Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: how far have they gone?

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Abstract

Over the past decade, a range of sensor technologies became available on the market, enabling a revolutionary shift in air pollution monitoring and assessment. With their cost of up to three orders of magnitude lower than standard/reference instruments, many avenues for applications have opened up. In particular, broader participation in air quality discussion and utilisation of information on air pollution by communities has become possible. However, many questions have been also asked about the actual benefits of these technologies. To address this issue, we conducted a comprehensive literature search including both the scientific and grey literature. We focused upon two questions: (1) *Are these technologies fit for the various purposes envisaged*? and (2) *How far have these technologies and their applications progressed to provide answers and solutions*? Regarding the former, we concluded that there is no clear answer to the question, due to a lack of: sensor/monitor manufacturers' quantitative specifications of performance, consensus regarding recommended end-use and associated minimal performance targets of these technologies, and the ability of the prospective users to formulate the requirements for their applications, or conditions of the intended use. Numerous studies have assessed and reported sensor/monitor performance under a range of specific conditions, and in many cases the performance was concluded to be satisfactory, e.g. (Castell et al. 2017, Han et al. 2017, Sousan et al. 2017). The specific use cases for sensors/monitors included outdoor in a stationary mode, outdoor in a mobile mode, indoor environments and personal monitoring. Under certain conditions of application, project goals, and monitoring environments, some *sensors/monitors were fit for a specific purpose*. Based on analysis of 17 large projects, which reached applied outcome stage, and typically conducted by consortia of organizations, we observed that a sizable fraction of them (~ 30%) were commercial and/or crowd-funded. This fact by itself signals a paradigm change in air quality monitoring, which previously had been primarily implemented by government organizations. An additional paradigm-shift indicator is the growing use of machine learning or other advanced data processing approaches to improve sensor/monitor agreement with reference monitors. There is still some way to go in enhancing application of the technologies for source apportionment, which is of particular necessity and urgency in developing countries. Also, there has been somewhat less progress in wide-scale monitoring of personal exposures. However, it can be argued that with a significant future expansion of monitoring networks, including indoor environments, there may be less need for wearable or portable sensors/monitors to assess personal exposure. Traditional personal monitoring would still be valuable where spatial variability of pollutants of interest is at a finer resolution than the monitoring network can resolve.

Keywords: low cost sensor/monitor; air pollution sensing; sensor data utilization; air sensor/monitor performance; personal exposure monitoring.

1. Introduction

Low-cost air pollutant sensors/monitors are technologies which promise a revolutionary advance in air quality monitoring, through massive increases in spatial and temporal data resolution, thus providing answers to scientific questions and applications for end users. It is therefore not surprising that most of the research groups with interest in air quality, and government organizations with responsibility for it, focus to develop their own programs to assess and utilize low-cost sensors/monitors. Some report disappointing outcomes, others varying degrees of success. Scientific papers on the topic are multiplying, as are grey literature and web-based sources. The complexity and multi-dimensionality of the topic make it difficult to comprehensively track all projects being undertaken.

The paradigm shift of air pollution monitoring from being based on standardized government-operated networks, consisting of reference instruments, to mixed networks involving both reference-grade monitors as well as emerging sensor/monitor technologies was recognised several years ago by the U.S. EPA (Snyder et al. 2013, White et al. 2012). The emergence of low-cost air monitoring technologies was also recognised in Europe and was recommended to be included in the next Air Quality Directive (Borrego et al. 2015). In its Draft Roadmap for Next Generation Air Monitoring, the U.S. EPA proposed a five-Tier system for general consideration that includes low-cost technologies (USEPA 2013). Each Tier corresponded to a group of specific applications and their anticipated users (Table S1). Both the U.S. and the European Union (EU) have funded projects to evaluate low-cost air quality monitoring technologies and establish networks for trial purposes (CITI-SENSE 2016, USEPA 2016). There is a consensus that the low-cost air quality monitoring equipment should be characterised carefully to meet the expectations for their specific applications, be it ambient air or indoor monitoring (Castell et al. 2013, Lewis and Edwards 2016).

Since the publication of Snyder et al. (2013), which recognised the role of low-cost sensors/monitors in the future of air quality monitoring, there have been a number of reviews on the development and applications of low-cost monitors and their networks (Borghi et al.

2017, Castell et al. 2013, Clements et al. 2017, Jovasevic-Stojanovic et al. 2015, Kumar et al. 2015, Kumar et al. 2016, McKercher et al. 2017, Rai et al. 2017, Spinelle et al. 2017a, Thompson 2016, Wang and Brauer 2014, Woodall et al. 2017). These reviews either focused on characterizations and descriptions of one group of sensors/monitors, such as for monitoring of particulate matter - PM (Borghi et al. 2017, Jovasevic-Stojanovic et al. 2015); for gaseous pollutants (Baron and Saffell 2017, McKercher et al. 2017, Spinelle et al. 2017a); crowd-sourced monitors (Thompson 2016); or offer a general overview of the state-of-the-art and the relevant applications (Castell et al. 2013, Clements et al. 2017, Kumar et al. 2015, Kumar et al. 2016, Wang and Brauer 2014, Yi et al. 2015).

There has been significant focus on the *fitness-for-purpose* of the monitors/networks, acknowledging that applications are many and varied, and therefore differing in the requirements for the type and quality of the data to be obtained. For example, McKercher et al. (2017) discussed the fit-for-purpose question of monitors of gaseous pollutants. Recently, Rai et al. (2017) discussed the advacement in sensor/monitor technology from the end-users perspective.

The ultimate vision is that when the technology matures, there will be ubiquitous networks of sensors/monitors present everywhere, someone owning and operating them (governments, municipalities – or individuals), and many end user applications will be available. Also, anyone, not necessarily an expert in air pollution monitoring, will be able to purchase the right type of sensors/monitors for their intended application, install them and obtain data which will address their questions although there could be issues concerning data interpretation by non-experts. To test whether this vision is already within the reach, two questions can be formulated: (1) *Are these technologies fit for the various purposes envisaged?* and (2) *How far have these technologies and their applications progressed to provide answers and solutions* (beyond just demonstrations that they can be utilised)?

The aim of this review is to provide answers to the above questions based on systematic literature search and review of peer reviewed publications, as well as grey literature (e.g. non-peer reviewed industry/government documents and/or web-based sources).

2. Conceptual framework for utilisation of low-cost air quality sensors/monitors

The term “low cost” is relative, depending on the users and the specific purposes, and has been used loosely in the literature. For example, U.S. EPA Tier III instrument (US$2000 - US$5000) could be low cost for a regulatory authority but unaffordable for community monitoring (U.S. EPA, 2013). The term “low cost” has colloquially been identified by the U.S. EPA as devices costing < $2500 namely because this is the limit often defining capital investment limits by citizen scientists (Air Sensor Toolbox). Additionally, the term “sensor/monitor” was sometimes used to refer to both the measuring component (e.g. the Shinyei PPD42NS sensor by Austin et al. (2015)), as well as the whole monitoring systems, including one or multiple sensors/monitors, enclosure, data display (optional), battery or other power source connection, and varying components for data storage, transmission, and retrieval (e.g. AQMesh and Air-Sensor Box by Borrego et al. (2016)). In this paper, we will use the term “sensor” for the measuring component and the term “monitor” for the whole monitoring system, as per the definition adopted by McKercher et al. (2017). Since the “sensor” alone will be of little use without the supporting components, most of the information reported in the literature is actually about “monitors” and their networks. Therefore, we define hereafter that for the purposes of individual/community applications and/or personal monitoring, a low cost sensor must be <US$100 and a low cost monitor consisting of one or several sensors and communication/data components must be <US $1000.

To be able to answer the set questions, we first need to encompass all the elements, which constitute the entire pathway from the sensor(s) to the answer. Fig. 1 presents the conceptual framework with the progressive phases A to F, with A being a sensor, and F, an outcome of the application of low-cost sensors for air quality monitoring and/or exposure assessment. The outcomes may be pollutant concentration values (current, averaged over time); live air quality maps; apportionment of personal exposure; and citizen/community science information, which can be accessible from websites or via mobile phone applications, etc.

Which phases are implemented, and by which projects, depends to a larger extent who is undertaking them and for what purpose. For example, a multidisciplinary research team may go from A to F, with the outcome being a live air quality map, while an individual may buy a monitor (Phase B), view the readings (Phase D: viewing), and compare them to the national standards (Phase F: outcome). Our review will consider each of these phases separately first, before addressing the overall state-of-the-art of the air sensor technology field.

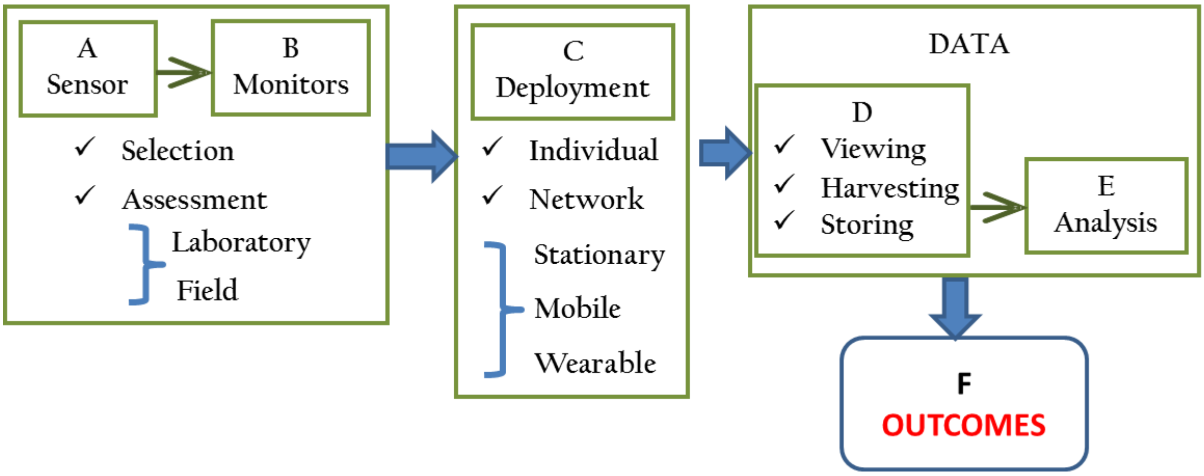


Figure 1. Conceptual framework for the utilisation of low-cost sensing technologies

3. Method for review

This review follows the "state-of-the-art review" approach, which addresses current matters using the grey literature (as explained below) in addition to the scientific literature (Grant and Booth 2009). The air sensors field is progressing rapidly, with new developments and information often published outside of traditional peer-reviewed literature, therefore this broader search was necessary to fully grasp the state of the field. The search was conducted using the scientific databases, including Scopus, Web of Science, IEEE Xplore Digital Library and via a general Google (Scholar), with publication date until August 2017. The separate keywords employed in the search were general to include as many documents as possible, and included:

- "low-cost sensor" and "air quality" in Scopus, Web of Science.
- "sensor network" and "air quality network" for IEEE Xplore Digital Library, Google.

The search was limited to the English language. We note that the search could have missed some publications, because other terms such as sensing network, sensor system, and air pollution could have been used as an alternative for "low-cost", "sensor" and "air quality" in different publications. The search outcomes were screened to identify relevant papers and websites to be used in this review. Relevant returns (based on queries of Title and Abstract fields) were collected and organized in EndNote (version X7.5, Web of Science).

In addition to the peer-reviewed papers, we also screened 'grey literature' using the Google search engine with the same set of keywords. Due to a large number of results from each Google search (usually > 1 million), only the first 100 results of each search were scanned for relevance and those related to applications of the low-cost sensor were recorded.

4. Sensors and Monitors

4.1 Existing sensors and monitors

Tables S2 and S3 (Supplementary Information Section 1) summarize, respectively, all the identified particulate matter (PM) and gaseous sensors and monitors reported in the peer-reviewed literature up to November 2017. The Google search for non-peer-reviewed publications identified a range of low-cost sensor projects and networks, which are presented in later sections.

A general conclusion, based on the peer-reviewed literature, is that there is a limited number of companies that presently manufacture air quality sensors. These include six companies that manufacture PM sensors and four that manufacture gas sensors. It was also noted that some of these manufacturers provide a number of different models of the same sensor. There are many more companies utilising combinations of sensors, as well as ancillary components to build different types of monitors.

The operation of all the identified PM sensors is based on the light scattering principle. The, aerosols are carried in the air flow across a focused beam of visible or infra-red light and the intensity of the scattered light in a selected direction ismonitored by a photodetector. PM sensors are classified into two types – volume scattering devices and optical particle counters (OPCs). In the former the light is scattered from the ensemble of particles and the photodetector provides a single digital or analog output. The output reading is usually converted to a particle mass concentration by comparison to a reference monitor using some test aerosol. The Shinyei PPD42 is an example of such a sensor. On the other hand, OPCs count and estimate the sizes of individual particles, following which the readings are converted to a particle mass concentration, based on the assumption that the particles are spherical and of consistent bulk density and refractive index. An example of such a sensor is the Plantower particle sensor).

Unlike PM sensors, the principles of operation of gaseous sensors involve measuring changes in specific properties of a sensing material (e.g. electrical conductivity, capacitance, mass) upon exposure to a gas species (Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Liu et al. 2012). These changes can be measured directly or indirectly. A typical gas sensor consists of a sensing layer, deposited on a transducing platform, which is in contact with the environment, together with a transducer that produces a measurable output signal. The performance of a gas sensor is evaluated by considering several indicators: sensitivity, selectivity, speed, stability, power consumption, and reversibility. Details of different gas sensing principles are discussed in Supplementary Information Section 2.

In the future, nanotechnology is expected to have a significant impact on the field of gas sensing. In particular, this includes potentially enabling the development of portable and inexpensive sensors that exhibit operational advantages such as enhanced sensitivity and responsivity, selectivity, and low operation power, as well as high integration flexibility with respect to their conventional counterparts. Nanostructured materials have shown a great potential for use as sensing layers due to their unique properties including high surface to volume ratio, greater surface active sites, high specific surface area as well as the effect of crystal facets with high surface reactivity (Comini 2016, Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Zhang et al. 2016). However, developing portable gas sensors with high performance, operating at room temperature, still presents a challenge..

4.2 Assessment of sensors and monitors

Testing protocols

Currently, manufacturer's specifications of low-cost sensors/monitors are of limited use in many cases, as they do not normally conduct sufficient testing that cover the range of desired applications. To address this gap, a number of researchers or government organizations have undertaken evaluation of real-world sensor/monitor performance for a specific use mode and environment of application. Tables S1 and S2 present information regarding the applications of sensors/monitors in various projects reported in the literature, together with information on any assessments conducted and their outcomes. One issue, however is that there is variability in how the different assessments were conducted and to what degree their findings are comparable. Over the last few years, several testing protocols have been proposed and utilized. In particular, the European Metrology Research Programme of EURAMET proposed and applied a protocol to evaluate the performances of single commercial gas sensor (Spinelle et al. 2013), (Spinelle et al. 2015, 2017b). Also, the U.S. EPA initiated its own sensor evaluation efforts in the laboratory and field (Jiao et al. 2016b, Long et al. 2014, Williams et al. 2014b) and issued a general guideline for evaluation and use of low-cost air quality sensors, including suggested performance goals for the sensors (Williams et al. 2014a). Other U.S-based groups saw value in the systematic evaluation of sensors and began developing performance research protocols (SC-AQMD 2017).

Of the 57 studies on sensor/monitor evaluation found in the peer reviewed literature, only 5 studies reported use of or made references to available protocols in the literature . In particular (Jiao et al. 2016b, Zikova et al. 2017) made reference to U.S. EPA protocol; and (Castell et al.

2017, Spinelle et al. 2015, 2017b) used the European protocol. The majority of the studies, however, developed their own, study specific protocols. Given the current wide variety of approaches to evaluating sensors/monitors – including varying duration of testing, measurement environments, number of replicate technologies, and benchmark reference monitors utilized – there are limitations to how the outcomes of testing can be combined across studies or utilized for applications or environments that differ from the original testing setups.

Performance criteria to assess sensors/monitors, based on reviewing the testing protocols, have been developed and utilized by individual studies. A comprehensive list of such criteria includes: (1) linearity; (2) accuracy; (3) precision; (4) response time; (5) detection limit; (6) detection range; (7) impact of temperature and relative humidity (RH); and (8) co-pollutant interference. The definitions of these terms are provided in Table S4.

It is important that the sensors/monitors are tested under both laboratory and field conditions. While all of the criteria listed above are important for laboratory testing, such testing typically includes linearity (against reference instrument); accuracy and the impact of temperature and RH (Williams et al. 2014c). On the other hand, field evaluation exposes the sensor/monitor to the actual air pollution and environmental conditions under which it is expected to operate, and it usually involves collocation of the sensor/monitor with the relevant reference instruments. Field evaluation tests are easier and less costly to conduct, especially when the existing air quality monitoring stations can be utilised with their sets of reference instrumentation for comparison. According to the evaluation protocol proposed by the State of California South Coast Air Quality Management District, the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), sensors are to be tested under field conditions at two different monitoring stations, with subsequent laboratory testing conducted if the field testing results are promising (SC-AQMD 2017). This method of testing has also been recommended as the first choice for citizen/community groups. Fishbain et al. (2017), with this application in mind, proposed a Sensor Evaluation Toolbox (SET) for evaluating Air Quality Micro Sensing Units (MSU) by a range of criteria, to better assess their performance in varied applications and environments. Of the 57 sensor/monitor testing studies found, 30 performed field tests only, 14 laboratory tests only, while 13 studies conducted both field and laboratory tests. It is not surprising that more than half of the studies performed only field tests, and the outcomes of such testing enable utilisation of the sensors/monitors in the same general area where the tests were performed but not necessarily elsewhere.

Particulate matter sensor performance

While most of these performance criteria are clearly defined and, therefore, straightforward to incorporate into the testing protocols, the complexity arises when testing PM sensor performance. The complexity is much greater than that when testing gaseous sensors and therefore it is discussed here separately. Since airborne particles vary in size (and encompass a large spectrum of sizes), and in composition, the questions are: (i) what type of aerosol should be used?; (ii) within what concentration range? (iii) how do the composition and concentration of the test aerosol differ from the ambient aerosol in the study area? (iv) if only field intercomparison is conducted, how well does it account for the impact of all the relevant environmental conditions (variation in aerosol composition, concentration, temperature or RH)?. While the AQ-SPEC protocol does have an option for testing particles of different sizes, it does not specify the data analysis that should be conducted in order to conclusively assess the sensor performance (the European protocol was designed only for gas sensors).

Several studies investigated PM sensors under laboratory conditions and considered the above aspects. Different aerosols have been used in those tests, ranging from test particles, such as ammonium sulfate, polystyrene latex, (Austin et al. 2015, Northcross et al. 2013, Wang et al. 2015), sodium chloride, methylene blue, fluorescein sodium (Liu et al. 2017), sucrose, and ammonium nitrate (Wang et al. 2015), to naturally generated aerosols such as wood smoke, cigarette, stick incense, fried foods such as bacon, chicken, and hamburgers (Dacunto et al. 2015, Olivares and Edwards 2015). A commonly used test aerosol is Arizona road dust (Manikonda et al. 2016, Sousan et al. 2016a, 2017, Sousan et al. 2016b). Such tests allowed the researchers to achieve very high concentrations of PM, of up to 1000 μg/m^3 (Wang et al. 2015) or even several mg/m^3 (Sousan et al. 2016a, 2017, Sousan et al. 2016b) to cover a wide range of occupational conditions.

In general, low cost sensors perform well, with a high degree of linearity, in the laboratory However, they suffer significant response factor changes when used under natural conditions. This is one of the major drawbacks of laboratory-based calibrations. Among the many constraints of laboratory testing compared to field testing is that it is normally difficult to maintain a low concentration of PM, of the level expected in ambient air, for a sufficiently long period of time. Further, the composition and concentration of the test aerosol may not be representative of the ambient aerosol in the study area, or in the area where the sensor/monitor is to be deployed. However, the range of naturally generated aerosols such as wood, cigarette or incense stick smoke could be suitable if the sensors/monitors are to be used indoors. In studies where only field tests were conducted, it was suggested that the sensor/monitor should be deployed in several regions of different ambient PM concentrations and compositions (Jiao et al. 2016b, Johnson et al. 2016, Steinle et al. 2015). In conclusion, the general recommendation for users of low-cost sensors/monitors is that they should be pre-tested/calibrated under the condition in which it is intended to be used (Austin et al. 2015). It is interesting to note that there are many studies that did not conduct any sensor/monitor testing, but based their technology selection and expectations on performance solely on the manufacturer's information. This includes studies such as the bicycle-mounted sensors to observe traffic-related air pollution (Liu et al. 2015, Van den Bossche et al. 2015), establishment of urban or school sensor networks (Ali et al. 2015, Arvind et al. 2016), personal exposure estimation (Arvind et al. 2016, Zhang et al. 2017) and indoor air quality monitoring (Plessis et al. 2016).

Sensors'/Monitors' fitness for the purpose

The main applications of the sensors/monitors have included outdoor monitoring (Bart et al. 2014, Castell et al. 2017, Gao et al. 2015, Jiao et al. 2016b, Olivares and Edwards 2015, Olivares et al. 2012), indoor monitoring (Dacunto et al. 2015, Jackson-Morris et al. 2016, Semple et al. 2015) or both (Steinle et al. 2015), and personal monitoring (Delgado-Saborit 2012b, Jerrett et al. 2017, Steinle et al. 2015). It can be seen that these applications are diverse, and therefore it is reasonable to expect that they will have different performance requirements. For example, PM sensors/monitors used for traffic-related pollution will need to have the capacity to detect smaller size particles, while sensors/monitors used for construction dust will only need to detect coarser size particles. In other words, the sensors/monitors need to be *fit for the purpose*, with the purpose clearly identified. Therefore, one question is whether it makes sense to discuss 'a standard protocol' for testing or should it be related to the purpose, if there should be different protocols, with fewer criteria to be included. Additionally, the acceptable performance of sensors/monitors for various purposes needs to be delineated. It should be noted that variation in potential acceptability targets have been considered by the U.S. EPA (Williams et al. 2014a).

Based on the review of sensor/monitor performance and the manner in which they were tested, there is no clear answer to the question stated by this review, namely: *Are these technologies fit for the various purposes envisaged?* This is because neither have the relevant quantitative specifications of the sensors/monitors been provided by the manufacturers (i.e., their performance at different concentrations, particle size, RH), nor have the users formulated the requirements for the applications or conditions under which they intended to apply the monitors. However, as discussed above, numerous studies have assessed and reported sensor/monitor performance under a range of specific conditions. While some of these studies simply reported results without assigning a “pass or fail”, in many cases it was concluded that the performance was satisfactory, with the judgment criteria of “good enough’ varying between the studies. In other words, *the sensors/monitors were fit for the specific purpose*. The U.S. EPA in their Sensor User Guidebook pointed out that not every sensor need be useful for every type of monitoring (Williams et al. 2014a). The “fit for purpose” approach amplifies that consideration. This points out to the necessity of formulating the requirements for sensors/monitors when intending to apply them for specific purposes and specific locations, and based on this identifying the most suitable sensors/monitors from the published work. The review above and Tables S1 and S2 serve as a useful guide in this respect.

A philosophical comment can be made that it is hardly a novel conclusion that users need to understand the conditions under which they want to use a product. The difference, however, between applications of low cost sensors for air quality monitoring and many other technologies is that many potential users do not have an in-depth background in atmospheric science and consider that no background is necessary. This review suggests that, currently, in-depth expertise is needed to identify appropriate sensor technologies for specific application as well as to understand potential measurement artifacts that could affect data interpretation.

