amines (methylamine, dimethylamine, isopropylamine, diethylamine, butylamine)
Sulphur dioxide, SO_2	Perfluorinated hydrocarbons
Hydrogen sulphide, H_2S	Petroleum hydrocarbons (38 components)
Carbon disulphide, CS_2	Monoterpenes (a-pinene, b-pinene, D3-carene)
Ozone, O_3	Styrene and its derivatives (*a*-methylstyrene, *o*-chlorostyrene, styrene-7,8-oxide)
Hydrogen fluoride, HF	Polychlorinated biphenyls
Hydrogen cyanide, HCN	Formic and acetic acids
Arsenium hydride, AsH_3	Aldehydes (formaldehyde, acetaldehyde, glutaraldehyde)
Mercury, Hg	1,3-butadiene
^{222}Radon, ^{222}Rn	Isoprene
	Polyaromatic pollutants
	Dioxane
	Naphthalene
	Gasoline oxygenates (MTBE, TBEE, TAME)
	Vinyl chloride
	Acetates
	Alcohols
	Acetone
	Ketones (methyl-ethyl, methyl-isobutyl, etc.)
	Tetraethyl lead
	Acrylonitrile
	Ethylene oxide
	Halothane, enflurane and isofluranes (anaesthetics)
	Reactive gases in atmospheric air (1-pentene, isoprene, 1-hexene)
	Hydrazines (hydrazine, methyl hydrazine, dimethyl hydrazine)
	3-ethenylpyridine (marker for environmental tobacco smoke)
	Polychlorinated aromatic hydrocarbons

2.3 Mobile Monitoring

Mobile monitoring relies on a mobile platform (typically a vehicle) equipped with continuous air pollution monitors and a global positioning system (GPS) to relate high-density measurements to precise locations within an area of interest. (75) Mobile sampling capitalizes on the ability to be in motion while gauging pollution concentrations at proximal or distal distances from sources. (76) Mobile sampling is efficient due to the capacity to traverse large distances in a confined timeframe with limited real-time instrumentation collecting at high frequencies. (57,59) As long as there is a continuous monitor for the specific pollutant(s) of interest, sampling is not constrained by what can be measured. In order to account for temporal changes due to meteorology or emission patterns, repeated samples can be collected and a mobile campaign can include a fixed-location reference site. (75) For example, Larson et al. (19) applied temporal adjustments from fixed-site data to their mobile measurements to develop a highly resolved composite map of wintertime woodsmoke in Vancouver. In another study, Su et al. (78) used the same principles to create an emissions surface of residential woodsmoke in a non-urban setting in New York State.

This measurement approach is highly malleable and can identify spatial patterns in woodsmoke, (20) road dust, (79) conditions associated with temperature inversions, (27) and within street canyons. (80) Mobile nephelometry played a critical role in spatial pattern and hotspot determination of particulate air pollution in a study of five communities in Northern British Columbia (Terrace, Telkwa, Smithers, Houston and Burns Lake) and the assessment of the impacts of a residential wood stove exchange program. (75,81) In Nanaimo, a similar mobile initiative shed light on wood smoke ($PM_{2.5}$) hotspots. (82)

Alternatively, mobile monitors can be stationed at designated locations (e.g. a high traffic intersection) for a predetermined time period on the scale of hours to days to act as a pseudo monitoring station. (75) An example of the latter function of mobile monitoring is the use of a mobile air monitoring station to collect data on NO, NO_2, SO_2, $PM_{2.5}$ and particulate matter less than 10 microns (PM_{10}) at a site near the cruise ship terminal. (83) In another application, mobile monitoring data revealed patterns in pollution resulting from beach fires and regional wildfires. (84)

By employing mobile air quality monitors to enhance the information obtained from isolated fixed monitors, spatial resolution is enriched (85,86) and hotspot detection becomes possible for pollutants varying across small spatial scales. In the course of monitoring, mobile platforms may perhaps provide data for model development or evaluation. (75) Isakov et al. (87) demonstrated a method to depict spatiotemporal varying air toxic levels. In Los Angeles, mobile monitoring equipment for black carbon (BC), ultrafine particles (UFP), $PM_{2.5}$, particulate matter-phase PAHs, NO_X, CO and carbon dioxide (CO_2) established concentration differences among freeways, arterial roads, and residential streets. (88) Bowker et al. (89) verified a Quick Urban and Industrial Complex model for studying the effects of roadside barriers on pollution patterns from a highway through mobile monitoring of UFP spatial distributions.

Mobile monitoring is also suitable for screening and comparing new siting locations for traditional monitors, assessing pollutant concentrations within cityscapes (e.g. bridges, buildings, tunnels), and even pinpointing areas that may require more in-depth pollutant characterization. (75,85) Vardoulakis et el. (90) operated a parked mobile monitor in an asymmetric street canyon in Paris to appraise the performance of the permanent proximal monitoring station, suggesting that the fixed site measurements were misleading in approximating air quality and hence were inappropriate for exposure studies. (90)

Further, mobile monitoring can more accurately communicate the exposures of traveling inhabitants by participating in urban traffic flow in vehicles, (91–93) bicycles (93,94) or as pedestrians. (91,92,95) Hankey et al. (96) modeled non-motorized traffic (pedestrian and cycling) with negative binomial and ordinary least squares regression to estimate 12-hour non-motorized traffic counts in Minneapolis. As mobile units instantaneously integrate data, finer temporal variations like those noticed during vehicular acceleration, deceleration, cruising and idling might be acquired. (97) In Boston, a community-based approach involving high school students carrying mobile monitors in backpacks showed that urban neighborhood spatiotemporal variability was more prominent for UFP compared to $PM_{2.5}$. (98) Mobile monitoring campaigns using bus and truck chasing tactics were at the heart of investigations of on-road transportation emissions (CO, BC, UFP) in Beijing leading up to the 2008 Olympics. (99,100)

Despite all the benefits of mobile monitoring, drawbacks do exist. Firstly, this technique is not appropriate for routine use as it is very resource intensive. Secondly, confirmation of temporal trends can be difficult, since temporal coverage is incomplete. This results from the discontinuity of the sampling campaigns. Thirdly, inconsistent GPS signals may negatively impact uncertainty. (101) Finally, if the goal of sampling is to evaluate a specific pollutant source (e.g. wood smoke), then the sampling strategy must either be carefully tailored to meet these needs (e.g. cold, winter nights when ambient traffic is less of a confounder), or a more source-specific measurement approach should be used. (75)

2.4 Intra-Urban Air Pollution Modeling

In addition to the use of mobile monitoring and passive samplers to provide information on fine-scale spatial variability, modeling approaches have also proved to be useful.

Land Use Regression (LUR) models have gained popularity since their initial application to air quality by Briggs et al. in the 1990's. (102) LUR models use geographic covariates in the context of a geographic information system (GIS) to predict concentrations that are measured as part of a spatial monitoring campaign. (103) With stochastic modeling, the ambient concentration serves as the dependent variable in a multivariate regression with numerous independent variables (e.g. road type, traffic intensity, population density and land cover) to explain the spatial distribution. (75,103,104) Enhancements to LUR models incorporate street canyon indicators (105) and meteorological covariates (e.g. wind speed and direction, cover or isolation) in source area LUR models. (106) Once the model is developed, pollutant concentrations can be predicted for unmeasured locations falling within the study domain since values of predictive variables are available at all locations. (103,104,107)

These empirical models are cost-effective (107,108) and support efforts to identify hotspots. (109) Monitoring data can be gathered routinely (i.e. by traditional fixed networks); however, unless these characterize the full distribution of pollutant concentrations and predictor variables, the model applicability will be limited. Models developed with purpose-designed monitoring (normally passive samplers for gases, active samplers for PM, or mobile monitoring campaigns) are preferred, as monitoring locations can be selected to ensure they are representative of the full spatial extent of ambient pollution and the predictive variables. (75,107) Purpose-designed monitoring tends to integrate data from one to four campaigns lasting one to two weeks each; consequently, associated costs are higher than routine monitoring alone. (107) The major shortcoming of LUR models is their inability to resolve meaningful short-duration temporal trends. (109,110) To preserve the predictive power of LUR, calibrations and/or adjustments are needed, especially if the model is used in hindcasting applications in temporally unstable environments. (111)

At present, LUR models for TRAP have been developed and applied in nine Canadian cities for use in epidemiological studies. (1) In Vancouver, LUR models have been generated for pollutants including BC, (112) $PM_{2.5}$, (110) UFP, (113) and NO_x. (110,111) A recent review describes 25 land-use regression models from North America and Europe as applied to pollutants such as NO_x, $PM_{2.5}$, and VOCs. (107) National LUR models have been generated for 5 pollutants (NO_2, $PM_{2.5}$, benzene, ethylbenzene and 1,3-butadiene) in Canada to capture both between-city and within-city variability. (38) In the United States, a national LUR for NO_2 has also been developed. (114) Within Canada, researchers have assessed the intercity transferability of LUR models and concluded that it is feasible; however, the predictions will largely depend on consistencies between the urban designs of these cities. (115,116) A study in the Greater Vancouver Regional District compared 3 methods (LUR, spatial interpolation and a community multi-scale air quality model) for assessing spatiotemporal variability. (42) The results implicated LUR models as having the finest spatial resolution (neighborhood-scale) compared to the other approaches (representing urban-scales). (42)

Dispersion models calculate receptor level concentrations based on idealistic Gaussian pollutant dispersion parameters incorporating inputs from emissions inventory databases, atmospheric conditions, topography, source-receptor distances and time. (75,108,117) These models have been applied to both urban (e.g. episodic pollution events) and regional scales (e.g. pollution migration events). (108) Although regulatory uses are possible, dispersion models are constrained by a demand for high-quality input data and in some applications the need for high-power computing. (118) Comparisons between LUR and dispersion models indicate similar success in explaining variability in measured concentrations of air pollutants. (119)

Although their spatial resolution is defined by the availability of monitoring data, spatial interpolation methods (e.g. kriging), can be applied to construct continuous surfaces for pollution across large areas (118) when monitor placement is sufficiently dense. (108,120) In many instances, a high temporal resolution is achieved with accompanying measures of standard error to estimate uncertainty. (108) A concern is that artifacts may results from interpolation, especially edge effects and poor characterization of pollutant sources and sinks. (108) One study in Los Angeles showed that universal kriging and an ad-hoc 2-step approach consistently outperformed LUR modeling in summer, autumn and winter months. (121)

As conventional monitoring sites only provide a partial representation of air pollution with limited spatial coverage, modeling supported by additional monitoring, can assist in extrapolations to un-sampled locations.

3.0 New Sensor Designs and Applications

New sensor designs offer potential solutions to the inability of traditional air monitoring networks to fully characterize spatial variability. Moreover, these innovations, which act as dispersed continuous monitors, should experience no problems in capturing time-varying components of air pollution. In fact, it is this feature that is absent in LUR models and oversimplified in dispersion models. Unlike passive sampling, mobile monitoring, and ambient pollution modeling, these new sensors can communicate in real-time (much like routine monitoring networks) to a central data-processing server. This is advantageous since these sensor arrays can in theory instantaneously deliver high-resolution spatiotemporal data. We first cover the potential applications of these sensors, and follow with a discussion of wireless sensor arrays and information on specific examples.

As new sensor technologies appear, major organizations are actively contributing to and paying close attention to the development and maturation of this growing research field. A European Union partnership project called CITI-SENSE is focused on evaluating the use of sensors in community directed environmental monitoring. (122) Likewise, the United States Environmental Protection Agency's (EPA) (35) "Draft Roadmap for Next Generation Air Monitoring" presented several strategies to assist technology advancement and testing while articulating some goals to overcome gaps in these rapidly emergent sensing systems.

New measurement technologies can be envisioned for use in four main avenues including fixed network augmentation, source or industrial site monitoring, personal exposure monitoring and participatory sensing. (41,101) The first strategy is to supplement static air quality monitoring networks by increasing sensor density to enhance spatiotemporal assessment in areas where fixed measures are unavailable. In this way, micro-sensors can be fixed at specified locations (e.g. schools, intersections) or be secured onto mobile platforms (to systematically resolve spatial patterns). (101)

A second approach surveys source emissions or industrial pollutants (within the facility or around the perimeter). (41) Sensor response is likely better at or near sources due to the higher concentrations. (101) Condensed monitoring networks (e.g. Geotech AQMesh and Cairpol CairNet) can thus be used to detect contributions from automotive exhaust, (123) industrial accidents, or fugitive emissions (leaks). (41) Fujita and Campbell (124) suggested that sensor networks may prove useful for early warnings of high releases at refineries. Wan et al. (125) have proposed the use of sensor networks in natural gas pipeline monitoring. Recently, Bennett et al. (126) applied an electrochemical gaseous sensor array to assess the effect of baffles on aircraft exhaust plumes at an airport perimeter. Mobile mounted platforms have also been used to test for the impact of ship emissions. (127,128) These examples illustrate the broad scope of applications that are conceivable with new sensor arrays.

