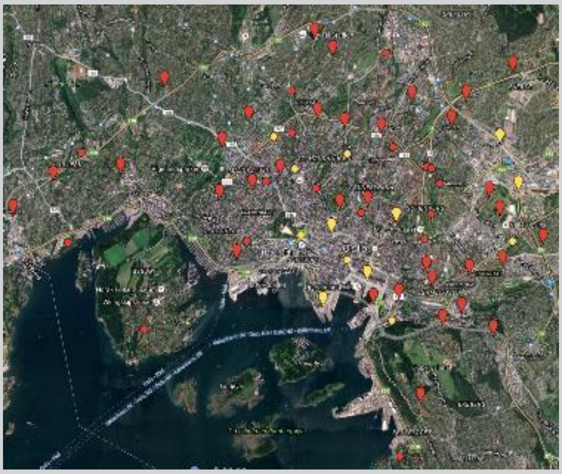
Low cost sensor systems for air quality assessment

Possibilities and challenges

April 2019

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Cover photo – *The map shows the placement of low cost sensor systems deployed in Oslo in 2015-2016. The red colour indicates placement in kindergartens, the yellow colour shows street placement, the circle and drop distinguish two waves of placement. Source: Castell and Grossberndt, 2018- Oslo Citizens' Observatory. Results from the Oslo Empowerment Initiative as part of the CITI-SENSE project. Kjeller, NILU report 26/2017, ISBN: 978-82-425-2897-1, available at https://www.nilu.no/pub/1623025/.*

The photo shows a monitoring station operated by NILU on behalf of the Oslo municipality, with sensor systems mounted on the roof for field co-location testing. Source: NILU

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Summary

Air quality is enjoying popular interest in the last years, with numerous projects initiated by civil society or individuals that aim to assess the quality of air locally, aided by new, low-cost monitoring technologies that can be used by "everyone". Such initiatives are very welcome, but in this highly technical and (in the western world) thoroughly regulated area, the professional community seems to struggle with communication with these initiatives, trying to reconcile the often highly technical aspects with the social ones. The technical issues include subjects such as monitoring techniques, air quality assessment methods, or quality control of measurements, and disciplines such as metrology, atmospheric science or informatics.

In this report, we would like to provide the reader with a practically oriented overview indicating the position of these new technologies in the ecosystem of air quality monitoring and measurement activities. Sensing techniques are rapidly evolving. This 'ever' improving capability implies among other, that there is currently no traceable method of evaluation of data quality. Despite the efforts of numerous groups, including within the European standardization system, a certification system will take some time to develop. This has important implications for example, when comparing measurements taken in time, by different devices (or different versions of the same sensor system device). Fitness for purpose – why are we measuring or monitoring and how do we intend to use the information we obtain – should always be the main criterion for the technological choice.

The report starts with an overview of elements of a monitoring system and proceed to describe the new technologies. Then, we give examples of how low-cost sensor technologies are being used by citizens. These examples are followed by reflections upon providing actionable information. Having learned from practical applications of sensor systems, we also discuss how the data from citizen activities can be used to develop new information, and provide some reflections on developing sensor systems monitoring on a larger scale.

We feel that the new technologies, while a disruptive change, provide many exciting opportunities, and we hope that this report will contribute to promote their use alongside with other assessment methods. We believe that increased understanding of technical issues we discuss will ultimately lead to better communication on air quality, and in its consequence, will enable further improvements in this domain.

1 Introduction and background

A change in air quality monitoring technologies is taking place globally (Snyder et al., 2013). Low cost devices are available to both the professional community and the public. These devices are enabled by advances in material science, information and communication technologies, miniaturization and development of new detection principles. They can be deployed in large quantities by non-professionals and professionals alike, and may have the potential to significantly contribute to air quality research and management. This disruptive technology, while promising, poses numerous challenges to the established assessment and information systems for air quality. These challenges need to be addressed.

This report aims to give a practical view on the use of the new technologies, to inform air quality managers in municipalities as well as other interested individuals or organizations. We give a systematic overview of the steps need for successful use of the new technologies. We review the current application areas of the low cost sensor systems and highlight the first practical experiences. We also address the relationship to existing monitoring systems, hoping that better understanding will help to maximize the benefits offered by the new technologies and to avoid misunderstandings and misuse.

1.1 Air quality monitoring context – European governance of air quality

Air quality, and air pollution, is in Europe thoroughly regulated, recognizing the paramount importance of the air we breathe for our health and well-being. Since the air pollution episodes and smog situations in the 1950's and acid rain of the 1970's and 1980's, European air has undergone a highly positive development. Not only has our understanding increased considerably, but Europe has been able to develop a comprehensive system of monitoring and assessment of air quality and polluting emissions, systemized in air quality directives and in directives and regulations regarding the most important anthropogenic pollution sources. It is well documented that the legislative instruments have led to significant reductions in the emissions to air for most pollutants since 1990's (EEA, 2015; EEA, 2018a, b, c). We can also observe improvements of ambient air for a number of pollutants (Colette et al., 2016), while the trends in ambient concentrations of other pollutants are not so positive, especially in urban areas (Henschel et al., 2015; Guerreiro et al., 2014). Overall, despite improvements, the efforts to clean the air have not reached all objectives (EEA, 2015; EEA, 2018a) and the air quality is not brought to "safe" levels. Also, Europeans perceive air quality as one of the most important environmental issues, as can be seen e.g., from the Eurobarometer survey (EU, 2017).

The legislative efforts (EC, 2004; EC, 2008) bring about the need to be able to compare measurements across vastly diverse environmental and climatic conditions, and throughout time. This of course is only possible if all methods are standardized, and if monitoring is subject to rigorous quality assurance and quality control systems. The countries spend substantial resources to ensure consistent measurements across the continent, and in time, enabled by the development of highly sophisticated monitoring instrumentation accompanied with quality assurance and quality control measures.

Thus, over time, countries in Europe have developed a system to measure, monitor and assess air quality, and to inform the public, as a collaboration between all governance levels – European, national, regional and local, with their respective roles defined in each country. Municipalities often have extensive responsibilities for air quality management and reporting and they have developed sophisticated systems for air quality management. In recent years, they are increasingly developing air quality dissemination solutions in collaboration with the public, responding both to the citizens needs and to the information requirements posed by the legislation.

1.2 Monitoring and measurements as one of air quality assessment methods

There are three main types of tools that in various combinations provide information on air quality:

- Monitoring and measurements
- Air quality modelling using both statistical and atmospheric dispersion/chemical transport models
- Assessment of air quality using a combination of measurements and models.

In this report, we address the monitoring and measurements component, though often, a combination of assessment methods is desirable to produce the required outcome. This combination will depend on the purpose of why we assess air. We will also indicate how the results of measurements by low cost sensor systems can be used to provide desirable information.

1.3 Selection of technologies to monitor or measure air quality

Hand in hand with the awareness of air quality, more and more assessments are done. Each assessment has a specific purpose that needs to be reflected in requirements on input data quality (see Table 1.1**Error! Reference source not found.** for examples). Fitness for purpose of the assessment tools is the main guiding principle for choice of input data, and it also affects the choice of monitoring technologies.

When considering the use of low cost sensor systems in relation to monitoring ambient air quality, it seems to be useful to consider two aspects: top-down and bottom-up technology selection. The top-down is defined by the current legislative requirements that have been driving the development of reference methods for monitoring technologies. The bottom-up is the increased public demand for information and action enabled by the opportunities provided by new technologies.

Top-down technology selection

In Europe, the air quality legislation since the 1996 (EC, 1996) has the following aims:

- to define common methods to monitor and assess air quality,
- to assess ambient air quality to monitor trends,
- to establish standards of air quality to achieve across the EU,
- to ensure that information on air quality is made public,
- to maintain good air quality and improving it where it is not good.

Related to the air quality legislation, a system to ensure comparability of measurements is in place (based on CEN/ISO standards). Quality requirements are covering the whole chain from monitoring (where, what and how to monitor), data gathering and quality control, reporting, assessments and information provision, and finally, requirements and procedures on what to do when air quality is not "good". This system ensures the ability to check compliance, and indeed, in the later years, countries have been taken to court for violating the directive. A review mechanism is in place for amending the legislation if deemed appropriate, usually using a consultation between the authorities, professional bodies, research and other stakeholders.

The selection of instruments for monitoring has to be in line with the legislative requirements where this is required. For example, compliant monitoring networks require the use of reference instrumentation or instruments for which equivalence with the reference methods has been demonstrated[1]. Any technology, including low cost sensor systems, that can be shown to comply with the requirements, can be used. Testing protocols have been developed for this purpose. All EU Member States have systems in place for how to approve instrumentation for use in their monitoring networks.

Bottom-up technology selection

The new low cost sensor systems can measure a range of air pollutants at ambient levels, and are affordable for the public. Unlike the measurement techniques used by ambient air quality monitoring networks, these measurement devices do not have any requirements for their outputs yet. Unlike information from the established monitoring networks, anybody who purchases a sensor system can readily see a “pollution reading” where they are and at any time, and on which they can act. This brings about a unique opportunity to engage the public who otherwise finds it difficult to orient themselves in air quality information.

However, such information can also lead to conflict situations between own measurements and the reference monitoring results. Without a complex metrology and scientific-technical background, it may be difficult to interpret own readings and relate them to the information originating in the ambient air quality monitoring networks implemented under the AQ Directive. In addition, the quality of the data from many of the low cost sensor systems on the market is very poor so that the information they give can be misleading for the general public.

EU member states are required to provide information about air quality (with minimum requirements on the amount information to be provided), but there are very limited studies that assess what information the public finds useful. Evidence of the many citizen science activities and activist’s efforts to address air pollution seems to indicate that the countries either do not have or have not adequately provided the information the general public requires, or that this information is not trusted. Hence, there is a large space occupied by various stakeholders’ efforts to generate and share what they consider relevant information, without regard of the origin and quality of such information.

In a recent study done in Norway (Castell and Grossberndt, 2018), people were asked what information they would like to have about air quality, and who do they think should take care of the problem of air pollution. The results indicate that the main interest is in accessing real time or up-to-date information, locally specific to whereabouts of people (see Figure 1.1).

[1] In the EU, this is defined in the EC (2008), Directive 2008/50/EC on ambient air quality and cleaner air for Europe.

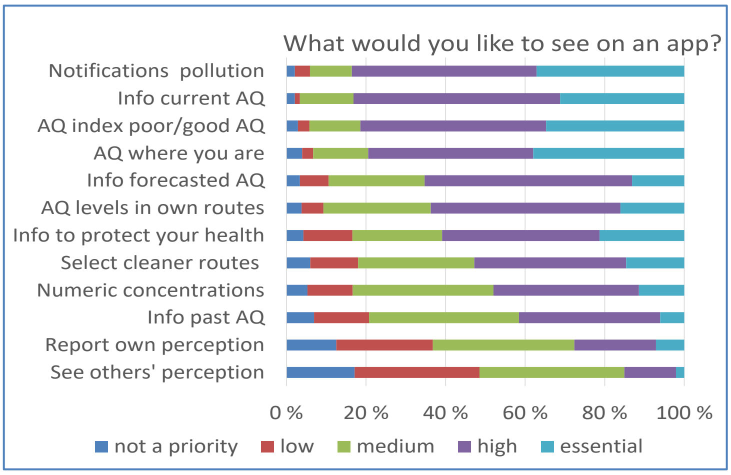

Figure 1.1 *Information on air quality that people would like to see on a mobile app (from Castell and Grossberndt, 2018)*

The top-down meets the bottom-up

We find ourselves in a situation where on one hand, we have available a large quantity of thoroughly quality controlled but unevenly spaced data on air quality across Europe provided by the monitoring systems built up according to the requirements of the legislation. Those data are made available to the public by the authorities or the designated bodies (top-down).