5. Deployment

A sensor network consists of a number of spatially distributed autonomous devices to monitor one or more physical or environmental parameters. The sensor nodes can be interconnected to transmit information and to control operations. This can be achieved by physically wiring the nodes together and to a central processing unit. Although this has some advantages such as superior quality of data, a wireless option offers much easier deployment, flexibility, and troubleshooting in an event that a sensor fails. While there is no doubt that Wireless Sensor Networks (WSNs) will play a major role in the future, it is soon expected to become the key technology for the Internet of Things. There are three main ways in which air quality sensors/monitors may be deployed for use, and they are discussed below.

5.1 Stationary

Here, one or more sensors/monitors are located at a number of fixed sites and monitoring is conducted over a period of time. Provided a sufficiently large number of sensors/monitors are deployed, the results can yield information on spatio-temporal variations, transport rates and sources of pollution. At the same time, it should be noted that a large number of monitors and locations does not necessarily constitute a network unless they are linked together or transmitting information to a central location, generally through wireless connectivity. Currently there are no standardized protocols defining the number of nodes to be placed within a network to achieve sufficient coverage of any environmental pollutant.

The large majority of the studies reviewed (and listed in Tables 1S and 2S) fall into the first category, i.e. stationary deployment. These were mostly conducted in the early days of low cost sensors. In this section, we restrict our analysis to studies involving monitoring at more than one location.

Of the reviewed studies, five monitored particulate matter concentration (Castell et al. 2017, Gao et al. 2015, Jiao et al. 2016b, Olivares and Edwards 2015, Zikova et al. 2017). The total number of sensors/monitors used ranged from 4 to 66 and the duration of the studies ranged from 2 days to 6 months. Three of these studies used either the Sharp or Shinyei low-cost PM sensor. Some stationary networks have been established such as Gao et al. (2015); Li et al. (2014); English et al. (2017) as pilot networks or such as Semple et al. (2015) as part of an epidemiological monitoring campaign. Further, 11 such studies have monitored gaseous pollutants (Al Rasyid et al. 2016, Bart et al. 2014, David et al. 2013, Heimann et al. 2015, Ikram et al. 2012b, Masson et al. 2015, Mead et al. 2013, Moltchanov et al. 2015, Sun et al. 2016a, Weissert et al. 2017a, Wen et al. 2013a). The number of sensors/monitors ranged from 3 to 44 and the gases monitored included nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3) and volatile organic compounds (VOCs). Study durations ranged from 3 days covering the marathon route during the Hong Kong marathon, up to a maximum of 1 year.

In general, the purpose of air sensor networks were to produce high resolution pollution maps that could be used for peak event identification, or linking pollution levels to people's exposure. The above studies suggested that sensor networks have the potential to provide a far more complete assessment of the spatio-temporal variability of pollution data of a particular area. This high-granularity of data supported a more precise characterization of human exposure (Mead et al. 2013). These networks were also able to identify the pollution hotspots by distinguishing them from the daily averaged values for the city, and generate high-resolution spatiotemporal pollution maps (Gao et al. 2015). It was acknowledged that the calibration and data accuracy of sensors constituting the networks was equally as important as that of sensors operating individually. However, the regular in-situ calibration of such sensor networks might face practical constraints (Rai et al. 2017). Thus the published studies tended to adopt alternative ways, such as advanced statistical techniques that included principal component analyses for fault detection and isolation (Harkat et al. 2006), network data correlations for quality check (Alavi-Shoshtari et al. 2013), and algorithms for mobile quality checks (Hasenfratz et al. 2015a).

As a special case it is important to note the expanding networks of stationary sensors for mapping and ultimately managing urban and regional air pollution in China. There is an increasing body of information available on this topic on the Internet (in Chinese), however, these studies were not published in peer-reviewed literature. According to rough estimates (personal communication), there are currently over 30,000 sensors operating to monitor concentration of air pollutants in China. More than 10,000 sensors were installed in north China, where the air pollution is the most serious, with more than 2,000 PM sensors operating in Beijing since 2016, to help evaluate air quality for the city (personal communication).

5.2 Mobile

Measurements are conducted using mobile platforms such as cars, bicycles and unmanned aerial vehicles (UAV), to provide data of high spatial resolution, higher than is possible with stationary platforms. Among the mobile platforms, the UAVs are of interest when extending the scope to include measurements of pollution in the vertical plane.

There have been a number of European-based projects employing portable sensors/monitors for mobile platforms (trams and buses) and citizen participatory initiatives for air quality monitoring; such as the Citi-Sense (http://co.citi-sense.eu) and Opensense (http://www.opensense.ethz.ch) projects (Hasenfratz et al. 2015a), as well as the more recent Luftdaten project (http://luftdaten.info). However, while the first two projects above employed portable particle sensors/monitors, which were cheaper than conventional reference instruments, they do not meet the requirements for low-cost sensors, as defined in this paper. The third project does however, and it currently operates an active network of over 2,000 PM monitors. Thompson et al. (2016) reviewed applications of air quality sensors/monitors in crowd-sourcing projects and drew attention to the importance of data communication and data quality control analysis prior to drawing any conclusion solely on the data measured by the sensors/monitors.

Although, many studies have used conventional particulate matter instruments on mobile platforms, hardly any have utilized low-cost sensing technologies for this purpose. Devarakonda et al. (2013) installed Sharp dust sensors on public transportation and Suriano et al. (2015) employed a Shinyei sensor in an AirBox monitor in a motor car. A somewhat larger number of studies have been conducted to monitor gaseous pollutants. Low cost gas sensors such as those from Alphasense have been used on bicycles and motor vehicles in several studies (Castell et al. 2013, Devarakonda et al. 2013, Elen et al. 2013, Hasenfratz et al. 2015a, Mead et al. 2013, Mueller et al. 2016, Suriano et al. 2015).

A new study conducted in Ji'nan, China, has been utilizing city taxis as mobile platforms for low-cost sensors. One hundred taxis were equipped with PM sensors monitoring $PM_{2.5}$ and PM_{10}. The taxis can collectively drive a distance of 23000 km, cover 95% of the road in the city and provide 1.2 million PM data points per day. It is hoped that with the help of this system, the city authorities will be able to evaluate the relationship between the air pollution and road emissions (including traffic, dust, near-road emission) to develop a more effective air pollution control strategy (Novafitness 2017).

Two studies have used low cost sensors mounted on UAVs for outdoor monitoring of dust. Alvarado et al. (2015) developed an unmanned sensing system aiming to characterise the dust levels at mining sites. "Dust" was referred to as particulate matter in this paper, although the particle cut-point as PM_{10} or $PM_{2.5}$ could not be clearly defined. The authors tested the performance of SHARP GP2Y10 and Samyoung DSM501A in measuring $PM_{2.5}$ and PM_{10} concentrations in the smoke from incense sticks against a TSI DustTrak 8520 monitor. As a result, the Samyoung sensor was excluded due to poor correlation with the TSI DustTrak 8520 ($R^2 = 0.5$), while the SHARP GP2Y10 showed better correlation for PM_{10} with a precision of 1 mg/m^3. The SHARP did not respond to particles from an open fire when deployed on the UAV up to altitude of 120m, but was able to detect talcum powder (classified as PM_{10}) that was dispersed in an open area. Although the method for using UAV for airborne measurement was feasible, the authors emphasised the need for further investigations on assessing the actual particle size cut-point measured by these types of sensors. Koval and Irigoyen (2017) designed and tested a UAV-based air pollution monitoring system using a catalytic sensor (TGS6812-D00) to measure and detect leakage of hydrogen, methane, and liquid petroleum (LP) gas. All the data processing was done at the ground station, which incorporated a robot operation system (ROS Indigo and Ubuntu 14.04) coupled with a drone autonomy package (by Autonomy Lab of Simon Fraser University). The main limitation of the system was identified as the sensor's lag time in measuring concentrations at any point in time. The results of these two studies suggested that further improvement is needed for low cost sensors/monitors to be used effectively on UAV platforms.

In summary, there are limitations in long-term deployment of sensors/monitors on mobile platforms, especially due to the associated costs in maintaining the data collection and generating outputs (e.g. air pollution maps). However, this area of air pollution monitoring appears to be of high interest within the scientific and public communities and is rapidly progressing with availability of new technologies in modifying monitoring platforms; e.g. both in terms of monitoring sensors/monitors and data processing and communication capabilities.

5.3 Wearable

Sensors/Monitors worn or carried by individuals are used to provide estimates of personal exposure to various types of pollution. Similar to the mobile platforms, the data collected by wearable sensors/monitors together with concurrent GPS data can be used to estimate spatial distributions of the measured air pollutants in different (micro) environments.

This field of research has grown rapidly in recent years; however, there is only a small number of research papers published on the use of low-cost sensors for personal exposure monitoring due to the challenging technological aspects of developing such sensors/monitors. Cao and Thompson (2016a) described design, capabilities, and performance of a low-cost ($150 USD), portable ozone sensor for personal exposure monitoring purposes. The testing was conducted by 8 volunteers using the sensor during daytime on the weekdays and weekends over the winter (January to March) in 2015 in Texas, USA. The designed personal ozone monitor used a MiCS-2614 metal oxide semiconductor ozone sensor from SGX Sensortech. The MiCS-2614 performed best for concentrations of 20-100ppb and had a response time of 1 min. Although the results showed that the volunteers in this study were exposed to concentrations much higher than 20ppb, the sensor response to low concentrations was one of the limitations of this study. Another limitation was powering the monitor, which requires eight AAA rechargeable batteries lasting for up to 10 hours. Jerrett et al. (2017) reported on the performance of personal sensing monitor built at Cambridge University, UK and used for personal exposure monitoring of 56 participants during two epidemiological studies for over one year (September 2013 – February 2014) in Barcelona, Spain. The monitor provided the data every 10s and used Alphasense CO, NO and NO_2 sensors as well as sensors for temperature, GPS and General Packet Radio Service (GPRS) transmitter. The results showed that the system was able to detect concentrations of the pollutants in different microenvironments. Comparisons with the reference instruments indicated that the sensors for primary gases (CO and NO) had a better performance than for the secondary gases (NO_2). Another low-cost personal exposure monitoring system (M-Pods) developed by Piedrahita et al. (2014), was capable of collecting, analysing and sharing the data via an Android mobile phone app. The system used sensors for CO, total VOCs, NO_2, and O_3 (metal oxide semiconductor sensors SGX Corporation models MiCS-5525, MiCS-5121WP, MiCS-2710, and MiCS-2611), and CO_2 (NDIR sensor ELT, S100) along with sensors for temperature, relative humidity and light. GPS data were collected using the mobile phone app. Six volunteers used M-Pods over 3 weeks and the M-Pods were tested and calibrated against reference instruments before and after the deployment. Although the actual deployment period was rather short, the comparisons between before and after calibration results showed good agreements and the system was able to perform within the limitation of the sensors' detection limits. With respect to fine particulate matter ($PM_{2.5}$), Steinle et al. (2015) used a Dylos1700 for 17 volunteers who provided 35 personal exposure profiles. Two other studies were carried out using the Sharp GP2Y1010 dust sensor (Wong et al. 2014, Zhuang et al. 2015). Wong et al., developed an Integrated Environmental Monitoring Device (IEMD), which linked the collected $PM_{2.5}$, temperature, humidity, ultraviolet (UV) and sound level data to an Android-based mobile phone app using a web-based database, with the location data obtained from the mobile phone's GPS system. The system provided the measured data in real-time as well as data visualisation through the mobile phone app and was tested for a short period of time by one volunteer in Hong Kong. The results showed that the system was able to respond to changing environments, such as between indoors and outdoors. Zhuang et al. (2015), desgined and tested a similar platform for personal exposure monitoring, called AirSense, which used sensors for GPS, dust, temperature, humidity, and accelerometer in New York, USA. The authors outlined the primilinary tests on the performance of the AirSense, which were performed in stationary locations for each individual sensor. The AirSense reponse to changing microenvironments, such as changes in commuting modes, activity levels (stationary vs moving), during activities at home (e.g. cooking) were tested using data collected over short periods of times (up to 6-hour) by one participant. The results supported the suitability of AirSense for personal exposure monitoring as well as for complementing routine ambient monitoring.

Overall, personal exposure monitoring platforms using low-cost wearable sensors/monitors is of high interest in relation to fine-scale exposure and ambient data required for health impact assessments and epidemiological studies, as well as citizen science applications. Similar to the mobile platforms, the current limitations in their implementation are power restriction; reliability and accuracy of miniaturized sensors under dynamic conditions of use; and robustness to withstand use by individuals.

6. Data: communication, storage, cloud services, processing, and dissemination

Behind every sensor/monitor network there is an underlying data architecture which supports the collection, processing and dissemination of the data (Castell et al. 2015). The complexity and capacity of the sensor/monitor network architectures is proportional to the number of sensors/monitors deployed, the predicted future capacity of the network, the amount of data gathered per sensor, the required level of availability/reliability the backend services require, the post-processing requirements and the data dissemination methods desired (Guo et al. 2012).

The solution each project implements is tailored to these various factors, subsequently there is no one best practice for the development of supporting data services for sensor/monitor data. Any architecture designed for a sensor/monitor network system is about a balance of trade-offs between cost, reliability, scalability and longevity.

6.1 Data Communication

The data sent from sensors/monitors, in terms of traditional internet capacities, would be considered very small in size, and low in frequency. The main limitation found in low-cost sensors/monitors is not in the storage of the data once it is received by the centralised network, but more in the capacity of the device to send data due to power limitations, network availability and security protocol support on low-computing hardware (Lin et al. 2012). Another consideration is data security (Breitegger and Bergmann 2016). Many sensors/monitors require data transmission back to centralized servers for processing or data hosting, or transmit to a cloud-based system. Few if any of the current sensor/monitor manufacturers have achieved compliance with official cloud-based data security standards (e.g., FedRAMP for the United States federal government).

As with any solution design, there are trade-offs to be considered when designing hardware. In the case of low-cost sensors/monitors, the main driving factor is power consumption and data storage. The methods of data communication once the device has captured environmental information can range from mobile networks, Wi-Fi, Bluetooth and direct physical serial connections (Breitegger and Bergmann 2016). Generally, a sensor/monitor will use more power when it uses the always available communication protocols like WiFi and Bluetooth. Lower power usage can be achieved through the implementation of on-demand protocols like mobile networks which only connect and transmit data at pre-defined intervals. This demand for low-power usage is only a need for sensors/monitors in remote locations without access to hardwired power. The nature of air quality sensing often drives a need for sensing in remote and diverse locations, hence power consumption is often a consideration, although the improvement in solar and battery efficiency is reducing the impact of this design consideration (Kadri et al. 2013).

With the emergence of more efficient circuit boards and components which provide greater computing power for the power usage, implementation of stronger security protocols is allowed, leading to a more robust and secure network. This security factor becomes more important as the scale of networks increases, and the potential for breaching or manipulation of sensor/monitor devices and their associated data. The nature of changes in security best practices and increases in breaching of devices in more recent times means that this is becoming a more important design consideration.

It must also be stated that in many situations, data transmission cannot occur due to a lack of Wi-Fi or cellular service. It is imperative that sensors/monitors have sufficient internal storage to ensure that data are not lost if/when data transmission cannot be secured or maintained.

6.2 Databases and Storage

A common aspect of all sensor/monitor data services is the need to store spatial data, which provides context and meaning to environmental conditions at a given location. While the concept of storage of location information is not a new field, over time there has been a filtering and trend to towards the use of certain databases which have been proven to be the most scalable, fast and reliable for this need.

The most common database used for the storage of sensor/monitor data is PostgreSQL with PostGIS providers attached (Ježek 2011). This allows the querying of large quantities of geo-spatial data in a flexible manner, while maintaining performance as the capacity grows. PostgreSQL has a theoretically unlimited row-storage capacity which is only limited by physical storage size on the database cluster. It is not uncommon to be storing 1 million rows per day into one of these databases with no impact on performance and reliability, while still slowing complex geo-spatial queries to be performed.

An additional storage need for these sensor/monitor systems is the storage of metadata associated with the sensors/monitors sending data into the network. There is more flexibility in which type of database is used in this area as many database providers can handle the capacity required for metadata. Traditionally this will be done using Relational Database Management System (RDBMS) which provides more complex query capacities and the ability to create ‘relationships’ between different components of the data itself. Some common RDBMS employed by sensor/monitor networks include Oracle, Microsoft SQL Server and MySQL.

This metadata storage service can contain information relating to the sensor/monitor owner, service types, hardware settings, sensing capabilities, maintenance schedule and more. This area is flexible, and can be tailored to suit the needs of the particular sensing network while being decoupled from the raw geo-spatial sensor/monitor data stored in the main PostgreSQL database.

6.3 Cloud Service Providers

There is a clear tendency for the more recently developed sensing network data services to be hosted in cloud computing environments (Mehta et al. 2016b). Although mainly driven by cost savings, the benefits of high availability computing that scales as needed is perfectly tailored to the requirements of large scale sensing data.

There are 3 main commercial cloud computing providers which offer tailored, scalable and pay-as-you-go computing services. The main providers in this now mature computing space are Amazon Web Services (AWS), Microsoft Azure and Google Cloud Computing (Fioccola et al. 2016).

Low-cost sensors/monitors are sometimes referred to under the moniker of “Internet of Things” (IoT), where the sensors/monitors referred to as “things” and data feed into a cloud-hosted database. Currently, the majority of cloud-hosted sensor/monitor networks have been built on the AWS system, supports IoT data inputs, scalable infrastructure and low-cost long-term storage. AWS is the most mature of the cloud providers in this field and has been shown to iterate faster with new services and economy of scale cost reductions.

6.4 Data Processing

There are needs for processing of sensor data once it reaches the internal storage architecture, although this can vary depending on the sensor types and the data dissemination requirements.

In some cases, the sensor/monitor only sends raw voltage readings, without calibration and conversion occurring at the hardware level. In this case the network needs the ability to support the calibration, and in some cases iterative re-calibration, of the data before it is outputted for consumption.

In more complex sensors/monitors hardware, calibration is often done during build and deployment, so the data received by the network have already undergone its conversion (Schneider et al. 2017b). This has benefits of consistency when the sensor/monitor is deployed, but also can lead to data slowly 'sliding' out of its initial calibration over time as the sensor/monitor hardware ages, unless drift-over-time is incorporated into the calibration. On-board data conversion also reduces data post-processing needs as well as supports offline use of sensors/monitors. Keeping the sensors/monitors well calibrated during deployment is a challenge and various approaches for calibration/data adjustment have been proposed including the following:

1. Sensor/Monitor is collocated with a reference monitor as a "training period", where a machine learning algorithm is developed. The specific parameters and adjustments that are appropriate for inclusion are of debate. These algorithms are often kept proprietary by the manufacturer as their intellectual property.
2. Sensor/Monitor calibration algorithms are developed by the manufacturer and are applied either on-board or in the cloud. These also are often kept proprietary.
3. Sensors/Monitors in a network have their data adjusted based upon expected agreement with a reference monitor located some distance away – for example, isolating middle of the night time periods and using the sensor/monitor vs. reference comparison to make adjustments to the data baseline.

An emerging issue for data integrity is the use of proprietary algorithms, which may include algorithms changing through time, applied on servers or in data post-processing. A number of commercial entities are utilizing proprietary data adjustment algorithms, generally conducted on a server or cloud, which is their key intellectual property given the commonality of the OEM sensor/monitor components. This creates questions of data integrity and reproducibility. A general comment on cloud-based, machine learning that is proprietary and opaque to the user is that if the algorithms are changing over time and the details of the adjustments are not known to the user, this can cause a data integrity issue.

6.5 Data Dissemination and Communication

After the point of measurement, how the data are communicated and shared varies based upon the objective of the organization implementing the monitoring. Public-facing data streams are challenged to provide meaningful interpretation of the data at the timebase it is reported. Until recently, many organizations implementing sensors/monitors would utilize the U.S. EPA

Air Quality Index (AQI), or similar indices from other countries, as their means to provide messaging of their sensor/monitor data. However, this approach was in conflict with the AQI system, which was designed for generally long-averaging periods and applied for regional-scale air monitoring sites based on a body of health research. Newer approaches, such as the U.S. EPA Sensor Scale, have been introduced to provide an alternative guide on communicating high time-resolution sensor data (EPA 2017).

With every sensor/monitor network developed, there is an obvious need to communicate the data back once it has been collected. There are many ways in which this has been implemented, but given that the data storage networks are all internet hosted, the obvious and most efficient method for data publishing is through internet services which are supported by the sensing networks data store. This can be tightly coupled to the data store, for instance directly querying the spatial database, or more loosely associated through the publication of services which provide access to raw, collated or aggregated data (Park et al. 2011).

Some common raw data formats employed by the reviewed sensor/monitor networks include XML, JSON, KML, RDF, GeoRSS and CSV. Typically, these are delivered through web based HTTP REST services, often unauthenticated for public consumption. This gives users and researchers access to the data itself, in both raw and calibrated formats. Other networks hide these services from public consumption and provide web and mobile app interfaces to view and consume the data in a decoupled manner.

The security models implemented around the data dissemination vary depending on the public nature of the data and the projects desired publication outcomes. Some providers are catering to the public consumption and interpretation of their collated data, and hence require no authentication or registration to consume the data. Other providers are locked down and only allow data to be accessed to registered users, applications or websites for publication.

Some further decoupled data services can include the production of visualizations through interactive and static mapping, heat maps, graphing and the creation of service orientated alert systems over SMS, email and social media notifications (Castell et al. 2015, Schneider et al. 2017b).

7. Applied outcomes of low-cost sensors/monitors projects

This review identified references to over 17 projects which reached the *Deployment* stage (C – see Figure 1), followed by utilisation of the *Data* (viewing, harvesting, storing - D and analysis - E) and *Outcomes* (F). It should be stressed that in addition to the identified large projects, which reached the outcome stage (F), with the outcomes documented in peer-reviewed literature and/or on the project websites, our literature search found also many other, smaller projects, often based at a university, or run by small commercial companies (usually related to technology development). The large projects were always consortia, not single universities, organisations or companies (with the exception of the U.S. EPA). Supplementary Information Section 3 lists all the projects found, many of them through search of grey literature. In most cases the information available was insufficient to conclude on the outcomes of the project.

Table 1 provides a list of the selected projects, together with the periods of their duration, funding source (government or commercial/crowd), summary of applied outcomes (as listed on projects' websites), and specifically whether there is an operating network of sensors/monitors (left by projects which ended or operating in case of ongoing projects). More detailed information about these projects is provided in Supplementary Information Section 3.

It can be seen from Table 1 that out of the 17 projects, 11 are/were government funded and 6, commercial/crowd funded. There are two avenues of government funding of such research: either via competitive national/multinational grants – which is/was the case for majority of projects, or directly, which is the case for the two U.S. EPA funded projects (CAIRSENSE and Village Green). The fact that such a sizable fraction of the large projects is commercial/crowd funded (about 30%) is by itself very significant and may signal the paradigm change in air quality monitoring: a shift from it being controlled by government agencies and conducted for regulatory purposes, to being conducted with the contribution from many stakeholders, and potentially providing information beyond regulatory compliance.