In view of the fact that people are constantly on the go, moving between environments and changing their time-activity patterns, fast-response sensors can be used to improve estimates of individual-level exposures and the parameters that predict them. For instance, information from smartphone embedded sensors can be gathered to make better estimates of travel patterns (e.g. Personal Environmental Impact Report), locations visited, and hence, exposures. (129) Body-worn sensors (e.g. Sensorcon Sensordrone), universal serial bus (USB) pluggable sensors (e.g. Cairpol CairClip), and Bluetooth transmissible sensors for cellular devices (e.g. CitiSense) all facilitate personal exposure monitoring. (101) These sensors may be beneficial to sensitive populations, such as asthmatics. (101)

Finally, citizen science (also called crowdsourcing, citizen observation or participatory monitoring) is the notion that data accumulated by individuals (scientists and nonscientists, alike) can be pooled to produce distributed datasets on personal, regional or global scales. This shift from restricting monitoring to professional organizations (e.g. researchers or government) to everyday people is made possible by cheaper and easy-to-operate instruments. Participant sensing initiatives have even begun projects to build and operate do-it-yourself sensors and sensor networks (e.g. Air Quality Egg and AirCasting). However, citizen science can also be a source of concern as it is prone to issues in data quality, data consistency, data interpretation and user privacy. To avoid such uncertainties, efforts should be made early on to educate users on the use and potential limitations of crowd-sourced data. (35,101)

Before new technologies are introduced in the following sections, it is important to emphasize the difference between sensors, and the devices and networks that contain them. Air pollution units, nodes, monitors, devices and systems may include one of two (or both) categories of sensors in their designs. Individual sensors can be created in-house by the vendor of the device (to match the needs of the monitor, i.e. purpose-driven designs) or they can be purchased from other manufacturers as ready to install, off-the-shelf sensors. Few sensing systems seem to integrate new purpose-designed sensors (e.g. Cairpol CairNet and Sensorcon Sensordrone); instead, monitors tend to depend on commercially available sensors.

3.1 Sensor Operation

The abundant sensor technologies available today have exciting implications for personalized air quality monitoring, community-led sensing initiatives, network supplementation, and source and facility management as they are shrinking in size and becoming more affordable. Regardless of how they are applied, these new sensors and their use in distributed networks have the potential to improve spatial resolution, support air pollution research, and boost public awareness. (35)

Sensor developments have focused on measurement of gaseous criteria pollutants; however, sensors for hazardous air pollutants (HAPs) and particles to aid enforcement and compliance regulations are also in need. (35) Our review has highlighted what Paprotny et al. (130) already identified—there is a lack of commercially available miniaturized direct-reading PM mass (e.g. $PM_{2.5}$) sensors compared to those which provide information on particle number (e.g. Air Quality Egg, Sensaris EcoPM) or non size-selective measures (e.g. CanarIT).

Recently, researchers and manufacturers have begun to work towards satisfying this growing need. For example, Northcross et al. (131) adapted a light scattering Dylos Air Quality Monitor to develop a prototype ambient particle mass instrument. Research by Paprotny et al. (130) also holds promise of a micro-electro mechanical system air-microfluidic sensor for PM monitoring. There is also a deficiency in devices to measure the chemical speciation of PM, with the exception of the micro-Aethalometer for BC measurements. (41,132) Finally, HAPs detectors are few and far between; yet, the available ones tend to not be actively tested when exposed to complex mixtures of HAPs. (41)

As most of the sensors discussed are gas sensors, a brief overview of the qualities and limitations of electrochemical, metal oxide semiconductor (MOS) and infrared (IR) sensors are provided. From the units surveyed, the most prominent sensor types are the electrochemical and MOS sensors. More detailed information on their principles of operation is available in Appendix A.

Electrochemical sensors measure analyte concentrations related to changes in potential after the gas undergoes an electrochemical reaction with the sensing electrode. (133) Electrochemical sensors tend to be used to measure common air pollutants such as NO, NO_2, CO and O_3. (101,134) New miniaturized sensors (roughly 20 mm) are low in cost and power consumption. (101) Mead et al. (134) demonstrated the ability of new electrochemical sensors to achieve low detection limits to the parts per billion level, while providing low noise and high linearity. Fairly consistent deviations in linearity of 2-5 % (sometimes up to 10 %) can occur in electrochemical gas sensors. (101) To maintain long-term stability of 2-15 % per year, oxygen exposure is continually needed. (101) Interference cannot be eliminated (101); however, optimizing the sensing electrode’s selectivity, integrating electrolytes efficient in carrying charge, and installing chemical scrubber filters (e.g. activated charcoal) above the sensing electrode can all reduce cross sensitivity. (133)

On the other hand, if an electrochemical sensor is highly sensitive, the capillary is less restricted and the membrane is more porous, thereby compromising sensor signal and operating life as it deteriorates with faster electrolyte evaporation. Life expectancy is generally 1-3 years but differs with gas exposure and environmental conditions. Temperature sensitivities are managed with internal temperature compensation mechanisms. Humidity fluctuations change the ability of water vapor to pass the hydrophobic barrier; if a sensor is compatible for measuring low gas concentrations, the barriers are more porous and can pose a greater problem. (133)

MOS sensors measure gas concentrations by monitoring resistance or conductivity changes in the metal oxide sensing layer when gases undergo electrochemical reactions at this boundary. (101) These sensors weigh a few grams and are roughly a dozen millimeters in size. (101) MOS sensors are used frequently as a result of their low cost, short response time, and long lifetime. (135,136) In addition to this, they respond to a wide range of gas concentrations (few ppb to thousands of ppm). (101)

MOS sensors suffer from poor selectivity and high cross-sensitivity. (136) A limitation of this sensing method occurs when temperatures digress too far from the optimal sensing temperature, thus allowing non-target gas components to be more reactive than the desired gas. (136) On the other hand, if two gases had a large enough gap separating their optimal sensing temperatures, then one sensor could be adapted with a thermostatic cycle (for the sensing element) to relay between the temperatures in order to detect both constituents. (136) To compensate for drift in MOS sensors, recalibration efforts are necessary. (101)

Because some resistive sensors need elevated temperatures for measurement, moderation of power consumption is important. One solution incorporates micro-heaters (with mixed tin dioxide particles and multi-walled carbon nanotubes) (137,138) and uses temperature pulsed methods with brief heating intervals. Finally, prolonged recovery times may render MOS sensors impractical for certain devices when gas concentrations vary suddenly. (136)

When an IR light source is incident on a gas, the radiated energy is absorbed and the detector converts the electromagnetic energy or temperature changes into measurable electrical signals. (139) Increases in IR sensors have occurred in parallel with the advances in powerful amplifiers and electronic components. (139) IR gas detectors are small (often a few millimeters in size) and consume only a few hundred milliwatts of power. (101)

As gases are frequently reactive and/or corrosive, they may shorten sensor lifetime and induce drift. (139) This is prevented in IR instruments, since the target gas does not interact directly with the detector; instead, it only contacts the light beam and the chamber's entrance (which can be made anticorrosive or replaceable). (139) Therefore, sensor life expectancy is more than 10 years. (139) IR sensors do not experience loss of sensitivity since they are created to recognize gas molecules by their unique absorption peaks. (139) Cross sensitivities can occur in hydrocarbon detection with IR sensors because they share similar absorption characteristics (for the carbon-hydrogen bond). (101) Conversely, CO_2 detection is highly sensitive as these molecules have distinctive absorption bands. (101) By performing zero calibration checks, accuracy is preserved. (139)

Concerns with IR gas sensors include time dependent light intensity changes from contamination leading to a zero drift. One way to guard against this is to use a two-detector arrangement where one acts as an active detector and the other as a reference. Because IR detectors sense temperature, they are susceptible to ambient temperature fluctuations and perform even worse with sudden changes. Ambient temperatures are slow to alter, so performance outdoors is not severely hindered. If water vapor condenses on the optics or detector, the units may become faulty. For this reason, the sensors are run at temperatures marginally above surrounding temperatures. IR analyzers can die if humidity is especially high, as contamination and corrosion become serious issues. (139)

3.2 Wireless Sensor Networks

Wireless sensor networks (WSNs) can provide real-time communication while gathering and processing massive amounts of data. WSNs have been applied to environmental monitoring as well as agriculture (e.g. monitoring temperature, humidity, animal behavior and movement patterns), indoor living (e.g. home security systems and fire detection), industry (e.g power grid and oil and gas pipeline sensing), medicine (e.g. body area sensor networks for monitoring vital signs in patients), and the military (e.g. ad-hoc deployment to detect and track enemy intrusion). (140–145) Their environmental applications include monitoring and management of traffic conditions, weather, and air quality. Sensors integrated in these networks are typically small, inexpensive, and power efficient. Battery-powered sensor nodes have four components: sensors and microcontrollers that accomplish the task of pollutant measurement and data processing; memory which stores data; transceivers that transmit and receive data; and a power unit. Because sensor nodes are densely deployed, they can rely on cooperative multi-hop communication to selectively transmit partially processed, pertinent data. This multi-hop communication to the sink node for data fusion expends less power than single hop communications. Remote control of these nodes is possible by users via the Internet once all sensor nodes communicate with one another and the sink node. (140,146)

Wireless sensor arrays have the potential to form the foundation of dynamic, real-time, dense monitoring networks for use in a wide variety of applications. Because these devices are inexpensive compared to traditional fixed-site regulatory stations, it is feasible to complement existing networks by placing wireless sensors at new locations. Additionally, a wireless dispersed sensor array can augment the power of public communication tools such as the AQHI to support the public in conscientious decision-making (e.g. route planning) based off of fine-scale spatially resolved air pollution levels. (147) The portability and ease of use of these sensors can also allow researchers the opportunity to study horizontal and vertical spatial patterns in pollutant dispersion, which may in turn provide insight to exposure mitigation.

The primary concerns for WSNs are sensor performance (i.e. data validity and data quality). (148,149) While much of the available and emerging WSNs are accessible to consumers, only a limited few have undergone evaluations. In addition, signal connectivity, reliable maintenance, hardware failure, and flexibility in adding, removing or changing the number of stations may also limit their performance. (140) Other limitations may surface such as the sensor's energy efficiency (that could compromise network lifetime), usability, standardization, security, and area coverage (dependent upon the number of deployed sensors). (148,149)

The following section reviews the Geotech AQMesh, Libelium Waspmote Plug & Sense, Cairpol CairNet, AirBase CanarIT 1.0, Sensaris SensPods, Smart Citizen, Air Quality Egg and Envirologger CO_2 as examples of currently available WSNs.

3.2.1 Geotech AQMesh

These battery-powered wireless units were designed in partnership with the University of Cambridge to monitor five gaseous pollutants with Alphasense sensors (Table 2). AQMesh units are well suited for installations on lampposts, signposts, fences or walls and can function in network arrays with hundreds of units. This technology incorporates electrochemical gas sensors with a fourth electrode to increase stability and combat drift. Precision is maintained by reducing noise levels in the circuit to a few parts per billion. According to the manufacturer, it also uses proprietary catalyst loading and stack structure to certify steady operation at low concentrations. Relying on mobile general packet radio service (GPRS) technology limits signal access, but roaming with modern telecom networks can overcome this problem. Battery trickle charging gives short power bursts to connect the wireless GPRS link for data transmission. The data is uploaded to a multi-user, password controlled web browser-based server where data is processed, accessed, and downloaded. Algorithms correct for temperature sensitivities, calibration coefficients and factors for each sensor pod. (150–152)

The small size and battery operation of these devices makes them adaptable to urban hotspot and traffic monitoring, fence line monitoring, or industrial plant fugitive emissions monitoring. Although not currently available, future updates will likely include particulate matter ($PM_{2.5}$ and PM_{10}) monitoring and gas sensors for hydrogen sulfide, and carbon dioxide. (153) The AQMesh system has undergone some field-testing against reference air quality monitors. Figure 1 shows the results from a comparison conducted by Geotech during November 2012. (150,151)

Table 2. Geotech AQMesh Specifications (154)

Electrochemical Gas Sensors	Range (ppb)	Accuracy (ppb)[2]	Limit of Detection (ppb)
NO	0-20000	±5	<3
NO_2	0-200	±5	<5
O_3[1]	0-200	±5	<5
CO[3]	0-50000	±10	<5
SO_2[3]	0-100000	±10	<5
Other Sensors	**Range**	**Accuracy[2]**	**Limit of Detection**
Pod Temperature (°C)	-20 to 100	±2	0.1
Pressure (mb)	500-1500	±5	1
Humidity (%RH)	0-100	±5	1

[1]Reading given using digital signal processing, thus needs a number of data points to give comparable readings to reference instruments; last readings will be projected in a straight line. Data is retrospectively corrected with new input data.
[2]Under stable temperature and humidity, without interference at 20 °C and 80 %RH.
[3]Optional sensors

Properties:

Communications: GPRS, multi-band worldwide operation (154)
Dimensions: 150 x 180 x 200 mm (154)
Weight: <2 kg (154)
Sensor lifetime: up to 2 years (154)
Battery lifetime: up to 2 years (154)
Cost: $5500-$7200 for 3 gases (NO, NO_2, O_3); $6300-$8100 for 4 gases; $7100-$9000 for 5 gases (153,155)

Field Evaluation:

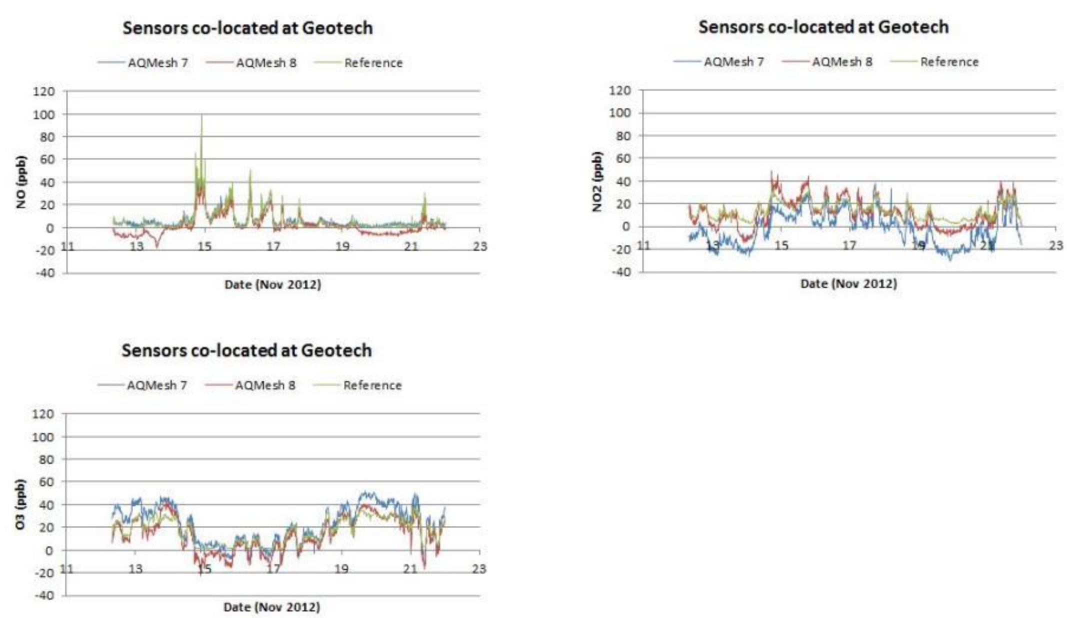

Figure 1. AQMesh co-location test results for nitrogen monoxide, nitrogen dioxide and ozone. Reprinted from (151).