On the other hand, we have clusters of data of unknown quality and uneven information value that seem to address the concerns and needs of the public. Mostly located in urban areas, they are often used for the purpose to raise awareness of the authorities of local air quality problems. Miniaturized sensor systems pose an opportunity for the public, as they allow obtaining instantaneous information directly relevant to individuals (bottom-up).

The challenge is to make these two systems work together to create a more efficient monitoring and information system. For example, for the municipalities, there is a challenge to engage with the public in new ways: they could use the public as a resource and harvest data from large numbers of diverse miniaturized sensor systems. This requires Internet-of-Things approaches, and quality control and quality assessment of a new type.

1.4 Elements of a monitoring system

To achieve the best results in terms of protection from air pollution (with its huge health and societal implications), we need to support both the top-down and bottom-up monitoring and measurement systems, because they answer different but complementary needs. The steps necessary to provide information to the end user are similar for both systems:

A. Data collection by (a) monitoring unit(s)
B. Data quality control related to individual unit
C. Data transfer into a repository
D. Data quality control in the repository
E. Data availability to external entities including the public

F. Development of information products, including web sites and apps.

For example,

- An individual user may purchase a monitoring unit (step A). This monitoring unit sends data to the vendor's web site (step C). The user then may access their measurement results at the web site of the vendor (step F). The vendor may - or may not – include steps B and D as part of their product, and may or may not make the data available to external users – step E.
- A citizens group decides to address an air quality issue together; they will support their members for example, to purchase the same kind of monitoring unit, and will go through the steps A and C. In step F, they may wish to see all data together, and may e.g., negotiate a fit-for-purpose solution with the monitoring unit manufacturer.
- In the deployment of a monitoring network, the project owner has to implement all the steps A-F, and each of these steps has prescribed procedures how to achieve them.
- A municipality may be using many different inputs in step A, and faces then a challenge how best to access the data from each of them, and how to combine these.

The above shows that technologies for connectivity of the sensor systems need to be considered. Often, even technically skilled users such as municipalities seem to be thinking only about the monitoring technology, but in a large-scale application of low cost sensor systems, both the monitoring technology and the information and communication technologies pose equally important problems. Further, the citizens should not be required to have technical knowledge to evaluate the performance of products they are using (e.g., in step A) - they should be able to trust that the products are providing the indicated services. Citizens deserve to have good quality data that they can compare to the results of monitoring networks.

It is also important to mention that in the established ambient air quality monitoring networks, if there is a change in instrumentation or procedure (such as a calibration procedure change, step B of the above), information about this is recorded and becomes part of the air quality database. For the low cost sensor systems, the calibration and data correction procedures both in step B and D above are often based on data algorithms. The users often purchases a device together with a data service that allows them to access their measurements online, but do not have information about the algorithms for data correction. The algorithms employed are often proprietary and subject to frequent changes as new ways to correct data are implemented by the service provider, for example as new and more sophisticated machine learning correction algorithms are implemented. Good practice, and a requirement for networks that operate in compliance with the EU legislation on air quality, is to keep track of any such changes. For low cost sensor systems, efforts should be made to keep track of the algorithms used and their changes, e.g., by including appropriate meta-data in the repository.

1.5 This report

In this report, we provide basic information on the new monitoring technologies, and show examples of successful use.

In Chapter 2, we provide an overview of the basics of the low cost air sensing technologies.

In Chapter 3, we have collected examples of successful projects with citizen participation related to air quality in Europe. They are using both the traditional monitoring technologies and low cost sensor systems.

In Chapter 4, we give examples how the data from low cost sensor systems can be used for different purposes by decision makers or other users seeking actionable information.

In Chapter 5, we give a short overview of the information and communication technologies that are required for successful use of the low cost sensor systems.

Chapter 6 briefly summarizes issues related to deployment of the low cost sensor systems.

The last Chapter 7 provides some final reflections.

Disclaimer

In this report, we use numerous examples of existing technologies and instruments, often identified by their brand names. We would like to stress that any mention of such technologies is solely done for the purpose of illustration, and does not imply any kind of endorsement or recommendation of the technology or device.

Table 1.1 Examples of the most common purposes for air quality assessment

Purpose of assessment	**Who is responsible for the assessment**	**What technology/method is used for the assessment**	**Data quality objectives**[2]
Monitoring - regulatory compliance	Local and national governments or municipalities; entities responsible for activities that require legislative compliance with air quality legislation (e.g., building construction or road transport)	Reference or equivalent method	Prescribed in legislation
Monitoring policies or trends, accountability studies[3]	Authorities	Reference or equivalent method	Defined based on the size of change that is expected or hypothesized
Burden of disease/ health and environmental assessments	International organizations (e.g., WHO, UNEP)	Preferably reference or equivalent method, but any measurements may be included to improve coverage	Guidance is provided by the authors
Atmospheric research	Researcher, scientist	Research instrumentation, often reference or equivalent or higher precision	Based on study aims and hypothesis
Exposure assessment/health and public health research	Responsible health authority	Reference or equivalent method combined with documented models	Based on study aims and hypothesis
Exposure assessment/health and public health research	Researcher, scientist	Research instrumentation and models	Based on study aims and hypothesis

[2] Data Quality Objectives (DQO) are qualitative and quantitative statements of the quality of data needed to support specific decisions or regulatory actions
[3] For information on accountability studies, see Henneman et al., 2016

Purpose of assessment	**Who is responsible for the assessment**	**What technology/method is used for the assessment**	**Data quality objectives**[2]
Information to the public	Local and national governments or municipalities, health authorities	Reference or equivalent method	Based on ambient air quality monitoring and on the capabilities of the available modelling systems
Information to the public	Other than authorities (interest groups, other stakeholders)	Information is often not provided	Depends on use case; often not considered and unknown
Citizen science	Citizen science owner, e.g. NGO, group of citizens, schools	All available, including low cost devices, self-built or commercially available	Depends on use case; often not considered and unknown
Personalized information	Citizens, individuals	All available, including low cost devices, self-built or commercially available	No requirement; often not considered and unknown
Contribution to “Smart Cities”	Any entity	Any method	No requirement; often not considered and unknown

2 Pollutant detection technology for low cost sensor systems

This chapter gives a brief introduction on (low cost) sensor technologies in view of the technologies available to monitor, and the methods to assess quality of measurements using measurements/lab and field calibration. Recently, WMO (2018) provided a science-based overview of current low cost sensor technologies for atmospheric composition detection, and we refer an interested reader to this report for more details.

2.1 Definitions

Before discussing the different sensor approaches currently available to monitor atmospheric pollutants, it is necessary to agree on the terminology. Different studies use different terms such as sensor, sensing device, node, platform, etc. In the present report, the following terminology is used:

1) Sensor: the basic component of technology that actually makes the analytical measurement (CEN, 2018; WMO, 2018). Gas or particle concentrations are typically monitored as electrical signals. Examples include sensors for temperature and pressure, electrochemical sensors, metal oxide sensors, or optical light scattering sensors.

2) Sensor system: the combination of one or several sensors (for single or multiple pollutants) with a power source (internal or external), an enclosure and optionally a processor to convert electrical signals to concentration units and data storage and transmission systems (CEN, 2018; WMO, 2018). Sensor systems can be therefore used as stand-alone units to monitor pollutant concentrations. They can be deployed individually or in groups.

3) Reference instrument: instruments which are certified by an official regulating body, and which are used for regulatory compliance purposes in air quality monitoring networks. They are not low cost monitors.

4) Online platform: online data collection, storing and (optionally) processing repository, to which data are transmitted when monitors have data transmission capabilities.

Figure 2.1 Examples of individual sensors (left, from WMO (2018)) and sensor system (right; source: http://aircasting.org/).

2.2 Types of sensors

The measurement principles vary as a function of the type of pollutant:

Gas sensors:

The two main types of gas sensors are metal-oxide and electrochemical sensors (Baron and Saffell, 2017):

- Metal-oxide sensors are sensitive to pollutant concentrations based on the electric conductivity of their metal surface. In clean air, donor electrons in the metal (e.g., tin dioxide) are attracted toward oxygen on the surface of the sensing material, preventing electric current flow. In the presence of pollutant concentrations (e.g., reducing gases) the surface density of adsorbed oxygen decreases as it reacts with the reducing gases. Electrons are then released into the metal surface, allowing current to flow freely through the sensor (Figure 2.2). This current, measured by the sensor, is proportional to the pollutant concentration. The main limitations of these sensors are that their response is limited at high concentrations (e.g., ozone sensors) and that they have been shown to have interferences with other gases present in the atmosphere (Fine et al., 2010; Peterson et al., 2017; Wetchakun et al., 2011; Rai et al., 2017).
- Electrochemical sensors are composed of noble metal electrodes in an electrolyte. The electrolyte is normally an aqueous solution of strong inorganic acids. When a reducing gas (e.g., carbon monoxide) diffuses to the sensing electrode it is oxidised, causing the potential of the sensing electrode to shift. This generates a small current proportional to the concentration of the gas. In its simplest form, an electrochemical sensor consists of a diffusion barrier, a sensing-electrode (sometimes called the working-electrode, measuring-electrode, or anode), a counter-electrode (sometimes called the cathode) and an electrolyte (Figure 2.3). These sensors have been shown to have interferences with relative humidity and temperature, requiring additional measurements to be made in order to obtain reliable results (Aleixandre and Gerboles, 2012; Cross et al., 2017; Wei et al., 2018). They have also been shown to have interferences with other gases present in the atmosphere. For instance, NO2 sensors have interferences with O3, however, some newer NO2 sensor include a filter for O3 in order to reduce the interferences (Castell et al., 2017).