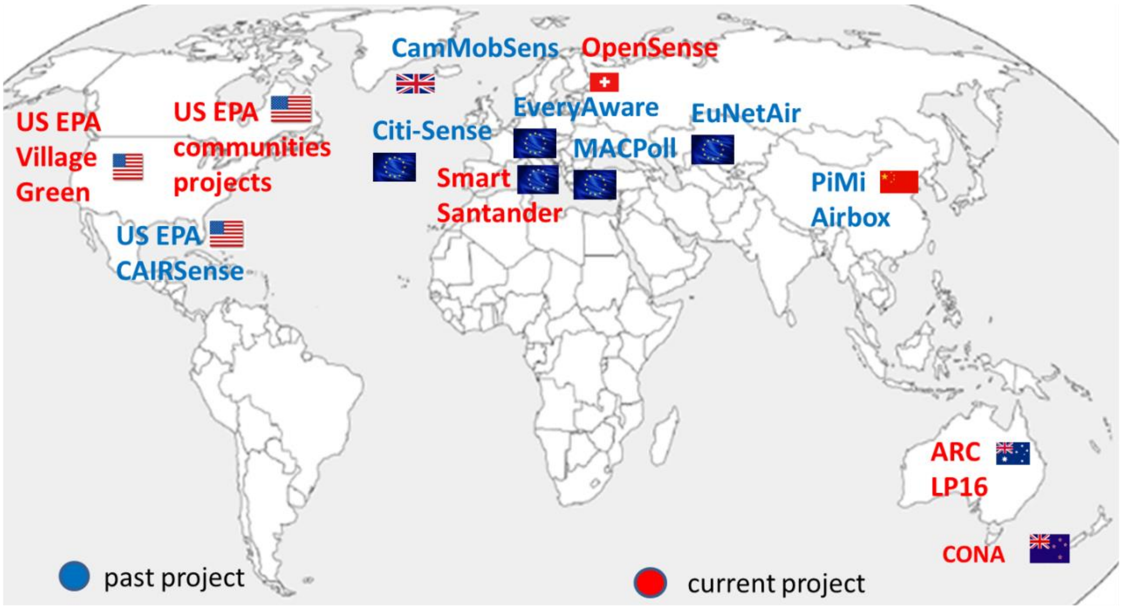
Table 1. Summary of applied outcomes of selected large low-cost sensor/monitor projects

Government-funded projects						
Project name	**Project period**	**Type of project**	**Applied outcomes**	**Operating network**	**Data access**	**Location**
ARC- LP16	2016-2020	Network development	Low cost sensor/monitor networks in several cities	In progress		Australia
EuNetAir	2012-2016	Network on New Sensing Technologies	Development and evaluation of new sensors/monitors	n.a.	n.a.	Europe
EveryAware	2011–2014	Enhance Environmental Awareness	Games, and temporary personal monitoring campaign	n.a.	n.a.	Europe

CamMobSense	-2010	Small scale deployment of sensor/monitor		n.a.	n.a.	UK
Citi-Sense	2012-2016	Developing technological platforms for distributed monitoring	Multi-country sensor/monitor testing/monitoring network	Commercial products still in development including AQMesh	Data accessible through the Citizens Observatory Toolbox (COT)	Europe
Citi-Sense-MOB	2013-2015	establish mobile air quality measurements	exhaustive evaluation of low-cost platforms	n.a.	n.a.	Norway
OpenSense	2010-2013 2014-2017	investigating community-based sensing using wireless sensor/monitor network	Air pollution map based on mobile sensing platform. Phone-app for route planning	Currently available	Data accessible online over the project’s Global Sensor Network (GNS) at http://data.opensense.ethz.ch/	Switzerland
Community Observation Networks for Air (CONA)	2015 ~	Establishing low-cost sensor/monitor network	Monitors developed, network building	In progress	n.a. (provided report for participants)	New Zealand
PiMi Airbox	2013 ~ 2016	Indoor Air-quality Monitoring and Large Sensory Data Mining	Monitors developed, network testing	n.a.	n.a.	China
Smart Santander	2010-2013	applications and services for a smart city	Network of internet-based device including air quality	Still available but not very active	Data stored in a repository and can be accessed once authenticated and authorised by using a web service interface	Europe
U.S. EPA CAIRSENSE	2013-2016	Evaluate long-term performance of sensors/monitors and network	Sensors/Monitors tested	n.a.	n.a.	US
U.S. EPA Village Green	2013 – 2014 2015 - 2016 2017 ~	Building autonomous monitoring systems	Units built and installed in limited number of sites	Online data for limited sites	Data accessible online	US
U.S. EPA grants Air Pollution Monitoring for Communities	2016-2019	Development and application of low-cost sensor/monitor network	Sensor/Monitor testing facility established	In progress	Data not accessible to the public yet project still ongoing	US
Commercial/crowd funded projects						
Project name	**Project period**	**Type of project**	**Applied outcomes**	**Operating network**	**Data access**	**Location**
AirVisual	2015 ~	Global network of air quality monitors	Map of fixed sites and app developed for all users	Network and monitors available	Data accessible by a free AirVisual app and website	Global (US-based)

Air Quality Egg	2012 ~	community-led air quality sensing network	Map and data function developed for all users	Network and monitors available	Data accessible through an air quality egg, phone app and a website	Global (US-based)
AirCasting (AirBeam monitor)	2012~	a platform for recording, mapping, and sharing health and environmental data using your smartphone	Map of data from AirBeam monitors and app developed for all users	Network and monitors available	Data accessible through an air beam, phone app and a website	US
SMARTCITIZEN	n.a.	a platform to generate participatory processes of people in the cities	Map of data from Smart Citizen monitors and app developed for all users	Network and monitors available	Data accessible through an Smart Citizen kit, phone app and a website	Europe
Purple Air	2015 ~	An air quality monitoring network built on a new generation of "Internet of Things" sensors/monitors	PurpleAir Map displays the points using the U.S. EPA Air Quality Index (AQI) scale	Network and monitors available	Must be a registered user to access data	Global (US-based)

From a global perspective, of interest is the geographical spread of the application of low-cost sensors/monitors, and to obtain a better understanding of this, the projects were placed on the map of the world, separately for government (Figure 2a), and commercial/crowd funded projects (Figure 2b).



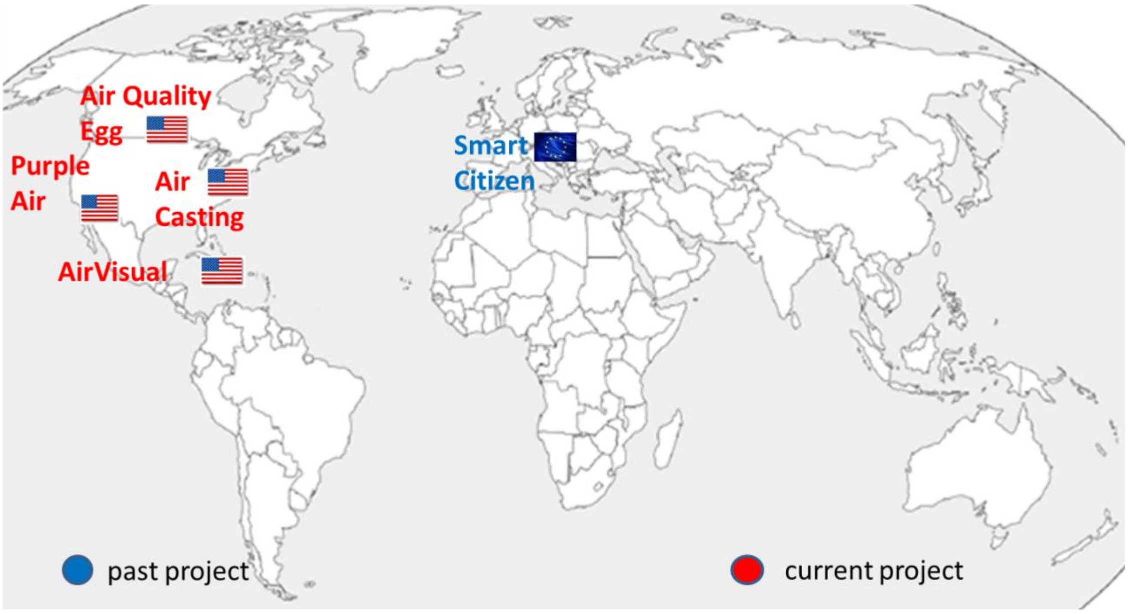


Figure 2 Geographical locations of low-cost sensor/monitor network hubs (while the networks themselves range from covering a single country to being global): a) government funded projects, and b) commercial/crowd funded projects.

It can be seen that the majority of the government funded projects were/are conducted in the US and Europe, with one project conducted in China, one in Australia and one in New Zealand. As for the commercial/crowd funded projects, the U.S. has four current projects while Europe has one project in latent mode. There are currently some limited sensor/monitor activities in low and middle income countries (LMICs) and their consideration for use in this context has motivated several recent workshops and a white paper in development by World Bank, U.S. EPA, LMICs representatives, and others.

An overarching issue in the use of sensor/monitor technology is the level of expertise required for successful use and interpretation of the data. Sensors/Monitors are often marketed as easy to use and interpret; however, air monitoring experts have demonstrated the current technology can have significant complexity in both implementation and data analysis. Not only does one have to have an understanding of what sensors/monitors might serve the best purpose, but one must also have the skills to often deal with highly complex, high frequency, and sometimes erroneous data. These issues often confound many new entrants to air monitoring, who are attracted by the low price point of sensor/monitor technology, including community groups, researchers from other fields, and private sector use.

Secondly, we may ask what the life span of individual projects is. To answer this question Figure 3 compiles the projects together with their duration (as stated on the relevant websites). Here we focused on projects which started more than three years ago, to consider only those which passed the typical duration of government funding, of three to four years. An interesting observation can be made from inspecting Figure 3 that two of the commercial/crowd funded projects which started the earliest (Air Quality Egg and Air Casting) still continue, while most of all the government funded projects appear to have finite life.

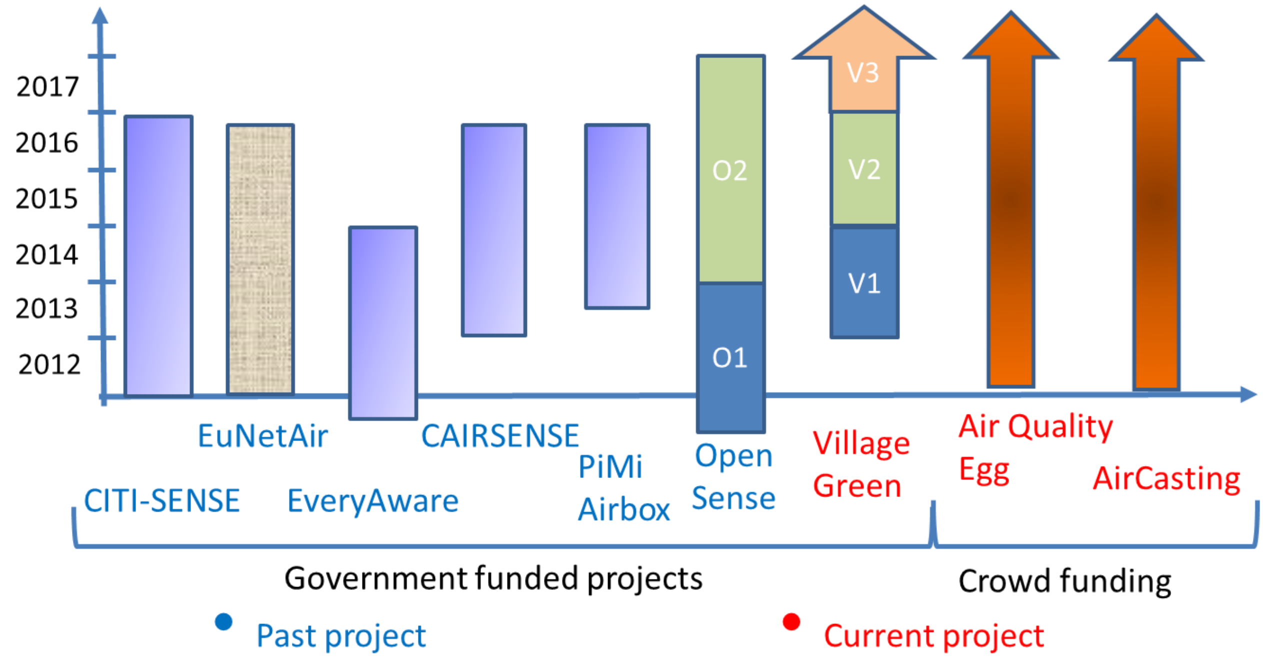


Figure 3 Life span of the selected low-cost sensor/monitor projects (O1, O2, V1, V2, and V3 are different phases of the project).

There are many different types of potential applied outcomes of the projects, and they include:

Peer reviewed journal publications. Each of the large government funded projects generated peer reviewed publications, and thus contributed to scientific body of information. Many of the publications focused on the technology itself, or demonstration of the proof of concept (that sensors, monitors or their networks can be deployed and utilised), however, fewer publications provided new information, not available from the existing monitoring networks, on some aspects of pollution, source emissions or exposures. For example, within Citi-Sense project, Moltchanov et al. (2015) demonstrated the feasibility of wireless sensing network in urban area while Castell et al. (2017) evaluated the performance of a commercial low-cost air quality sensor platform (AQMesh); Jiao et al. (2016) described the outcome of the U.S. EPA funded project CAIRSENSE in evaluating the performance of different sensors/monitors.

Website information. All the projects except PiMiAirBox, have their website providing updates on the progress of the projects, as well as information on air pollution, source emissions or exposures, and rising awareness. AirVisual is a good example of website that contains up-to-date information about air pollution.

Information sessions open to the public. Many projects organised workshops, or seminars to engage with citizens. Some project also developed social media platforms including building apps to facilitate communication between the project partners, and to facilitate citizens' engagement, participation and network building e.g. Citi-Sense project or U.S. EPA Air pollution monitoring for communities grant.

School children education. Recognising that education of children have lasting, lifelong effect on the children, projects like Citi-Sense have developed a program that enables schools to take part in air quality monitoring.

Operating networks of sensors/monitors with data being utilised. Utilisation includes making data available on the website, providing visual maps on air pollution on the websites or through mobile phone applications, information about personal exposure, and warnings of high pollution/exposure. While most government-funded projects did not result in an operating network many crowd-funded projects currently maintain maps of sensor/monitor networks (e.g. AirCasting, Air Quality Egg, AirVisual and PurpleAir). It is most likely a result of the low maintenance cost and the interest of participants in the networks.

In the context of the conceptual framework outlined in Figure 1, two large projects listed in Table 1 are discussed below to highlight their applied outcomes.

Citi-Sense (http://co.citi-sense.eu) operated between 2012 and 2016 in nine European cities, covering a variety of climatic and cultural conditions, from Oslo (Norway) to Haifa (Israel) and Edinburg (United Kingdom) to Beograd (Serbia). Sensor/Monitor networks were deployed to investigate three use cases: ambient air quality, indoor environment at schools, and the quality of urban spaces. The project broadly followed the steps outlined in Figure 1, first in a pilot and then in a field study.

For the ambient air quality and indoor environment, the project's technical starting point were eight existing operational sensor platforms for monitoring air pollution, assuming that they were ready for deployment in sufficient numbers across the participating cities. All sensors/monitors in the devices came from the same manufacturer, but the devices' designs varied in most aspects. The project also assumed that it would be possible within a realistic time to build a common communication platform. This communication platform was designed to facilitate access to data and information to citizens, supporting the ultimate aim of the project to empower them on air quality. A number of tools and products were suggested for end users, and stakeholders in each use case were asked to participate on their final development.

In each of the steps of Figure 1, a number of practical issues had to be solved. Prior to delivery of sensor platforms, it was necessary to solve platform malfunctions, to develop a testing protocol to ensure data comparability across the locations, and thus ultimately, to support further development of the platforms. In the field study, four platforms were used across the two air related use cases, each for a different purpose (stationary and wearable platforms for outdoor use, a stationary platform for indoors, and a stationary radon unit for indoors). The pollutants measured were NO_2, oxides of nitrogen (NO_x), O_3, PM and carbon dioxide (CO_2), but not all platforms were configured for all the pollutants. The deployment of the units in the field by the city teams required agreements on a number of levels and which was technically challenging. For the communication platform, data ingestion and data provision were based on common standardized protocols, and a common data model for the whole project. Efficient retrieval of the collected data was dependent on the internal architecture of the data repository. The functioning steps A-D of the Figure 1 were required for development of the products that were to be the basis of the citizen empowerment. Web portal for simultaneous visualisation of all project measurements and a derived map for air quality was the main project product, complemented by a number of assessment questionnaires and questionnaires on air quality perception and knowledge, and a kit for assessment of outdoor spaces.

In the final 12 months of the project, CITI-SENSE was able to deploy the full chain A-F of Figure 1, and demonstrate a full technical implementation. At one time for over one month, the project operated a network of more than 330 sensor platforms for air quality providing data for hourly updates of air quality information in eight cities. The project outcomes, including computer codes, project deliverables describing all steps summarized above as well as publications, are publicly available.

Village Green – The Village Green was first deployed in 2014 with a single pilot station in Durham, NC. The station was designed to be a test platform involving compact, solar-powered monitoring system informing local communities about continuous near real-time environmental data. The station was evaluated for measurement performance against a nearby reference monitoring station (Jiao et al. 2016), whereby it was determined to have reasonable performance despite its solar-powered operation that subjected monitoring equipment to ambient environmental conditions and power interruptions. The pilot station success prompted the deployment of seven additional stations throughout the US, that were competitively selected from state and local air quality agency proposals based upon their intended location and application purpose. Public parks, libraries, museums and other locations of high public access linked the stations to local partners devoted to sustainable energy practices, environmental awareness, and educational opportunities. The Village Green has provided a wealth of community-based knowledge and data from these sites are being used to assist the U.S. EPA in establishing short-term data messaging (Jiao et al. 2015).

Two commercial/crowd funded projects, AirVisual and Purple Air, which are listed in Table 1 but not included in Figure 3 because both started only two years ago, should be highlighted separately due their consistent and global progress.

AirVisual is a global project, monitoring $PM_{2.5}$ and CO_2 using the AirVisual Node as a monitor and providing air pollution app. The app offers free access to a large air quality database of 9,000+ cities globally with more than 8,000 AirVisual nodes distributed in 44 countries around the world. The app and AirVisual website provide a 3-day pollution forecast, using machine learning and artificial intelligence, together with a 3-D air pollution map. AirVisual map utilise the data from the AirVisual nodes as well as from the regulatory monitoring stations.

Purple Air has grown rapidly over the past year or two, and has about 900 Purple Air nodes that measure PM_1, $PM_{2.5}$ and PM_{10} across 5 continents although the majority of them operate in the US and Europe, with the number of nodes growing currently by about 30 a day. Purple Air provides information on air pollution as color-coded AQI, together with the actual concentration of PM at the monitoring point, and the data can also be accessed by researchers upon request for academic purposes.

8. **Concluding remarks**

As for the first question set by this review, we have concluded that *the sensors/monitors were fit for many specific purposes* for which they were applied. Regarding the second question (*How far these technologies and their applications have progressed to provide answers and solutions, beyond just demonstrations that they can be utilised?)*, it is clear that while different projects had/have different objectives and focused on different set of outcomes, overall, application of low cost sensors/monitors have already changed the paradigm of air pollution monitoring, and application of these technologies is set to grow. In particular, the current low-cost sensing technologies are able to fulfil two of the four tasks recommended by Snyder et al. (2013), including: (1) *supplementing routine ambient air monitoring networks*, and (2) *expanding the conversations with communities*. With some of the commercial/crowd funded projects of global reach and fast expanding, both these tasks are fulfilled beyond single authorities responsible for air quality management, and beyond single communities. There is still more work to do on point (3), *enhancing source compliance monitoring*, which is of particular necessity and urgency in developing countries. Also, there has been somewhat less progress in wide scale *monitoring of personal exposures* (4) because the personal exposure monitoring is more demanding, for example, than stationary deployment as it requires engagement and commitment from the study volunteer. Furthermore, the bulkiness and power requirement of the sensors/monitors is another restraint. Improvement in downscaling the sensor and its power consumption will further this field of research. It can be argued that with a significant expansion of monitoring networks, and with not only the data on concentrations available to the individuals, but also practical information (on for example whether the air quality is good or bad), individuals will not have to carry sensors/monitors to be able to assess their exposure to outdoor air pollution. Personal exposure monitoring, would however still be important to provide information on the fraction of exposure at home, and resulting from operation of indoor sources, as well on exposure to combustion products, such as ultrafine particles (< 0.1 µm). Concentrations and exposures to ultrafine particles (measured in terms of number, rather than mass concentrations) are not correlated with those of $PM_{2.5}$, as they have different sources (although at very high concentration of ultrafine particles, when they rapidly grow by coagulation, there could be a measurable contribution to mass). At this point, however, no low-cost technologies are available to monitor ultrafine particles.

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The opinions expressed in this paper are those of the author and do not necessarily reflect the views or policies of the Government of the Hong Kong Special Administrative Region, nor does mention of trade names or commercial products constitute an endorsement or recommendation of their use. The U.S. Environmental Protection Agency through its Office of Research and Development participated in the development of this article. It has been reviewed by the U.S. EPA and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The authors have no conflicts of interest or financial ties to disclose.

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SUPPLEMENTARY INFORMATION

Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: how far have they gone?

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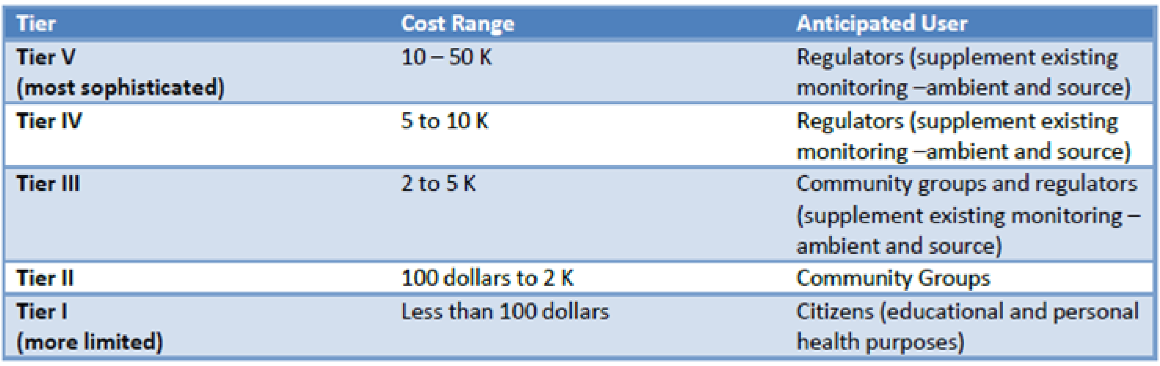
Supplementary Information Section 1: Table S1 – S4

Table S1. Tier uses and users of air monitoring instruments (US EPA, 2013).