3.2.2 Libelium Waspmote Plug & Sense

Waspmote Plug & Sense is a wireless, scalable device enclosed in a waterproof casing that can be installed on streetlights and building fronts. (156) Every Plug & Sense device possesses six sockets for up to six sensor probes at one time. (156) Eight sensor configurations (ambient control, smart cities, smart parking, smart environment, smart agriculture, smart security, smart metering and radiation control) with over 60 commercial sensors are currently being marketed. (156,157) Waspmote Plug & Sense uses some calibrated gas sensors (presented in Table 3) and other uncalibrated sensors for relative gas levels (e.g low, medium or high). (158)

All Waspmotes have a built-in 3-axes accelerometer, to detect free fall and directional changes, and a temperature sensor (with a detection range of -40 °C to 85 °C and a resolution of 0.25 °C). Discrete nodes can connect to a standard digital subscriber line (DSL), a cable-connected Wi-Fi router, or the Meshlium Internet Gateway (recommended for outdoor settings), to send data to the Internet. The sensor nodes can be programmed to a router or gateway (the "access point") before sending the data to other network devices (e.g. laptop or smartphone). An ad-hoc Wi-Fi network topology can create point-to-point networks so that each Wi-Fi module is linked to all other Wi-Fi devices (e.g. iPhone or Androids) in the network directly. Libelium uses over the air programming such that it enables firmware upgrade, change, or upload, without needing physical access. Four encryption libraries ensure confidentiality of gathered information. Nodes can be reset using an external magnet. Additionally, GPS receivers can be incorporated into the network. The internal or external solar panels can help power the system. (159)

The Waspmotes were applied in three different field network arrays. As part of the European Union's Pervasive Air-quality Sensors Network for an Environmental Friendly Urban Traffic Management (RESCATAME project), 35 calibrated Waspmotes were deployed in 2 arrays (of 10 and 25 nodes, each with their own Meshlium Gateway) along 2 streets in Salamanca, Spain. The networks aimed to assess pollution from vehicular fuel combustion with 7 parameters (CO, NO_2, O_3, noise, particles, temperature and humidity). If any parameter exceeded a threshold, the network would analyze the inputs to identify the location to alarm the central Meshlium node. (160)

In two Serbian cities, Belgrade and Pancevo, a total of 65 Waspmotes with gas board connected sensors were used in the EkoBus project to measure 5 atmospheric parameters (CO, CO_2, NO_2, temperature and humidity) periodically from the roof of buses; the data was visualized on the Web and through Android applications to manage public transportation. (161) An early alert warning system based on CO, CO_2, temperature and humidity, was created from 90 Waspmotes for forest fire detection across 210 hectares in North Spain. (162) In all instances, the nodes were autonomous because of the rechargeable battery and fixed solar panels. Additionally, they conserved battery power by running on a hibernation mode. (160–162)

Table 3. Libelium Waspmote Plug & Sense Specifications (158,163)

Gas Sensors	Range (ppm)	Accuracy (ppm)
Air Pollutants I (H_2, CO, CH_4, C_4H_{10}, CH_3CH_2OH)[1]	1~30	±4
Air Pollutants II ($C_6H_5CH_3$, H_2S, CH_3CH_2OH, NH_3, H_2)	1~100	±4
Alcohol Derivatives (H_2, CO, CH_4, C_4H_{10}, CH_3CH_2OH)	50~5000	±10
Methane (CH_4)	500~10000	±100
Oxygen (O_2)	0~30 %	±1 %
Carbon Monoxide (CO)	30~1000	±4
Ammonia (NH_3)	10~100	±3
Liquefied Petroleum Gases (H_2, CH_4, Ethanol, Isobutene)	500~10000	±200

[1]Air Pollutants I, CO_2, NO_2, VOC, O_3 and NH_3 not calibrated because the internal sensor operations do not allow set reference points

Properties:

Communications: 7 radio modules: XBee-802.15.4-Pro; XBee-ZigBee-Pro; XBee-868 MHz; XBee-900 MHz; Wi-Fi; GPRS; 3G/GPRS) (159)

Weight of Waspmote Plug & Sense: ~800 g (159)

Ambient temperature range: -10 to 50 °C (159)

Standard sensor specifications: Sensor probes are ~150mm long and 20 g (159)

Internal storage: Internal secure digital card can support up to 2GB (159)

Lifetime of Sensors: (159)

- Gas sensors (3 months to 2 years)
- Humidity and Temperature (6 months to 2 years)
- Dust and Particles (3 months to 2 years)

Battery: 2 options: Rechargeable 6600mAh or non-rechargeable 26Ah (159)

Real Time Clock: Built-in; variability of 1 min/year (159)

Cost: (156)

- Communication Options: ~$550~$920
- Power Options: ~$50~$110
- Individual sensors: ~$20~$750
- Meshlium Internet Gateway: ~$1040~$2000

3.2.3 Cairpol CairNet

Cairpol makes and employs in-house amperometric micro-sensors called CairSens for real-time display and data logging capabilities. (164) These sensors for O_3, NO_2, hydrogen sulphide (H_2S), methanethiol (CH_3SH, NH_3) and VOCs are utilized in three sensor devices: CairNet (a wireless network version), CairTub (an autonomous version) and CairClip (a portable version). (164) Manufacturer’s sensor information is available in Tables 4 and 5.

CairNet can be setup as wireless radio communicating, autonomous (solar panel and battery powered) networks. Hundreds of units can be deployed in these networks created to survey fugitive emissions, if the individual nodes lie within a 200 m radius of the wireless receiver. Radio communications use Wavenis (for open fields or indoor environments with a maximum reach of 150 m) Xbee, (for indoor environments with a maximum reach of 50 m without obstacles) and the Global System for Mobile communications (GSM)/GPRS (for wide meshings greater than 1 km). The CairMap software can cartographically represent CairNet data in real-time as color-coded points with daily or monthly histograms. The CairWeb software lets operators remotely access real-time data from the Internet or their smartphone. (165,166)

The CairClip is a USB connected device (for personal computer (PC) download) that can be secured on a belt, helmet or around the neck to measure personal or occupational exposures. (167) CairTub is autonomous for 21 days and is suited to indoor or outdoor deployments for exposure assessments in urban or isolated environments. (168) The CairSoft software is the user interface for data storage and visualization on the PC for CairClip and CairTub. (169) Data storage duration can range from 10 days to 10 months based on the average stored time interval (of 1 min or 15 mins). (169) CairChronic connects the CairSens sensors to PCs for workplace surveys (of up to 200 devices) while maintaining staff confidentiality. (169)

Table 4. Cairpol CairSens Specifications (170–181)

Electro-chemical Gas Sensors	Range	Repeatability at zero and 80% range (Uncertainty)	Limit of Detection	Short-term Drift, Long-term Drift	Temperature (°C) and Effect on Sensitivity (per °C)	Humidity (%RH)
H_2S-CH_4S[1]	0-1000 ppb	±5 ppb, ±10 % (< 30 %)	10 ppb	<4 ppb/24hr, <8 ppb/mo	-20 to 40, <0.5 %	15-90
	0-2000 ppb	±10 ppb, ±15 % (<30 %)	20 ppb	<5 ppb/24hr, <10 ppb/mo	-20 to 40, <0.5 %	15-90
	0-20 ppm	±10 ppb, ±15 % (<30 %)	30 ppb	<5 ppb/24hr, <10 ppb/mo	-20 to 40, <0.5 %	15-90
	0-200 ppm	±200 ppb, ±15 % (<30 %)	200 ppb	<50 ppb/24hr, <100 ppb/mo	-20 to 40, <0.5 %	15-90
O_3-NO_2[2]	0-250 ppb	±7 ppb, ±15 % (< 30 %)	20 ppb	< 5 ppb/24 hr, <10 ppb/mo	-20 to 40, <0.5 %	10-90
NO_2[3]	0-250 ppb	±7 ppb, ±15 % (<30 %)	20 ppb	<5 ppb/24hr, <10 ppb/mo	-20 to 40, <0.5 %	10-90
NH_3[4]	0-25 ppm	±0.2 ppm, ±15 % (<30 %)	0.5 ppm	<0.1 ppm/24 hr, <1 ppm/mo	-10 to 40, <1 %	15-90
SO_2[5]	0-1000 ppb	±10 ppb, ±15 % (<25 %)	50 ppb	<2 ppb/24hr, <10 ppb/mo	-20 to 50, <0.2 %	15-90
CH_2O[6]	0-1000 ppb	±5 ppb, ±20 % (<30 %)	10 ppb	<0.5 ppb/24hr, <5 ppb/mo	-10 to 40, <1 %	15-90
CO[7]	0-20 ppm	±0.05 ppm, ±15 % (<25 %)	0.05 ppm	<0.2 ppm/24hr, <0.4 ppm/mo	-20 to 50, <1 %	15-90
Photo-ionization Gas Sensor	**Range**	**Repeatability at zero and 80% range (Uncertainty)**	**Limit of Detection**	**Short-term Drift, Long-term Drift**	**Temperature (°C) and Sensitivity (per °C)**	**Humidity (%RH) and Effect (per %RH)**
VOC[8,9]	0-16 ppm	±10 ppb, ±15 % (< 30 %)	10 ppb	<0.5 %/24hr, <15 %/mo	-20 to 40, <1 %	0-90, <0.5 % signal
Light Scattering Infrared Sensor	**Range (Particle Size)**	**Repeatability at zero and 80% range (Uncertainty)**	**Limit of Detection**	**Short-term Drift, Long-term Drift**	**Temperature (°C) and Effect on Accuracy and Zero Offset (per °C)**	**Humidity (%RH) and Effect (per %RH)**
$PM_{2.5}$[10]	0-250 μg/m^3, 0.1-2.5 μm	±5 μg/m^3, ±10 % (±50 %)	5 μg/m^3	<0.5 %/24hr, <5 %/mo	-10 to 40, <0.5 %, 0.3 μg/m^3	0-75, <2 % if slow (<9 % if pulse)

[1]Inteference: other VRSC (OCS, C_2H_6S, $C_2H_6S_2$): <100%; Oxidant species negative interference (0_3, NO_2): ~30%
[2]Interference: Cl_2: around 80%; Reduced sulfur compounds: negative interference
[3]Interference: Cl_2: around 80%; Reduced sulfur compounds: negative interference; 0_3: possible interferences if high concentration
[4]Interference: SO_2: 20 ppm induces -7 ppm; H_2S: 20 ppm induces 7 ppm; NO: 20 ppm induces -1 ppm; NO_2: 20 ppm induces -20 ppm; Cl_2: 20 ppm induces -55 ppm
[5]Interference: NO_2, O_3: ~ -125%; H_2S: ~5%; CO, H_2: <1%
[6]Interference: H_2: ~3%; CO: ~14%; possible interferences from reducing gases (e.g. alcohols)
[7]Interference: H_2: <60%; long term high concentration levels (>CO) of H_2S, NO_X, SO_2 or acid gases may interfere
[8]Interferents: heavy compounds, silicone, NH_3, H_2S
[9]Isobutylene was the calibration gas
[10]Interferents: Wind >2 m/s; %RH pulses, high luminosity, vibrations, pressure variations, liquid aerosols, NO_2, etc.

Properties:
Communication: Wavenis, Xbee, GSM/GPRS (165)
Lifetime: 1 year without maintenance or calibration (164,182)
Ambient temperature range: -20 to 45 °C (164,182)
Ambient pressure range: 10-90 %RH (164,182)
Cost: (183)

- CairSens: ~$60~$1400 for all sensors except VOC
- CairTub: ~$90~$1200, depends on 1 or 3 sensor version
- CairNet: ~$1100~$2800, depends on 1 or 3 sensor version; ~$5400 for a full operational network of 10 CairNets monitoring O_3/NO_2, NO_2 and CO

Table 5. Cairpol Dimensions and Product Information (165,167,168)

Cairpol	Dimensions (mm)	Battery or Charger	Battery Autonomy	Optional Accessories
CairClip	—	100 V-240 V/ USB	24-36 hrs	—
CairTub	80 x 80 x 125	4.2 V[1, 3]	21 days	1500 mm telescopic foot (diameter 28 mm)
CairNet	80 x 80 x 125[2]	4.2 V[3]	10 days[4]	1500 mm telescopic foot (diameter 28 mm)

[1]Power supply rechargeable
[2]Solar panel dimensions are 210 mm x 150 mm x 18 mm
[3]Lithium polymer battery
[4]If solar panel refilled in one day, then 10 days without sunshine

Field Evaluations:

In a lab-based study, CairClip hydrogen disulfide (H_2S) sensor (n=5) performance at concentrations of 0-1000 ppbv was compared with gas chromatography coupled-flame photoionization detector (GC-FCD) measurements. The minimum signal detection of CairClips was 6 ± 2 ppbv with a high repeatability and reproducibility (a standard deviation of 1% at 50% of the range). At a wastewater treatment plant, field-testing of 3 CairClip sensors against a UV fluorescence spectroscopy total reduced sulfur analyzer (CTRS) showed high agreement. Results are summarized in Figure 2. Two CairClip sensors were highly correlated with each other (R^2=0.999), with sensitivities of 1.028 and 1.010, when exposed to H_2S generated by an olfactometer. The authors suggest that these findings may support the use of CairClips in industrial process management and as supplementary tools in odor pollution assessment. (184)

Thirty sulfuric gas CairNets equipped with H_2S and methyl-mercaptan sensors were used to record concentrations each minute in a wastewater treatment facility in southern France. (185) The CairClip sensors were crafted to include dynamic air uptake to sustain steady flow and increase sensitivity. (185)

Zoauak et al. (186) utilized four CairNet devices with the H_2S sensors in an Odorant Dispersion and Emissions Monitoring System at a compost plant in France. An Impact 3D model simulated air dispersion near the fermentation area where the CairNets were situated. Results suggest this network as having the potential to improve model predictions while exhibiting agreement with past assessments (e.g. peak exposures during opening hours).