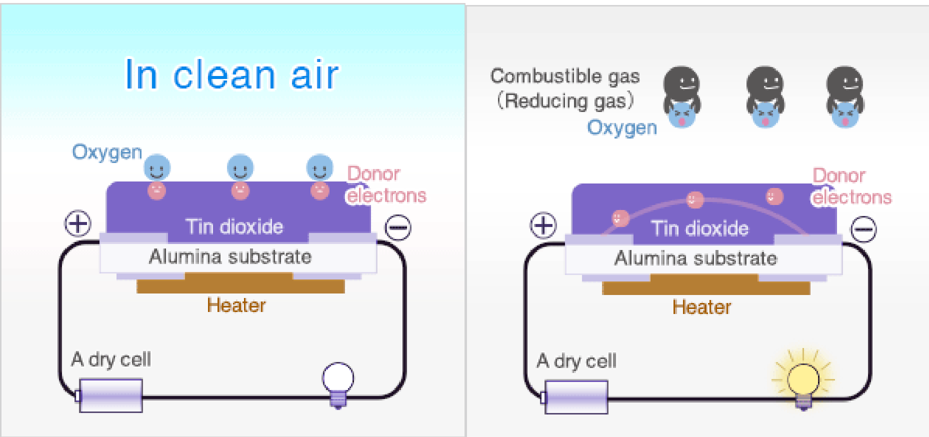

Figure 2.2 *Schematic operation of metal-oxide sensors. (source: http://www.figaro.co.jp/en/technicalinfo/principle/mos-type.html).*

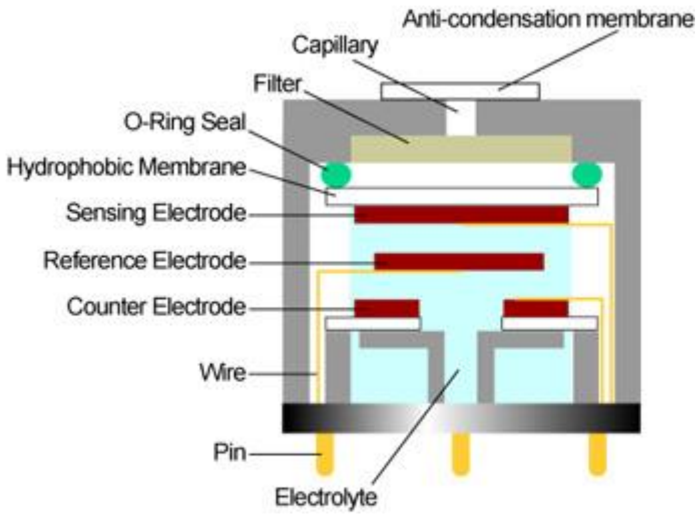

Figure 2.3 Schematic design of an electrochemical sensor (source: http://www.membrapor.ch/electrochemical-gas-sensors/).

Particle sensors

Particle sensors most commonly rely on optical measurements, typically light scattering. Conversely, reference instruments are based on particle gravimetry. The principle of operation of particle sensors is based on a source of light (LED, laser) which is shone onto the particles introduced into the monitor by a small pump or an induced thermal gradient. The light scattered by the particles is monitored using a photo detection device. The particle concentration is proportional to the scattered light intensity. The actual measurement is typically carried out by:

- Nephelometry, which measures particle light scattering of the total aerosol, or
- Optical particle counting, which detects particle size and number of individual particles.

Neither of these techniques measure particle mass directly, and assume a certain particle density to convert particle number into particle mass concentrations (in the case of optical counters) or must be compared to a reference instrument (in the case of nephelometers). The particle sizes detected depend on the specific particle sensor monitors, and it should be highlighted that none of the monitors currently available are able to detect ultrafine particles (<100nm in diameter), their lower limit frequently being >300 nm (Wang et al., 2010). Low cost sensors for PM suffer from interferences with relative humidity. As they do not have any system to dry the particles, when the relative humidity is high (above 80-90%) the sensor system measures also water droplets thus overestimating particle matter mass (Wang et al., 2015).

2.3 Applications

Sensor systems have the potential to be used in a number of applications, which range from awareness raising, citizen science, air pollution monitoring and mapping, and personal exposure monitoring (see Table 1.1). In addition to these, low cost technologies are especially attractive for emerging applications and thus may have new applications, yet to be defined by the users, in the near future (Rai et al., 2017; Hubbell et al., 2018). However, low cost sensor systems have higher uncertainty and lower precision and accuracy than reference instrumentation. In order to use this type of technology as indicative measurements they need to comply with the uncertainty levels defined in the EU air quality directive (EC, 2008).

The potential uses of sensor data depend on data quality required, and as a result, each of their applications has different requirements and limitations. For example, sensors used for personal exposure assessment should exhibit low interference with other environmental variables (such as humidity) and capture fast temporal variations in pollutant concentrations, given that exposure varies rapidly as the person moves from one micro-environment to another.

Long battery lifetime or access to the electric grid is required for a monitor suited for urban air quality monitoring and mapping, given that the monitor deployment should not be limited by lack of power outlets. Further, a citizen science or other assessment comparing air pollutant concentrations simultaneously e.g., in different modes of transportation would likely require a high degree of comparability between different units of the same sensor system type.

The above are examples of requirements considered in a “fit-for-purpose” concept, which refers to the varying needs and limitations of low cost sensor systems as a function of their application. This concept also applies to data quality required for the different applications (see **Error! Reference source not found.**).

2.4 Quality assessment

Data quality is a key issue determining the use or interpretation of data generated by low cost systems. Data quality mainly refers to the performance of the sensors and sensor systems when compared with reference instrumentation, but it may also include data availability (e.g., the ability of the low cost sensor systems to produce data time series sufficient for the assessment of the environmental issue targeted). While the first has mainly to do with the performance of the sensor, the second is mostly related to the data processing and transmission systems.

The performance of low cost sensor systems is evaluated by assessing a number of parameters, including (WMO, 2018):

- Sensitivity (their ability to reach high or low concentrations)
- Selectivity (the lack of interference from other pollutants)
- Temporal resolution
- Reproducibility (comparability between different units of the same monitor)
- Stability over time.

The way to assess each of these indicators is by comparing the data generated by the low cost sensor system with that of a reference instrument, for the single or group of pollutants selected. This process is typically referred to as calibration, and it results in a set of coefficients or algorithms which enable the correction of the data generated by the low cost sensor system to resemble those from a co-located reference instrument. Different options are available to calibrate sensor systems, with different requirements and resulting in varying levels of data quality (Figure 2.4).

Sensors are initially tested during their manufacturing process, mainly for operation and technical malfunctions. Then they are calibrated in the laboratory (by the manufacturer or a research institution), in chamber experiments with a known gas mix and gas or particle concentrations. Numerous studies showed that sensor performance in chamber experiments cannot be extrapolated to ambient (or even indoor) air due to the interference from the actual aerosol and gas mix or other environmental variables such as relative humidity and temperature (Castell et al., 2017; Jayaratne et al., 2018). Therefore, field calibrations are essential to guarantee the correct assessment of the performance of low cost monitors.

In the field, sensor systems are calibrated by collocation. The sensor systems are deployed in close proximity (<10 m) (WMO, 2018) to a reference instrument (preferably close to the air intake of the reference instruments, which is usually on the top of the station), and compared to reference data in order to obtain a field calibration algorithm (Cross et al., 2017; Borrego et al., 2015, 2016, 2018; Spinelle et al., 2017; Ripoll et al., 2019). Because of changing environmental conditions and drifts in sensor performance over time, this kind of comparison should preferably be carried out on a regular basis (at least, the comparison should cover the different seasons) and take between 2-3 weeks (Spinelle et al 2017, Castell et al., 2017; Ripoll et al., 2019). At RIVM, calibration work is in progress that uses nightly concentration values to perform a calibration on a daily basis, correcting for drift. The assumption is that during the night, there are only limited variations of NO_2 concentrations over a given area (due to uniformly low intensity of traffic). Then, the calibration of the sensors can be adjusted using the results of the previous night, using data from a nearby reference station or an interpolation. In this way, data quality from sensor systems that could not be collocated at reference station, might be enhanced. Whenever possible, citizens are encouraged to contact their local air quality network and take part in collocation exercises for sensor systems used in citizen science initiatives.

Finally, machine learning techniques (ranging from sophisticated linear regression models to artificial neural networks) are currently being applied to the calibration of sensor networks (Spinelle et al., 2017). These techniques consider several variables (i.e. temperature, relative humidity, other gases) instead of only considering the targeted gas (WMO, 2018; Spinelle et al., 2017). Machine learning is based on statistical learning across sensor systems, where sensors are calibrated against each other while always including the comparison of a number of units in the network with reference instrumentation (once again, by collocation). Machine learning techniques are currently being tested, with positive results so far (WMO, 2018).

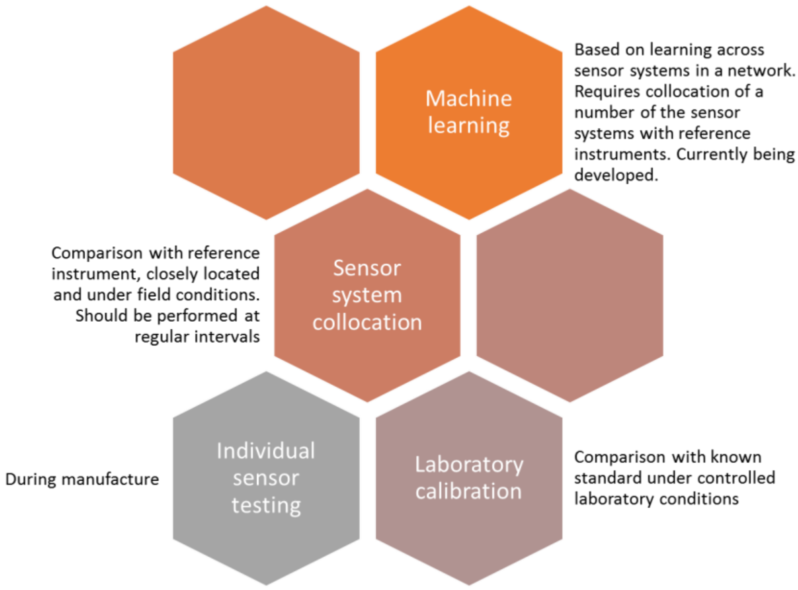

Figure 2.4 Options available for calibration of low cost sensor systems. Source: Ripoll et al. (2019).

A number of examples are available in the scientific and grey literature regarding the assessment of the performance of different types of gas and particle low cost monitors (e.g. http://www.aqmd.gov). Whereas in certain cases the low cost monitor data compare well with those from the reference instrumentation under the environmental and pollutant concentrations evaluated (Figure 3.7, Figure 2.5, left), very frequently the lack of comparability is outstanding (Figure 2.5, right). Furthermore, because scientific and grey publications may be biased towards reporting of positive results, the studies which conclude on the poor performance of low cost sensors are likely under-represented in the literature. The need for rigorous quality checks for sensor data has even translated into a Nature Comment entitled "Validate personal air-pollution sensors" (Lewis and Edwards, 2016).