Tier	Cost Range	Anticipated User
Tier V (most sophisticated)	10 – 50 K	Regulators (supplement existing monitoring –ambient and source)
Tier IV	5 to 10 K	Regulators (supplement existing monitoring –ambient and source)
Tier III	2 to 5 K	Community groups and regulators (supplement existing monitoring – ambient and source)
Tier II	100 dollars to 2 K	Community Groups
Tier I (more limited)	Less than 100 dollars	Citizens (educational and personal health purposes)

Table S2. Utilisation of low cost particulate matter sensors in different monitors

Sensors	Monitors	Reference	Tests conducted	Aerosol type	Standard method used	Comparison period	Outcome
Sharp GP2Y1010AU0F /Sharp GP2Y1010	PAC MAN	(Olivares et al. 2012)	Field test	Indoor: lounge and kitchen, NZ	TSI AM510 'Sidepak'	27/7-03/8/2011	Preliminary test; can identify the magnitude of indoor emission but cannot identify the sources
	ODIN	(Olivares and Edwards 2015)	Field test	zero response; wood smoke impacted area	air quality monitoring station (TEOM-FDMS)	24/7 – 14/8/ 2014	performance of ODIN is worst for PM2.5 concentrations below 25 μgm−3.
	TSI AirAssure	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	Potential application in tracking air quality in developing countries and heavily polluted areas
	UB AirSense	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Zhuang et al. 2015)	Field test	Indoor and outdoor in different contexts	n.a.	hours	OK for mobile monitoring
	Foobot	(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	can provide reasonable estimates of PM2.5 in the workplace after site-specific calibration
	TECO Enviboard	(Budde et al. 2013)	Lab and Outdoor;	Chalk dust up to 600 mcg/m3 and ambient air	Lab: DustTrak DRX 8533 A; Field: Dustrak and Grimm	Lab/Outdoor; 18 h - 7days (winter 2012/13)	Require collocation with standard device for data quality control

	WSN node	(Tse and Xiao 2016)	Field test	ambient air	Shinyei PPD PMS1 (also a low cost sensor)	hours	n.a.
		(Ali et al. 2015)	Field test	Outdoor in school	n.a.	24h	n.a
	n.a.	(Liu et al. 2017)	Plexiglas chamber	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
Sharp GP & DN	n.a.	(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	having high Sdev; but after calibration could be suitable for occupational setting
Sharp DN7C3JA001	n.a.	(Harada and Matsumoto 2016)		In Japanese			n.a
Sharp DN7C3CA006	n.a.	(Cao and Thompson 2017)	Field test	personal exposure in Texas & Georgia	Grimm 1.109; AirAdvice 7100;	Oct-Nov 2015	could be used to monitor PM depending on performance requirement; not suitable for clean environment
Shinyei PPD-20V	n.a.	(Weekly et al. 2013)	Indoor test	Indoor air	GT-526S laser particle counter (Met-One)	29.5 hours	good potential
Shinyei PPD42NS,	PANDA	(Holstius et al. 2014)	Field test	Ambient, Oakland, California	BAM-1020, Met One; Model 1.108, GRIMM; DustTrak II;	15/04/- - 23/04/ 2013 for 1h data; 01/08-15/11/2013 for 24h data	Useful for enhancing the resolution of PM data. Useful in more polluted region. Temperature and humidity impact.
	Airbox ECN	(Borrego et al. 2016)	Field test	ambient (next to traffic in Portugal)	BAM (Environnemnent MP101M; Verewa F701)	2 weeks in October 2014	Poor performance
		(Hamm et al. 2016)	Field test	Ambient	Met One BAM	n.a.	Regular re-calibration is recommended.
	Air Quality Egg	(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	poor correlation with the FEM (r =−0.06 to 0.40).

	PUWP	(Gao et al. 2015)	Field test	Ambient, Shaanxi, China	TSI DustTrak II Model 8532; Airmetrics MiniVol Tactical Air Sampler; E-BAM	Collocation: 16-20/12/2013	PUWPs show promise as a viable lower cost aerosol sensor
	APOLLO	(Choi et al. 2009)	Sensor building	Ambient air and tobacco smoke	Not available		n.a.
	n.a.	(Austin et al. 2015)	Test chamber (0.3 m3)	polystyrene; polydisperse ASHRAE test dust #1; in lab test	TSI Aerodynamic Particle Sizer (APS) 3321 (0.5–20 microns)	hours	these sensors are appropriate for use as ambient particle counters for low and medium concentrations of respirable particles (< 100 ug/m3)
		(Johnson et al. 2016)	Lab and field tests	Lab: incense smoke Field: Atlanta & Dehli	E-BAM; TEOM; TSI DustTrak 8533 (lab test)	Lab: hours Field: days	Good correlation with E-BAM
		(Kelly et al. 2017)	Wind-tunnel experiments	Alumina dust	Grimm 1.109; DustTrack II 8530	hours	inconclusive
		(Liu et al. 2017)	Lab test	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	application in tracking air quality in developing countries and heavily polluted areas
	excluded	(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Unable to obtain reliable results.
Shinyei PPD60NS,	AirBeam	(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	poor correlation with the FEM

		(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	AirBeam not good for PM conc >200 mg/m3
		(Mukherjee et al. 2017)	Field test	Cuyama Valley in California	GRIMM 11-R; BAM-1020	14 April 2016, to 6 July 2016	useful for the assessment of short-term changes in the aerosol
	n.a.	(Johnson et al. 2016)	Lab and field tests	Lab: incense smoke Field: Atlanta & Dehli	E-BAM; TEOM; TSI DustTrak 8533 (lab test)	Lab: hours Field: days	The PPD42NS sensor has problems with stray light penetration; low R2
Nova SDS011;	n.a.	(Harada and Matsumoto 2016)					In Japanese
Plantower 1003/3003	Purple Air	(Kelly et al. 2017)	Wind-tunnel experiments and field test	Lab: Alumina dust Field: Ambient air	Grimm 1.109; DustTrack II 8530 Field: TEOM	hours	PMS 1003/3003 correlates well with FRMs, FEMs, & research-grade instrumentation
SYhitech DSM501	PiMi	(Li et al. 2014)	Lab test	Arizona dust	TSI-8530	hours	good potential
	Speck	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Poorer performance compared to Foobot, no recommended application
		(Zikova et al. 2017)	Field test (indoor & outdoor)	Indoor and outdoor ambient PM	Grimm 1.109; AirAdvice 7100; CO monitor to distinguish sources	Oct-Nov 2015	could be used to monitor PM depending on performance requirement; not suitable for clean environment

Samyoung DSM501A	n.a.	(Liu et al. 2017)	Lab test	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	application in tracking air quality in developing countries and heavily polluted areas
		(Weekly et al. 2013)	Indoor test	Indoor air	GT-526S laser particle counter (Met-One)	29.5 hours	good potential
OPC-N2		(Sousan et al. 2016a)	Lab test	salt, welding fume, and Arizona dust with homogeneity test	Grimm PAS-1.108	hours	good agreement with the reference instruments
		(Crilley et al. 2018)	Field test	Ambient urban background and roadside	TSI 3330; Grimm PAS-1.108	5 weeks + 2 weeks	reasonable agreement for a low-cost sensor to the measured mass concentrations of PM
Dylos DC1100		(Dacunto et al. 2015)	Lab	cigarette, stick incense, fried bacon, fried chicken, and fried hamburger	a Mettler-Toledo M3 microbalance, SidePak	64 experiments	likely most useful for providing instantaneous feedback and context on mass particle levels in home and work situations for field-survey or personal awareness applications.
		(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	n.a.
		(Jones et al. 2016)	Field test: indoor	in the farrowing room	an aerosol photometer pDR-1200; A microbalance (MT5, Metler-Toledo,	18 days within 2 months	good correlation but not satisfy EPA and NIOSH criteria --> qualitative monitoring
		(Manikonda et al. 2016)	Air quality chamber (21.4 m^3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	moderate relative precision, adequate for temporal and spatial trend if properly calibrated
Dylos DC1700		(Han et al. 2017)	Field test	backyard of a residential home, Houston, Texas	GRIMM 11-R	12 days December 2015	Low correlation for coarse particles; Hd>60% influence the reading but can be used for large scale campaign.

		(Holstius et al. 2014)	Field test	Ambient, Oakland, California	BAM-1020, Met One; Model 1.108, GRIMM; DustTrak II;	15/04/-23/04/ 2013 for 1h data; 01/08-15/11/2013 for 24h data	Useful for enhancing the resolution of PM data. Useful in more polluted region. Temperature and humidity impact.
		(Jovasevic-Stojanovic et al. 2015)	Lab test Field test	cigarette smoking; ambient (Serbia)	TSI 3330 OPS (lab)/ GRIMM Model 1.108 (field)	Lab: hours Outdoor:2 wks	Good correlation between Dylos and other instruments
		(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	moderate relative precision, adequate for temporal and spatial trend if properly calibrated
		(Semple et al. 2015)	Field test: indoor:	non-smoking and smoking, Scotland	Sidepak AM510	Days in 34 households	may underestimate PM2.5 concentrations towards the higher end (>600 µg/m3), be useful in air quality-based intervention
		(Steinle et al. 2015)	Field test	Individual volunteers in the UK; Outdoor rural, outdoor urban, Indoor, UK	TEOM-FDMS; MARGA-Monitor for Aerosols & Gasses in Ambient Air; OSIRIS Airborne Particle Monitor	10t-15th of April 2013; 30th Sept to 4th Oct 2013	Yes for indoor, No for mobile / personal monitoring
		(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Useful for in estimating aerosol mass concentration workplace monitoring
		English et al., 2017	Field test Lab test	Details not available	Details not available	Details not available	Used for community network of 40 sites

Table S3. Utilisation of low cost gas sensors in different monitors

Sensors	Measur	Monitor name	Reference	Tests conducted	Power supply	Standard method used	Comparison period	Outcocome / Fit for	Application in reference	Protocol in

	ing principle			Lab test	Field test				application purpose		Reference
CO sensors											
Alphasense CO-B4	EC		(Castell et al. 2017)	Y	Y	battery	gas standards /CEN reference analyzers	April to September 2015	cross-interferences, effect of temperature and relative humidity	Suit for citizen science applications, unsuitable for air quality legislative compliance applications	The test protocol consists of a multi-point calibration.
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
			(Hasenfratz et al. 2015b)		Y	Power by streetcar		2 years	Air pollution map	na	na
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/ Dual Column SRI 8610C GC	7/8/2015–25/8/2015(20 nodes)	work in progress	na	na
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ CO analyzer Thermo Electron 48c	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		CamPerS	(Jerrett et al. 2017)	Y	Y	battery	Monitor Labs 9830B, Q-trak model 7565	September 2013 and February	variable capacity (NO and CO were measured more	have potential to reduce exposure measurement	Validation protocol

								2014	accurately than NO2,)	error in epidemiological studies and provide valid data for citizen science studies	
		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Good inter-correlation (r=0.79-0.82)	Application in in an outdoor, suburban setting	CAIRSENSE project
		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	non-dispersive infrared spectroscopy (EN14626)	13th April 2015 to 24th June 2015/24 nodes	significant uncertainties at the individual sensor level	high-resolution maps of urban air quality at high temporal resolution	
		(MAS) system	(Sun et al. 2016b)	Y	Y	battery	comparing with AQMS data	16 January 2015 to 18 January 2015	Promising (RH effect)	monitor the air along the Marathon route in urban Hong Kong	na
		Modular Sensor System (MSS)	(Yi et al. 2018)	N	Y	two batteries with charging system	Collocated with equipment of authorized agencies	23 days	Acceptable accuracy	$R^2 = 0.91$ with reference value, accuracy: ±32 ppb	na
Alphasense CO-AF	EC		(Heimann et al. 2015,	Y	Y	battery	gas standards	2.5 months/ 45 nodes	Feasible for ambient monitoring (NO on NO2 had a	Source attribution	na

			Mead et al. 2013)						cross interference of 1.2%)		
City Technology CO 3E300	EC	AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na
Figaro TGS 2442	MOS	uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
		IPOM	(Rasyid et al. 2016)			battery			Testing process	na	na
Figaro TGS-5042	MOS		(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution

KWJ CO sensor model RCO100F	EC		(Chaiwatpongsakorn et al. 2014)	Y	Y	Solar panel /battery	NDIR Analyzer and gas standard	over two weeks	comparable with the CO-NDIR reference method	Ambient monitoring	na
Membrapor CO/ CF-200	EC	VIEW	(Ikram et al. 2012a)		Y	Solar panel/battery	standardized environmental pollution sensor equipment		Fit for Urban air pollution monitoring	Urban air pollution monitoring	na
SGX MiCS-5521	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
SGX MiCS-5525	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
		Air quality egg	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Poor inter-agreement (r=-0.40—0.17)	Application in in an outdoor, suburban setting	CAIRSENSE project

			(Wen et al. 2013b)		Y	battery		July to September 2010	monitor more detailed air pollutants	na	na
SGX MiCS-4514		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
			(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
NO2/NO sensors											
Aeroqual NO2 series 500	EC		(Delgado-Saborit 2012a)			Battery/wall charge		12th July 2011 to 1st October 2011	Fit for human exposure	Human exposure to combustion related pollutants	Personal exposure protocol
			(Lin et al. 2015)		Y	Mains power	chemiluminescence NO2 analyser	> 2 months	potentially useful ambient air monitoring instruments	ambient air monitoring	na

			(Deville Cavellin et al. 2016)		Y			three seasons in 2014	great potential for capturing temporal variability	na	na
Alphasense Ltd NO-B4 NO2-B42F, NO2-B4/ O3-filtered NO2-B4	EC	Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/(Air Quality Design Inc)	7/8/2015–25/8/2015	work in progress	na	na
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ nitrogen oxides analyzer Teledyne 200E	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		CamPerS	(Jerrett et al. 2017)	Y	Y	battery	Monitor Labs 9830B, Q-trak model 7565	September 2013 and February 2014	variable capacity (NO and CO were measured more accurately than NO2,)	have potential to reduce exposure measurement error in epidemiological studies and provide valid data for citizen science studies	Validation protocol
		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Weak inter-correlation (r=0.14-0.32) for NO2, High correlation (r>0.88) for NO	Application in in an outdoor, suburban setting	CAIRSENSE project

		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	chemiluminescence (EN14211)	13th April 2015 to 24th June 2015	significant uncertainties at the individual sensor level	high-resolution maps of urban air quality at high temporal resolution	na
			(Spinelle et al. 2015, 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
			(Hasenfratz et al. 2015b)	Y	Power by street car		2 years	Air pollution map	na	na	
		(MAS) system	(Sun et al. 2016b)	Y	Y	battery	comparing with AQMS data	16 January 2015 to 18 January 2015	Promising (RH effect)	monitor the air along the Marathon route in urban Hong Kong	na
		Modular Sensor	(Yi et al. 2018)	N	Y	two batteries	Collocated with	23 days	Acceptable accuracy	$R^2 = 0.42$ with reference	na

		System (MSS)				with charging system	equipment of authorized agencies			value, accuracy: ±3 ppb	
Alphasense NO-A1, NO2-A1	EC		(Heimann et al. 2015, Mead et al. 2013)	Y	battery	gas standards	2 months	Feasible for ambient monitoring (NO on NO2 had a cross interference of 1.2%)	Source attribution	na	
AppliedSensors iAQ-100	MOS	CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na
Cair Clip NO2 sensors	EC		(Duvall et al. 2016)	Y	Y	solar panel/battery system/wall charge	FRM/FEM analyzers	4–27 September 2013/14 July -12 August 2014	showed little to no agreement with reference data likely	community application	na
Cairclip NO2/O3	EC		(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Inter-correlation(r=0.42-0.76)	Application in in an outdoor, suburban setting	CAIRSENSE project
City Technology NO2 3E50, NO 3E100		AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na

			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
			(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution

Figaro TGS 2106	MOS	GASDAS	(Tsujita et al. 2005)	Y		Batteries/USB/Solar Panels			FIT (Local air pollution)	na	na
SGX MiCS-2714	MOS	uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
SGX MiCS-2710	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
		Air quality egg	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Inter-correlation(r=-0.25-0.22)	Application in in an outdoor, suburban setting	CAIRSENSE project
		M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibrati

											on of Low-cost Gas Sensors for the Monitoring of Air Pollution
SGX MICS-4514-NO2			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
O3 sensors											
Aeroqual O3 S500	gas-sensitive semiconducting		(Bart et al. 2014)		Y	Solar power	26 Routine air quality monitoring stations	May–September 2012	Fit for accurate surface ozone monitoring	Potential application in monitoring in remote areas	na
			(Miskell et al. , Weissert		Y	Solar power	UV photometric	January to	sufficiently precise/ capable of capturing	Spatial variability/ intra-urban variability	na

	oxide (GSS)		et al. 2017b, Williams David et al. 2013)				based ozone analysers	December 2015	wider concentration trends	ofO3 concentrations	
			(Deville Cavellin et al. 2016)		Y			three seasons in 2014	great potential for capturing temporal variability	na	na
			(Lin et al. 2015)		Y	Mains power	UV-absorption reference O3 analyser	> 2 months	potentially useful ambient air monitoring instruments	ambient air monitoring	na
Aeroqual SM50 O3, SM50 SO2	MOS	VIEW	(Ikram et al. 2012a)		Y	Solar panel/battery	standardized environmental pollution sensor equipment		Fit for Urban air pollution monitoring	Urban air pollution monitoring	na
			(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/ >7 months for WSN	Very high inter-correlation(r>0.91)	Application in in an outdoor, suburban setting	CAIRSENSE project
		CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na

Alphasense Ltd OX-B421, SO2-B4	EC		(Castell et al. 2017)	Y	Y	battery	gas standards /CEN reference analyzers	April to September 2015	cross-interferences, effect of temperature and relative humidity	Suit for citizen science applications, unsuitable for air quality legislative compliance applications	The test protocol consists of a multi-point calibration.
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/ Thermo Environmental Instruments (TEI) 49C UV absorption analyser	7/8/2015–25/8/2015	Good agreement (R2> 0.9) between median sensor and reference	na	na
Alphasense O3-B4		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Weak inter-correlation (r=0.39-0.45)	Application in in an outdoor, suburban setting	CAIRSENSE project
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ ozone analyzer Teledyne 400E,	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	V photometry (EN14625)	13th April 2015 to 24th June 2015	significant uncertainties at the individual sensor leve	high-resolution maps of urban air quality at high	

										temporal resolution	
			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
		Modular Sensor System (MSS)	(Yi et al. 2018)	N	Y	two batteries with charging system	Collocated with equipment of authorized agencies	23 days	O3 sensor reacts to both ozone and nitrogen dioxide	R² = 0 with reference value, calibration method is not suitable for this O3 sensor	na
Cair Clip O3/NO2	EC		(Duvall et al. 2016)	Y	Y	solar panel/battery system/wall charge	FRM/FEM analyzers	4–27 September 2013/14 July -12 August 2014	showed little to no agreement with reference data likely	community application	na
			(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate	high inter-correlation(r>0.82)	Application in in an outdoor, suburban setting	CAIRSENSE project

								sensors/>7 months for WSN			
City Technology O3 3E1F,	EC	AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na
SGX MiCS-2614	MOS		(Cao and Thompson 2016b)		Y	battery		January–March of 2015.	Applicable for personal exposure	personal exposure	na
		uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
SGX MiCS-2610	MOS		(Velasco et al. 2016)	Y	Y		local environmental agency		complement official monitoring systems	personal exposure	na
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
SGX MiCS-2611	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na

SGX MiCS-OZ-47			(Hasenfratz et al. 2015b)		Y	Power by streetcar		2 years	Air pollution map	na	na
SO2											
Alphasense SO2-B4	EC	AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	High inter-correlation (r=0.94)	Application in in an outdoor, suburban setting	CAIRSENSE project
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards	7/8/2015–25/8/2015	work in progress	na	na
VOCs											
Applied Sensors iAQ-100	MOS	CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na
Applied Sensors AS-MLV	MOS	EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
Figaro TGS 2201	MOS	EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
Figaro TGS 2602	MOS		(Caron et al. 2016)	Y		na	Ion Flow Tube Mass	na	TGS2602 has a higher sensitivity for	Indoor air quality (IAQ) monitoring	Experimenta

							Spectrometer SIFT-MS		toluene, o-xylene, acetone and acetaldehyde than TGS2620		l protocol
Figaro TGS 2620	MOS		(Caron et al. 2016)	Y		na	Agilent 689N gas phase chromatograph with a flame ionization detector and a mass spectrometer	na	TGS2620 is two times more sensitive to formaldehyde than TGS2602	Indoor air quality (IAQ) monitoring	Experimental protocol
SGX MiCS-5135	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
SGX MiCS-5125--WP	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
SGX MiCS-5521	MOS	AQMesh	(Jiao et al. 2016a, Schneider et al. 2017a)		Y	battery	non-dispersive infrared spectroscopy (EN14626)	13th April 2015 to 24th June 2015	fit if it is a network of sensors	Application in in an outdoor, suburban setting	CAIRSENSE project

Table S4. Performance criteria of sensors/monitors used in testing protocols

	Criteria	**Definition**
	Linearity	Correlation (R^2) between concentrations measured by tested sensor and by standard/reference instruments
	Accuracy	The degree of closeness of concentrations measured by tested sensor to the actual concentration value measured by standard/reference instruments
	Precision	variation around the mean of repeated measurements of the same pollutant concentration
	Response time	The time requires of the tested sensor to respond to changing concentrations
	Detection limit	The lowest concentration of air pollutant that the tested sensor or standard/reference instruments can reliably detect
	Detection range	The nominal minimum and maximum concentrations that the tested sensor is capable of measuring
	Impact of temperature (T)& Relative Humidity (RH)	Positive or negative measurement response caused by variations in T and RH
	Co-pollutant interference	Positive or negative measurement response caused by a pollutant other than the one being measured

Supplementary Information Section 2:
Different principles of gas sensing

Gas sensors can play an important role in the new paradigm of low-cost sensor monitoring (Baron and Saffell 2017) but there are many types of sensors using different technologies and principles (Franke et al. 2006, Korotcenkov 2007, Liu et al. 2012) that are able to provide accurate, stable, high resolution and low cost sensing. Different environmental factors including temperature, humidity, shock and vibrations can influence the sensors performance. Hence, it is essential to consider these parameters when selecting an approach to sensing. In this section, the predominant gas sensing technologies will be briefly presented: conductometric, capacitive, optical spectroscopy, electrochemical potential and current, resonant frequency of acoustic wave devices such as Quartz Crystal Microbalance (QCM).

S2. 1. Conductometric and capacitive methods

Conductometric (resistive) and capacitive transducers are amongst the most commonly applied sensing devices due to their simple and inexpensive fabrication, low production cost, miniaturization and simple operation (Comini 2016, Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Zhang et al. 2015). In a typical conductometric and capacitive sensors, an active sensing material is placed between conducting electrodes (Fig. S1a) or is deposited on interdigital transducers (IDTs) (Fig. S1b), to which a voltage is applied to measure the conductivity or capacitance (Fig. S1a). The interaction between the sensing layer and the target gas molecules takes place on the surface; therefore, the number of atoms present at the sensing layer's surface is critical for the control of the sensing performance. Nanostructured materials have a much larger portion of surface atoms as compared to the bulk atoms, hence gas sensors based on nanostructured materials exhibit enhanced performances (Comini 2016, Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Zhang et al. 2015).

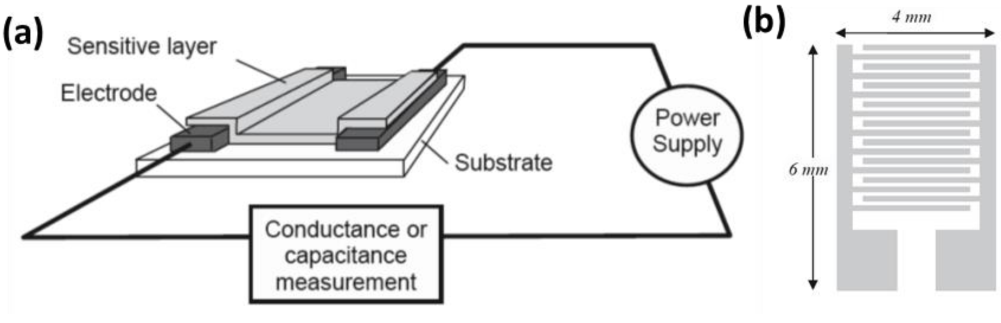


Figure S1. (a) Typical setup for conductometric or capacitive sensing measurements and (b) Interdigital transducer (IDT). [adopted from (Kalantar-Zadeh and Fry 2008)]

The gas sensing mechanism of nanostructured based conductometric sensors have been reviewed by different researchers (Korotcenkov 2007). Here we explain it briefly as the reactions occurring at the surface of the sensitive layer when is exposed to the target gas molecules. It involves adsorption of oxygen on the surface followed by a charge transfer during the reaction of the adsorbed oxygen with the gas molecules. Upon exposure to reducing or oxidizing agents, carriers or electrons transfer into (or binds with) the material, respectively and therefore, results in a measurable change in the electrical properties of the sensitive layer.