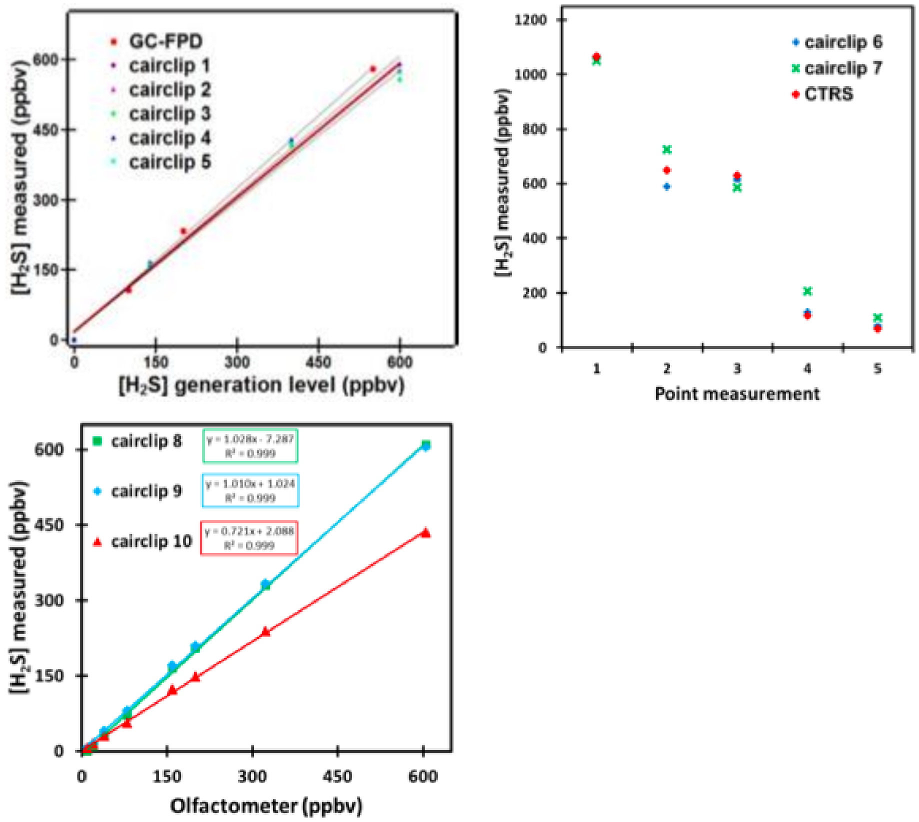

Figure 2. Graphs comparing CairClip measurements to GC-FCD lab findings (upper left), CTRS field results (upper right) and an olfactometer (bottom). Reprinted from (184).

3.2.4 AirBase CanarIT 1.0

The CanarIT 1.0 is a multi-parameter device. The basic unit (Table 6) is configured to measure O_3, NO_2, VOCs, dust, noise, temperature and humidity. Modifications are possible: the user can replace the O_3 sensor with ammonia, carbon monoxide, hydrogen, hydrogen sulfide, methane, perchloroethylene, sulfur dioxide or odor sensors (Table 7). (187)

AirBase algorithms enhance the commercial MOS gas sensors that operate in a plug and play mode to sample every 20 sec. (188,189) Benefits of the nano-technology in this device include reduced costs, power requirements, and size. (188) Additionally, inter-sensor repeatability, long-term stability, and stability to temperature and humidity fluctuations are enhanced. (188)

The CanarIT has an in-situ end unit (ie. the wireless air quality monitoring station) and a backend section (i.e. the cloud-based server). Field sensors periodically sample data to store this on the memory board. These measurements are transmitted to the Internet (using Wi-Fi/GSM networks) and to the cloud server for storage and analysis. The software presents the data in many formats including its raw form, the real-time concentrations, time period configurable data charts, and GIS compatible data. Data retrieval is accomplished through personal computers or mobile devices, while alerts can be sent via short message service (SMS) or e-mail. The backend server uses Microsoft SQL and Microsoft Azure cloud technology. (190)

CanarIT passes internal quality assurance and is calibrated upon purchase. Subsequent calibrations are performed remotely through the Internet. (187)

Table 6. AirBase CanarIT Specifications (187,190,191)

Semi-conductor Gas Sensors	Range (ppb)	Accuracy (ppb)	Resolution (Lower Detection Limit) (ppb)	Response Time (sec)	Temperature (°C)	Humidity (%RH)
NO_2[1]	10-2000	5	5 (10)	0.2	-40 to 85	5-95
O_3[2]	0-150 or 0-500	6.5	1 (1)	65	-5 to 40	5-95
VOCs[3]	Dynamic (ppm)	20	(5)	secs	-40 to 120	5-95
CO	0-10					
CH_4	0-200					
C_3H_8	0-20					
C_2H_6O	0-3					
C_2H_4O	0-20					
C_4H_8O	0-20					
C_7H_8	0-5					
Temperature and Humidity Sensors	Range	Accuracy/ Repeatability	Resolution	Response Time (sec)		
Temperature (°C)	-40 to 125	±0.30/ ±0.10	0.04	30		
Humidity (%RH)	0-100	±2 / ±0.1	0.7	30		
Other Sensors	Range	Accuracy	Sensitivity	Sensing Pulse Cycle	Temperature (°C)	Humidity (%RH)
TSP (dust)[4]	10-300 mg/m^3	±20 mg/m^3	0.1 mg/m^3	10 msec	-10 to 65	5-95
Noise[5]	65-130 dB	—	(-) 44 dB	—	-25 to 45	5-95

[1]NO_2 combusts in reactions with oxygen from the crystal lattice at the sensor interface thereby removing electrons causing a lower conductivity.
[2]Range fixed after order. Validation with reference instrument (Thermo Electron TEI 49C ozone analyzer with UV photometer with US EPA Designated Method EQOA-0880-047) showed low drift and readings falling within accuracy levels (<± 8 ppb for 0-0.1 ppm and <± 10 % for 0.1-0.5 ppm).
[3]VOCs (alcohols, aldehydes, amines, aliphatic/aromatic hydrocarbons and organic acids) combust in reactions with oxygen from the crystal lattice at the sensor interface thereby releasing electrons causing a higher conductivity. The sensor is heated to temperatures of ~ 300 °C.
[4]Minimum detection limit of 10 mg/m^3; optical sensing using an infrared emitting diode and a phototransistor to measure reflected light.
[5]Measures omnidirectional noise in the frequency range of 100-10,000 Hz with a signal to noise ratio of 55 dB.

Table 7. AirBase CanarIT Ozone Sensor Replacements (191)

Sensor	Range (ppm)	Maximum Exposure (ppm)	Minimum Detection Limit (ppm)	Accuracy of Calibration (ppm)	Response Time (sec)	Operational Temperature Range (°C)	Operational RH Range (%)
NH_3	0-100	200	0.5	<±5	<60	-20 to 40	5-95
CO, 0-100 ppm	0-100	200	0.2	<±2, 0-20 ppm; <±10 %, 20-100 ppm	<150	0 to 40	5-95
CO, 0-1000 ppm	0-1000	2000	1	<±10 %	<150	0 to 40	5-95
H_2	0-5000	20000	5	<±10 %,	<90	-20 to 40	5-95
H_2S	0-10	25	0.01	<±0.5	<60	-20 to 40	5-95
CH_4	0-10000	10000	—	<±15 %	<60	0-40	30-80
C_2Cl_4	0-200	250	1	<±5, 0-50 ppm; <±10 %, 50-200 ppm	<5	0-40	30-80
SO_2	0-10	20	0.2	<±0.5 ppm	<60	-20 to 40	5-95
Odor[1]	0-5000 OUE/m^3	2 OUE/m^3	1 OUE/m^3	—	—	-10 to 45	10-95

[1]Based on the European Odor Unit (OUE) concentration scale using the response to 40 ppb of n-butanol as defined in EN 137725.

Properties:

Communications: 2 options: Wi-Fi or GSM (Cellular), GPRS Class 10 (187)

Dimensions: 18 x 16 x 6.5 cm (190)

Weight: 2.5 kg (190)

Lifetime: 5 years (excluding sensors) (190)

Power: 12V DC (190)

Data transition: every 20 sec (190)

Universal time stamp: Unix time server (190)

Cost: \$1500-\$1800 (192)

Field Evaluation:

Dr. Ben Barratt at King's College London carried out an evaluation of two CanarIT units against reference methods for O_3, NO_2 and PM_{10} (for comparison with the total suspended particles (TSP) sensor) during December 2012 and January 2013 when they were co-located at Marylebone Road. Temperature and humidity assessments were run against non-reference instruments. Linear correlation functions from precision testing showed near perfect outcomes for temperature, humidity and O_3 with R^2 values of 0.99, 0.99 and 0.98, respectively. Inter-sensor correlation for NO_2 was good (R^2=0.92) while TSP had poorer results (R^2=0.57). (193)

R^2 values for the accuracy of temperature and humidity were 0.89 and 0.76 (with an offset of 18%), respectively. The accuracy of the O_3, NO_2, and TSP sensors had R^2

values of 0.81 (with an offset of 6.8%), 0.04, and 0.04, respectively. NO_2 accuracy was potentially compromised by interference, primarily from O_3. The TSP sensors seemed irresponsive to concentration changes and remained at 50 µg/m^3. See Figure 3 for time-series plots and scatter plots. The noise sensors may have been faulty as they responded uniformly at 89 ± 1 dB. (193)

The findings suggest precision levels are adequate with the exception of the TSP sensor. Accuracies for temperature, humidity and O_3 sensors were sufficient for many expected uses. In contrast, the noise, TSP and NO_2 sensors appeared to be inadequate for proper monitoring performance. Implementing post-processing computations to remove interfering gas signals can optimize NO_2 sensing ability. (Barratt B., Personal Communication, 2013 (193))

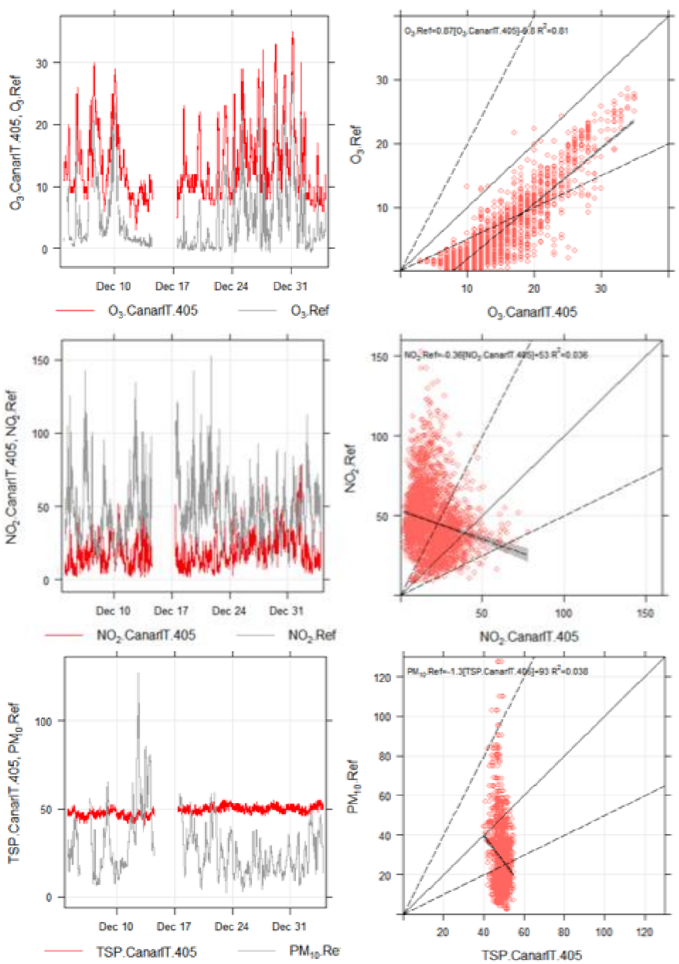

Figure 3. Time-series (left panel) and scatter plots (right panel) for O_3, NO_2, and TSP sensors versus reference instruments using a 15-minute resolution. The scatterplot shows the line of best fit (solid) and three reference lines (dashed) with 1:1, 2:1 and 1:2 relationships (Barratt B., Personal Communication, 2013 (193)).