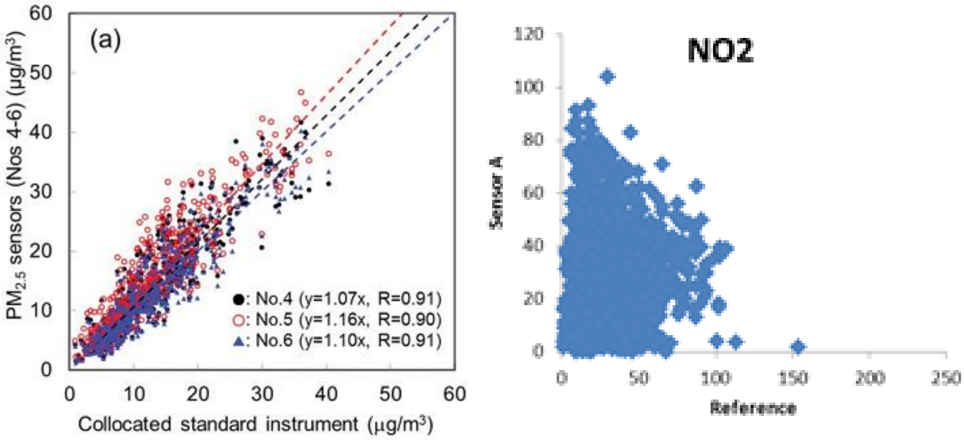

Figure 2.5 *Example of the comparability between low cost monitors and reference instrumentation. Sources: Left, Nakayama et al. 2017. Right, Castell et al, 2013.*

Aside from the comparability with a reference instrument at a given point in time, another relevant parameter to be assessed is stability over time, i.e., the influence of drifts. While a given monitor may compare well with the reference during its calibration phase, studies have identified drifts in sensor performance over time, during periods as short as three months. Because of the large variability of sensor performance (linked to their low cost), correcting for drifts is still a challenge for the scientific community. As a result, data quality and performance for low cost monitors should not only be assessed at the start of the operating life of the monitor, but also monitored over time to account for, and minimise, drifts (Figure 2.4).

It must be stated that most of these studies (e.g., Figure 2.5) assess sensor performance for air quality research purposes, for which the data quality requirements are the highest. Following the fit-for-purpose principle, as stated above, data quality requirements should be aligned with the application the low cost monitors are used for (Hubbell et al., 2018). For instance, for awareness applications it might be sufficient if the sensor system is able to distinguish between low, medium and high pollution, whereas for regulatory or research studies sensor systems need to be able to give accurate concentration levels.

Although the European Committee for Standardization (CEN) Technical Committee (TC) 264, Working group (WG) 42 is working on the subject, there is currently no standard protocol recognised internationally to assess sensor performance, meaning that sensor system manufacturers do not have a set of guidelines they need to comply with before they offer a sensor system to the public. This makes it very difficult for authorities and the public to know if a sensor system will be fit-for-purpose before acquiring it. Moreover, technology is changing so fast that often when research centres publish the assessment results for a given sensor system, a new version of the system is already available on the market.

This is currently the topic studied by several initiatives (e.g. WMO, 2018; VACUUMS, 2018). Different studies investigate different aspects such as intra-unit comparability, stability of long-term time series or drifts over time. A number of tools are available free, which may help with the assessment of sensor system performance, for instance, the Air Sensor Toolbox (US EPA, 2018) and the SET Toolbox (Fishbain et al., 2017). However, the quality assessment may still be out or reach for most citizens as the tools are quite technical. For citizens interested in monitoring air quality by themselves, the best way is to contact local or national initiatives on citizen science, research institutes or the local authorities.

At present, a number of international initiatives are compiling overviews of studies available on low cost sensor system performance. Examples of these are the AirMonTech (http://dbairmontech.jrc.ec.europa.eu/) or the EDUCEO project Wiki (www.snuffle.org). A national initiative in the Netherlands provides an information website https://www.samenmetenaanluchtkwaliteit.nl/ with information to the public about sensor performances as well as references to projects and information about air quality indicators. Similar national projects would increase the uptake of the technologies and understanding their possibilities and limitations, as they provide information to citizens in their local language.

In France, national protocols have been established by the national reference laboratory (LCSQA) for performance evaluation in laboratory of low cost sensor systems for indicative measurement of PM and inorganic gaseous pollutants (www.lcsqa.org). Moreover, a field inter-laboratory comparison was carried out over 6 weeks in the first quarter of 2018, challenging around 50 low cost sensors (around 20 different sensor systems) with reference methods used in parallel. Targeted pollutants were nitrogen dioxide (NO_2), ozone (O_3) and particulate matter ($PM_{2,5}$ and PM_{10}) (Redon and Spinelle, 2018). The LCSQA is also building a national database with results of local tests performed by the regional associations responsible for air quality monitoring (AASQAs), offering a comprehensive view about low cost sensor system performances in various environmental conditions.

3 Citizens' participations in assessments of air quality

The low cost sensor technologies have enabled citizen participation in assessing air quality. Such activities include contributory projects (designed by scientists, with members of the public contributing), collaborative (designed by scientists but members of the public may help to refine project design or disseminate data), and co-created (designed by scientists and members of the public working together) (Muller-Rushing et al (2012)).

The projects mentioned here were initiated by research institutions, non-governmental organizations, or citizen groups. Their aims vary. Some try to better understand all aspects of use of the low cost sensor systems, others want to provide information about air quality or to raise awareness of a problem that needs attention of the local authorities. Thus, a substantial number of initiatives have been providing local communities with information about local air quality, largely unconnected to national or local air quality monitoring by authorities.

3.1 luftdaten.info ('Measure Air Quality Yourself')

An example of a large-scale and successful Citizen Science project is luftdaten.info. It was set up in Germany by an Open Knowledge Lab, with the aim of making particulate matter (PM) visible in places where it is not officially measured. The project started at the local level in Stuttgart, it is now supported in seven languages and has now participants from all over the world (over 4,000 unique locations).

How can air quality be measured and visualized? What effects does the high traffic volume have on our air? How high is the exposure of PM in residential areas? These and other questions are addressed by building a PM sensor and visualizing the data in an overall picture thereby quickly demonstrating differences between countries.

luftdaten.info offers interested people a shopping list, pre-programmed software and a technical manual to build their own PM sensor (Nova SDS011 sensor, Figure 3.1). However, the graphical representation or symbols used on their map to indicate the measurement location could to a lay user suggest a larger representativeness of each measurement than is realistic. The sensor was compared with a more advanced optical monitor. On some days there is a good agreement, but especially at higher air humidity, the sensor overestimates giving peak values that are not reflecting true concentrations[4]; such information should be conveyed to the end users (public). Project members are looking for algorithms to minimize the impact of high humidity on PM readings. Until then, still the data provide information, for example about the variation in time or differences between locations.

The public measurement data from luftdaten.info and all the other information can be found on the Luftdaten website (https://luftdaten.info/en/home-en/).

Figure 3.1. Luftdaten.info sensor implementation in Europe (left) and its major components (right).

3.2 Citizen Science during New Year's Eve

During New Year's Eve 2017/18, about 130 Dutch people shared their PM measurements at the newly developed experimental data portal of the National Institute for Public Health and the Environment (RIVM On average, the 5-minute averaged PM concentrations, as measured with the citizens' sensors, increased by a factor of 17 during the fireworks event compared to levels before the event. The official measurements of the National Air Quality Monitoring Network (hourly averaged) showed an even larger increase (see Figure 3.2).

[4] http://www4.lubw.baden-wuerttemberg.de/servlet/is/268831/messungen_mit_dem_feinstaubsensor_sds011.pdf

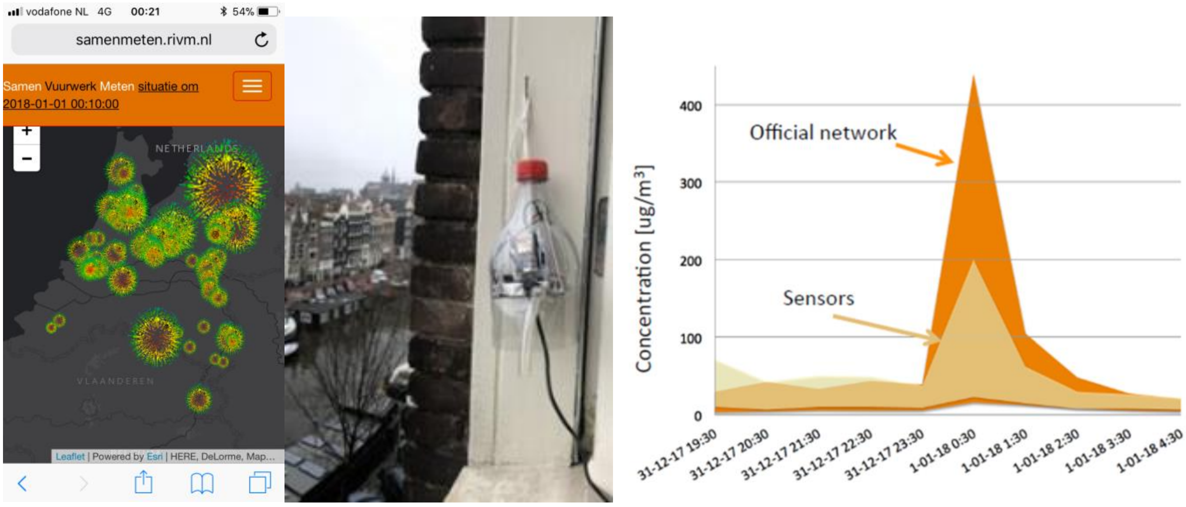

Figure 3.2 Air Quality measurements during New Year's Eve 2017/2018 (left: a real time assimilation of all measurement; middle: one example of PM sensor; right: comparison to official data). Source: RIVM

RIVM provided a number of sensors for civil measurement projects in Dutch cities. Participants had to make a weatherproof housing for the sensor devices themselves in order to promote the feeling of responsibility. The data were transferred to the RIVM data portal through Wi-Fi and LoRa[5]. In addition, individual citizen initiatives provided their measurement data. The data set was extended with data from other projects (e.g., luftdaten.info project and RIVM sensor projects in cities).

The participants used different types of sensor systems. Because the absolute concentration levels are often not comparable between sensor systems due to the lack of standardization of the measurement method, the visualization showed results as relative changes. The measured peaks were short-lived everywhere in the Netherlands. In cooperation with the various participants, RIVM will carry out further research into calibration of the sensor data by comparing with official measuring stations.

The results of the experiment can be found on the project page (https://www.samenmetenaanluchtkwaliteit.nl/vuurwerkexperiment-20172018, in Dutch). A video of the presentation given during The Things Network Conference can be found on YouTube (https://youtu.be/FgvghFFSQ6c, in English).

3.3 The making of a Smart Citizen Kit and what can go wrong

An example that demonstrates the importance of making good choices with respect to the sensor systems is the Smart Citizen Kit (SCK) project in Amsterdam implemented by Waag Society (2014, http://waag.org/en/article/smart-citizen-kit-next-steps). This pilot examined to what extent Amsterdam residents would be able to collect data about their environment with relatively cheap electronics and sensors. Questions that were formulated at the start: How polluted is the air around our houses? How easy is it to measure, share and compare with others in real-time? Do measurements lead to behavioural change?

After a call in the newspaper, participants were selected with the aim to obtain a good distribution of sensor systems covering the city. The reasons for joining were diverse, the most prominent ones were interest in air quality and technology, and being part of a social experiment.

[5] LoRa - Long Range - is a patented digital wireless data communication technology, *https://www.lora-alliance.org/technology*

The sensor kit allowed to measure carbon monoxide (CO) and nitrogen dioxide (NO_2) as well as temperature and relative humidity for a period of three months. The project infrastructure consisted of open source hardware, a website where the data was collected, an online application programme interface (API) and a mobile app.