It is well known that the surface of sensitive layer (compact or porous) adsorbs oxygen molecules from air and forms O_2^-, O^- and O^{2-} ions by extracting electrons from the conduction band depending on the temperature (Esser and Gopel 1980, Wilson et al. 2001). It was found that oxygen in molecular (O_2^-) and atomic (O^-) forms ionsorb over the metal-oxide surface in the operating temperature ranging between 100 and 500°C (Barsan and Weimar 2001); because O_2^- has a lower activation energy, it is dominates up to about 200°C and at higher temperatures beyond 200°C, the O^- form dominates.

In *n*-type semiconducting oxides, given sufficient adsorption of oxygen, the positively charged oxide surface and negatively charged adsorbed oxygen ions form an effective depletion layer at the surface. This layer causes a decrease in the carrier concentration and consequently an increase in the nanostructures' resistance (Das et al. 2010, Liao et al. 2007). In addition, a high surface to volume ratio in nanostructured morphology provides a large number of surface atoms for interaction, which can lead to the insufficiency of surface atomic coordination and high surface energy (Das et al. 2010, Liao et al. 2007). Therefore, when the surface is highly active, it promotes further adsorption of oxygen from the atmosphere.

As electron depletion occurs at the surface by a chemisorption process, a space charge layer is formed. The thickness of the space charge layer, λ_D (also expressed by the Debye length) is defined using Poisson's equation (Mosely and Tofield 1987):

$$\lambda_D = \frac{Q_S}{eN_D} = \sqrt{\frac{2K\varepsilon_o V_S}{eN_D}} \qquad (1)$$

where N_D is the number of ionized donor states per unit volume, Q_s is the surface charge density, e is the carrier charge, K is the static dielectric constant of the oxide, ε_o is the permittivity of the vacuum and V_s is the surface potential barrier height.

Materials for conductometric/capacitive sensors

Many reports are available in literature on the development of different nanomaterials for gas sensing applications using conductometric or capacitive devices. These nanomaterials include: metal-oxide semiconducting nanomaterials such as SnO_2, TiO_2, ZnO, WO_3, MoO_3, CuO and In_2O_3 (Comini 2016, J. Yu et al. 2009, Shafiei et al. 2011, Shafiei et al. 2010a, Shafiei et al. 2010b, Zhang et al. 2015) ; nanostructured organic semiconductors including polyaniline (PANI), poly(3, 4-ethylenedioxythiophene) (PEDOT), Polydimethylsiloxane (PDMS), Polyepichlorohydrin (PECH), metal-TCNQ and -$TCNQF_4$ (Amírola et al. 2005, F. Hoshyargar et al. 2016, R. Arsat et al. 2011, Shafiei et al. 2015, Zhang et al. 2015); carbon nanostructures (Arsat et al. 2009, Piloto et al. 2016, Piloto et al. 2014, Shafiei et al. 2010a, Zhang et al. 2015). To date, different strategies have been developed in order to improve the sensing performance providing increasing sensitivity, room or low operation temperature and decreasing response kinetics or detection limits. These approaches include surface modification, development of hybrid or composite nanostructures and utilization of photo-illumination. However, there are still challenging issues including selectivity, reproducibility, reliability, and stability which are required to be addressed for commercialization.

S2. 2. Acoustic wave methods: Quartz Crystal Microbalance (QCM)

A very precise method of measuring gas concentrations is to monitor the subtle changes in resonant frequency of an acoustinc resonator exposed to the gas, such as a quartz crystal microbalance (QCM) (Comini et al. 2008, Gründler 2007, Kalantar-zadeh and Fry 2007). QCM is the most promising platform for the development of ultra sensitive gas sensors operating at RT with low fabrication costs (Bahreyni and Shafai 2007, Ding et al. 2009, Khoshaman and Bahreyni 2012, Khoshaman et al. 2012a, Minh et al. 2013a, Wang et al. 2012, Xie et al. 2014, Zheng et al. 2008).

Gas sensors based on QCM offer superior sensitivity and resolution compared to other types of sensors because frequency is a quantity that can be measured with a very high degree of accuracy and precision. QCMs are cost-effective and eliminate the need for time-consuming sample preparation. Other benefits of QCM sensors include their RT operation and simple packaging requirements. QCMs are usually fabricated from thin disks of quartz with circular electrodes patterned on both sides, onto which electrical signals are applied. The piezoelectric crystal transforms the electric signal applied on the metal pads to acoustic waves. In a simplified model due to Sauerbrey (Sauerbrey 1959) the wavelength of the oscillation is half the crystal thickness. The natural frequency of the resonant acoustic waves is determined by the crystal thickness, and when a mass is deposited on the crystal it increases the thickness, increasing the wavelength of the acoustic waves, i.e. decreasing the frequancy, as shown **Error! Reference source not found.**S2.

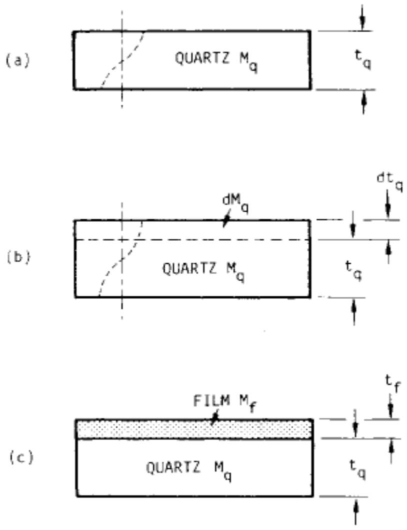


Figure S2. A simplified model of the quartz microbalance (a) at resonance the wavelength is equal to half of the quartz plate thickness (b) an increase of the quartz plate thickness results in a decrease of the resonant frequency (increase of the wavelength). (c) The mass of the deposited film is treated as an equivalent amount of the quartz mass [adapted from (C. Lu and A. W. Czanderna 2012)]

The relationship between the change in the oscillation frequency, Δf of a QCM to the change in mass added to the surface of the crystal, Δm, is given by the *Sauerbrey* equation (Sauerbrey 1959):

$$\Delta f = \frac{-2\Delta m f_0^2}{A\sqrt{\rho u}} = \frac{-2\Delta m f_0^2}{A\rho v} \qquad (2)$$

where f_0 is the resonant frequency of the crystal, A is the area of the crystal, and ρ, u and v are the density, shear modulus and shear wave velocity of the substrate, respectively. As can be seen, any increase in Δm results in a decrease in operational frequency Δf. Clearly, the oscillating frequency dependence on mass change makes the QCM ideally suited for sensing applications. The mass sensitivity can be defined as the change in frequency per change in mass on the unit area of the device. The sensitivity can be enhanced by adding a sensitive layer on its surface. As observed in equation 2, increasing the operational frequency (or the reduction in the crystal thickness) will increase the QCM sensitivity. For a 10 MHz device, the mass detection limit of a QCM can be calculated to be approximately less than 1 ng/cm^2 (Wang and Wu 2012).

Materials for QCM sensors

To date, different type of materials with different morphologies including ZnO nanorods, nanoporous TiO_2, ZnO colloid spheres, polyaniline-TiO_2 composite, and metal organic framework (MOF) crystals have been developed for QCM based gas sensing (Bahreyni and Shafai 2007, Ding et al. 2004, Khoshaman and Bahreyni 2012, Khoshaman et al. 2012b, Minh et al. 2013b, Wang et al. 2012, Xie et al. 2014, Zheng et al. 2008). Electrospun nanofibres such as ZnO (Horzum et al. 2011), TiO_2 (Wang et al. 2012) and organic compounds (polyacrylic acid-polyvinyl alcohol (Ding et al. 2004), polyethyleneimine-polyvinyl alcohol (Wang et al. 2010) and Cyptophane A (Khoshaman et al. 2012b)) have also been employed in the development of QCM based gas sensors. These electrospun nanofibers exhibit enhanced specific surface areas, superior mechanical properties, nano-porosity and improved surface characteristics such as uniformity and stability (Teo and Ramakrishna 2006, Zhang and Yu 2014). Therefore, creating such porous nanostructures provides a great opportunity to adsorb analytes effectively and increase sensitivity due to their remarkable specific surface area and high porosity (~70-90%) (Haghi and Zaikov 2011) attributed to the small and large pores (Ding et al. 2010).

S2. 3. Optical methods

Optical gas sensing is a wide research field under fast development, with the perspective of achieving single molecules detection.

Most optical techniques rely on the general Lambert-Beer law: for a monochromatic incident radiation I_0, delivered through a sample where no chemical changes occurs, is possible to determine the transmitted light as $I = I_0 \exp{(-\alpha\, l)}$, where α is the wavelength-dependant sample absorption coefficient and l is the cell optical pathlength. The interaction with the radiation causes changes in the sample state (a gas or a solid interacting with the gas), which can be used to obtain a precise fingerprint of the gas composition in different region of the electromagnetic spectrum, ranging from the UV to the low IR.

Under this general scenario different spectrophotometric techniques have been developed, the most common being absorbance/transmittance/reflectance, Raman, FTIR spectroscopy and Surface Plasmon Resonance (SPR).

Gas sensors are set to detect a change with respect to a baseline signal due to variation of the gas concentration, so a light source with a narrow linewidth, such as a laser or a LED are ideal to obtain the best sensitivity.

Recent technological development in nanofabrication techniques like sputtering or focused ion beam (FIB) (Chen et al. 2016) opened new avenues in the production of nanostructures with shapes and sizes suitable to harness the localized surface plasmon resonance (LSPR) for gas sensing. The plasmonic effect can be explained with the Drude theory (Drude 1900) as the resonant oscillation of conduction electrons in a metal stimulated by incident light and it is nowadays widely used in gas sensor applications.

A more conventional technique for the direct analysis of gaseous compounds is UV-Vis absorbance or reflectance spectroscopy: it has been used especially for monitoring pollutant gases in the atmosphere such as O_3 and NO_2 (Wu et al. 2006) and volatile organic compound (VOC) (Lin et al. 2004). A typical UV-Vis configuration uses a broadband source, such as a deuterium-tungsten lamp, and allow the selection of a narrow frequency region by a dispersion elements (grating, prism) coupled to a collimator; however also a narrow source as a laser or a LED can be used.

As a matter of fact, the most common spectroscopic measurements of gases are performed in the IR region of the spectrum where the vibrational and rotational transitions are located. The use of IR spectroscopy in gas sensing is optimized in the **Surface Enhanced Raman spectroscopy** (SERS) a powerful surface-sensitive technique that enhances Raman scattering by molecules adsorbed on rough metal surfaces or by nanostructures such as plasmonic nanoparticles; in 2010 Khan and Rae (Rae and Khan 2010) achieved an enhancement factor (EF) of $4x10^5$ for CO and $1x10^5$ for NO at room temperature using a mixture of AgPd nanoparticles as SERS substrate. The choice of the substrate is of paramount importance to get a high EF: recently several research groups (Ling et al. 2009, Qiu et al. 2013) started to use new two-dimensional materials such as graphene as SERS substrate, expecting an enhancement of the effect due to the confinement in two dimensions. Reich et al in 2012 (Heeg et al. 2012) used 100nm long gold nanoparticles separated by 30nm to amplify SERS signal on a suspended layer of graphene, achieving an EF of $4x10^3$. Detection of 600 ppb for toluene and 10 ppm for 1,2Dichlorobenzene has been demonstrated (Myoung et al. 2014) by Hwang et al, using silver nanoparticles on SiO2 encapsulated with 1-propanethiol.

The cavity ringdown spectroscopy is based on the measurement of the time constant in the exponential decay of the light intensity within a cavity formed by highly reflective dielectric mirrors. In 2006 Vogler et al. (Vogler and Sigrist 2006) were able to detect 20 ppb of acetylene in synthetic air and 160 ppb of acetylene in ethylene atmosphere using a near-IR diode laser cavity ringdown spectroscopy.

Fourier transform infrared (FTIR) spectroscopy is another widely used optical technique suitable for sensors applications. Luoh (Luoh and Hahn 2006) was the first to use this technique for gas sensing, by employing a polymer (polyacrylonitrile) as a precursor for nanocomposite fiber mats as a sensitive layer for CO_2. The FTIR sensitivity was enhanced by adding ZnO and Fe_2O_3 nanoparticles to increase the signal to noise ratio. Recent works (Arunajatesan et al. 2007) demonstrate better sensitivity by using different oxide materials with appropriate doping levels. FTIR is an excellent and easy gas sensing method, although it is insensitive to most of the homonuclear molecules who don't have a net charge. Portable commercial FTIR devices are now available, capable to identify the gas through the spectrum fingerprint and to perform a quantitative analysis through a spectral database, although their price is still too high to be used in a wide sensor networks.

Materials for optical sensing

The use of optical fibres is essentially targeted at improving the sensitivity and the speed of analysis (Eckhardt et al. 2007), but they can also be used as gas sensors as demonstrate by Windeler et al. in 2002 (Hoo et al. 2002) who detected acetylene with microstructure optical fibres (MOFs). Different type of structure and materials have been used for gas sensing purposes with the aim of improving the detection limit (Fini 2004, Webb et al. 2007).in particular, a sensitivity of 0.2 and 0.5 ppm for NH_3 and xylene respectively was reached by Wu et al. (Wu et al. 2014) using a microfiber Bragg grating (micro FBG) coated with graphene.

Optical fibres have also been used to enhance the surface plasmonic resonance: a quite reasonable amount of experiments has been done (Hlubina et al. 2014, Hosoki et al. 2013, Tabassum and Gupta 2015) removing the clad from the optical fiber and depositing a sensible layer which contains also metallic nanoparticles that act as probe for SPR. Metal nanoparticles, when excited with an external radiation, are really sensible to the environment so it is possible to convert small variation in the refraction index in a spectral shift (Anker et al. 2008).

In the last few years, a new concept of optical gas sensor is being under development; several groups (Mehta et al. 2016a, Zu et al. 2016) are trying to create nanoscale array and pattern of metal nanoparticles (mostly silver and gold) combined with sensitive materials such as highly pourouse oxides films and two dimensional materials. The concept is taking advantage of the metal structure for exciting the plasmonic resonance and using some particular geometry to create a nano-optical antenna to enhance the signal. Despite the idea is pretty simple, the fabrication and realization is really challenging due to the small dimensions that need to be achieved.

The demonstration of single molecule detection has been achieved by Alivisatos et al. (Liu et al. 2011) who created a tailored nanoantenna made of a single nanoparticle of palladium placed at the focus of a gold triangular-shaped antenna capable to detect a single molecule of H_2 by magnifying the plasmonic resonant shift.

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Supplementary Information Section 3:
Introduction on selected projects using low-cost sensors

Introductory information of the projects presented in section 7. The information was taken from the websites or reports of the relevant projects.

Government funding

1	ARC-LP16: Establishing advanced networks for air quality sensing and analysis
Funding period	**(2017-2020)**
Funding agency	Australian Research Council
Description	The project will deliver innovative, cost-effective, high-resolution air quality networks, and will engage the community in this process. The outcomes will include an open access database and its utilisation for quantification/visualisation of intra-urban air pollution and human exposure and for developing air quality maps and smoke pollution management tools. The benefits will be advancement in the evidence-based management of air as a resource, increasing economic prosperity and enhancing human health and quality of life.
Outcomes	n.a.
Website	https://research.qut.edu.au/ilaqh/projects/establishing-advanced-networks-for-air-quality-sensing-and-analysis/ (Website last updated: n.a.)
Access date	29 November 2017;
2	EuNetAir: European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability
Funding period	**(2012-2016)**
Funding agency	European COST Action
Description	EuNetAir is a European COST Action focused on new sensing technologies for air quality control. It consists of working groups on (i) sensor materials and nanotechnologies; (ii) sensors, devices and systems for air quality control; (iii) environmental measurements and air pollution modelling; (iv) protocols and standardization methods.
Outcomes	EuNetAir project published peer-reviewed articles, newsletters and organized many scientific workshops. This project only tested and

	validated several low-cost sensor packages for commercial usages and therefore had very limited community engagement.
Website	http://www.eunetair.it/ (Website last updated: n.a.)
Access date	29 November 2017;
3	EveryAware: Enhance Environmental Awareness through Social Information Technologies
Funding period	**(2011-2014)**
Funding agency	the European Union's Seventh Framework Programme
Description	EveryAware is an FP7 EU project intending to integrate environmental monitoring, awareness enhancement and behavioural change by creating a new technological platform combining sensing technologies, networking applications and data-processing tools. EveryAware project developed a mobile application to report noise pollution, a low-cost air quality sensor package, and an online game to reduce the gap between researchers and general people which are available on the project website. A sensor box for measuring air quality has been developed within the project. The data recorded by the sensor box can be visualized in the app AirProbe, also developed in the project. The sensor box records the concentration of pollutants in the surrounding environment, marks them with GPS coordinates and sends them continuously to AirProbe. AirProbe actuates as an intermediate point between the data collected from sensor box and the server that stores them. The application is available for Android phones and it is designed to: (i) show information about the current air quality; (ii) record the user trip; (iii) let the user to annotate his/her journey; (iv) let the user see a real time graph showing pollutants, (v) share data on social networks. The parameters recorded are: BC, CO, NO2, O3, VOCs, temperature and humidity. Additionally noise pollution is also targeted in the project. An app has been developed within the project that allows using the phone as a sensor.
Outcomes	This project and its findings were published in peer-reviewed journals. The project was ended in 2014, and currently, there is no observed progress of this project.
Website	http://www.everyaware.eu/ (Website last updated: n.a.)
Access date	29 November 2017;

4	CamMobSens: Cambridge Mobile Urban Sensing
Funding period	**(~ 2010)**
Funding agency	It was part of the MESSAGE project, a collaboration between Cambridge University, Imperial College London, Leeds University, Newcastle University and Southampton University
Description	CamMobSens is an air pollution monitoring initiative by the Cambridge University and it was part of the MESSAGE project (finalized in 2009). The project employs both handheld units carried by pedestrians and slightly larger units fixed to lamp-posts. CamMobSens conducted a large scale deployment, lasting three months, in the greater Cambridge area in the spring/summer of 2010. An extended project has deployed an improved version of these devices, incorporating a novel particulates/aerosol sensor, at ~60 locations around Heathrow airport.
Outcomes	Findings of the project were published peer-reviewed articles.
Website	http://www.escience.cam.ac.uk/mobiledata/ (Website last updated: 2011)
Access date	29 November 2017;
5	Community Air Sensor Network (CAIRSENSE) project
Funding period	**(2013-2016)**
Funding agency	US EPA
Description	To understand the capability of emerging air sensor technology, the Community Air Sensor Network (CAIRSENSE) project deployed low cost, continuous and commercially-available air pollution sensors at a regulatory air monitoring site and as a local sensor network over a surrounding ~2 km area in Southeastern U.S. CAIRSENSE project was funded by US EPA to evaluate the long-term performance of sensors. Co-location of sensors measuring oxides of nitrogen, ozone, carbon monoxide, sulfur dioxide, and particles revealed highly variable performance, both in terms of comparison to a reference monitor as well as whether multiple identical sensors reproduced the same signal.
Outcomes	The project finding was published in a peer-reviewed journal (Jiao et al., 2016) and presented at international conferences

Website	https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=332451 (Website last updated: n.a)
Access date	29 November 2017;
6	CITI-SENSE: Development of Sensor-based Citizens' Observatory Community for Improving Quality of Life in Cities
Funding period	**(2012-2016)**
Funding agency	the European Union's Seventh Framework Programme
Description	CITI-SENSE aims to develop and test an environmental monitoring and information system focused on atmospheric pollution in cities and agglomerations, which will enable citizens to contribute to and participate in environmental governance by using novel technological solutions. This project was designed on three pillars: (i) technological platforms for distributed monitoring; (ii) information and communication technologies; (iii) societal involvement. The project data is available online to all citizens. This project also developed a mobile application, CityAir, in which a user can rate surrounding air quality and post it on an online map. Until now this project published 12 peer-reviewed articles using collected data over the last four years. While the project was completed in 2016, it has now offered a range of tested low-cost sensor packages for both individual and commercial purpose usages, and the collected data can be visualised on a web platform.
Outcomes	The project findings were disseminated through the regular newsletter and workshops as well as published in peer-reviewed journals and at international conferences.
Website	http://www.citi-sense.eu/ (Website last updated: n.a)
Access date	29 November 2017;
7	Citi-Sense-MOB: Mobile services for Environment and Health Citizen's Observatory
Funding period	**(2013-2015)**
Funding agency	European Mobile and Mobility Industries Alliance fund

Description	The aim of CITI-SENSE-MOB is to create and use innovative technology to continuously measure, share and communicate environmental data. By the use of mobile sensing platforms it will contribute to create a dynamic city infrastructure for real-time city management and sustainable progress.
Outcomes	The project delivered a toolbox for better management of air pollution for end-users. Findings were published in peer-reviewed journals and at international conferences.
Website	www.citi-sense-mob.eu/ (Website last updated: n.a)
Access date	29 November 2017;
8	OpenSense: Open sensor networks for air quality monitoring
Funding period	**(2010-2013; 2014-2017**)
Funding agency	Nano-Tera.ch
Description	OpenSense is an open platform whose major scientific objective is to investigate community-based sensing using wireless and mobile sensors to monitor air pollution. In OpenSense sensing units have been deployed and mounted on mobile vehicles (buses) and stationary monitoring stations around the city of Lausanne, Switzerland. The sensor units monitor atmospheric pollutants: O3 (e2V), CO (Alphasense), NO2 (Alphasense), CO2, and ultrafine particles (Matter Aerosol). The measurement platform is based on the prototype platform developed within the projects Nano-Tera5 and XSense6 and further extended for monitoring air pollution. The station supports GPRS/UMTS and WLAN for communication and data transfer, a GPS for location tracking, an accelerometer, and receives the door release signal once installed on a tram to assist recognition of halts and tram stops to minimize position uncertainty. The station is supplied with power from the tram.
Outcomes	The project findings were disseminated through mass media as well as published in peer-reviewed journals and at international conferences.
Website	www.opensense.ethz.ch/ (Website last updated: 03/2016)
Access date	29 November 2017;
9	Community Observation Networks for Air (CONA)

Funding period	**(2015 ~)**
Funding agency	n.a.
Description	“The aim of the CONA projects is to accelerate the reduction of emissions and improvement of air quality. The hypothesis is that this can be achieved by producing more timely monitoring data, for more locations in a form that encourages citizen participation and engagement in the issues. New technologies offer a chance for citizens, businesses and agencies to work together to solve air quality problems. This work has a particular focus on low-cost monitoring, integration of such devices into adaptive monitoring networks, data sharing and ‘data interventions’”
Outcomes	The project progress were disseminated through blog as well as published in peer-reviewed journals.
Website	www.niwa.co.nz/cona (Website last updated: 03/2016)
Access date	29 November 2017;
10	PiMi Airbox: Crowd-sourced Indoor Air-quality Monitoring and Large Sensory Data Mining
Funding period	**(2010-2013)**
Funding agency	n.a.
Description	“PiMi Airbox is a low-cost air quality monitor which creates a crowdsourced map of indoor air pollution in Beijing. PiMi Airbox developed by Tsinghua University. Individual devices achieve a much higher level of accuracy than similar low–cost sensors and they also upload all the data they collect to create a crowdsourced map of indoor air pollution in Beijing.”
Outcomes	The project progress was published in conference proceeding.
Website	http://sensor.ee.tsinghua.edu.cn/ (Website last updated: n.a.) See Li et al. (2014) and (Zheng et al. 2014) for more information.
Access date	25 April 2017; Not accessible when accessed again on 27 March 2018.