3.2.5 Sensaris SensPods

Sensaris SensPods carry off-the-shelf sensors in their wireless units. SensPods can be used in conjunction with Android applications once the pod and a smartphone are paired. Alternatively, networks can be fashioned by connecting SensPods to a gateway for data access with the Web interface (Sensdots). These devices are low power, real-time communicators that may be integrated into existing systems. Four variations of the SensPods are available: ECOsense (for CO, NO_X, noise, temperature and humidity), ECO_2sense (for CO_2), EcO_3sense (for O_3, luminosity, temperature and humidity) and EcoPM (for particles exceeding 1 µm). These are reviewed in Tables 8 and 9. ECOsense and EcO_3sense are uncalibrated nodes that use correction curves. ECO_2sense is "pre-calibrated". No information is available on the calibration efforts for EcoPM. Data storage is either local (on an SD Card) or distant (sent to a server). (194)

Table 8. Sensaris SensPods Specifications (194–200)

Semi-conductor Gas Sensors	Range	Heater Power (mW)	Sensing Resistor Temperature (°C)		Sensitivity Factor	
CO[1]	1-1000 ppm	76 (reducing sensor) and 43 (oxidizing sensor)	—		1.2-50[2]	
NO_2[1]	0.05-10 ppm		—		2[3]	
O_3[4]	10-1000 ppb	80	430		1.5-4[5]	
Temperature and Humidity Sensors	**Range**	**Accuracy (Repeatability)**	**Response Time (sec)**	**Resolution**	**Drift**	
Temperature(°C)[6]	-40 to 123.8	±0.4 (±0.1)	5-30	0.04-0.01	<0.04 °C per year	
Humidity (%RH)[6]	0-100	±3.0 (±0.1)	8	0.4-0.05	<0.5 % per year	
Other Sensors	**Range**	**Accuracy (Repeatability)**	**Response Time (sec)**	**Temperature (°C)**	**Humidity (%RH)**	**Maximum Sensitivity**
CO_2[7]	0-5000 ppm	±30 ppm, ±5%	60	0 to 50	0 to 95	—
Noise	30-140 dB	—	—	—	—	—
Luminosity[8]	220-370 nm	—	—	—	-25 to 70	350 nm
PM[9]	≥1 µm (0-28,000 pcs/L)	—	—	0-45	≤95	—

[1]MiCS-4514 metaloxide semiconductor
[2]R_s of CO at 60 ppm ÷ R_s in air (manufacturer indicated "R_s in air divided by R_s at 60 ppm CO", but it was presumed to be an error); test conditions of 23 ± 5 °C and 50 ± 10% RH
[3]R_s of NO_2 at 0.25 ppm ÷ R_s in air; test conditions of 23 ± 5 °C and 50 ± 5 %RH (manufacturer indicated "<5 ± 5 %RH", but it was presumed to be an error)
[4]MiCS-2610 metaloxide semiconductor
[5]R_s of O_3 at 100 ppb ÷ R_s of O_3 at 50 ppb; test conditions of 25 ± 2 °C and 50 ± 5 %RH
[6]Sensirion SHT11
[7]ELT S-100 non-dispersive infrared (NDIR) sensor
[8]SG Lux AG38S broadband photodiode (UVA+UVB+UVC)
[9]Shinyei PPD42NS

Properties:

Communications: (194)

- Bluetooth Class 2 radio (range of 30 m in free air)
- Mediatek GPS chip (optional) with patch antennae

Processor: TI MSP430 (194)

Battery: 3.7 V rechargeable lithium ion battery (USB connection) (194)

Storage: 2 GB or 4 GB SD Card (194)

Cost: ~$500~$650 (201)

Table 9. Sensaris SensPods Dimensions and Weight (194)

SensPods	Dimensions of W x L x H (mm)	Weight (g)
ECOsense	50 x 80 x 20	66
ECO_2sense	50 x 80 x 35	92
ECO_3sense	50 x 80 x 20	66
EcoPM	75 x 97 x 46	133

3.2.6 Smart Citizen

Smart Citizen is an open-source platform designed by Fab Lab Barcelona for participatory sensing to collect ambient data using commercial sensors (see Table 10): MiCS-5525 for CO, MiCS-2710 for NO_2, MaxDetect RHT03 for temperature and humidity, Excelitas Tech VT935G for light intensity, and the Pro Signal ABM-705-RC for noise. The noise and light intensity sensors are analogue, so their range is infinite. Data visualization and community sharing can occur via the Smart Citizen webpage or through the RESTful application programing interface (API). Interactive mobile applications are available for both iOS and Android. The rechargeable battery can power the device for a few consecutive days. (202–204)

Table 10. Smart Citizen Specifications (204–207)

Semiconductor Gas Sensors	Range	Heater Power (mW)	Sensing Resistor Temperature (°C)	Sensitivity Factor
CO	1-1000 ppm	76	~340[1]	5-50[2]
NO_2	0.05-5 ppm	43	~220	6-100[3]
Other Sensors	**Range**	**Accuracy**	**Resolution**	**Repeatability**
Temperature(°C)	-40 to 80	±0.5	0.1	±0.2
Humidity (%RH)	0-100	±2 to ±5	0.1	±1

[1]At an ambient temperature of ~20 °C in air

[2]R_s of CO at 60 ppm ÷ R_s in air (manufacturer indicated “R_s in air divided by R_s at 60 ppm CO”, but it was presumed to be an error); test conditions of 23 ± 5 °C and 50 ± 10 % RH

[3]R_s of NO_2 at 0.25 ppm ÷ R_s in air; test conditions of 23 ± 5 °C and 50 ± 5% RH (manufacturer indicated “<5 ± 5 %RH”, but it was presumed to be an error)

Properties:
Communication: Wi-Fi (203)
Dimensions: 62.53 mm x 56.41 mm for the electronic board (203)
Microcontroller: 8 bit-ATEL Mega 32U4-AU (204)
Battery: 3.7V Rechargeable Battery (by USB) or Solar Panel Charger (204)
Storage: micro SD card (203)
Clock Speed: 16 MHz (203)
Cost: (203)

- $175 for the Pre-assembled Smart Citizen Kit: Hardware
- $40 for the Solar Panel
- $15 or $35 for the Laser-Cut or 3D-Printed Enclosure, respectively

3.2.7 Air Quality Egg

The Air Quality Egg is a do-it-yourself community-led sensing network that began in New York City and Amsterdam to monitor gases using the MiCS-2710 NO_2 sensor and the MiCS-5525 CO sensor, as well as temperature and humidity with the Aosong AM2303 sensor. Outdoor sensors are plugged into walls and use radio frequency (RF) transmission to wirelessly send data to an egg base station indoors. The base station is Ethernet connected and sends the real-time data to Xively (an open access data service and an API) for storage. In Xively, the user can view graphs, and generate tweets or SMS alerts. (208,209)

Web developers can exploit the aggregated data in the API to design web or mobile applications. The sensors are fitted without calibration efforts and their precision and sensitivity is described by the makers as "mediocre.” (210)

These sensors (manufacturer’s specifications in Table 11) report both a “raw” and a “calculated” measurement. The former is the change in resistance and the latter is an interpretation of resistance as concentration based on empirical relationships. Each sensor has its own nominal resistance; however, the shields do not incorporate the sensor’s own nominal resistance, but rather a “typical” value in the correction to the “calculated” value. The Air Quality Egg does not account for the relationship between sensor response and temperature and humidity. (211)

Table 11. Air Quality Egg Specifications (198,199,205,206,212,213)

Semiconductor Gas Sensors	Range	Heater Power (mW)	Sensing Resistor Temperature (°C)	Sensitivity Factor
CO	1-1000 ppm	76	~340[1]	5-50[2]
NO_2	0.05-5 ppm	43	~220	6-100[3]
O_3	10-1000 ppb	80	~430	1.5-4[4]
VOCs	1-1000 ppm[5]	76	~340	1.8-6.6[6]
Other Sensors	**Range**	**Accuracy**	**Resolution**	**Repeatability**
Temperature(°C)	-40 to ~125	±0.2	0.1	±0.2
Humidity (%RH)	0-100	±2 to ±5	0.1	±1
PM[7]	≥1 µm (0-28,000 pcs/L)	—	—	—

[1]At an ambient temperature of ~20 °C in air
[2]R_s of CO at 60 ppm ÷ R_s in air (manufacturer indicated "R_s in air divided by R_s at 60 ppm CO", but it was presumed to be an error); test conditions of 23 ± 5 °C and 50 ± 10 % RH
[3]R_s of NO_2 at 0.25 ppm ÷ R_s in air; test conditions of 23 ± 5 °C and 50 ± 5% RH (manufacturer indicated "<5 ± 5 %RH", but it was presumed to be an error)
[4]R_s of O_3 at 100 ppb ÷ R_s of O_3 at 50 ppb; test conditions of 25 ± 2 °C and 50 ± 5 %RH
[5]Range based on CO detection
[6]R_s of CO at 60 ppm ÷ R_s of CO at 200 ppm; test conditions of 23 ± 5 °C and 50 ± 10 %RH
[7]Operating temperature and humidity are 0 to ~45 °C and ≤ 95 %RH, respectively

Properties:
Communications: RF transmitter and wired Ethernet (208)
Cost:

- $185 for the Air Quality Egg (214)
- $95 for the Air Quality Sensor Shield (214)
- $58 for each of the add-on sensors: MiCS-2610/2611 O_3 sensor (214); MiCS-5521 VOCs sensor (215); or Shinyei PPD42NS particle counter for particles at least 1 µm in size (199,216)

3.2.8 Envirologger CO_2

Envirologger CO_2 is a wireless system for monitoring CO_2 that transmits data from up to 80 sensor nodes. The commercial COZIR optical infrared sensor measures CO_2. A transceiver is required for the Envirologger Internet gateway to allow data access by desktop, tablet or smartphone. Temperature and humidity sensor options are possible (see Table 12). Transmission distances can reach up to 20 miles, as long a line of sight is maintained between the antennas. (153,217,218)

Table 12. Envirologger CO_2 Specifications (219)

NDIR Gas Sensor	Range (ppm)	Accuracy	Non-linearity	Response Time	Temperature (°C)	Humidity (%RH)
CO_2	0-2000, 0-5000, or 0-10000 (1%)	±50 ppm, ±3% of reading	<1% of FS	3 sec to 2 min	0 to 50 or -25 to 55 (extended range)	0-95
Temperature and Humidity Sensors[1]	**Range**	**Accuracy**	**Resolution**		**Repeatability**	
Temperature (°C)	-25 to 55	±1 (0 to 55 °C); ±2 (full range)	0.08		±0.1	
Humidity (%RH)	0-95	±3 (20-55 °C); ±5 (full range)	0.08		±0.1	

[1]Sensirion SHT21 chip

Properties:
Communication: Broadband /ADSL (868 MHz or 433 MHz), cellular GPRS or 3G (217)
Power: Plug-in to 12V transformer, solar power or batteries (217)
Cost: (153)

- ~$830 for the Wireless Node (with COZIR sensor)
- ~$550 for the Wireless Transceiver
- ~$2800 or ~$3320 for Gateway, depending on uplink (Ethernet only, or Cellular or Ethernet, respectively)
- ~$440 or ~$660 Annual Gateway Fee, depending on SIM card/ data bundle exclusion or inclusion

3.3 Wearable or Smartphone Compatible Personal Sensors

With the proliferation of smartphones and the price drops in sensors, personalized air quality monitoring demands have risen. Smartphone compatible sensors are personalized monitors with the capacity to transmit data to smartphone users in real-time or for on-the-go applications. Some devices are already marketed (i.e. CitiSense, Sensorcon Sensordrone, AirCasting Air Monitor, Cairpol CairClip and Speck/GPSpeck) while others are in development (e.g. AirWaves Mask). A summary of all the next generation air monitors (from section 3.2 and 3.3) is provided in Table 17 of Appendix B.

3.3.1 CitiSense

A team of computer scientists at the University of California, San Diego, developed a portable smartphone compatible air pollution system named CitiSense. The goal of this system is to use participatory sensed data from users as they go about normal activities to engage them in monitoring their exposures. CitiSense also integrates this aggregated data and wirelessly shuttles the real-time maps back to individuals and public health regulators after analysis by central computers. (220,221)

CitiSense monitors the most frequent vehicular pollutants: CO, NO_2 and O_3 (and temperature, pressure and humidity) using Open Rich Services Architecture. The commercial sensors are Alphasense CO-AX, Alphasense NO_2-A1, Sensoric O3-3E-1, MS5534 (for temperature and pressure) and SHT11 (for temperature and humidity), respectively (Table 13). The sensor network uses Latent Variable Gaussian Regression (an artificial intelligence process) to retrieve high-quality data in uncontrolled environments. As sensor communications drain battery life, a remaining obstacle involves resolving this concern. To counter this problem, measurements may be uploaded periodically. Alternatively, it is possible to turn off the phone's GPS when stationary. Another challenge must be met: to ensure sensors stay calibrated in the field, and continue to detect ambient pollution. (220–225)

The wearable nodes can be fastened with Velcro straps to purses, backpacks and bicycle frames. Angling the sensors can achieve better airflow. To pair wirelessly to the smartphone, the microcontrollers must communicate with Bluetooth. The smartphone stores, analyzes and amasses this data with inputs from the mobile phone's built-in sensors and delivers this to a backend server. Sensor redundancy is avoided by using non-overlapping CitiSense sensors (i.e. gas and environmental sensors) and mobile phone sensors (e.g. GPS, timestamp and location sensors). An Android application permits the user to visualize exposures while daily readings are provided on a personalized webpage. Electrochemical gas sensors were selected over metal oxide semiconductors (MOSs) for reasons of minimizing energy consumption—as MOSs require a heating phase of many seconds with energy expenditures of roughly 75 mW. Electrochemical sensors also generate proportional currents to gas concentrations whereas resistances change nonlinearly for MOS sensors (and are subject to influence by temperature and humidity). (224,226)

Table 13. CitiSense Specifications (196,227–230)