For the majority of the participants (primarily interested in air pollution) it was a disappointing experiment and answers to the above mentioned questions could only partially be given. The (industrial) sensors provided in the kit appeared not sensitive enough to measure the ambient air pollution concentrations in the city as the sensor was only able to register the peak values. A comparison between the data of different participants (and with those of the official network) was not possible. On the positive side was that a great deal has been learned about air quality (e.g., how difficult it is to measure air quality), measurement technology, data interpretation, and so on. If the experiment lead to a higher awareness and a change in behaviour remained unclear.

3.4 Making Sense research project

Making Sense, http://making-sense.eu/, was a 2-year research project funded by EU Horizon 2020 program, aiming to bring participatory sensing to citizens. Underlying goals were to provide citizens and communities with appropriate tools in order to enhance their everyday environmental awareness, to enable an active attitude towards pollution issues and to change individual and collective practices.

One concrete challenge was to develop an air quality sensor that would answer urgent questions from citizens. To build this measurement tool, one used open source software and hardware, digital practices and an open design resulting in the 'Making Sense Toolkit' implemented in the Smart Citizen platform for citizen science.

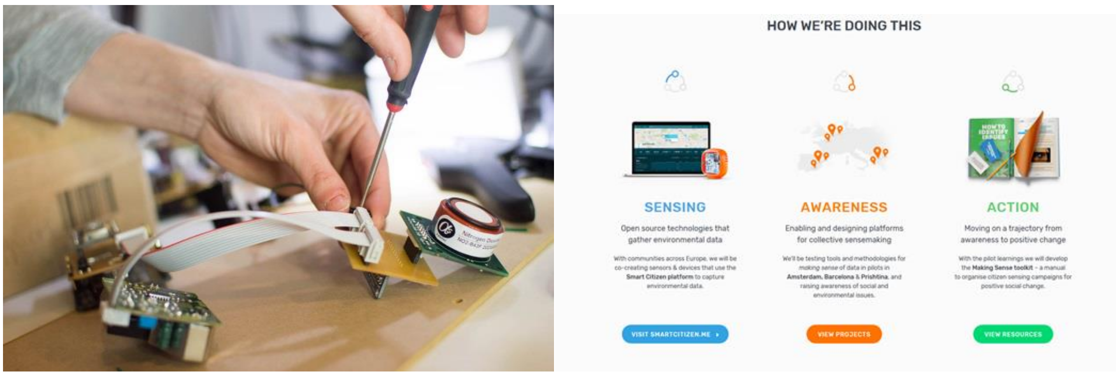

Figure 3.3 The "Making sense" project sensor system and web page. Source: Making Sense project

Pilots (also monitoring meteorological parameters and noise, (Figure 3.4)) were carried out in Amsterdam, Barcelona and Pristina. Based on these pilots, a conceptual and methodological framework for participatory environmental maker practices was created.

Making Sense ran from November 2015 to the end of 2017. The consortium consisted of partners in the Netherlands, UK, Kosovo, Spain and Belgium. The experiences within the "Making Sense" project resulted in a recent publication titled "Citizen Sensing – A Toolkit" that provides recommendations and tools for successful bottom-up citizen sensing projects http://waag.org/sites/waag/files/public/citizen-sensing-a-toolkit.pdf.

Figure 3.4 *Participant in Citizen Science project Urban AirQ as part of the Making Sense project (Source: Waag Society, http://waag.org//nl/project/urban-airq)*

3.5 hackAIR – Collective awareness platform for outdoor air quality

hackAIR (www.hackair.eu) aims to raise citizens' awareness about their exposure to particulate matter ($PM_{2.5}$ and PM_{10}), with pilots in local communities in Norway, Germany, Belgium and Greece. It is supported through the EU H2020 programme on "Collective Awareness Platforms for Sustainability and Social Innovation" until December 2018. The hackAIR platform composed of a website and a complementary mobile application that enables users to access, collect and improve air quality information in Europe. Currently, hackAIR app is available for Android and iOS (Figure 3.5), connected to an online platform at www.hackair.eu , where citizens in Europe can check the air quality in their neighbourhood based on available ambient air quality monitoring data and see the data from hackAIR own measurements.

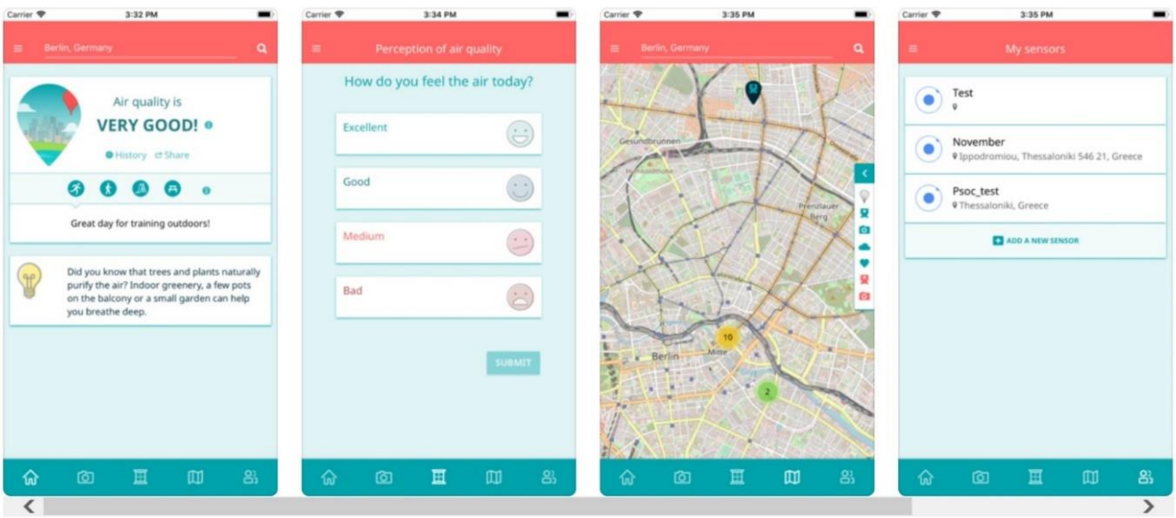

Figure 3.5 *Screen shot of hackAIR mobile app.*

hackAIR offers four ways for users to contribute their own air quality data: (i) They can submit photos of the sky using the hackAIR app. An algorithm then gives a rough estimate of air pollution levels; (ii) They can build a simple cardboard sensor that uses the discoloration of petroleum jelly to get an estimate of the amount of particulate matter pollution; (iii) hackAIR provides manuals (http://www.hackair.eu/hackair-home) and workshops to build stationary (Figure 3.6) and portable microcomputer air quality sensor systems. These sensor systems, similar to those used in the Luftdaten project, are cheap, easy-to-build and provide data that for $PM_{2.5}$ have been shown to correlate well with reference measurements under specific conditions (Figure 3.7); (iv) Experienced users can submit and access data using an API. Further, a video tutorial for hackAIR stationary and portable sensor is available on YouTube.

Figure 3.6 *hackAIR stationary sensor system components (left), sensor casing (middle, modified from luftdaten.info sensor casing), and sensor co-located at one official air quality monitoring station in Oslo, Norway.*

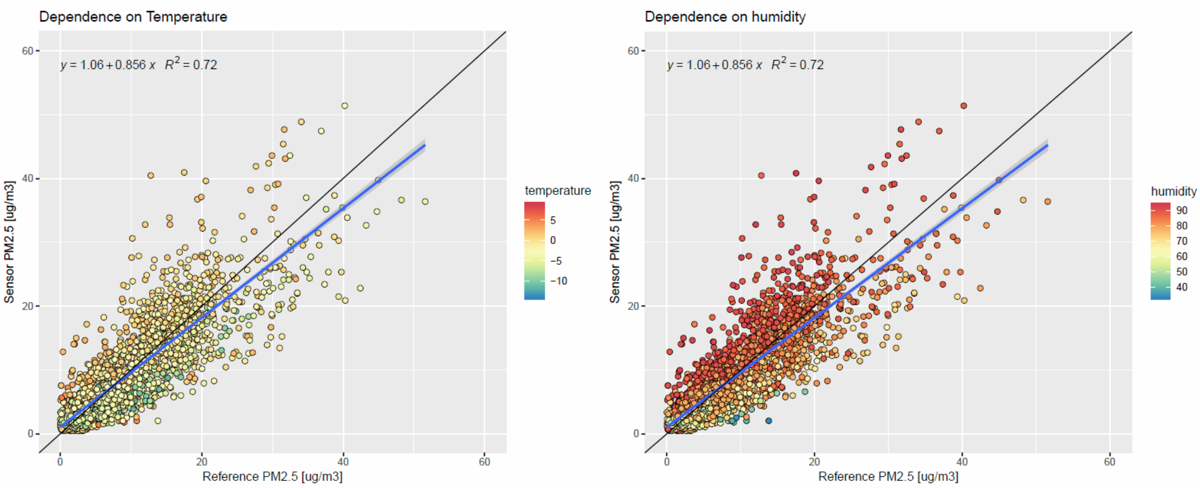

Figure 3.7 *Comparison of hourly $PM_{2.5}$ mass from an air quality monitoring station with corresponding measurements from the hackAIR sensor over a three month period. The colour of each point indicates the temperature (left panel) and relative humidity (right panel) at the time of measurement. The blue line indicates a linear regression fit and the black line represents the 1:1 line for reference.*

3.6 CAPTOR - Monitoring ozone pollution in collaboration with local air quality networks

Another example or large-scale deployment of sensor systems is found in the EU H2020 project CAPTOR (https://www.captor-project.eu), running in the period 2016-2018. In this research project, low cost ozone (O_3) sensor systems were deployed in volunteer homes in three regions in Spain, Austria and Italy (Figure 3.8). The project's aim is to raise awareness about the problem of ozone pollution in rural areas, which are affected by the emissions of O_3 precursor gases from nearby urban areas. The sensor systems were operated by research teams and NGOs, and the data were made available through an online platform. The regional authorities, participating in the project expressed their concern that the sensor data may create social alarm. This is a sensitive issue: scientific literature provides ample evidence that the current sensor systems very rarely provide data that can be used for compliance checking, but a dialogue with citizens on these issues is at this time considered difficult.

Figure 3.8 Examples of CAPTOR O_3 sensor system.

To support the authorities and provide contextual information for the CAPTOR volunteers, sensor and official data were compared (Table 3.1). Results show a systematic bias with the low cost sensor system data being below reference data. This was interpreted as the sensor system being always more conservative than reference instrument, reassuring both the authorities and citizens that no social alarm was created.

Table 3.1 Comparison between reference data and data from sensor systems located at volunteer homes in the vicinity of the reference stations. Results from the 2017 monitoring campaign from H2020 project CAPTOR.