11	SmartSantander: Future Internet Research and Experimentation
Funding period	(**2010-2013**)
Funding agency	the European Union's Seventh Framework Programme
Description	“SmartSantander proposes a unique in the world city-scale experimental research facility in support of typical applications and services for a smart city. The project envisions the deployment of 20,000 sensors in Belgrade, Guildford, Lübeck and Santander, exploiting a large variety of technologies. The project is focused on the validation and development of IoT applications and services. The Belgrade pilot utilizes public transportation vehicles in the city of Belgrade and the city of Pancevo to monitor a set of environmental parameters (CO, CO2, NO2, temperature, humidity) over a large area as well as to provide additional information for the end-user like the location of the buses and estimated arrival times to bus stops.”
Outcomes	The project findings were disseminated through mass media, blogs as well as published in peer-reviewed journals and at international conferences.
Website	http://www.smartsantander.eu/ (Website last updated: n.a.)
Access date	29 November 2017;
12	US EPA Village Green
Funding period	(**2013 – 2014; 2015 – 2016; 2017 ~**)
Funding agency	the US EPA
Description	“The Village Green Project is a community-based activity to demonstrate the capabilities of new real-time monitoring technology for residents and citizen scientists to learn about local air quality. The goal of the project is to provide the public and communities with information previously not available about their local air quality and engage communities in air pollution awareness. The US EPA funded Green Village project aimed to develop a low-cost air quality sensing network across parks in the USA powered by wind and solar energy. In this project, local communities actively participated

	as the sensors were installed inside park benches. The local communities can access the real-time air quality measurements online as well as the project data is available online for scientific research. The project is currently ongoing, and US EPA is developing a detail design of this monitoring package and distribute it to everyone for free.”
Outcomes	The project findings were disseminated through website as well as published in peer-reviewed journals and at international conferences.
Website	https://www.epa.gov/air-research/village-green-project (Website last updated: n.a.)
Access date	29 November 2017;
13	US EPA Air Pollution Monitoring for Communities Grants:
Funding period	**(2016-2019)**
Funding agency	the US EPA
Description	“Air sensor technology has advanced rapidly in recent years, providing less expensive, more portable air pollution sensors that can be used by the public to learn about local air quality. The goals of the studies are to address the following questions about the technology and their use by the public: • How accurate and reliable are the sensors used by the public? • What is the quality of the data the sensors produce? • How can sensors be used by communities and individuals to monitor air pollution exposure? • How can the information help communities and individuals understand and reduce harmful air pollution exposures? Researchers conducting the diverse portfolio of studies will work with communities in many states and cities to address local challenges.”
Outcomes	The outcomes of the individual (7) projects findings will be disseminated by the individual research teams.
Website	https://www.epa.gov/air-research/air-pollution-monitoring-communities-grants (Website last updated: n.a.)
Access date	29 November 2017;

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Commercial/crowd-funding projects

1	Air Visual
Starting point	2015
Funding source	Crowd and commercially-funded
Description	“AirVisual provides the world’s #1 international air pollution app, which offers anyone free access to the world’s largest air quality database, spanning 9000+ cities globally. The app and AirVisual website were the very first to offer a 3-day pollution forecast, developed in-house using machine learning and artificial intelligence, which enables you to plan ahead and ensure that your weekly activities are optimized for the healthiest times.” “AirVisual’s air quality monitor, the AirVisual Node, was launched in September 2016 after a successful crowdfunding campaign. The Node brings the latest developments in laser sensor technology and big data within anyone’s reach, as an affordable air monitor with unprecedented accuracy to monitor real-time airborne pollutants, and users can see the air quality parameters real-time on mobile screen. The Node can also be placed outdoors, and with an internet connection can broadcast outdoor conditions onto the global air quality map. The device can provide a 72-hours prediction of air pollution concentrations”
Outcomes	Operating network of AirVisual Nodes with visualized map of air quality status. Air quality forecast function
Website	https://airvisual.com/
Access date	29 November 2017;
2	Air Quality Egg
Starting point	2012
Funding source	Crowd and commercially-funded
Description	“The Air Quality Egg project is not centralized at any institute or university but is instead developed by a community effort, born out of groups from the Internet of Things Meetups in New York City and Amsterdam. Designers, technologist, developers, architects, students and artists form the Air Quality Egg work group, and the community is open and new people can easily join and contribute.

	Air Quality Egg is a commercially available product which can be purchased by anyone and monitor concentrations of airborne pollutants. The users can connect the Egg with Wi-Fi and observe the real-time measurements via phone app as well as share and compare the data with other Egg users. In addition, the users can store and share their data on the Web platform.”
Outcomes	Operating network of Air Quality Eggs with map of air quality status in14 countries.
Website	https://airqualityegg.wickeddevice.com/
Access date	29 November 2017;
3	Aircasting App with Airbeam
Starting point	2012
Funding source	Crowd-funded
Description	“AirCasting is a community-led non-profit, open source air quality sensing network. The Aircasting effort is an open-source solution for collecting and displaying health and environmental data on smartphones. One measurement module is called the Airbeam, and it uses nephelometry to measure fine particulate matter (PM2.5). A Bluetooth connection transmits data at 1 Hz to the Aircasting Android App which maps and graphs resultant data. An interesting feature regarding the Aircasting effort is that it is open-source. This allows developers to easily integrate data from alternate measurement platforms into Aircasting. The AirCasting Air Monitor is equipped with carbon monoxide (CO), nitrogen dioxide (NO2), temperature, and relative humidity sensors that interface with the AirCasting App. Unfortunately, at present the sensors used within this device are not precise enough to report true concentrations of pollutants, but rather measure relative levels. The products include a monitoring device (AirBeam), a mobile application (AirCasting), and wearable LED accessories. It is an open source project so all data is stored online and anyone can access the data. It is an ongoing project, and approximately 1000 devices have been rolled out around the world until now.”
Outcomes	Operating network of Air Beams with map of air quality status.
Website	http://aircasting.org/
Access date	29 November 2017;

4	Purple Air
Starting point	2015
Funding source	Crowd and commercially funded
Description	“Purple Air node is a proven air quality monitoring solution. It uses a new generation of laser particle counters to provide real time measurement of (amongst other data), PM1.0, PM2.5 and PM10. PurpleAir sensors are easy to install, requiring a power outlet and WiFi. They use WiFi to report in real time to the PurpleAir Map. The PurpleAir Map displays the points using the Federal Environmental Protection Agency (EPA) Air Quality Index (AQI) scale. The AQI allows comparison for different pollutants with an easy to visualize color scheme. Data is also available on MesoWest's network and others. Raw data can be shared with researchers upon request..”
Outcomes	Operating network of Purple Air with map of air quality status in >20 countries.
Website	https://www.purpleair.com/
Access date	29 November 2017;
5	SMARTCITIZEN
Starting point	n.a.
Funding source	Crowd and commercially funded
Description	“For the SmartCiti-zen project, and Arduino based sensor module monitors CO, NO2, temperature, humidity, light intensity, and sound levels. Users can stream data to the project website. The device design files and schematics are open-source, allowing users to create their own sensor devices. The SmartCitizen project is a collaborative effort between the Fab Lab of Barcelona at the Institute for Advanced Architecture of Catalonia. Interestingly, this project originated from a Kickstarter campaign in 2013..”
Outcomes	Operating network of sensor kits with map of air quality status. According to the project website, there are currently > 800 sensor modules distributed on all continents except Antarctica
Website	https://smartcitizen.me

Access date	29 November 2017;

Other projects

#	Name	Website	Status
1	HAZEWATCH (**2011 ~**)	http://www2.ee.unsw.edu.au/~vijay /research/pollution/index.html	Non-active
2	OK Lab Stuttgart	http://luftdaten.info	**ACTIVE**
3	Common Sense: participatory urban sensing using a network of handheld air quality monitors	http://www.communitysensing.org/	**Non-active**
4	CitySense: An Open, City-Wide Wireless Sensor Network	http://ieeexplore.ieee.org/abstract/ document/4534518/	**N.A.**
5	CitiSense: Adaptive Services for Community-Driven Behavioral and Environmental Monitoring to Induce Change	https://sosa.ucsd.edu/confluence/	**Non-active**
6	AIR: Area's Immediate Reading	http://blog.nearfuturelaboratory.com/ 2006/09/24/old260/	**Non-active**

Commercial products for individual usage

#	Name	Website	Status
1	Speck movement	https://www.specksensor.com	Active
2	TZOA	http://www.tzoa.com	**Non-active**
3	AIRASSURE (TSI Inc.)	http://www.tsi.com/airassure-pm2-5-indoor-air-quality-monitor-en/	**Active**
4	AQMesh	http://www.aqmesh.com/	**Active**
5	Clarity	https://clarity.io/	**not yet released**
6	uHoo	https://uhooair.com/	**Active**
7	Foobot	https://foobot.io/	**Active**
8	Atmotube	http://atmotube.com/	**Active**
9	Awair	https://getawair.com/	**active**

SUPPLEMENTARY INFORMATION

Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: how far have they gone?

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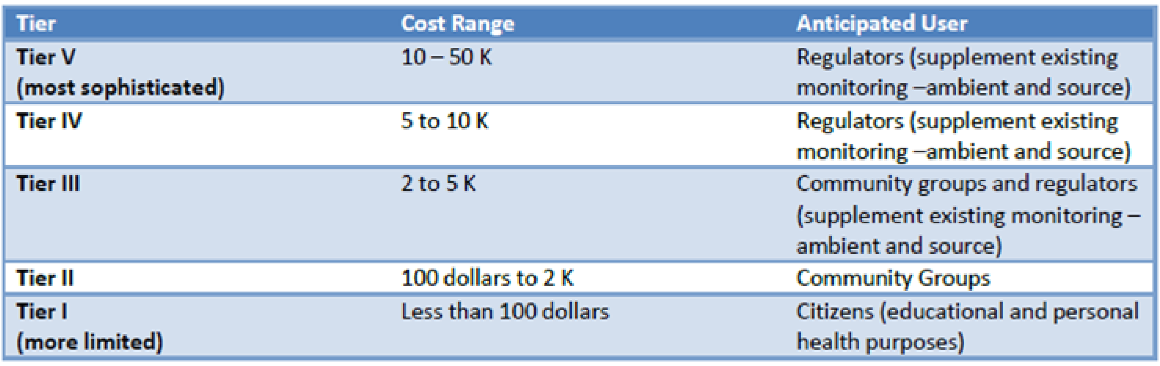
Supplementary Information Section 1: Table S1 – S4

Table S1. Tier uses and users of air monitoring instruments (US EPA, 2013).



Tier	Cost Range	Anticipated User
Tier V (most sophisticated)	10 – 50 K	Regulators (supplement existing monitoring –ambient and source)
Tier IV	5 to 10 K	Regulators (supplement existing monitoring –ambient and source)
Tier III	2 to 5 K	Community groups and regulators (supplement existing monitoring – ambient and source)
Tier II	100 dollars to 2 K	Community Groups
Tier I (more limited)	Less than 100 dollars	Citizens (educational and personal health purposes)

Table S2. Utilisation of low cost particulate matter sensors in different monitors

Sensors	Monitors	Reference	Tests conducted	Aerosol type	Standard method used	Comparison period	Outcome
Sharp GP2Y1010AU0F /Sharp GP2Y1010	PAC MAN	(Olivares et al. 2012)	Field test	Indoor: lounge and kitchen, NZ	TSI AM510 'Sidepak'	27/7-03/8/2011	Preliminary test; can identify the magnitude of indoor emission but cannot identify the sources
	ODIN	(Olivares and Edwards 2015)	Field test	zero response; wood smoke impacted area	air quality monitoring station (TEOM-FDMS)	24/7 – 14/8/ 2014	performance of ODIN is worst for PM2.5 concentrations below 25 μgm−3.
	TSI AirAssure	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	Potential application in tracking air quality in developing countries and heavily polluted areas
	UB AirSense	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Zhuang et al. 2015)	Field test	Indoor and outdoor in different contexts	n.a.	hours	OK for mobile monitoring
	Foobot	(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	can provide reasonable estimates of PM2.5 in the workplace after site-specific calibration
	TECO Enviboard	(Budde et al. 2013)	Lab and Outdoor;	Chalk dust up to 600 mcg/m3 and ambient air	Lab: DustTrak DRX 8533 A; Field: Dustrak and Grimm	Lab/Outdoor; 18 h - 7days (winter 2012/13)	Require collocation with standard device for data quality control

	WSN node	(Tse and Xiao 2016)	Field test	ambient air	Shinyei PPD PMS1 (also a low cost sensor)	hours	n.a.
		(Ali et al. 2015)	Field test	Outdoor in school	n.a.	24h	n.a
	n.a.	(Liu et al. 2017)	Plexiglas chamber	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
Sharp GP & DN	n.a.	(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	having high Sdev; but after calibration could be suitable for occupational setting
Sharp DN7C3JA001	n.a.	(Harada and Matsumoto 2016)		In Japanese			n.a
Sharp DN7C3CA006	n.a.	(Cao and Thompson 2017)	Field test	personal exposure in Texas & Georgia	Grimm 1.109; AirAdvice 7100;	Oct-Nov 2015	could be used to monitor PM depending on performance requirement; not suitable for clean environment
Shinyei PPD-20V	n.a.	(Weekly et al. 2013)	Indoor test	Indoor air	GT-526S laser particle counter (Met-One)	29.5 hours	good potential
Shinyei PPD42NS,	PANDA	(Holstius et al. 2014)	Field test	Ambient, Oakland, California	BAM-1020, Met One; Model 1.108, GRIMM; DustTrak II;	15/04/- - 23/04/ 2013 for 1h data; 01/08-15/11/2013 for 24h data	Useful for enhancing the resolution of PM data. Useful in more polluted region. Temperature and humidity impact.
	Airbox ECN	(Borrego et al. 2016)	Field test	ambient (next to traffic in Portugal)	BAM (Environnemnent MP101M; Verewa F701)	2 weeks in October 2014	Poor performance
		(Hamm et al. 2016)	Field test	Ambient	Met One BAM	n.a.	Regular re-calibration is recommended.
	Air Quality Egg	(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	poor correlation with the FEM (r =−0.06 to 0.40).

	PUWP	(Gao et al. 2015)	Field test	Ambient, Shaanxi, China	TSI DustTrak II Model 8532; Airmetrics MiniVol Tactical Air Sampler; E-BAM	Collocation: 16-20/12/2013	PUWPs show promise as a viable lower cost aerosol sensor
	APOLLO	(Choi et al. 2009)	Sensor building	Ambient air and tobacco smoke	Not available		n.a.
	n.a.	(Austin et al. 2015)	Test chamber (0.3 m3)	polystyrene; polydisperse ASHRAE test dust #1; in lab test	TSI Aerodynamic Particle Sizer (APS) 3321 (0.5–20 microns)	hours	these sensors are appropriate for use as ambient particle counters for low and medium concentrations of respirable particles (< 100 ug/m3)
		(Johnson et al. 2016)	Lab and field tests	Lab: incense smoke Field: Atlanta & Dehli	E-BAM; TEOM; TSI DustTrak 8533 (lab test)	Lab: hours Field: days	Good correlation with E-BAM
		(Kelly et al. 2017)	Wind-tunnel experiments	Alumina dust	Grimm 1.109; DustTrack II 8530	hours	inconclusive
		(Liu et al. 2017)	Lab test	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	application in tracking air quality in developing countries and heavily polluted areas
	excluded	(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Unable to obtain reliable results.
Shinyei PPD60NS,	AirBeam	(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	poor correlation with the FEM

		(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	AirBeam not good for PM conc >200 mg/m3
		(Mukherjee et al. 2017)	Field test	Cuyama Valley in California	GRIMM 11-R; BAM-1020	14 April 2016, to 6 July 2016	useful for the assessment of short-term changes in the aerosol
	n.a.	(Johnson et al. 2016)	Lab and field tests	Lab: incense smoke Field: Atlanta & Dehli	E-BAM; TEOM; TSI DustTrak 8533 (lab test)	Lab: hours Field: days	The PPD42NS sensor has problems with stray light penetration; low R2
Nova SDS011;	n.a.	(Harada and Matsumoto 2016)					In Japanese
Plantower 1003/3003	Purple Air	(Kelly et al. 2017)	Wind-tunnel experiments and field test	Lab: Alumina dust Field: Ambient air	Grimm 1.109; DustTrack II 8530 Field: TEOM	hours	PMS 1003/3003 correlates well with FRMs, FEMs, & research-grade instrumentation
SYhitech DSM501	PiMi	(Li et al. 2014)	Lab test	Arizona dust	TSI-8530	hours	good potential
	Speck	(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	adequate for temporal and spatial trend if properly calibrated
		(Sousan et al. 2017)	Plexiglas chamber (0.2 m3)	salt, welding fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Poorer performance compared to Foobot, no recommended application
		(Zikova et al. 2017)	Field test (indoor & outdoor)	Indoor and outdoor ambient PM	Grimm 1.109; AirAdvice 7100; CO monitor to distinguish sources	Oct-Nov 2015	could be used to monitor PM depending on performance requirement; not suitable for clean environment

Samyoung DSM501A	n.a.	(Liu et al. 2017)	Lab test	Methylene Blue (MB), Fluorescein Sodium (FS) and NaCl	DustTrak 8533; TEOM 1405; PDM3700	hours	proper interpretation of readouts from low-cost optical PM sensors requires users to calibrate them using representative ambient particles
		(Wang et al. 2015)	Acrylic glass chamber (0.1 m3)	Incense burning; Atomized NaCl, sucrose, and NH4NO3 particles; Atomized PSL spheres with 300, 600, 900 nm	SidePak; SMPS;	hours	application in tracking air quality in developing countries and heavily polluted areas
		(Weekly et al. 2013)	Indoor test	Indoor air	GT-526S laser particle counter (Met-One)	29.5 hours	good potential
OPC-N2		(Sousan et al. 2016a)	Lab test	salt, welding fume, and Arizona dust with homogeneity test	Grimm PAS-1.108	hours	good agreement with the reference instruments
		(Crilley et al. 2018)	Field test	Ambient urban background and roadside	TSI 3330; Grimm PAS-1.108	5 weeks + 2 weeks	reasonable agreement for a low-cost sensor to the measured mass concentrations of PM
Dylos DC1100		(Dacunto et al. 2015)	Lab	cigarette, stick incense, fried bacon, fried chicken, and fried hamburger	a Mettler-Toledo M3 microbalance, SidePak	64 experiments	likely most useful for providing instantaneous feedback and context on mass particle levels in home and work situations for field-survey or personal awareness applications.
		(Jiao et al. 2016b)	Field test	State of Georgia monitoring stations	MetOne BAM 1020 FEM PM2.5 monitor	> 7 months at several sites	n.a.
		(Jones et al. 2016)	Field test: indoor	in the farrowing room	an aerosol photometer pDR-1200; A microbalance (MT5, Metler-Toledo,	18 days within 2 months	good correlation but not satisfy EPA and NIOSH criteria --> qualitative monitoring
		(Manikonda et al. 2016)	Air quality chamber (21.4 m^3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	moderate relative precision, adequate for temporal and spatial trend if properly calibrated
Dylos DC1700		(Han et al. 2017)	Field test	backyard of a residential home, Houston, Texas	GRIMM 11-R	12 days December 2015	Low correlation for coarse particles; Hd>60% influence the reading but can be used for large scale campaign.

		(Holstius et al. 2014)	Field test	Ambient, Oakland, California	BAM-1020, Met One; Model 1.108, GRIMM; DustTrak II;	15/04/-23/04/ 2013 for 1h data; 01/08-15/11/2013 for 24h data	Useful for enhancing the resolution of PM data. Useful in more polluted region. Temperature and humidity impact.
		(Jovasevic-Stojanovic et al. 2015)	Lab test Field test	cigarette smoking; ambient (Serbia)	TSI 3330 OPS (lab)/ GRIMM Model 1.108 (field)	Lab: hours Outdoor:2 wks	Good correlation between Dylos and other instruments
		(Manikonda et al. 2016)	Air quality chamber (21.4 m3)	Cigarette smoke; Arizona Test Dust	a Grimm 1.109; an APS 3321; an FMPS 3091	hours	moderate relative precision, adequate for temporal and spatial trend if properly calibrated
		(Semple et al. 2015)	Field test: indoor:	non-smoking and smoking, Scotland	Sidepak AM510	Days in 34 households	may underestimate PM2.5 concentrations towards the higher end (>600 µg/m3), be useful in air quality-based intervention
		(Steinle et al. 2015)	Field test	Individual volunteers in the UK; Outdoor rural, outdoor urban, Indoor, UK	TEOM-FDMS; MARGA-Monitor for Aerosols & Gasses in Ambient Air; OSIRIS Airborne Particle Monitor	10t-15th of April 2013; 30th Sept to 4th Oct 2013	Yes for indoor, No for mobile / personal monitoring
		(Sousan et al. 2016b)	Plexiglas chamber (0.2 m3)	salt, welding & diesel fume, and Arizona dust with homogeneity test	SMPS C5.402; APS 3321; pDR-1500	hours	Useful for in estimating aerosol mass concentration workplace monitoring
		English et al., 2017	Field test Lab test	Details not available	Details not available	Details not available	Used for community network of 40 sites

Table S3. Utilisation of low cost gas sensors in different monitors

Sensors	Measur	Monitor name	Reference	Tests conducted	Power supply	Standard method used	Comparison period	/	Outcocome Fit for	Application in reference	Protocol in

	ing principle			Lab test	Field test				application purpose		Reference
CO sensors											
Alphasense CO-B4	EC		(Castell et al. 2017)	Y	Y	battery	gas standards /CEN reference analyzers	April to September 2015	cross-interferences, effect of temperature and relative humidity	Suit for citizen science applications, unsuitable for air quality legislative compliance applications	The test protocol consists of a multi-point calibration.
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
			(Hasenfratz et al. 2015b)		Y	Power by streetcar		2 years	Air pollution map	na	na
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/ Dual Column SRI 8610C GC	7/8/2015–25/8/2015(20 nodes)	work in progress	na	na
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ CO analyzer Thermo Electron 48c	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		CamPerS	(Jerrett et al. 2017)	Y	Y	battery	Monitor Labs 9830B, Q-trak model 7565	September 2013 and February	variable capacity (NO and CO were measured more	have potential to reduce exposure measurement	Validation protocol

								2014	accurately than NO2,)	error in epidemiological studies and provide valid data for citizen science studies	
		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Good inter-correlation (r=0.79-0.82)	Application in in an outdoor, suburban setting	CAIRSENSE project
		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	non-dispersive infrared spectroscopy (EN14626)	13th April 2015 to 24th June 2015/24 nodes	significant uncertainties at the individual sensor level	high-resolution maps of urban air quality at high temporal resolution	
		(MAS) system	(Sun et al. 2016b)	Y	Y	battery	comparing with AQMS data	16 January 2015 to 18 January 2015	Promising (RH effect)	monitor the air along the Marathon route in urban Hong Kong	na
		Modular Sensor System (MSS)	(Yi et al. 2018)	N	Y	two batteries with charging system	Collocated with equipment of authorized agencies	23 days	Acceptable accuracy	R^2 = 0.91 with reference value, accuracy: ±32 ppb	na
Alphasense CO-AF	EC		(Heimann et al. 2015,	Y	Y	battery	gas standards	2.5 months/ 45 nodes	Feasible for ambient monitoring (NO on NO2 had a	Source attribution	na

			Mead et al. 2013)						cross interference of 1.2%)		
City Technology CO 3E300	EC	AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na
Figaro TGS 2442	MOS	uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
		IPOM	(Rasyid et al. 2016)			battery			Testing process	na	na
Figaro TGS-5042	MOS		(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution

KWJ CO sensor model RCO100F	EC		(Chaiwatpongsakorn et al. 2014)	Y	Y	Solar panel /battery	NDIR Analyzer and gas standard	over two weeks	comparable with the CO-NDIR reference method	Ambient monitoring	na
Membrapor CO/ CF-200	EC	VIEW	(Ikram et al. 2012a)		Y	Solar panel/battery	standardized environmental pollution sensor equipment		Fit for Urban air pollution monitoring	Urban air pollution monitoring	na
SGX MiCS-5521	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
SGX MiCS-5525	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
		Air quality egg	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Poor inter-agreement (r=-0.40—0.17)	Application in in an outdoor, suburban setting	CAIRSENSE project

			(Wen et al. 2013b)		Y	battery		July to September 2010	monitor more detailed air pollutants	na	na
SGX MiCS-4514		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
			(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
NO2/NO sensors											
Aeroqual NO2 series 500	EC		(Delgado-Saborit 2012a)			Battery/wall charge		12th July 2011 to 1st October 2011	Fit for human exposure	Human exposure to combustion related pollutants	Personal exposure protocol
			(Lin et al. 2015)		Y	Mains power	chemiluminescence NO2 analyser	> 2 months	potentially useful ambient air monitoring instruments	ambient air monitoring	na

			(Deville Cavellin et al. 2016)		Y			three seasons in 2014	great potential for capturing temporal variability	na	na
Alphasense Ltd NO-B4 NO2-B42F, NO2-B4/ O3-filtered NO2-B4	EC	Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/(Air Quality Design Inc)	7/8/2015–25/8/2015	work in progress	na	na
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ nitrogen oxides analyzer Teledyne 200E	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		CamPerS	(Jerrett et al. 2017)	Y	Y	battery	Monitor Labs 9830B, Q-trak model 7565	September 2013 and February 2014	variable capacity (NO and CO were measured more accurately than NO2,)	have potential to reduce exposure measurement error in epidemiological studies and provide valid data for citizen science studies	Validation protocol
		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Weak inter-correlation (r=0.14-0.32) for NO2, High correlation (r>0.88) for NO	Application in in an outdoor, suburban setting	CAIRSENSE project

		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	chemiluminescence (EN14211)	13th April 2015 to 24th June 2015	significant uncertainties at the individual sensor level	high-resolution maps of urban air quality at high temporal resolution	na
			(Spinelle et al. 2015, 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
			(Hasenfratz et al. 2015b)	Y	Power by street car		2 years	Air pollution map	na	na	
		(MAS) system	(Sun et al. 2016b)	Y	Y	battery	comparing with AQMS data	16 January 2015 to 18 January 2015	Promising (RH effect)	monitor the air along the Marathon route in urban Hong Kong	na
		Modular Sensor	(Yi et al. 2018)	N	Y	two batteries	Collocated with	23 days	Acceptable accuracy	$R^2 = 0.42$ with reference	na

		System (MSS)				with charging system	equipment of authorized agencies			value, accuracy: ±3 ppb	
Alphasense NO-A1, NO2-A1	EC		(Heimann et al. 2015, Mead et al. 2013)	Y	battery	gas standards	2 months	Feasible for ambient monitoring (NO on NO2 had a cross interference of 1.2%)	Source attribution	na	
AppliedSensors iAQ-100	MOS	CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na
CairClip NO2 sensors	EC		(Duvall et al. 2016)	Y	Y	solar panel/battery system/wall charge	FRM/FEM analyzers	4–27 September 2013/14 July -12 August 2014	showed little to no agreement with reference data likely	community application	na
Cairclip NO2/O3	EC		(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Inter-correlation(r=0.42-0.76)	Application in in an outdoor, suburban setting	CAIRSENSE project
City Technology NO2 3E50, NO 3E100		AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na

			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
			(Spinelle et al. 2017b)		Y	battery	non-Dispersive Infrared Gas-Filter Correlation Spectroscopy Horiba APMA 370	March to July 2014	Fit for indicative methods	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution

Figaro TGS 2106	MOS	GASDAS	(Tsujita et al. 2005)	Y		Batteries/USB/Solar Panels			FIT (Local air pollution)	na	na
SGX MiCS-2714	MOS	uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
SGX MiCS-2710	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
		Air quality egg	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Inter-correlation(r=-0.25-0.22)	Application in in an outdoor, suburban setting	CAIRSENSE project
		M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibrati

											on of Low-cost Gas Sensors for the Monitoring of Air Pollution
SGX MICS-4514-NO2			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
O3 sensors											
Aeroqual O3 S500	gas-sensitive semiconducting		(Bart et al. 2014)		Y	Solar power	26 Routine air quality monitoring stations	May–September 2012	Fit for accurate surface ozone monitoring	Potential application in monitoring in remote areas	na
			(Miskell et al. , Weissert		Y	Solar power	UV photometric	January to	sufficiently precise/ capable of capturing	Spatial variability/ intra-urban variability	na

	oxide (GSS)		et al. 2017b, Williams David et al. 2013)				based ozone analysers	December 2015	wider concentration trends	ofO3 concentrations	
			(Deville Cavellin et al. 2016)		Y			three seasons in 2014	great potential for capturing temporal variability	na	na
			(Lin et al. 2015)		Y	Mains power	UV-absorption reference O3 analyser	> 2 months	potentially useful ambient air monitoring instruments	ambient air monitoring	na
Aeroqual SM50 O3, SM50 SO2	MOS	VIEW	(Ikram et al. 2012a)		Y	Solar panel/battery	standardized environmental pollution sensor equipment		Fit for Urban air pollution monitoring	Urban air pollution monitoring	na
			(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/ >7 months for WSN	Very high inter-correlation(r>0.91)	Application in in an outdoor, suburban setting	CAIRSENSE project
		CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na

Alphasense Ltd OX-B421, SO2-B4	EC		(Castell et al. 2017)	Y	Y	battery	gas standards /CEN reference analyzers	April to September 2015	cross-interferences, effect of temperature and relative humidity	Suit for citizen science applications, unsuitable for air quality legislative compliance applications	The test protocol consists of a multi-point calibration.
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards/ Thermo Environmental Instruments (TEI) 49C UV absorption analyser	7/8/2015–25/8/2015	Good agreement (R2> 0.9) between median sensor and reference	na	na
Alphasense O3-B4		AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	Weak inter-correlation (r=0.39-0.45)	Application in in an outdoor, suburban setting	CAIRSENSE project
		UPOD	(Masson et al. 2015)		Y		regulatory instruments/ ozone analyzer Teledyne 400E,	December of 2013 to November of 2014	Fit for most ambient monitoring	suitable for many ambient monitoring applications	na
		AQMesh v3.5	(Schneider et al. 2017a)		Y	battery	V photometry (EN14625)	13th April 2015 to 24th June 2015	significant uncertainties at the individual sensor leve	high-resolution maps of urban air quality at high	

										temporal resolution	
			(Spinelle et al. 2015)	Y	Y	battery	chemiluminescence Thermo 42C	March to July 2014	High temperature and gases interference	na	European Union: Protocol of Evaluation and Calibration of Low-cost Gas Sensors for the Monitoring of Air Pollution
		Modular Sensor System (MSS)	(Yi et al. 2018)	N	Y	two batteries with charging system	Collocated with equipment of authorized agencies	23 days	O3 sensor reacts to both ozone and nitrogen dioxide	$R^2 = 0$ with reference value, calibration method is not suitable for this O3 sensor	na
Cair Clip O3/NO2	E C		(Duvall et al. 2016)	Y	Y	solar panel/battery system/wall charge	FRM/FEM analyzers	4–27 September 2013/14 July -12 August 2014	showed little to no agreement with reference data likely	community application	na
			(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate	high inter-correlation(r>0.82)	Application in in an outdoor, suburban setting	CAIRSENSE project

								sensors/>7 months for WSN			
City Technology O3 3E1F,	EC	AirSensEUR	(Kotsev et al. 2016)			battery /wall charge	chemiluminescence analyzer/gas standards	~2.5 months	sensitive enough to measure ambient air pollution	na	na
SGX MiCS-2614	MOS		(Cao and Thompson 2016b)		Y	battery		January–March of 2015.	Applicable for personal exposure	personal exposure	na
		uSense	(Brienza et al. 2015)	Y	Y	battery	Known gases/local environmental control authority	1 May 2014-1 June 2014	cooperative air quality monitoring in urban areas	na	na
SGX MiCS-2610	MOS		(Velasco et al. 2016)	Y	Y		local environmental agency		complement official monitoring systems	personal exposure	na
		EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
SGX MiCS-2611	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na

SGX MiCS-OZ-47			(Hasenfratz et al. 2015b)		Y	Power by streetcar		2 years	Air pollution map	na	na
SO2											
Alphasense SO2-B4	EC	AQMesh (Gen. 3)	(Jiao et al. 2016a)		Y	battery	Regulatory monitoring stations	30-day testing period of duplicate or triplicate sensors/>7 months for WSN	High inter-correlation (r=0.94)	Application in in an outdoor, suburban setting	CAIRSENSE project
		Makerbot	(Lewis et al. 2016)	Y	Y		gas standards	7/8/2015–25/8/2015	work in progress	na	na
VOCs											
Applied Sensors iAQ-100	MOS	CanarIT™multi-sensor WDSN nodes	(Moltchanov et al. 2015)		Y		standard AQM station	71 days	possible to identify intra-urban pollutant “hot-spots”	na	na
Applied Sensors AS-MLV	MOS	EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
Figaro TGS 2201	MOS	EveryAware SensorBox	(Elen et al. 2012)		Y	Battery/wall charge			Ozone interference	community-based air quality monitoring	na
Figaro TGS 2602	MOS		(Caron et al. 2016)	Y		na	Ion Flow Tube Mass	na	TGS2602 has a higher sensitivity for	Indoor air quality (IAQ) monitoring	Experimenta

							Spectrometer SIFT-MS		toluene, o-xylene, acetone and acetaldehyde than TGS2620		l protocol
Figaro TGS 2620	MOS		(Caron et al. 2016)	Y		na	Agilent 689N gas phase chromatograph with a flame ionization detector and a mass spectrometer	na	TGS2620 is two times more sensitive to formaldehyde than TGS2602	Indoor air quality (IAQ) monitoring	Experimental protocol
SGX MiCS-5135	MOS	APOLLO	(Choi et al. 2009)			battery			suitable for HVAC	air pollutant monitoring applications	na
SGX MiCS-5125--WP	MOS	M-Pods	(Piedrahita et al. 2014)	Y	Y	battery	gas standards /regulatory monitoring station(gas analyzer)	over 4 weeks	cross-sensitivity effects	na	na
SGX MiCS-5521	MOS	AQMesh	(Jiao et al. 2016a, Schneider et al. 2017a)		Y	battery	non-dispersive infrared spectroscopy (EN14626)	13th April 2015 to 24th June 2015	fit if it is a network of sensors	Application in in an outdoor, suburban setting	CAIRSENSE project

Table S4. Performance criteria of sensors/monitors used in testing protocols

	Criteria	**Definition**
	Linearity	Correlation (R^2) between concentrations measured by tested sensor and by standard/reference instruments
	Accuracy	The degree of closeness of concentrations measured by tested sensor to the actual concentration value measured by standard/reference instruments
	Precision	variation around the mean of repeated measurements of the same pollutant concentration
	Response time	The time requires of the tested sensor to respond to changing concentrations
	Detection limit	The lowest concentration of air pollutant that the tested sensor or standard/reference instruments can reliably detect
	Detection range	The nominal minimum and maximum concentrations that the tested sensor is capable of measuring
	Impact of temperature (T)& Relative Humidity (RH)	Positive or negative measurement response caused by variations in T and RH
	Co-pollutant interference	Positive or negative measurement response caused by a pollutant other than the one being measured

Supplementary Information Section 2:

Different principles of gas sensing

Gas sensors can play an important role in the new paradigm of low-cost sensor monitoring (Baron and Saffell 2017) but there are many types of sensors using different technologies and principles (Franke et al. 2006, Korotcenkov 2007, Liu et al. 2012) that are able to provide accurate, stable, high resolution and low cost sensing. Different environmental factors including temperature, humidity, shock and vibrations can influence the sensors performance. Hence, it is essential to consider these parameters when selecting an approach to sensing. In this section, the predominant gas sensing technologies will be briefly presented: conductometric, capacitive, optical spectroscopy, electrochemical potential and current, resonant frequency of acoustic wave devices such as Quartz Crystal Microbalance (QCM).

S2. 1. Conductometric and capacitive methods

Conductometric (resistive) and capacitive transducers are amongst the most commonly applied sensing devices due to their simple and inexpensive fabrication, low production cost, miniaturization and simple operation (Comini 2016, Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Zhang et al. 2015). In a typical conductometric and capacitive sensors, an active sensing material is placed between conducting electrodes (Fig. S1a) or is deposited on interdigital transducers (IDTs) (Fig. S1b), to which a voltage is applied to measure the conductivity or capacitance (Fig. S1a). The interaction between the sensing layer and the target gas molecules takes place on the surface; therefore, the number of atoms present at the sensing layer's surface is critical for the control of the sensing performance. Nanostructured materials have a much larger portion of surface atoms as compared to the bulk atoms, hence gas sensors based on nanostructured materials exhibit enhanced performances (Comini 2016, Comini et al. 2009, Kalantar-Zadeh and Fry 2008, Zhang et al. 2015).

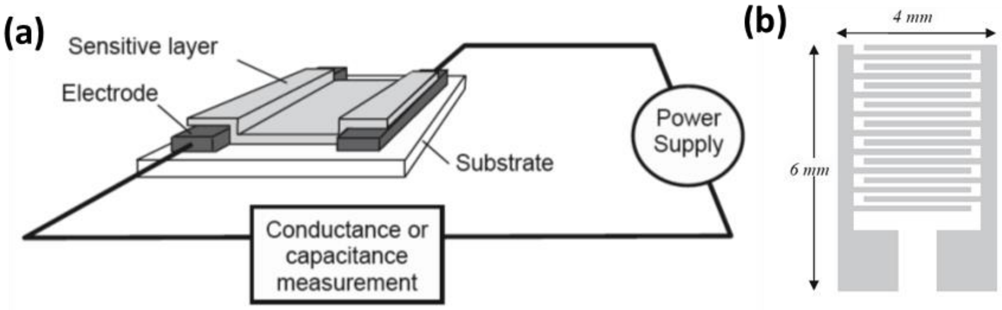


Figure S1. (a) Typical setup for conductometric or capacitive sensing measurements and (b) Interdigital transducer (IDT). [adopted from (Kalantar-Zadeh and Fry 2008)]

The gas sensing mechanism of nanostructured based conductometric sensors have been reviewed by different researchers (Korotcenkov 2007). Here we explain it briefly as the reactions occurring at the surface of the sensitive layer when is exposed to the target gas molecules. It involves adsorption of oxygen on the surface followed by a charge transfer during the reaction of the adsorbed oxygen with the gas molecules. Upon exposure to reducing or oxidizing agents, carriers or electrons transfer into (or binds with) the material, respectively and therefore, results in a measurable change in the electrical properties of the sensitive layer.

It is well known that the surface of sensitive layer (compact or porous) adsorbs oxygen molecules from air and forms O_2^-, O^- and O^{2-} ions by extracting electrons from the conduction band depending on the temperature (Esser and Gopel 1980, Wilson et al. 2001). It was found that oxygen in molecular (O_2^-) and atomic (O^-) forms ionsorb over the metal-oxide surface in the operating temperature ranging between 100 and 500°C (Barsan and Weimar 2001); because O_2^- has a lower activation energy, it is dominates up to about 200°C and at higher temperatures beyond 200°C, the O^- form dominates.

In *n*-type semiconducting oxides, given sufficient adsorption of oxygen, the positively charged oxide surface and negatively charged adsorbed oxygen ions form an effective depletion layer at the surface. This layer causes a decrease in the carrier concentration and consequently an increase in the nanostructures' resistance (Das et al. 2010, Liao et al. 2007). In addition, a high surface to volume ratio in nanostructured morphology provides a large number of surface atoms for interaction, which can lead to the insufficiency of surface atomic coordination and high surface energy (Das et al. 2010, Liao et al. 2007). Therefore, when the surface is highly active, it promotes further adsorption of oxygen from the atmosphere.

As electron depletion occurs at the surface by a chemisorption process, a space charge layer is formed. The thickness of the space charge layer, λ_D (also expressed by the Debye length) is defined using Poisson's equation (Mosely and Tofield 1987):

$$\lambda_D = \frac{Q_S}{eN_D} = \sqrt{\frac{2K\varepsilon_O V_S}{eN_D}} \qquad (1)$$

where N_D is the number of ionized donor states per unit volume, Q_s is the surface charge density, e is the carrier charge, K is the static dielectric constant of the oxide, ε_o is the permittivity of the vacuum and V_s is the surface potential barrier height.

Materials for conductometric/capacitive sensors

Many reports are available in literature on the development of different nanomaterials for gas sensing applications using conductometric or capacitive devices. These nanomaterials include: metal-oxide semiconducting nanomaterials such as SnO_2, TiO_2, ZnO, WO_3, MoO_3, CuO and In_2O_3 (Comini 2016, J. Yu et al. 2009, Shafiei et al. 2011, Shafiei et al. 2010a, Shafiei et al. 2010b, Zhang et al. 2015) ; nanostructured organic semiconductors including polyaniline (PANI), poly(3, 4-ethylenedioxythiophene) (PEDOT), Polydimethylsiloxane (PDMS), Polyepichlorohydrin (PECH), metal-TCNQ and -$TCNQF_4$ (Amírola et al. 2005, F. Hoshyargar et al. 2016, R. Arsat et al.

2011, Shafiei et al. 2015, Zhang et al. 2015); carbon nanostructures (Arsat et al. 2009, Piloto et al. 2016, Piloto et al. 2014, Shafiei et al. 2010a, Zhang et al. 2015). To date, different strategies have been developed in order to improve the sensing performance providing increasing sensitivity, room or low operation temperature and decreasing response kinetics or detection limits. These approaches include surface modification, development of hybrid or composite nanostructures and utilization of photo-illumination. However, there are still challenging issues including selectivity, reproducibility, reliability, and stability which are required to be addressed for commercialization.

S2. 2. Acoustic wave methods: Quartz Crystal Microbalance (QCM)

A very precise method of measuring gas concentrations is to monitor the subtle changes in resonant frequency of an acoustinc resonator exposed to the gas, such as a quartz crystal microbalance (QCM) (Comini et al. 2008, Gründler 2007, Kalantar-zadeh and Fry 2007). QCM is the most promising platform for the development of ultra sensitive gas sensors operating at RT with low fabrication costs (Bahreyni and Shafai 2007, Ding et al. 2009, Khoshaman and Bahreyni 2012, Khoshaman et al. 2012a, Minh et al. 2013a, Wang et al. 2012, Xie et al. 2014, Zheng et al. 2008).

Gas sensors based on QCM offer superior sensitivity and resolution compared to other types of sensors because frequency is a quantity that can be measured with a very high degree of accuracy and precision. QCMs are cost-effective and eliminate the need for time-consuming sample preparation. Other benefits of QCM sensors include their RT operation and simple packaging requirements. QCMs are usually fabricated from thin disks of quartz with circular electrodes patterned on both sides, onto which electrical signals are applied. The piezoelectric crystal transforms the electric signal applied on the metal pads to acoustic waves. In a simplified model due to Sauerbrey (Sauerbrey 1959) the wavelength of the oscillation is half the crystal thickness. The natural frequency of the resonant acoustic waves is determined by the crystal thickness, and when a mass is deposited on the crystal it increases the thickness, increasing the wavelength of the acoustic waves, i.e. decreasing the frequancy, as shown **Error! Reference source not found.**S2.

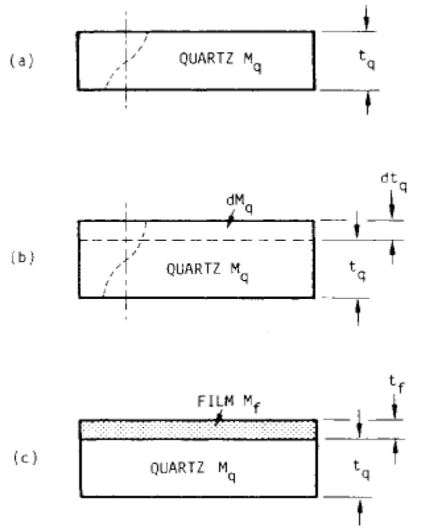


Figure S2. A simplified model of the quartz microbalance (a) at resonance the wavelength is equal to half of the quartz plate thickness (b) an increase of the quartz plate thickness results in a decrease of the resonant frequency (increase of the wavelength). (c) The mass of the deposited film is treated as an equivalent amount of the quartz mass [adapted from (C. Lu and A. W. Czanderna 2012)]

The relationship between the change in the oscillation frequency, Δf of a QCM to the change in mass added to the surface of the crystal, Δm, is given by the *Sauerbrey* equation (Sauerbrey 1959):

$$\Delta f = \frac{-2\Delta m f_0^2}{A\sqrt{\rho u}} = \frac{-2\Delta m f_0^2}{A\rho v} \qquad (2)$$

where f_0 is the resonant frequency of the crystal, A is the area of the crystal, and ρ, u and v are the density, shear modulus and shear wave velocity of the substrate, respectively. As can be seen, any increase in Δm results in a decrease in operational frequency Δf. Clearly, the oscillating frequency dependence on mass change makes the QCM ideally suited for sensing applications. The mass sensitivity can be defined as the change in frequency per change in mass on the unit area of the device. The sensitivity can be enhanced by adding a sensitive layer on its surface. As observed in equation 2, increasing the operational frequency (or the reduction in the crystal thickness) will increase the QCM sensitivity. For a 10 MHz device, the mass detection limit of a QCM can be calculated to be approximately less than 1 ng/cm^2 (Wang and Wu 2012).

Materials for QCM sensors

To date, different type of materials with different morphologies including ZnO nanorods, nanoporous TiO_2, ZnO colloid spheres, polyaniline-TiO_2 composite, and metal organic framework (MOF) crystals have been developed for QCM based gas sensing (Bahreyni and Shafai 2007, Ding et al. 2004, Khoshaman and Bahreyni 2012, Khoshaman et al. 2012b, Minh et al. 2013b, Wang et al. 2012, Xie et al. 2014, Zheng et al. 2008). Electrospun nanofibres such as ZnO (Horzum et al. 2011), TiO_2 (Wang et al. 2012) and organic compounds (polyacrylic acid-polyvinyl alcohol (Ding et al.

2004), polyethyleneimine-polyvinyl alcohol (Wang et al. 2010) and Cyptophane A (Khoshaman et al. 2012b)) have also been employed in the development of QCM based gas sensors. These electrospun nanofibers exhibit enhanced specific surface areas, superior mechanical properties, nano-porosity and improved surface characteristics such as uniformity and stability (Teo and Ramakrishna 2006, Zhang and Yu 2014). Therefore, creating such porous nanostructures provides a great opportunity to adsorb analytes effectively and increase sensitivity due to their remarkable specific surface area and high porosity (~70-90%) (Haghi and Zaikov 2011) attributed to the small and large pores (Ding et al. 2010).

S2. 3. Optical methods

Optical gas sensing is a wide research field under fast development, with the perspective of achieving single molecules detection.

Most optical techniques rely on the general Lambert-Beer law: for a monochromatic incident radiation I_0, delivered through a sample where no chemical changes occurs, is possible to determine the transmitted light as $I = I_0 \exp(-\alpha\, l)$, where α is the wavelength-dependant sample absorption coefficient and l is the cell optical pathlength. The interaction with the radiation causes changes in the sample state (a gas or a solid interacting with the gas), which can be used to obtain a precise fingerprint of the gas composition in different region of the electromagnetic spectrum, ranging from the UV to the low IR.