Electrochemical Gas Sensors	Range (ppm)	Sensitivity Drift	Response Time (sec)	Resolution (ppm)	Temperature (°C)	Humidity (%RH)
CO[1]	0-2000	<6 %/yr	<30[2]	<0.5	-30 to 50	15-90
NO_2[3]	0-20	<10 %/yr	<50[4]	<0.02	-20 to 50	15-90
O_3[5]	0-1	<10 %/6mo[6]	<15 or <60[7]	<0.02	-20 to 40	15-90
Temperature and Humidity Sensors	**Range**	**Accuracy/ Repeatability**	**Response Time (sec)**	**Resolution**	**Drift**	
Temperature (°C)[8]	-40 to 123.8	±0.4 (±0.1)	5-30	0.04-0.01	<0.04 °C per year	
Humidity (%RH)[8]	0-100	±3.0 (±0.1)	8	0.4-0.05	<0.5 % per year	
Pressure (mbar)[9]	10-1100	±1.5	—	0.1	—	

[1]Cross sensitivity to H_2, NO_2, Cl_2, NO, SO_2, C_2H_4, NH_3
[2]From zero to 400 ppm CO
[3]Cross sensitivity to H_2S, Cl_2, NO, SO_2, CO, H_2, C_2H_4, NH_3, CO_2, O_3
[4]From zero to 10 ppm NO_2
[5]Cross sensitivity at 20 °C: Br_2/ I_2; Cl_2: 1 ppm induces 1.2 ppm; ClO_2: 1 ppm induces 1.5; N_2H_4: 3 ppm induces -3 ppm; H_2S: 20 ppm induces -1.6 ppm; NO_2: 10 ppm induces 6 ppm
[6]At 20 °C and 30-50 %RH
[7]At roughly 30 ccm/min (minimum gas flow: 5 L/hr)
[8]Sensirion SHT11
[9]MS5534 Sensor

Properties:

Communications: Bluetooth (WT12 module) (224)
Dimensions: 6.7 x 11 x 4 cm (224)
Firmware: 12226 Bytes Flash (9.3%) and 1541 Bytes RAM (9.4%) (224)
Node Lifetime/ Battery: 5.23 days of continuous sampling using 7200 mWh Li-ion battery (224)
Cost: Currently $1000 per unit (Equipment costs~$500) (220,222)

Field Evaluation:

Zappi et al. (224) conducted two field studies consisting of 16 participants carrying CitiSense for two to four weeks while commuting to and from work, although sensor accuracy and precision were not evaluated. Evaluations found that sampling every 5 seconds but reducing smartphone connections to once a day (to relay user data) compared to sampling and continuously forwarding data at 5-second intervals resulted in power savings of 20% (44.8 mW compared to 56.0 mW). Overall, users were eager to learn about personal air exposures. They even shared the data with social networks (e.g. Facebook, Twitter). Interviews concluded that the sensor board was easy to operate. Another conclusion indicated that users learned about temporal and spatial pollution changes and made proactive choices (e.g. closing windows facing freeways) to reduce exposures.

Nikzad et al. (226) piloted a month-long (n=16) commuter study requiring at least a 20 minute commute in both directions to and from campus. The phone screen displayed both current air quality and historical data. Hotspots were noticed near roads; however, car commuters tended to have lower exposures from cabin filter absorption.

Thirty users (UC San Diego commuters and Jacobs School of Engineering computer science department faculty, staff and students) carried the sensors for a four-week duration. Once again, sensor testers gained an understanding of the buildup of pollutants in hot spots (e.g. intersections) and temporal changes (e.g. rush hour). Behavioral modifications included cyclists biking one block away from heavily trafficked streets, or commuters avoiding tail pipe emissions. San Ysidro, San Diego County's air quality is being studied with CitiSense to try to acquire a grant from the National Institutes of Health to study measures of lessening exposures in asthmatic children. (220,221)

3.3.2 Sensorcon Sensordrone

The Sensordrone is a keychain or necklace attachable, programmable sensor computer for running several applications. Gas monitoring can be electrochemical (e.g. carbon monoxide, alcohol, hydrogen) or MOS-based for assessments of oxidizing gases (e.g. chlorine, ozone, nitrogen dioxide) and reducing gases (e.g. methane propane, alcohols). This limits the applications of Sensordrone to situations where the user knows what gas they expect to find (e.g. natural gas leak identification). Non-specific gas sensing may cause artifacts (i.e. seemingly high combined response, or signal cancellation from an oxidizing and reducing gas being present simultaneously). (231,232)

Sensors for temperature, humidity, pressure, non-contact temperature, proximate capacitance, color intensity, and illumination also included. The sensors are built in-house and their specifications are presented in Table 14. (233) Three types of operation are call-response mode (which requests the most recent data) streaming mode (giving continuous real-time data) and data logging mode (where data is stored in memory until ready for later download). (231,232)

Table 14. Specifications of Sensorcon Sensordrone (232)

Sensors	Range	Accuracy	Resolution	Response Time (sec)	Power (mW)
Precision Gases[1]	0-2000 ppm	±10% of reading	1 ppm	10-20 sec to 90% of 1st signal	Low power, sensor always on
Oxidizing Gases- NO_2[2,3]	0-5 ppm	—	50 ppb	30-90	~45
Reducing Gases- CO[2,4]	0-1000 ppm	—	5 ppm	30-60	~75
Temperature (°C)[5]	-20 to 60	±0.5 (±1°C at ends of range)	—	20-60 sec to 90% of signal	Low power, on often
Humidity (%RH)[6]	0-100	±2 (20-80 %RH); else ±4	—	10-180	Low power, on often
Pressure (kPa)[7]	30-110	±0.1 kPa	1.5 Pa/0.3 m	1	Low power, on often
Non-contact Temperature (°C)[8]	-20 to 60 (-40 to +125, higher error)	±1 to ±3	—	1-5	~1,
Capacitance (pF)	0-0.5, 0-1, 0-2 or 0-4	—	0.0005[9]	<1	~0.5
Light[10]	—	—	—	<1	~30

[1]Electrochemical sensor pre-calibrated for CO, but multiplying CO level by sensitivity factors can afford other gas concentrations (e.g. H_2 is 10-20% of CO).
[2]Metal oxide semiconductor sensors; the specifications are outlined for the gases (NO_2, CO) shown in the table.
[3]E.g. O_3, NO_2, Cl_2
[4]E.g. alcohols, natural gas, hydrocarbons, H_2, CO and VOCs
[5]Silicon bandgap sensor type
[6]Capacitive sensor type
[7]MEMS sensor type
[8]Infrared sensor type
[9]In lowest range, else 12bit of full scale
[10]Photodiode for red, green, blue and clear are wavelength dependent

Properties:

Communication: Bluetooth 2.1 and 4.0 for Android 2.2 (Froyo) and Bluetooth 4.0 for iOS (e.g. iPhone, iPad); Blackberry, Windows and Linux not supported yet (231,232)

Battery: Rechargeable Lithium polymer battery (231)

Battery Life: hours to weeks (231)

Weight: 8 oz. (234)

Cost: $199 (234)

3.3.3 AirCasting Air Monitor

The AirCasting Air Monitor (ACAM) was designed at the New York City College of Technology's Mechatronics Technology Center and is to be used with the AirCasting open source web platform for recording, mapping, annotating and sharing data with smartphones via the AirCasting app. The ACAM is a do-it-yourself buildable monitor with 2 gaseous sensors (Figaro TGS 2442 CO sensor and MiCS 2710 NO_2

sensor) that reports concentrations with a generic response indicator scale rather than in parts per million or parts per billion. Temperature and humidity sensors (TMP 36 and HIH-4030) are also included. Table 15 outlines the specifications of the commercial sensors. (235,236)

Data is uploaded from ACAM and other devices for heart rate (Zephyr BioHarness 3 and Zephyr HxM) onto AirCasting. With personal air exposures and physiological indicators paired together, studies such as the ones conducted by Brook et al. (237,238) and He et al. (239) are made much simpler. Additionally, self-assemble apparel, AirCasting Luminscence, can visualize sensor measurements with LED lights. Future updates to AirCasting will include laser particle counters (using Dylos DC1700 and Shinyei PPD42NS sensors). This device is being used as an educational tool to inspect air quality in Bronx and Manhattan. (235,236,240)

Table 15. AirCasting Air Monitor Specifications (206,241–243)

Semiconductor Gas Sensors	Range	Heater Power (mW)	Sensing Resistor Temperature (°C)	Sensitivity Factor
CO	30~1000 ppm	~14	—	0.13~0.31[1]
NO_2	0.05-5 ppm	43	~220	6-100[2]
Other Sensors	**Range**	**Accuracy**	**Response Time**	**Repeatability**
Temperature(°C)	-40 to 125	±0.2	—	—
Humidity (%RH)	0-100	±3.5	5 sec	±0.5

[1]R_s of CO at 300 ppm ÷ R_s of CO at 100 ppm; test conditions of 20 ± 2 °C and 65 ± 5 %RH
[2]R_s of NO_2 at 0.25 ppm ÷ R_s in air; test conditions of 23 ± 5 °C and 50 ± 5 %RH (manufacturer indicated "<5 ± 5 %RH", but it was presumed to be an error)

Properties:
Communication: Bluetooth (235)
Cost: ACAM components ~$180 (235); Casing: $90 (244)

3.3.4 Speck and GPSpeck

The Carnegie Mellon University CREATE Lab initially developed a prototype for a portable, pocket-sized, lightweight wearable airborne pollutant monitor called AirBot—for use in Citizen Science. Six prototypes have been assembled to date with a set market price of $99. The new prototypes were renamed Speck and GPSpeck. Speck contains off-the-shelf sensors for PM, temperature and humidity. Its display is a 320 x 240 full color thin-film-transistor liquid-crystal display (TFT LCD) touch screen. A USB port allows data transfer to the open-source Speck Gateway. GPSpeck enhances Speck with an added GPS and a larger battery. In November 2013, Speck and GPSpeck were projected to start pilot production of 150 and 50 units, respectively. (245–247)

3.3.5 AirWaves Mask

In China, during an international competition, Frog Design Shanghai envisaged the fusion of two concepts (an air pollution mask supplemented with particle sensors and a mobile apps alert systems) into one smart air pollution device. The AirWaves mask would observe, collect and visualize on smartphones, location-specific real-time air quality, within and outside the mask. Bluetooth technology permits data sharing among crowd sourced network users to alert the public of exceptionally hazardous areas all while filtering particles from inhaled air as a personal climate intervention. (248–250)

4.0 Sensor Performance and Characterization

Presently, there is a lack of testing to ensure adequate sensor performance prior to marketing such instruments. While manufacturers and sales representatives are able to provide detailed specification sheets, there is little guarantee that the specifications can actually be met in a real-world setting. (135) In comparison, existing reference stations housed in proper enclosures can be fairly exact when it comes to meeting monitor descriptions. (226) Data quality is a pertinent concern as poor or unknown quality may be worse than a lack of data and can lead to incorrect or inappropriate decisions. (41) A diagram of the range of applications compared to the necessary data quality is available in Figure 4. (35) The US EPA (35) recognizes that data from new monitors may not be on par with data generated by reference instruments; however, they expect that reliability will grow with time.

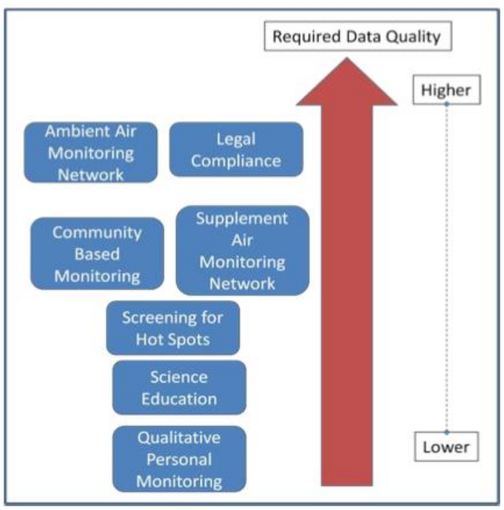

Figure 4. The Relationship Between Data Quality and Conceivable Applications Reprinted from (35).

In the meantime, next generation air monitoring should be classified into 5 tiers by cost of instrument and the anticipated user group. (35) Snyder et al. (41) argue that monitoring objectives may not demand that sensors meet robust monitoring benchmarks; rather, users need to acknowledge the uncertainty and performance specifications. By using sensors in larger arrangements, confidence in measurements may be improved; this is the concept of “do more – less well”. (35,41) Because of this, it is critical to match data quality requirements to sensor performance and network scope. Table 16 organizes the new technologies discussed above into the 5 tier classification scheme. The discussion below focuses on two phases of data quality assessment (laboratory and field evaluations). Afterwards, we examine calibration, data integration and processing.

Table 16. Next Generation Air Monitors Classified by US EPA Tiers, Cost Range and Anticipated Users (35)

Tiers	Cost Range	Anticipated User	Air Monitors[1]
V (most sophisticated)	10 to 50 K	Regulators[2]	—
IV	5 to 10 K	Regulators[2]	Geotech AQMesh
III	2 to 5 K	Community Groups and Regulators[2]	Libelium Waspmote Plug & Sense
II	$100 to 2 K	Community Groups	AirBase CanarIT Cairpol CairTub and CairNet Envirologger CO_2 CitiSense Sensaris SensPods Sensorcon Sensordrone Air Quality Egg Smart Citizen AirCasting Air Monitor
I (more limited)	<$100	Citizens[3]	Speck and GPSpeck

[1]In organizing the next generation air monitors into tiers, the cost took precedence over the anticipated user group for consistency in classification.
[2]Supplement exiting monitoring: ambient and source
[3]Educational and personal health purposes

4.1 Laboratory Evaluations

Controlled laboratory testing of sensors is a necessary step; so, standardized protocols should be developed to evaluate next generation air monitors. According to the EPA, most sensors have not undergone validation and few developers have air quality expertise; therefore, they advocate the creation of tables to help developers and users understand pollutants (e.g. sources, health effects, ambient ranges, acceptable detection limits), performance objectives (e.g. accuracy, precision, detection limit), the frequency of monitoring specific pollutants, and how appropriate mobile or stationary monitoring may be with the application on hand. (35)

Parameters that should be evaluated include accuracy, which measures how exact values are (in comparison to reference instruments or known concentrations) and precision (assessing inter-sensor correlations in high density networks). The closeness of agreement between successive measurements at same conditions (repeatability) and at different conditions (reproducibility) should also be determined. (133) Selectivity, sensitivity and interference all describe the ability of a sensor to discriminate a constituent within a mixture.