Air Quality standard	**Averaging period**	**Concentration**	**Reference station#1**	**Sensor system# 1**	**Reference station#2**	**Sensor system# 2**
Human health target value	Maximum daily 8-hr mean	100 µg µg/m^3 (WHO)	77	74	70	58
		120 µg/m^3, not to be exceeded >25 days per year averaged over 3 years	31	12	29	26
Information threshold	1 hour	180 µg/m^3	7	0	12	0
Alert threshold	1 hour	240 µg/m^3	0	0	0	0

The data generated by the CAPTOR project also allow tracking of pollutant concentrations, e.g., by monitoring ozone concentrations along a 90 km transect downwind of a major urban area (Barcelona). In this way, it is possible to observe ozone formation resulting from the urban plume (Figure 3.8), provided that there is enough quality control of the sensor system output.

Figure 3.9 Mapping of ozone concentrations along a 90 km transect downwind of the Barcelona city emission plume. Source: H2020 project CAPTOR (www.captor-project.eu).

3.7 Curieuze Neuzen ('Curious noses')

Curieuze neuzen is a scientific research project carried out in Flanders, Belgium, supported by a.o. Flanders Environment Agency and VITO. In this project, citizens collected data on air quality (nitrogen dioxide (NO_2)) under the guidance of professional scientists. The aim is to map air quality throughout Flanders in detail, both in the city and in the countryside. The passive sampling method used in the project is a screening method used for many years already, thoroughly tested and known to provide quite precise and accurate results.

Around 20 000 devices were distributed amongst households, companies and schools. The simple measurement set up can be mounted on a window of the participants' home, apartment or building (Figure 3.10). During the entire month of May 2018, the concentration of NO_2 in the air was measured.

Figure 3.10 Examples of Curious noses.

Curieuze Neuzen uses a standardized measurement setup: the measurement of NO_2 in the open air takes place with diffusion tubes. At each measuring point, two tubes were suspended in the open air for four weeks. After four weeks, the tubes went to the laboratory for analysis. Results were calibrated on the basis of a comparison with the official NO_2 measurements of the Flanders Environment Agency. The data collected during this study will be used to improve a computer model for air quality and, on the long run, to assess the effects of NO_2 on health and to provide policy makers with better information and recommendations (https://curieuzeneuzen.be/). The results were published in September 2018, in the Belgian newspaper “De Standaard” (Figure 3.11).

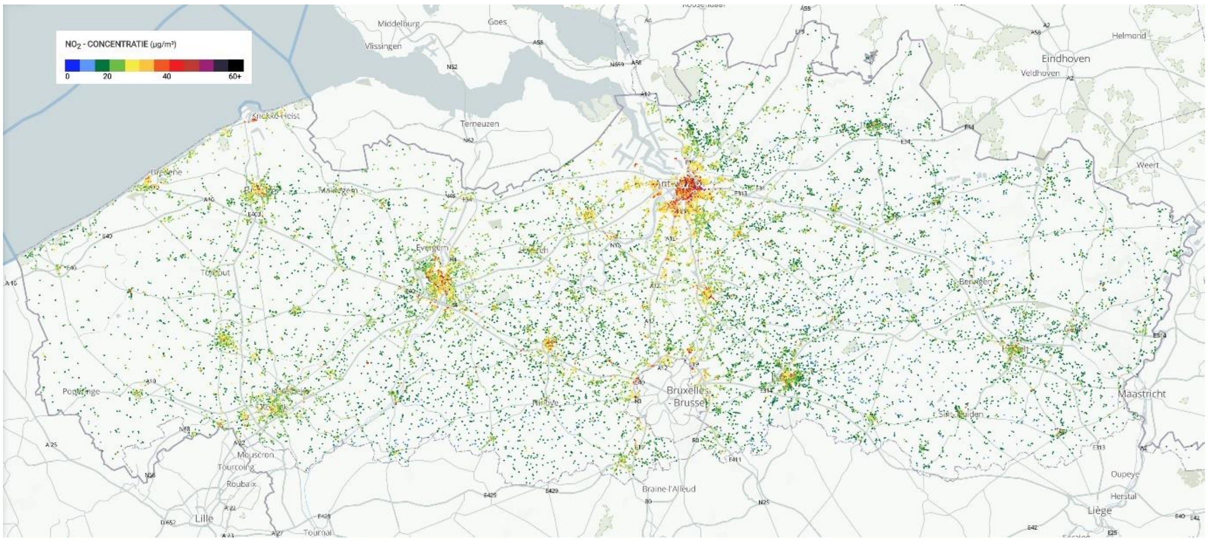

Figure 3.11 Results of Curious noses, source: http://www.standaard.be/curieuzeneuzen/map.

This project is the largest project of its kind, but passive samplers were used in a number of citizen science projects in Europe for a number of years already. For example, in London, both citizen-initiated[6] and local authorities initiated[7] projects have been running for a number of years. In Italy, a NGO “Cittadini del’Aria” has been using the same technology in several urban areas, first of them being Milan [8] in 2017.

[6] mappingforchange.org.uk/wp.../Barbican-Final-Report-draft_12012015_edited.pdf ;
[7] http://lovecleanair.org/about-air-quality/how-pollutants-measured/diffusion-tubes/#.W6y73GhLiSS
[8] https://www.cittadiniperlaria.org/nasce-la-prima-mappa-dellinquinamento-da-no2-dellaria-di-milano-creata-dai-cittadini-per-i-cittadini-2-2/

4 Providing actionable information and the role of low cost sensor systems

The previous chapter looked at examples of citizen contribution to air quality information. This chapter gives examples on how authorities or decision makers are providing information on air quality and how the new low cost sensor systems can provide them with information they require but cannot obtain by more traditional means, often due to high cost.

A central theme regarding actionable information is the concept of Open Data. Open data is data that anyone can access, use and share. Open data becomes usable when made available in a common, machine-readable format. Open data must be licensed. Its licence must permit people to use the data in any way they want, including transforming, combining and sharing it with others, even commercially. Providing open data means that public data are not only made available freely, but also in a way that the data can be easily retained and used.

Governments increasingly start to acknowledge the benefits of Open Data. Economic growth is one of the arguments for this, assuming that governmental data might get commercial value once other parties enrich these data. Open data and openness of information are seen as key values to enhance the development of low cost sensor technologies and the application of sensor data.

4.1 Information to the public provided by the authorities

Regulatory compliance is an important reason why we monitor air in Europe. The assessed pollutant levels information obtained from the regulatory ambient air quality monitoring networks should be representative for the entire zone[9] and near the fixed stations. A way to enlarge the spatial coverage of the assessment is to conduct indicative measurements[9] which have lower requirements for e.g. precision. Many however argue that local gradients in air quality are not adequately described by the monitoring networks supplemented by indicative measurements, with the consequences this may have for e.g. health protection or perception of clear relevance by the public that if not able to find relevant information, seeks other sources of information.

The EEA Member States use different strategies to make air quality data publicly available, but little if any research exists regarding which strategies improve public knowledge on air quality, and fulfil the needs of citizens. A recent survey of ten cities (EEA, 2018d) shows that web pages are the most commonly used communication channel, supplemented in some cases by other communication channels such as social media, public displays, and information through traditional media.

An example of a national portal can be taken from the Netherlands. The national portal 'www.luchtmeetnet.nl' presents all air quality measurement results (see Figure 4.1). Menu options include the display of calculated air quality on a map, predictions up to two days, and the possibility to download the measurement data (once validated) and annual reports.

[9] "Zone" and "indicative measurement" as defined in the EC, 2008.

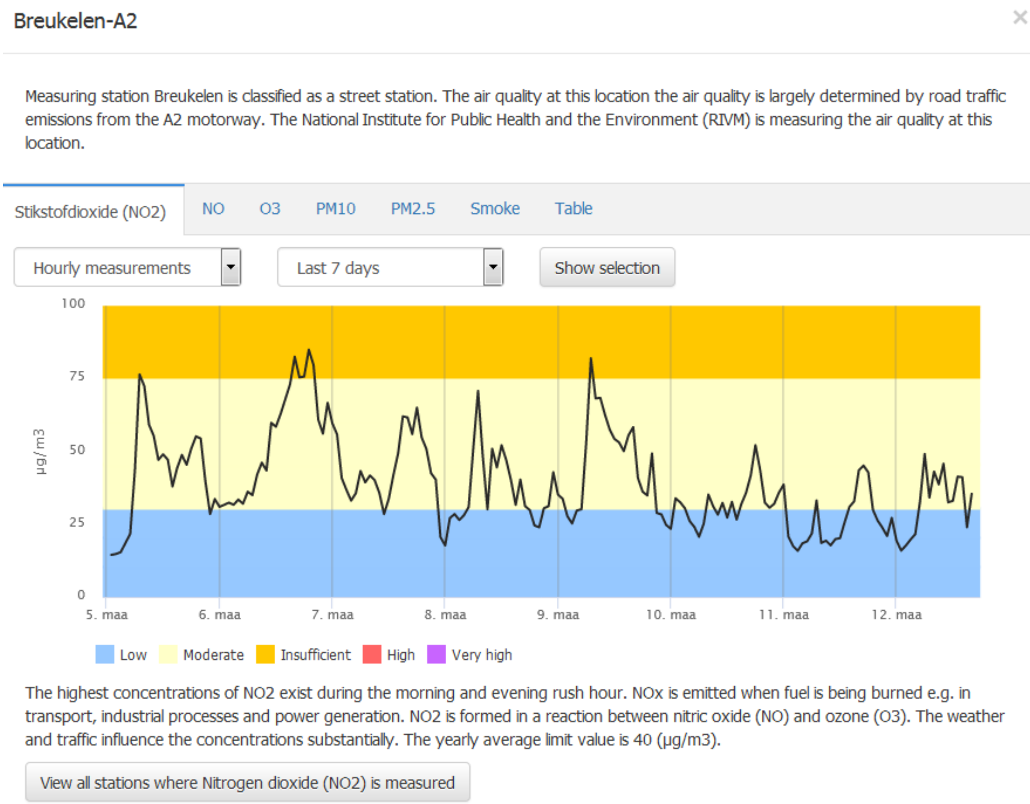

Figure 4.1 Still from a time series as given at www.luchtmeetnet.nl

Quick access to 'on-line' data is important during periods with elevated levels but measurement data are also used for compliance and trend evaluation. Data validation is then required and may lead to rejection or correction of data at a later stage. In anticipation of the strong wish for accessing the unvalidated (near) real-time data RIVM already provides the data from her monitoring stations through the sensor data portal (see Section 5.3), following governmental open data policy.

'Mijn Luchtkwaliteit'. With this free app, everyone can see the air quality in their living environment. It provides information about the air quality at neighbourhood level, an air quality forecast and an action advice based on the (Dutch) air quality index (Figure 4.2). In addition, the app offers the possibility to set a personal alert to receive warnings when certain levels are expected.