Under this general scenario different spectrophotometric techniques have been developed, the most common being absorbance/transmittance/reflectance, Raman, FTIR spectroscopy and Surface Plasmon Resonance (SPR).

Gas sensors are set to detect a change with respect to a baseline signal due to variation of the gas concentration, so a light source with a narrow linewidth, such as a laser or a LED are ideal to obtain the best sensitivity.

Recent technological development in nanofabrication techniques like sputtering or focused ion beam (FIB) (Chen et al. 2016) opened new avenues in the production of nanostructures with shapes and sizes suitable to harness the localized surface plasmon resonance (LSPR) for gas sensing. The plasmonic effect can be explained with the Drude theory (Drude 1900) as the resonant oscillation of conduction electrons in a metal stimulated by incident light and it is nowadays widely used in gas sensor applications.

A more conventional technique for the direct analysis of gaseous compounds is UV-Vis absorbance or reflectance spectroscopy: it has been used especially for monitoring pollutant gases in the atmosphere such as O_3 and NO_2 (Wu et al. 2006) and volatile organic compound (VOC) (Lin et al. 2004). A typical UV-Vis configuration uses a broadband source, such as a deuterium-tungsten lamp, and allow the selection of a narrow frequency region by a dispersion elements (grating, prism) coupled to a collimator; however also a narrow source as a laser or a LED can be used.

As a matter of fact, the most common spectroscopic measurements of gases are performed in the IR region of the spectrum where the vibrational and rotational transitions are located. The use of IR spectroscopy in gas sensing is optimized in the **Surface Enhanced Raman spectroscopy** (SERS) a powerful surface-sensitive technique that enhances Raman scattering by molecules adsorbed on rough metal surfaces or by nanostructures such as plasmonic nanoparticles; in 2010 Khan and Rae (Rae and Khan 2010) achieved an enhancement factor (EF) of $4x10^5$ for CO and $1x10^5$ for NO at room temperature using a mixture of AgPd nanoparticles as SERS substrate. The choice of the substrate is of paramount importance to get a high EF: recently several research groups (Ling et al. 2009, Qiu et al. 2013) started to use new two-dimensional materials such as graphene as SERS substrate, expecting an enhancement of the effect due to the confinement in two dimensions. Reich et al in 2012 (Heeg et al. 2012) used 100nm long gold nanoparticles separated by 30nm to amplify SERS signal on a suspended layer of graphene, achieving an EF of $4x10^3$. Detection of 600 ppb for toluene and 10 ppm for 1,2Dichlorobenzene has been demonstrated (Myoung et al. 2014) by Hwang et al, using silver nanoparticles on SiO2 encapsulated with 1-propanethiol.

The cavity ringdown spectroscopy is based on the measurement of the time constant in the exponential decay of the light intensity within a cavity formed by highly reflective dielectric mirrors. In 2006 Vogler et al. (Vogler and Sigrist 2006) were able to detect 20 ppb of acetylene in synthetic air and 160 ppb of acetylene in ethylene atmosphere using a near-IR diode laser cavity ringdown spectroscopy.

Fourier transform infrared (FTIR) spectroscopy is another widely used optical technique suitable for sensors applications. Luoh (Luoh and Hahn 2006) was the first to use this technique for gas sensing, by employing a polymer (polyacrylonitrile) as a precursor for nanocomposite fiber mats as a sensitive layer for CO_2. The FTIR sensitivity was enhanced by adding ZnO and Fe_2O_3 nanoparticles to increase the signal to noise ratio. Recent works (Arunajatesan et al. 2007) demonstrate better sensitivity by using different oxide materials with appropriate doping levels. FTIR is an excellent and easy gas sensing method, although it is insensitive to most of the homonuclear molecules who don’t have a net charge. Portable commercial FTIR devices are now available, capable to identify the gas through the spectrum fingerprint and to perform a quantitative analysis through a spectral database, although their price is still too high to be used in a wide sensor networks.

Materials for optical sensing

The use of optical fibres is essentially targeted at improving the sensitivity and the speed of analysis (Eckhardt et al. 2007), but they can also be used as gas sensors as demonstrate by Windeler et al. in 2002 (Hoo et al. 2002) who detected acetylene with microstructure optical fibres (MOFs).

Different type of structure and materials have been used for gas sensing purposes with the aim of improving the detection limit (Fini 2004, Webb et al. 2007).in particular, a sensitivity of 0.2 and 0.5 ppm for NH_3 and xylene respectively was reached by Wu et al. (Wu et al. 2014) using a microfiber Bragg grating (micro FBG) coated with graphene.

Optical fibres have also been used to enhance the surface plasmonic resonance: a quite reasonable amount of experiments has been done (Hlubina et al. 2014, Hosoki et al. 2013, Tabassum and Gupta 2015) removing the clad from the optical fiber and depositing a sensible layer which contains also metallic nanoparticles that act as probe for SPR. Metal nanoparticles, when excited with an external radiation, are really sensible to the environment so it is possible to convert small variation in the refraction index in a spectral shift (Anker et al. 2008).

In the last few years, a new concept of optical gas sensor is being under development; several groups (Mehta et al. 2016a, Zu et al. 2016) are trying to create nanoscale array and pattern of metal nanoparticles (mostly silver and gold) combined with sensitive materials such as highly pourouse oxides films and two dimensional materials. The concept is taking advantage of the metal structure for exciting the plasmonic resonance and using some particular geometry to create a nano-optical antenna to enhance the signal. Despite the idea is pretty simple, the fabrication and realization is really challenging due to the small dimensions that need to be achieved.

The demonstration of single molecule detection has been achieved by Alivisatos et al. (Liu et al. 2011) who created a tailored nanoantenna made of a single nanoparticle of palladium placed at the focus of a gold triangular-shaped antenna capable to detect a single molecule of H_2 by magnifying the plasmonic resonant shift.

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Supplementary Information Section 3:

Introduction on selected projects using low-cost sensors

Introductory information of the projects presented in section 7. The information was taken from the websites or reports of the relevant projects.

Government funding

1	ARC-LP16: Establishing advanced networks for air quality sensing and analysis
Funding period	**(2017-2020)**
Funding agency	Australian Research Council
Description	The project will deliver innovative, cost-effective, high-resolution air quality networks, and will engage the community in this process. The outcomes will include an open access database and its utilisation for quantification/visualisation of intra-urban air pollution and human exposure and for developing air quality maps and smoke pollution management tools. The benefits will be advancement in the evidence-based management of air as a resource, increasing economic prosperity and enhancing human health and quality of life.
Outcomes	n.a.
Website	https://research.qut.edu.au/ilaqh/projects/establishing-advanced-networks-for-air-quality-sensing-and-analysis/ (Website last updated: n.a.)
Access date	29 November 2017;
2	EuNetAir: European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability
Funding period	**(2012-2016)**
Funding agency	European COST Action
Description	EuNetAir is a European COST Action focused on new sensing technologies for air quality control. It consists of working groups on (i) sensor materials and nanotechnologies; (ii) sensors, devices and systems for air quality control; (iii) environmental measurements and air pollution modelling; (iv) protocols and standardization methods.
Outcomes	EuNetAir project published peer-reviewed articles, newsletters and organized many scientific workshops. This project only tested and validated several low-cost sensor packages for commercial usages and therefore had very limited community engagement.
Website	http://www.eunetair.it/ (Website last updated: n.a.)

Access date	29 November 2017;
3	EveryAware: Enhance Environmental Awareness through Social Information Technologies
Funding period	**(2011-2014)**
Funding agency	the European Union's Seventh Framework Programme
Description	EveryAware is an FP7 EU project intending to integrate environmental monitoring, awareness enhancement and behavioural change by creating a new technological platform combining sensing technologies, networking applications and data-processing tools. EveryAware project developed a mobile application to report noise pollution, a low-cost air quality sensor package, and an online game to reduce the gap between researchers and general people which are available on the project website. A sensor box for measuring air quality has been developed within the project. The data recorded by the sensor box can be visualized in the app AirProbe, also developed in the project. The sensor box records the concentration of pollutants in the surrounding environment, marks them with GPS coordinates and sends them continuously to AirProbe. AirProbe actuates as an intermediate point between the data collected from sensor box and the server that stores them. The application is available for Android phones and it is designed to: (i) show information about the current air quality; (ii) record the user trip; (iii) let the user to annotate his/her journey; (iv) let the user see a real time graph showing pollutants, (v) share data on social networks. The parameters recorded are: BC, CO, NO2, O3, VOCs, temperature and humidity. Additionally noise pollution is also targeted in the project. An app has been developed within the project that allows using the phone as a sensor.
Outcomes	This project and its findings were published in peer-reviewed journals. The project was ended in 2014, and currently, there is no observed progress of this project.
Website	http://www.everyaware.eu/ (Website last updated: n.a.)
Access date	29 November 2017;
4	CamMobSens: Cambridge Mobile Urban Sensing
Funding period	**(~ 2010)**
Funding agency	It was part of the MESSAGE project, a collaboration between Cambridge University, Imperial College London, Leeds University, Newcastle University and Southampton University
Description	CamMobSens is an air pollution monitoring initiative by the Cambridge University and it was part of the MESSAGE project (finalized in 2009). The project employs both handheld units carried by pedestrians and slightly larger units fixed to lamp-posts. CamMobSens conducted a large scale deployment, lasting three months, in the greater Cambridge area in the spring/summer of

	2010. An extended project has deployed an improved version of these devices, incorporating a novel particulates/aerosol sensor, at ~60 locations around Heathrow airport.
Outcomes	Findings of the project were published peer-reviewed articles.
Website	http://www.escience.cam.ac.uk/mobiledata/ (Website last updated: 2011)
Access date	29 November 2017;
5	Community Air Sensor Network (CAIRSENSE) project
Funding period	(**2013-2016**)
Funding agency	US EPA
Description	To understand the capability of emerging air sensor technology, the Community Air Sensor Network (CAIRSENSE) project deployed low cost, continuous and commercially-available air pollution sensors at a regulatory air monitoring site and as a local sensor network over a surrounding ~2 km area in Southeastern U.S. CAIRSENSE project was funded by US EPA to evaluate the long-term performance of sensors. Co-location of sensors measuring oxides of nitrogen, ozone, carbon monoxide, sulfur dioxide, and particles revealed highly variable performance, both in terms of comparison to a reference monitor as well as whether multiple identical sensors reproduced the same signal.
Outcomes	The project finding was published in a peer-reviewed journal (Jiao et al., 2016) and presented at international conferences
Website	https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=332451 (Website last updated: n.a)
Access date	29 November 2017;
6	CITI-SENSE: Development of Sensor-based Citizens' Observatory Community for Improving Quality of Life in Cities
Funding period	**(2012-2016)**
Funding agency	the European Union's Seventh Framework Programme
Description	CITI-SENSE aims to develop and test an environmental monitoring and information system focused on atmospheric pollution in cities and agglomerations, which will enable citizens to contribute to and participate in environmental governance by using novel technological solutions. This project was designed on three pillars: (i) technological platforms for distributed monitoring; (ii) information and communication technologies; (iii) societal involvement. The project data is available online to all citizens. This project

	also developed a mobile application, CityAir, in which a user can rate surrounding air quality and post it on an online map. Until now this project published 12 peer-reviewed articles using collected data over the last four years. While the project was completed in 2016, it has now offered a range of tested low-cost sensor packages for both individual and commercial purpose usages, and the collected data can be visualised on a web platform.
Outcomes	The project findings were disseminated through the regular newsletter and workshops as well as published in peer-reviewed journals and at international conferences.
Website	http://www.citi-sense.eu/ (Website last updated: n.a)
Access date	29 November 2017;
7	Citi-Sense-MOB: Mobile services for Environment and Health Citizen's Observatory
Funding period	**(2013-2015)**
Funding agency	European Mobile and Mobility Industries Alliance fund
Description	The aim of CITI-SENSE-MOB is to create and use innovative technology to continuously measure, share and communicate environmental data. By the use of mobile sensing platforms it will contribute to create a dynamic city infrastructure for real-time city management and sustainable progress.
Outcomes	The project delivered a toolbox for better management of air pollution for end-users. Findings were published in peer-reviewed journals and at international conferences.
Website	www.citi-sense-mob.eu/ (Website last updated: n.a)
Access date	29 November 2017;
8	OpenSense: Open sensor networks for air quality monitoring
Funding period	(**2010-2013; 2014-2017**)
Funding agency	Nano-Tera.ch
Description	OpenSense is an open platform whose major scientific objective is to investigate community-based sensing using wireless and mobile sensors to monitor air pollution. In OpenSense sensing units have been deployed and mounted on mobile vehicles (buses) and stationary monitoring stations around the city of Lausanne, Switzerland. The sensor units monitor atmospheric pollutants: O3 (e2V), CO (Alphasense), NO2 (Alphasense), CO2, and ultrafine particles (Matter Aerosol). The measurement platform is based on the prototype platform developed within the projects Nano-Tera5 and XSense6 and further

	extended for monitoring air pollution. The station supports GPRS/UMTS and WLAN for communication and data transfer, a GPS for location tracking, an accelerometer, and receives the door release signal once installed on a tram to assist recognition of halts and tram stops to minimize position uncertainty. The station is supplied with power from the tram.
Outcomes	The project findings were disseminated through mass media as well as published in peer-reviewed journals and at international conferences.
Website	www.opensense.ethz.ch/ (Website last updated: 03/2016)
Access date	29 November 2017;
9	Community Observation Networks for Air (CONA)
Funding period	**(2015 ~)**
Funding agency	n.a.
Description	"The aim of the CONA projects is to accelerate the reduction of emissions and improvement of air quality. The hypothesis is that this can be achieved by producing more timely monitoring data, for more locations in a form that encourages citizen participation and engagement in the issues. New technologies offer a chance for citizens, businesses and agencies to work together to solve air quality problems. This work has a particular focus on low-cost monitoring, integration of such devices into adaptive monitoring networks, data sharing and 'data interventions'"
Outcomes	The project progress were disseminated through blog as well as published in peer-reviewed journals.
Website	www.niwa.co.nz/cona (Website last updated: 03/2016)
Access date	29 November 2017;
10	PiMi Airbox: Crowd-sourced Indoor Air-quality Monitoring and Large Sensory Data Mining
Funding period	(**2010-2013**)
Funding agency	n.a.
Description	"PiMi Airbox is a low-cost air quality monitor which creates a crowdsourced map of indoor air pollution in Beijing. PiMi Airbox developed by Tsinghua University. Individual devices achieve a much higher level of

	accuracy than similar low–cost sensors and they also upload all the data they collect to create a crowdsourced map of indoor air pollution in Beijing.”
Outcomes	The project progress was published in conference proceeding.
Website	http://sensor.ee.tsinghua.edu.cn/ (Website last updated: n.a.) See Li et al. (2014) and (Zheng et al. 2014) for more information.
Access date	25 April 2017; Not accessible when accessed again on 27 March 2018.
11	SmartSantander: Future Internet Research and Experimentation
Funding period	(**2010-2013**)
Funding agency	the European Union's Seventh Framework Programme
Description	“SmartSantander proposes a unique in the world city-scale experimental research facility in support of typical applications and services for a smart city. The project envisions the deployment of 20,000 sensors in Belgrade, Guildford, Lübeck and Santander, exploiting a large variety of technologies. The project is focused on the validation and development of IoT applications and services. The Belgrade pilot utilizes public transportation vehicles in the city of Belgrade and the city of Pancevo to monitor a set of environmental parameters (CO, CO2, NO2, temperature, humidity) over a large area as well as to provide additional information for the end-user like the location of the buses and estimated arrival times to bus stops.”
Outcomes	The project findings were disseminated through mass media, blogs as well as published in peer-reviewed journals and at international conferences.
Website	http://www.smartsantander.eu/ (Website last updated: n.a.)
Access date	29 November 2017;
12	US EPA Village Green
Funding period	(**2013 – 2014; 2015 – 2016; 2017 ~**)
Funding agency	the US EPA
Description	“The Village Green Project is a community-based activity to demonstrate the capabilities of new real-time monitoring technology for residents and citizen scientists to learn about local air quality. The goal of the project is to provide the public and communities with information previously not available about their local air quality and engage communities in air pollution awareness. The US EPA funded Green Village project aimed to develop a low-cost air quality sensing network across parks in the USA powered by wind and solar

	energy. In this project, local communities actively participated as the sensors were installed inside park benches. The local communities can access the real-time air quality measurements online as well as the project data is available online for scientific research. The project is currently ongoing, and US EPA is developing a detail design of this monitoring package and distribute it to everyone for free.”
Outcomes	The project findings were disseminated through website as well as published in peer-reviewed journals and at international conferences.
Website	https://www.epa.gov/air-research/village-green-project (Website last updated: n.a.)
Access date	29 November 2017;
13	US EPA Air Pollution Monitoring for Communities Grants:
Funding period	(**2016-2019**)
Funding agency	the US EPA
Description	“Air sensor technology has advanced rapidly in recent years, providing less expensive, more portable air pollution sensors that can be used by the public to learn about local air quality. The goals of the studies are to address the following questions about the technology and their use by the public: • How accurate and reliable are the sensors used by the public? • What is the quality of the data the sensors produce? • How can sensors be used by communities and individuals to monitor air pollution exposure? • How can the information help communities and individuals understand and reduce harmful air pollution exposures? Researchers conducting the diverse portfolio of studies will work with communities in many states and cities to address local challenges.”
Outcomes	The outcomes of the individual (7) projects findings will be disseminated by the individual research teams.
Website	https://www.epa.gov/air-research/air-pollution-monitoring-communities-grants (Website last updated: n.a.)
Access date	29 November 2017;

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Commercial/crowd-funding projects

1	Air Visual

Starting point	2015
Funding source	Crowd and commercially-funded
Description	“AirVisual provides the world’s #1 international air pollution app, which offers anyone free access to the world’s largest air quality database, spanning 9000+ cities globally. The app and AirVisual website were the very first to offer a 3-day pollution forecast, developed in-house using machine learning and artificial intelligence, which enables you to plan ahead and ensure that your weekly activities are optimized for the healthiest times.” “AirVisual’s air quality monitor, the AirVisual Node, was launched in September 2016 after a successful crowdfunding campaign. The Node brings the latest developments in laser sensor technology and big data within anyone’s reach, as an affordable air monitor with unprecedented accuracy to monitor real-time airborne pollutants, and users can see the air quality parameters real-time on mobile screen. The Node can also be placed outdoors, and with an internet connection can broadcast outdoor conditions onto the global air quality map. The device can provide a 72-hours prediction of air pollution concentrations”
Outcomes	Operating network of AirVisual Nodes with visualized map of air quality status. Air quality forecast function
Website	https://airvisual.com/
Access date	29 November 2017;
2	Air Quality Egg
Starting point	2012
Funding source	Crowd and commercially-funded
Description	“The Air Quality Egg project is not centralized at any institute or university but is instead developed by a community effort, born out of groups from the Internet of Things Meetups in New York City and Amsterdam. Designers, technologist, developers, architects, students and artists form the Air Quality Egg work group, and the community is open and new people can easily join and contribute. Air Quality Egg is a commercially available product which can be purchased by anyone and monitor concentrations of airborne pollutants. The users can connect the Egg with Wi-Fi and observe the real-time measurements via phone app as well as share and compare the data with other Egg users. In addition, the users can store and share their data on the Web platform.”

Outcomes	Operating network of Air Quality Eggs with map of air quality status in14 countries.
Website	https://airqualityegg.wickeddevice.com/
Access date	29 November 2017;
3	Aircasting App with Airbeam
Starting point	2012
Funding source	Crowd-funded
Description	“AirCasting is a community-led non-profit, open source air quality sensing network. The Aircasting effort is an open-source solution for collecting and displaying health and environmental data on smartphones. One measurement module is called the Airbeam, and it uses nephelometry to measure fine particulate matter (PM2.5). A Bluetooth connection transmits data at 1 Hz to the Aircasting Android App which maps and graphs resultant data. An interesting feature regarding the Aircasting effort is that it is open-source. This allows developers to easily integrate data from alternate measurement platforms into Aircasting. The AirCasting Air Monitor is equipped with carbon monoxide (CO), nitrogen dioxide (NO2), temperature, and relative humidity sensors that interface with the AirCasting App. Unfortunately, at present the sensors used within this device are not precise enough to report true concentrations of pollutants, but rather measure relative levels. The products include a monitoring device (AirBeam), a mobile application (AirCasting), and wearable LED accessories. It is an open source project so all data is stored online and anyone can access the data. It is an ongoing project, and approximately 1000 devices have been rolled out around the world until now.”
Outcomes	Operating network of Air Beams with map of air quality status.
Website	http://aircasting.org/
Access date	29 November 2017;
4	Purple Air
Starting point	2015
Funding source	Crowd and commercially funded
Description	“Purple Air node is a proven air quality monitoring solution. It uses a new generation of laser particle counters to provide real time measurement of (amongst other data), PM1.0, PM2.5 and PM10. PurpleAir sensors are easy

	to install, requiring a power outlet and WiFi. They use WiFi to report in real time to the PurpleAir Map. The PurpleAir Map displays the points using the Federal Environmental Protection Agency (EPA) Air Quality Index (AQI) scale. The AQI allows comparison for different pollutants with an easy to visualize color scheme. Data is also available on MesoWest's network and others. Raw data can be shared with researchers upon request..”
Outcomes	Operating network of Purple Air with map of air quality status in >20 countries.
Website	https://www.purpleair.com/
Access date	29 November 2017;
5	SMARTCITIZEN
Starting point	n.a.
Funding source	Crowd and commercially funded
Description	“For the SmartCiti-zen project, and Arduino based sensor module monitors CO, NO2, temperature, humidity, light intensity, and sound levels. Users can stream data to the project website. The device design files and schematics are open-source, allowing users to create their own sensor devices. The SmartCitizen project is a collaborative effort between the Fab Lab of Barcelona at the Institute for Advanced Architecture of Catalonia. Interestingly, this project originated from a Kickstarter campaign in 2013..”
Outcomes	Operating network of sensor kits with map of air quality status. According to the project website, there are currently > 800 sensor modules distributed on all continents except Antarctica
Website	https://smartcitizen.me
Access date	29 November 2017;

Other projects

#	Name	Website	Status
1	HAZEWATCH (**2011 ~**)	http://www2.ee.unsw.edu.au/~vijay/research/pollution/index.html	Non-active
2	OK Lab Stuttgart	http://luftdaten.info	**ACTIVE**

3	Common Sense: participatory urban sensing using a network of handheld air quality monitors	http://www.communitysensing.org/	**Non-active**
4	CitySense: An Open, City-Wide Wireless Sensor Network	http://ieeexplore.ieee.org/abstract/document/4534518/	**N.A.**
5	CitiSense: Adaptive Services for Community-Driven Behavioral and Environmental Monitoring to Induce Change	https://sosa.ucsd.edu/confluence/	**Non-active**
6	AIR: Area's Immediate Reading	http://blog.nearfuturelaboratory.com/2006/09/24/old260/	**Non-active**

Commercial products for individual usage

#	Name	Website	Status
1	Speck movement	https://www.specksensor.com	Active
2	TZOA	http://www.tzoa.com	**Non-active**
3	AIRASSURE (TSI Inc.)	http://www.tsi.com/airassure-pm2-5-indoor-air-quality-monitor-en/	**Active**
4	AQMesh	http://www.aqmesh.com/	**Active**
5	Clarity	https://clarity.io/	**not yet released**
6	uHoo	https://uhooair.com/	**Active**

7	Foobot	https://foobot.io/	**Active**
8	Atmotube	http://atmotube.com/	**Active**
9	Awair	https://getawair.com/	**active**