Certainly, for a sensor to be valuable, the detection limit and range needs to encompass the concentrations found in ambient air. (135) Response and recovery times are particularly important during mobile campaigns because the measurements need to keep pace with the travelling monitor. Drift (the change in a zero or span calibration with time) and operating temperature and humidity conditions are also important for proper sensor function. (133) Controlled exposure facilities may provide an environment for sensor designers to test parameters like the ones listed above. (35)

Examples of some in-house, bench experiments that can be performed include bump tests, step tests and stability tests. In a bump test, the sensors are dosed with a gas concentration for a nominal time interval, followed by a no exposure period. This is then repeated. From this iterative testing protocol, sensor response, response rate and hysteresis (or the dependence of system on recent history) can be checked. Step tests are performed by successively increasing gas concentrations in phases (with or without intermediate zero air exposures). By this test, response time, and saturation can be determined. Alternating gases between step tests without air exposures verifies cross-sensitivities that may exist. Stability or drift tests are accomplished by letting the system respond to a stable gas concentration over a prolonged time. (135)

Other criteria to assess prior to enrolling sensors into the real-world testing phase should filter based on size, power, communications and data storage, cost, and availability. Systems should be of portable size for deployment on persons and ought to be suitable for setup in areas that are not enclosed with heating or cooling requirements. Having a battery powered option lasting several hours is preferable. These sensors need to provide real-time data communication or store data locally for subsequent export. Regarding cost, for feasible application in spatial arrays (i.e. near-road), a cost of a few hundred dollars per unit is preferred. Finally, sensing systems need to be commercially available or be adaptable for monitoring purposes. (135)

4.2 Field Evaluations

Once performance is deemed appropriate in controlled environments, a second stage of assessment should involve real world testing, as laboratory tests and performance cannot emulate field conditions entirely. (101) With small, focused field studies, operational issues that may arise during deployments may be evaluated beforehand. (135) Hence, it is advised that sensors be appraised next to reference monitors in a range of unknown environments to safeguard its performance.

Apart from the usual set of sensor parameters mentioned (to be tested in the lab), key elements for field investigations include linearity, environmental sensitivity and short-term responsiveness. Linearity between sensor pairs is typically appraised using ordinary least-squares regression models and coefficients of determination (for precision) and root mean squared error (for accuracy). (251) Real-world studies are scarcer than laboratory tests and sensors often show less convincing results in ambient conditions because of extraneous factors (e.g. meteorological conditions, real emission sources) that can influence performance. (101) In a paper by Holstius et al. (251), instrument sensitivity to three external factors—temperature, humidity and ambient light— were explored in their field testing strategy. The examiners also mentioned the logistic challenges of setting up observational calibration since it requires access to a monitoring site for an extended time period in close proximity to the co-located sensor. Short-term responsiveness of sensors should be measured in the real-world as sensor deviations from expected readings are possible (Figure 5). This parameter may be expressed as a number of deviations greater than or less than a percentage range (around the real concentration, as measured by the standard method).

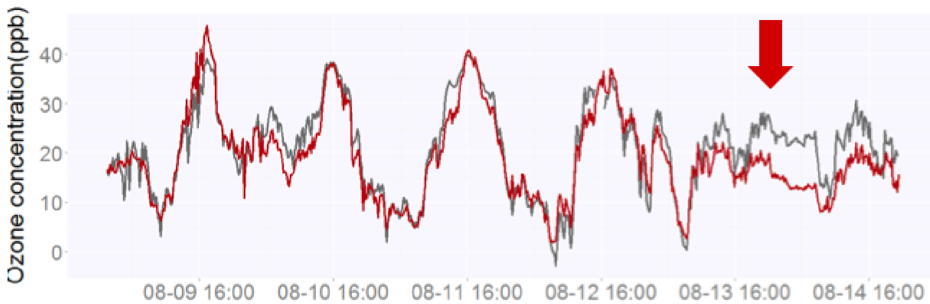

Figure 5. Co-location results from field test for an ozone sensor (grey) against an ozone monitor (red). The red arrow indicates one instance of sensor deviation from the reference. Reprinted from (252).

Other considerations that call for attention are data analysis and interpretation given the sensor platforms' variable responses to environmental conditions (e.g. temperature and relative humidity). Data privacy should also be an area of concern since confidential data must be secured (e.g. password protected access). With respect to user privacy, citizen science initiatives should be addressed since reverse engineering of data has the potential to expose private information (e.g. location). (253) To deploy sensors, usability is also a major concern. Here, issues such as the ease of installation, operation, data management, having a user-friendly interface and sufficient quality wireless communication need to be factored into the examination of sensors

4.3 Calibration, Data Integration and Processing

Quality control and quality assurance of data integration and processing begins with calibration. Calibrations are important to alleviate sensor aging effects, humidity effects and interference effects. Low-cost sensors are often purchased as uncalibrated or factory calibrated units not intended for low concentration (or ambient) measurements. Normally, manufacturer calibrations rely on 2-3 gas concentration measurements at one temperature and humidity; thus, users should re-calibrate devices to suit their needs. (254)

To tackle the problem of sensor calibration, one remedy is to use two nearby sensors. If two sensors are exposed in similar environments at similar times and experience similar gas concentrations, the sensors can improve one another's calibration quality. To do this, temporal and spatial filtering preserves relevant calibration tuples for input into calibration algorithms to compute calibration parameters. Hasenfratz et al. (254) proposed two novel on-the-fly calibration algorithms besides the traditional forward calibration based on measurements of a perfect sensor (a single-hop calibration). "Forward calibration" is completed with recent sensor readings to estimate new calibration parameters, "backward calibration" re-evaluates the latest calibrated sensor readings offline (causing a delay) to estimate calibration parameters, and "instant calibration" gains similar accuracies to backward calibration without delay by continually adjusting calibration parameters based on new calibration tuples and earlier calibration tuples stored in calibration memory. Instant calibration can reduce measurement error by a factor of 2 compared to forward calibrations. (254)

Multi-hop calibrations are used to calibrate sensors that are rarely or never near perfect; instead, they depend on unreliable sensor readings. Essentially, a concentration is computed by weighting measurements of unreliable sensors by the calibration age (i.e. time elapsed since most recent calibration and the quality of the reference used in that calibration). In short, accuracy can be maintained so long as the total number of calibration hops is limited. (254)

Three potential methods for data integration and processing are possible and will be outlined here. The first method is data fusion; it is implemented by sensor node cross-communication when tuning sensors within networks. (255) By aggregating sensed data from multiple nodes, the decision quality at the base station is improved. (255) Data fusion can be parallel, where all nodes send raw data to the base station directly, or serial, where routing is used, or hybrid. (255) Sensor fusion is complementary (sensors are independent but data is pooled to give a holistic perspective), cooperative (using independent sensors to get data that would not be acquired by a single node) or competitive (redundant measurements made with independent sensors). (255) Tan et al. (256) have suggested a two-tiered architectural framework where the first tier is a local calibration and the second tier is a system-level calibration.

The second method uses a "sensor array detection" whereby sensor replicates are incorporated into a single monitor. The underlying premise is that using redundant and multidimensional sensors for each pollutant of interest can increase sensitivity (by correcting for drift) all while detecting multiple pollutants and mixtures. From calibrations and near-road inter-comparison of instruments, Mykhaylova et al. (252) noted increasing correlation in ozone measurements (at ambient conditions) with increasing numbers of ozone sensor replicates (especially when 2 types of ozone sensors were used). When temperature and humidity sensors were added to further correct ozone measurements, the associations strengthened still. (252)

A third method relies heavily on server-based post-processing. This means there is a black box of algorithms that is run on the inputs prior to presenting the outputs to the user. One such instrument that does this is the Geotech AQMesh. When a cloud network processes data, two advantages are seen. First, the system may conserve power, as the processor requires less power. Secondly, sensor specific parameters are assimilated in the calculations during cloud computing to correct for gas responses. In the case of AQMesh, field measurements from each individual sensor undergoes correction factors specific to that sensor as documented at the time of production. These inherent corrections maintain accuracy and include temperature sensitivities and calibration coefficients. Another integral correction factor depends on the cross-sensitivities of gas sensors; this means the algorithm may be using the response of one gas to smooth the response of another gas. As alluded to earlier, AQMesh sensors contain a fourth electrode to stabilize measurements and prevent drift. This is also likely to be a part of the black box. (151)

5.0 Recommendations and Conclusions

From our assessment of new sensor technologies, it is clear that these innovations may be pertinent for a vast number of applications ranging from supplemental networks to enhance information on spatial patterns to personal sensors for citizen science and continuous feedback regarding exposures. Proper inclusion of these sensors in research can resolve complex problems such as intra-urban pollution patterns and their relationship to health effects. With these technologies, there is also promise of improved monitoring of fugitive emissions from industrial sites. Public education can be enhanced from these initiatives as a mechanism to promote understanding of local air quality.

A primary concern with new sensors and sensor arrays is data quality and control, as most have not undergone methodical evaluations. It is essential that standard guidelines or protocols be devised for sensor evaluations to align sensor performance with their intended applications. These documents ought to specify acceptable and practical methods for laboratory and field calibrations. Additionally, procedures for examining interference, drift, and environmental performance need to be outlined.

As next generation air monitoring expands, a working group should be launched to track new technologies as they become available. Guidance is even more important for consumers of citizen science products. Because these sensors are more affordable, the distribution can be widespread among the general public. A verification process could be implemented for these sensors before consumers gain access. By initial evaluation of sensors, consumers might be better prepared to operate and sample with these devices. Users of the instruments need to be informed about the capabilities of each sensor design, and how to interpret the output data appropriately.

Finally, a recommendation is made to regulatory agencies to sponsor workshops and facilitate meetings for the multi-disciplinary sensor development community—including manufacturers, do-it-yourself developers, government, and the public and private sectors. For the growing open community of users and developers, discussions and collaborations can be mediated through websites (e.g. CitizenAir.net). In sum, it is critical to understand the scope of use for each new sensor and outline effective guidelines for their use to make the most of these new technologies.

6.0 Appendix

6.1 Appendix A. Principles of Operation for Gas Sensors

Electrochemical Sensors

Electrochemical gas sensors determine the concentration of a target gas by measuring the electrical signal in an electrochemical cell. Electrochemical cells house two electrodes (the anode and cathode) each contacting an electrolyte. Reduction-oxidation (redox) reactions guide electron transfer between electrodes via the wire connection. Oxidation and reduction reactions occur at the anode and cathode, respectively. Electrons are lost at the anode and transferred to the cathode so the latter gains electrons. Electric potential energy drives the directionality of the redox half-reactions. The reaction with the higher potential will proceed in the forward direction (i.e. reduction) while the reaction with the lower potential proceeds in reverse (i.e. oxidation).

In practice, a gas must first pass a small capillary-like opening before diffusing across a gas permeable membrane (or hydrophobic barrier) with a specific pore size to reaching a sensing electrode. The barrier has a twofold function: to allow a suitable amount of gas to pass through and to counteract electrolyte leaks. At the contact surface, the analyte reacts by oxidation or reduction with the sensing electrode (designed for the gas of interest). The resister joining this electrode with the counter electrode has a measurable current proportional to the gas concentration flow between the electrodes. As current generation follows, this sensor is called amperometric. The reference electrode is maintained at a constant potential to fix the voltage of the nearby sensing electrode. Figure 6 provides a visual for that described above. (133)

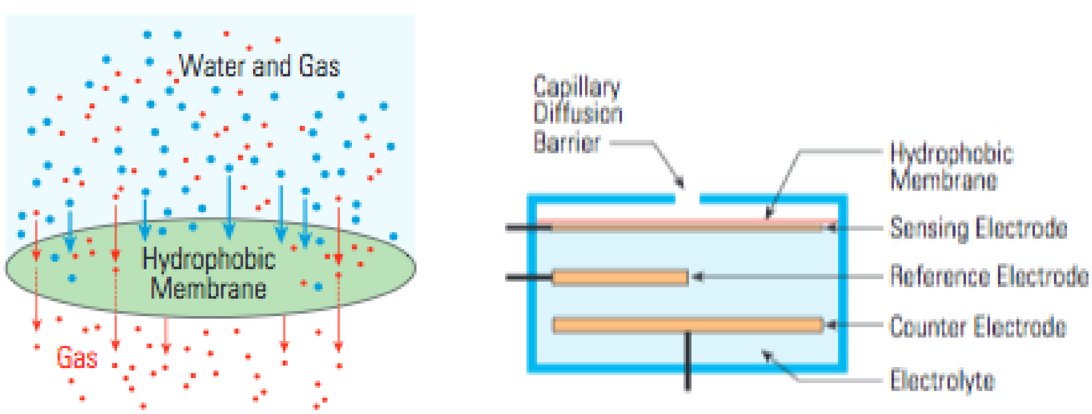

Figure 6. Hydrophobic Membrane and Electrochemical Sensor Schematic. Reprinted from (133).