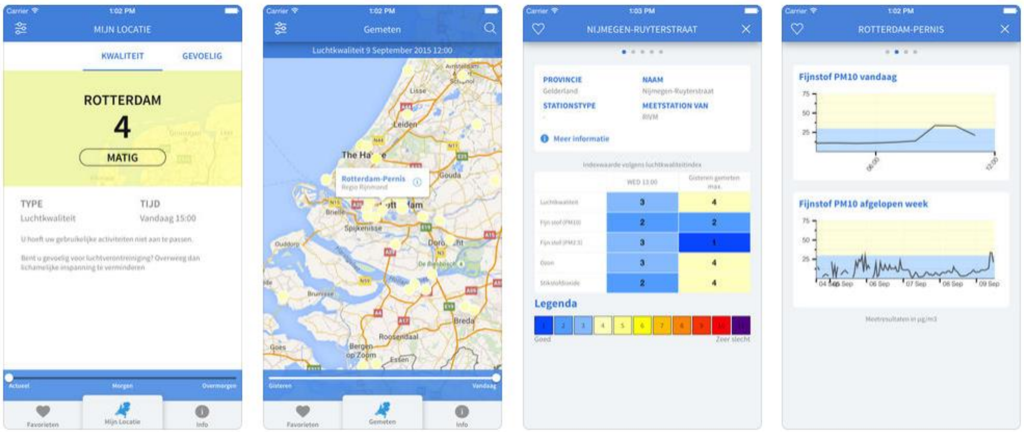

Figure 4.2 Still from smartphone app "Mijn Luchtkwaliteit – my air quality".

New information solutions are being launched also on European level. Every year the Member states have to report their air quality measurement data at a representative selection of stations for a number of pollutants. They provide data to the European Environment Agency Air Quality e-reporting database (formerly known as 'AirBase'), a publicly available database containing the air quality monitoring data for more than 30 participating countries throughout Europe. This air quality information system includes additional information such as what measurement techniques are used to produce the data, data validation information and quality assurance procedures. The annual reports and data are available for download from the database at http://www.eea.europa.eu/themes/air/airbase, and in interactive data viewers https://www.eea.europa.eu/themes/air/explore-air-pollution-data. In addition, the countries also provide up-to-date data https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/up-to-date-air-quality-data. Recently, these data are combined with model results on the European scale into an European air quality index (Figure 4.3) found at http://www.eea.europa.eu/themes/air/air-quality-index.

These efforts are not necessarily successful. In the recent project CITI-SENSE (http://co.citi-sense.eu), the research team has recruited volunteers who were willing to monitor air quality themselves using personal sensor systems. In Norway, these volunteers, despite having interest in air quality, seemed to have little knowledge of the existing information systems which in Norway are the result of over 30 years of nation-wide cooperation between authorities across sectors and administrative levels and research institutions. For example, the http://luftkvalitet.info/ provides air quality information to the public, and the http://luftkvalitet-nbv.no provides information on how the most important emission sources (including traffic or local heating) influence local air quality in all larger conurbations of Norway. While this information seemed surprising to the participants, it did not necessarily fulfil their information needs, as is indicated in Figure 1.1. This indicates a serious communication challenge.

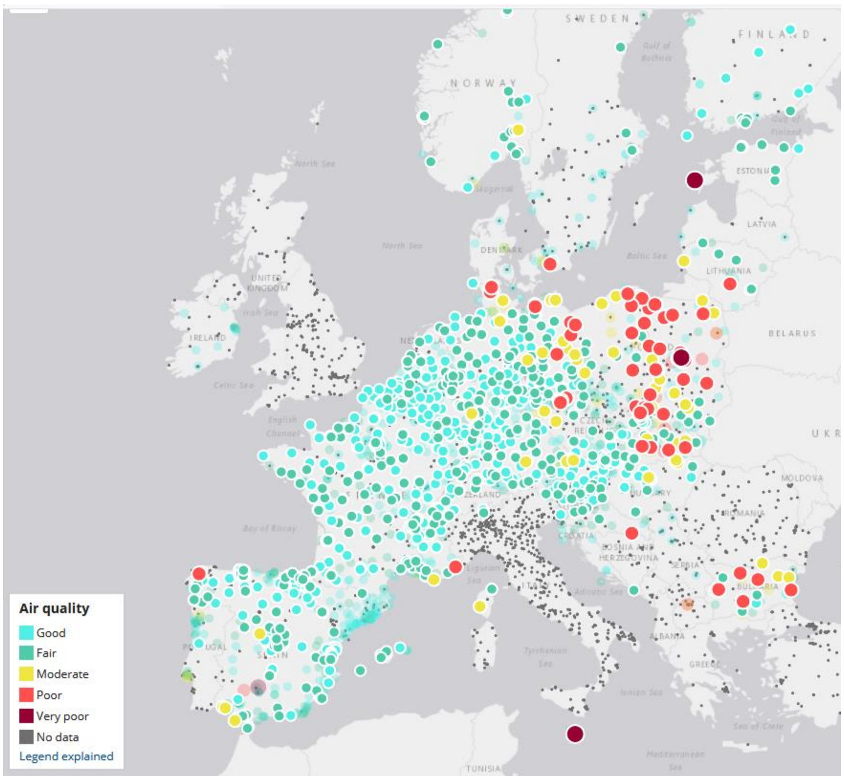

Figure 4.3 *Still from http://www.eea.europa.eu/themes/air/air-quality-index*

4.2 Filling the gaps in data using sensor systems

Supplementing routine networks with sensor systems seems attractive for several reasons, including the lower investment costs, and the possibility to cover larger geographic areas with dense measurements. Most of the available sensor systems are easy to deploy, but deploying large numbers, maintaining them and employing the necessary quality systems (at this time, not well defined) can offset the low investment cost by increasing operational costs. In terms of quality systems, for example, sensor networks would need to operate in parallel with reference stations. In many projects, minimum requirements are that the data provided by the sensor systems should be compared to reference data and corrected, e.g. using procedures described in Section 0. While the current state of technology may not be mature enough to allow the use of sensor networks in regulatory monitoring (considering the numerous requirements that safeguard that regulatory measurements are comparable), it is likely that such applications will be possible in the future.

New sensing technologies can be used for example, to build surveillance networks to monitor emissions of industrial plants or other sources. Traditionally, optical sensing methods can be used for remote sensing of sources, such as to monitor emissions of SO_2 (Gliss et al. 2017); this can complement the dedicated systems for emission monitoring as required by legislation. Monitoring the source has the advantage that concentrations are much higher, in ranges for which sensor sensitivity and accuracy are often very good. Although sensitivity and accuracy are still not at the required level for regulatory emissions, the data can supplement existing networks and provide monitoring to better capture, e.g., industrial incidents as chemical releases and fugitive emissions as well as gas pipeline monitoring.

To our knowledge, sensor systems such as discussed in Section 2, are not employed for these purposes on a regular basis. The EU Joint Research Centre has employed sensors mounted on an unmanned aerial vehicle to monitor emissions from ships and measured the exhaust plume concentration at the stack (Gerboles, 2012). Poopola et al (2018) describe a by-product from the use of a dense sensor network around an airport to assess aircraft emissions. Another example is the estimation of (variations) in emission strength of fugitive dust from dry bulk terminals in the Netherlands by use of fence line monitoring with a sensor network https://www.ecn.nl/nl/nieuws/item/ecn-meting-toont-aan-minder-fijnstof-bij-overslagbedrijf-igma-in-amsterdamse-haven/ (in Dutch). Sensors are also recently being tested for industrial indoor air applications (Asbach et al. 2018).

The application of 'E-Noses' (Figure 4.4) is an example on the surveillance of incidental emissions that can be found in the industrial area of Rotterdam Rijnmond. The electronic noses observe changes in air (VOC) composition but do not actually measure concentrations. The network today consists of more than 250 sites. With the help of targeted measurement campaigns, companies with a nuisance can be continuously monitored and the conditions under which odour nuisance arises can be traced. The technology is not an alternative to the current air network, but can be a valuable addition to the air monitoring stations at relatively low costs. The E-nose can contribute to the detection and warning of elevated BTEX / benzene concentrations. Sensors like these can be applied by the emitting companies (early detection of leaks allowing intervention) and by the enforcement authorities (early detection prior to complaints by inhabitants).

Figure 4.4 An E-nose (source: DCMR, https://www.dcmr.nl/projecten/e-nose-programma-rijnmond.html)

Schneider et al. (2017) provide another successful example of the use of sensor data for information purposes. This work has responded to the need to provide a real time air quality map. While measurements are easy to visualize in real time, even for a large number of sensor system units, processing the measurements to provide maps is usually computationally very demanding due to the type of physical-chemical models used for this purposes, and thus takes time. By taking advantage of having a larger number of observations from sensor systems within a limited geographical area, a real time map can be created using statistical data assimilation methods that generally require much less processing time. This approach illustrates perhaps the largest current benefit of a sensor network: real- time data with high spatial resolution can enable application of statistical methods that provide accurate timely information.

4.3 Individualized information and exposure assessment

The protection of human health is the most important reason why air quality monitoring is regulated by European legislation. However, estimating the personal exposures and exposure to sources is rather difficult due to the spatial and temporal variability of the air quality (especially in urban surroundings). Another complication is to estimate the time individuals spend in different environments (office, commuting, working out outdoors, etc.)

The most accurate way to establish an individual's exposure to environmental factors is to directly and continuously monitor the individual's personal space. One way of doing this is to use the location data of GPS devices like those embedded in smartphones. The location data is then merged with exposure models to assess the exposures at various locations per person.

Another way is to use wearable or portable sensors measuring air quality during daily activities. These sensors provide information about air pollution in the surroundings yielding an estimate of the personal exposure during daily tracks.

For vulnerable groups (children, asthmatics, elderly, etc.) or for those particularly interested in health issues, carrying sensors may be considered acceptable. However, for the major part of the population, carrying sensors may be problematic for privacy reasons (e.g. continuous location tracking). Therefore, the coexistence of different methods that not only rely on personal monitors to provide information to the citizens (e.g., conventional networks) still remains highly relevant.

Despite the challenges of personal monitoring, improving estimates of personal exposure is necessary for epidemiological studies, which often have to rely on limited ambient air monitoring data. Additionally, air pollution sensors can be linked with physiological sensors, thus providing a better estimate of human exposure. A popular example is the activity tracker ('Fitbit') usually applied as a watch and can be linked to a mobile phone and computer. It gives insight into activities during the day and relates to health aspects e.g. by measuring heart rate. It often includes a pedometer, calorie counter (movements and activities automatically linked to the counter), and sleep patterns (Figure 4.5)

Figure 4.5 Examples of health sensors.

4.4 Smart cities

Stimulated by fast advances in ICT and sensor technology, municipalities work on the concept of becoming a 'smart city'. The idea is that data collection from all kinds of sources, including low cost sensors, helps managing cities efficiently. In smart city projects, sensor networks are set up to experiment and find out how and to what extent sensors can contribute to spatial, strategic decisions. From real time action strategies such as traffic routing and individualized smog alarm, to energy saving lamp posts. Sometimes municipalities create an open space, for example a street corner or traffic sign, where any party can attach sensors. This initiative has proven to stimulate technology businesses and start-ups to further develop sensors and their peripheral equipment. The smart city concept might lead to better insight and understanding of local environmental management.

Regarding air quality, pilot projects have started or are being started in which air quality sensors are installed on lamp posts or other assets in public space. Many of these pilots are initiated in a top-down manner by local authorities. Different levels of citizen participation have been observed (for bottom-up project see under Citizen Science). Commercial enterprises are nearly always involved in pilots like these.