Infrared Sensors

IR sensors use the IR region of the electromagnetic spectrum to detect gases, as energy absorption in this range is both selective and unique. Gas molecules have unique fingerprints or absorption peaks in the 2-15 µm range such that molecules with more atoms have more absorption bands. Interatomic bond vibrations, specific for a molecule and structure, occur at the gas' natural frequency. Smaller gas molecules have fewer natural frequency modes. (139)

Components of an IR system include: an IR source; an optical filter; a gas cell and a detector (Figure 7). The IR source is typically a heated wire filament or an electronically produced source. Positioning of optical filters, either before the light source of in front of the detector, is detector dependent. Filters may be made dispersive with prisms or grating or nondispersive with bandpass filter. In nondispersive infrared (NDIR) sensors, the bandpass filter is responsible for target gas selectivity. The gas cell has an inlet and an outlet for light passage; the light path length is directly related to the radiation absorbed. Finally, the detector converts received electromagnetic energy or temperature displacements into electrical signals. (139)

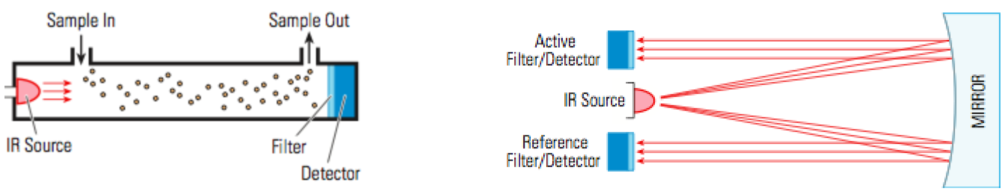

Figure 7. A Basic Infrared Gas Detector and A Two-Detector Layout. Reprinted from (139).

Two detection methods are possible stemming from the same premise: energy from the radiation matching the gas' natural frequency is absorbed whereas the rest is transmitted. When gases absorb radiation, the molecules vibrate more vigorously causing proportional temperature increases that are detectable. Conversely, the wavelength at which the gases absorbed radiation will show diminishing radiation energy that is measurable. (139)

Metal oxide Semiconductor Sensors

MOS sensors detect gases by redox reactions taking place between the gas and the oxide surface (Figure 8). (136) Metal oxides are the sensing layers in semiconductor sensors and are deposited by thick- or thin-film methods. (257) Tin oxide is frequently selected as the metal oxide because it is reactive with various gases and has large deflections in resistance. (101) As gases adsorb and desorb, the resistance of the metal oxides are altered. (194) Ideally, these reactions are reversible. (257) Environmental oxygen and water vapor-related species could be adsorbed at the surface of the sensing layer at ambient conditions. (258) Reducing gases (e.g. CO, H_2) react with these species to decrease the resistance. (258) In contrast, oxidizing gases (e.g. NO2 and O3) react with these species to increase resistance. (258) At large, the relationship between a sensor's resistance and target gas concentration obeys a power law. (258)

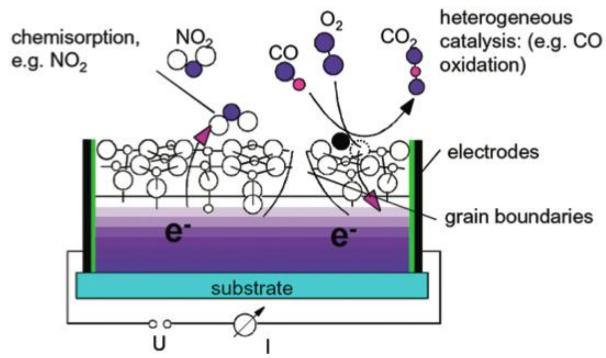

Figure 8. A Schematic for Metal Oxide Semiconductor Sensors. Reprinted from (258).

6.2 Appendix B. Summary Table of Next Generation Air Monitors

Table 17. Summary of Next Generation Air Monitors for Air Pollutants

Sensor	Pollutants	Range	Resolution	Limit of Detection	Accuracy	Precision	Field Testing	Cost	Communication
Geotech AQMesh (153–155)	NO	0-20000 ppb	—	<3 ppb	±5 ppb	—	Yes	3 gases (NO, NO_2, O_3): $5500-$7200; 4 gases: $6300-$8100; 5 gases: $7100-$9000	GPRS, multi-band worldwide operation
	NO_2	0-200 ppb	—	<5 ppb	±5 ppb	—			
	O_3	0-200 ppb	—	<5 ppb	±5 ppb	—			
	CO	0-50000 ppb	—	<5 ppb	±10 ppb	—			
	SO_2	0-100000 ppb	—	<5 ppb	±10 ppb	—			
Libelium Waspmote Plug & Sense (156,158,159, 163)	Air Pollutants I[1]	1~30 ppm	—	—	±4 ppm	—	No	Communication: ~$550~$920; Power: ~$50~$110 Individual Sensors: ~$20~$750; Meshlium Internet Gateway: ~$1040~$2000	7 radio modules: XBee-802.15.4-Pro; XBee-ZigBee-Pro; XBee-868 MHz; XBee-900 MHz; Wi-Fi; GPRS; 3G/GPRS)
	Air Pollutants II[2]	1~100 ppm	—	—	±4 ppm	—			
	Alcohol Derivatives[3]	50~5000 ppm	—	—	±10 ppm	—			
	CH_4	500~10000 ppm	—	—	±100 ppm	—			
	O_2	0-30 %	—	—	±1 %	—			
	CO	30~1000 ppm	—	—	±4 ppm	—			
	NH_3	10~100 ppm	—	—	±3 ppm	—			
	Liquefied Petroleum Gases[4]	500~10000 ppm	—	—	±200 ppm	—			
Cairpol CairSens (165,170–181,183)[5]	H_2S-CH_4S	0-1000 ppb	—	10 ppb	<30 %	±5 ppb, ±10 %	Yes	CairSens Sensors: ~$60~$1400 (except VOC); CairTub: ~$90~$1200, depends on 1 or 3 sensor version;	Radio communication: Wavenis, Xbee, GSM/GPRS
		0-2000 ppb	—	20 ppb	<30 %	±10 ppb, ±15 %			
		0-20 ppm	—	30 ppb	<30 %	±10 ppb, ±15 %			
		0-200 ppm	—	200 ppb	<30 %	±200 ppb, ±15 %			
	O_3-NO_2	0-250 ppb	—	20 ppb	<30 %	±7 ppb, ±15 %			
	NO_2	0-250 ppb	—	20 ppb	<30 %	±7 ppb, ±15 %			
	NH_3	0-25 ppm	—	0.5 ppm	<30 %	±0.2 ppm, ±15 %			
	SO_2	0-1000 ppb	—	50 ppb	<25 %	±10 ppb, ±15 %			
	CH_2O	0-1000 ppb	—	10 ppb	<30 %	±5 ppb, ±20 %			

	CO	0-20 ppm	—	0.05 ppm	<25 %	±0.05 ppm, ±15 %		CairNet: ~$1100~$2800, depends on 1 or 3 sensor version; ~$5400 for a full operational network of 10 CairNets monitoring O_3/NO_2, NO_2 and CO	
	VOC	0-16 ppm	—	10 ppb	<30 %	±10 ppb, ±15 %			
	$PM_{2.5}$	0-250 µg/m^3 (0.1-2.5 µm PM)	—	5 µg/m^3	±50 %	±5 µg/m^3, ±10 %			
AirBase CanarIT (187,190–192)	NO_2	10-2000 ppb	5 ppb	10 ppb	5 ppb	—	Yes	$1500-$1800	Wi-Fi or GSM (Cellular), GPRS Class 10
	O_3	0-150 or 0-500 ppb	1 ppb	1 ppb	6.5 ppb	—			
	VOCs CO CH_4 C_3H_8 C_2H_6O C_2H_4O C_4H_8O C_7H_8	Dynamic range, ppm 0-10 0-200 0-20 0-3 0-20 0-20 0-5	—	5 ppb	20 ppb	—			
	TSP (dust)	10-300 mg/ m^3	—	10 mg/m^3	±20 mg/m^3	—			
	NH_3[6]	0-100 ppm	—	0.5 ppm	<±5 ppm	—			
	CO, 0-100 ppm[6]	0-100 ppm	—	0.2 ppm	<±2 ppm, 0-20 ppm; <±10 %, 20-100 ppm	—			
	CO, 0-1000 ppm[6]	0-1000 ppm	—	1 ppm	<±10 %	—			
	H_2[6]	0-5000 ppm	—	5 ppm	<±10 %	—			
	H_2S[6]	0-10 ppm	—	0.01 ppm	<±0.5	—			

					ppm				
	CH_4[6]	0-10000 ppm	—	—	<±15 %	—			
	C_2Cl_4[6]	0-200 ppm	—	1 ppm	<±5 ppm, 0-50 ppm; <±10 %, 50-200 ppm	—			
	SO_2[6]	0-10 ppm	—	0.2 ppm	<±0.5 ppm	—			
	Odor[6]	0-5000 OUE/m^3	1 OUE/m^3	—	—	—			
Sensaris SensPods (194,195,197–199,201)	CO	1-1000 ppm	—	—	—	—	No	~$500~$650	Bluetooth Class 2 Radio or GPS chip
	NO_2	0.05-10 ppm	—	—	—	—			
	O_3	10-1000 ppb	—	—	—	—			
	CO_2	0-5000 ppm	—	—	±30 ppm	±5 %[7]			
	PM ≥1 µm	0-28,000 pcs/L	—	—	—	—			
Smart Citizen (203–206)	CO	1-1000 ppm	—	—	—	—	No	Kit: $175; Solar Panel: $40; Enclosure: $15 or $35	Wi-Fi
	NO_2	0.05-5 ppm	—	—	—	—			
Air Quality Egg (198,199,205, 206,208,213–216)	CO	1-1000 ppm	—	—	—	—	No	Air Quality Egg: $185; Sensor Shield: $95; O_3, VOC and PM Add-on sensors: $58 per	RF, wired Ethernet
	NO_2	0.05-5 ppm	—	—	—	—			
	O_3	10-1000 ppb	—	—	—	—			
	VOCs[8]	1-1000 ppm	—	—	—	—			
	PM ≥1 µm	0-28,000 pcs/L	—	—	—	—			
Envirologger CO_2 (153,217,219)	CO_2	0-2000 ppm, 0-5000 ppm, or 0-10000 ppm (1%)	—	—	±50 ppm, ±3 % of reading	—	No	Node: ~$830; Wireless Transceiver: ~$550; Gateway: ~$2800 or ~3320; Annual Gateway Fee: ~$440 or ~660	Broadband/ADSL (868 MHz or 433 MHz), cellular GPRS or 3G
CitiSense	CO	0-2000 ppm	<0.5 ppm	—	—	—	Yes	$1000	Bluetooth

(220,222,224, 227–230)	NO_2	0-20 ppm	<0.02 ppm	—	—	—		(Equipment ~$500)	(WT12 module)
	O_3	0-1 ppm	<0.02 ppm	—	—	—			
Sensorcon Sensordrone (231,232,234)	Precision Gases	0-2000 ppm	1 ppm	—	±10 % of reading	—	No	$199	Bluetooth 2.1 and 4.0 for Android 2.2 (Froyo); Bluetooth 4.0 for iOS
	Oxidizing Gases-NO_2[9]	0-5 ppm	50 ppb	—	—	—			
	Reducing Gases-CO[10]	0-1000 ppm	5 ppm	—	—	—			
AirCasting Air Monitor (206,235,241, 244)	CO	30~1000 ppm	—	—	—	—	No	ACAM parts: ~$180; Casing: $90	Bluetooth
	NO_2	0.05-5 ppm	—	—	—	—			
Speck / GPSpeck (245–247)	PM	—	—	—	—	—	No	$99	USB

[1]Includes H_2, CO, CH_4, C_4H_{10}, CH_3CH_2OH; air pollutants I and other gases (CO_2, NO_2, VOC, O_3 and NH_3) not calibrated because the internal sensor operations do not allow set reference points.
[2]Includes $C_6H_5CH_3$, H_2S, CH_3CH_2OH, NH_3, H_2
[3]Includes H_2, CO, CH_4, C_4H_{10}, CH_3CH_2OH
[4]Includes H_2, CH_4, Ethanol, Isobutene
[5]Repeatability at zero and 80 % of the range were reported in the precision column; uncertainty was reported in the accuracy column; all sensors experience some interference
[6]These sensors can replace the O_3 sensor
[7]Repeatability was reported in the precision column
[8]Range based on CO detection
[9]Specifications are for NO_2; other examples include O_3 and Cl_2
[10]Specifications are for CO; other examples include alcohols, natural gas, hydrocarbons, H_2 and V

7.0 Glossary

ACAM	AirCasting Air Monitor
API	Application programming interface
AQHI	Air Quality Health Index
CAPMoN	Canadian Air and Precipitation Monitoring Network
CO	Carbon monoxide
CO_2	Carbon dioxide
BC	Black carbon
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
DSL	Digital subscriber line
EPA	Environmental Protection Agency
GIS	Geographic information system
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global System for Mobile communications
HAP	Hazardous air pollutants
H_2S	Hydrogen disulfide
IR	Infrared
LUR	Land-use regression
MOS	Metal oxide semiconductor
NAPS	National Air Pollution Surveillance
NO_x	Nitrogen oxides (i.e. nitrogen monoxide, NO and nitrogen dioxide, NO_2)
O_3	Ozone
PAH	Polycyclic aromatic hydrocarbon
PC	Personal computer
PCB	Polychlorinated bisphenyl
PM	Particulate matter
$PM_{2.5}$	Particulate matter < 2.5 µm
PM_{10}	Particulate matter < 10 µm
RF	Radio frequency
RWC	Residential Wood Combustion
SMS	Short message service
SO_x	Sulfur oxides (e.g. sulfur monoxide, SO and sulfur dioxide, SO_2)
TRAP	Traffic-related air pollution
TSP	Total suspended particles (“dust”)
UFP	Ultrafine particles
USB	Universal Serial Bus
VOC	Volatile organic compound
WSN	Wireless sensor network

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