Challenges that arise in smart city projects are mainly in communication and sensor quality. Sensor quality challenges are data quality, sensor sensitivity, up- and downtime issues, and calibration requirements. Commercial enterprises are not always aware of these issues or do not take account for them, while offering sensors to smart city pilot projects. Such projects raise the question about the importance of quality data and assessing uncertainty levels. Poor quality data or unknown uncertainty levels lead to data misinterpretation and erroneous conclusions, not at all in line with cities wanting to be smart.

5 Data sharing and visualisation

Today, many sources are available that provide information about the state of the environment (Figure 5.1). Many professional bodies and organizations are dealing with how best to connect these sources. For scientific data, the FAIR Data Principles are a set of guiding principles in order to make data findable, accessible, interoperable and reusable (Wilkinson et al., 2016). These principles provide guidance for scientific data management and stewardship and are relevant to all stakeholders in the current digital ecosystem, and can serve as one of models for any data provision.

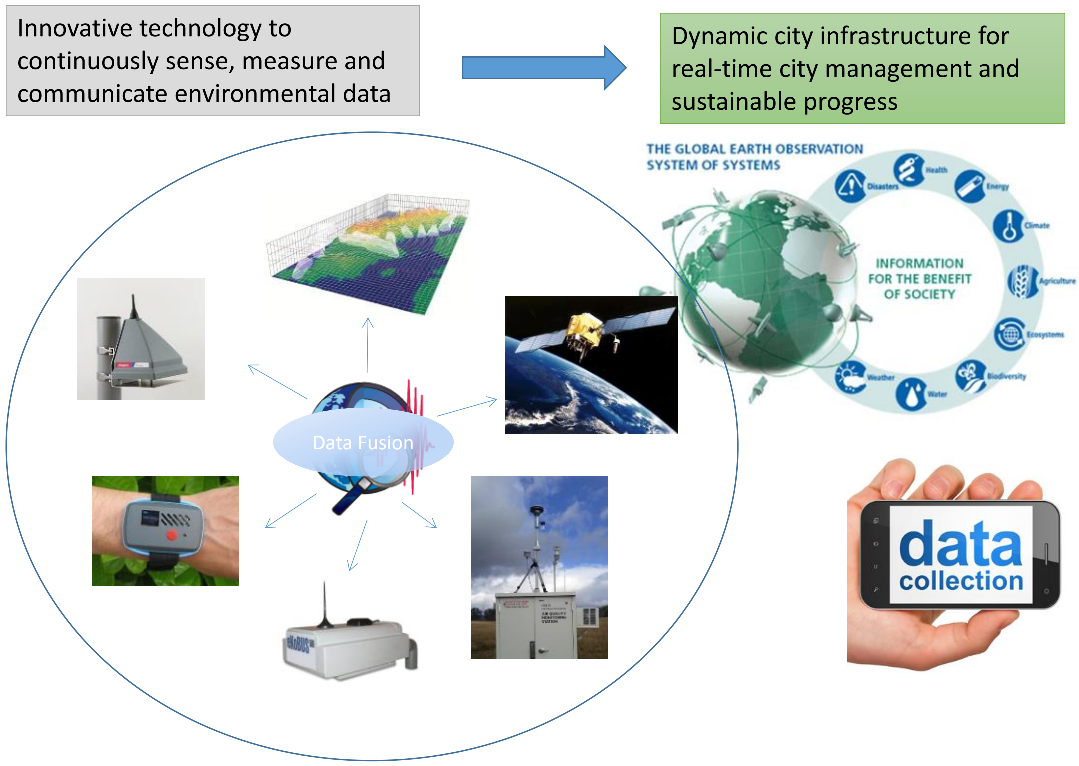

Figure 5.1 An illustration of connectivity of data sources. Source: NILU

Thus, it is clear that information and communication technologies are the second enabler of the use of low cost sensor systems, yet, the users tend not to include plans for such infrastructure when planning sensor systems deployments. In the current section, we have compiled the most commonly encountered issues.

5.1 Development of data flows and communication solutions

In any monitoring activity, data flow and communication solutions are an integral part of work. In early ambient air quality monitoring networks, data were stored at monitoring stations and manually transferred to a central database, or dedicated communication using e.g. SIM cards or a secure wireless transfer protocol has been used. Then, data are typically stored in a database, and displayed in real-time (prior to further quality checks), and after a certain period, available in the database after quality checks are performed.

For sensor networks, the need to manage communication of a larger number of units, and the fact that it is not possible to perform physical calibration or manual data quality checks on individual devices, pose specific problems. However, the parallel development of Information and Communication Technologies, especially the Internet of Things (IoT) approaches, provides a good basis for solving the communication issues in practice. A survey of commercially available sensors shows that most sensor providers are offering GPRS (General Packet Radio Services - wireless communication service for continuous connection to the Internet for mobile phone and computer users) of WIFI communication; some offer dedicated protocols such as LoRaWan (Low Range Wide Area Networks Protocol, *https://www.lora-alliance.org/technology)*. Yet others, typically portable devices, are using a bluetooth communication with a smartphone which then is used as the data transfer unit (utilizing whichever type of protocol for data transfer to the data repository).

From a user point of view, the choice of communication is important: often, it is difficult to modify a sensor system for use with other communication systems, as it requires a dedicated hardware. With larger numbers of devices/nodes, there also can be associated data transfer costs (e.g., costs of data package for a mobile subscription). However, with today's trend of Smart Cities and IoT infrastructure development, it is likely that these issues will not be limiting the proliferation of the sensor system technologies.

5.2 Visualization

Visualization of sensor data within the platform should aim at enabling users to look at the data in a way that meets their needs. As noted above, it should have enough diversity for different users. The most basic information is the actual measured concentration. However, users like citizens will always want to know what does the value mean? They have a need for indices with colour classes and phrases that qualify the air quality. The data platform of the Smart Emission project, initiated in Nijmegen the Netherlands, presents the actual data both in values, colours and descriptive qualification as seen in Figure 5.2.

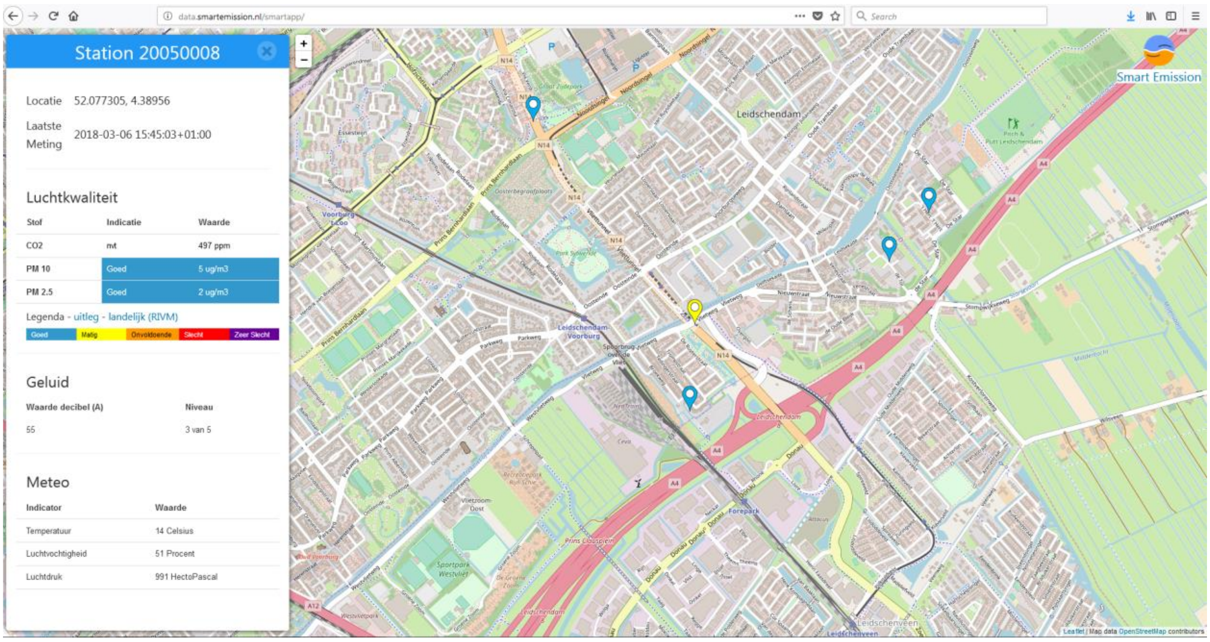

*Figure 5.2	Still from http://data.smartemission.nl/smartapp/*

This is rather tricky in cases where the quality of sensor data is unknown. Sensor data might easily be misclassified. Disclaimers like "indicative values" are easily overlooked when data are presented in colour classes. One might question if it is wise to present the sensor data in this way. On the other hand, looking for example at the data visualization of the bottom-up citizen science project Luftdaten below Figure 5.3), it is obvious that colours help to visualize differences between locations, in this case regions within Europe.

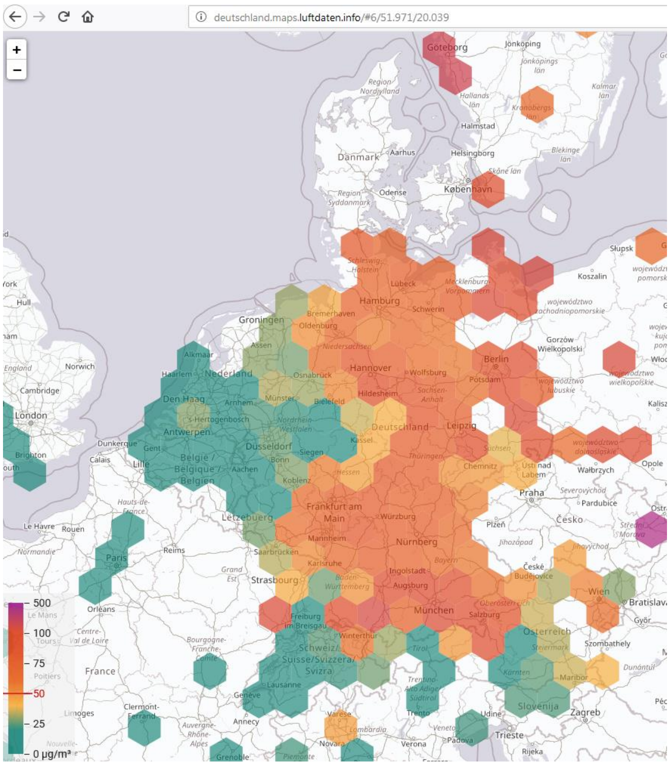

Figure 5.3 Still from http://deutschland.maps.luftdaten.info

In order to have some idea about the quality of the sensor data, it is good to have the option for comparison with (not validated) reference data from nearby stations. Plotting time series in the same graph can give a good indication of order of magnitude and correlation in time. Also, time series are a good way to learn about the variability in concentrations. Combining with meteorological data might give understanding of episodes of elevated background concentrations and local sources. For those who want to identify sources, pollution wind roses might be provided. At the experimental data portal of RIVM in the Netherlands, samenmeten.rivm.nl, these features are provided after user consultation, see the example in Figure 5.4.

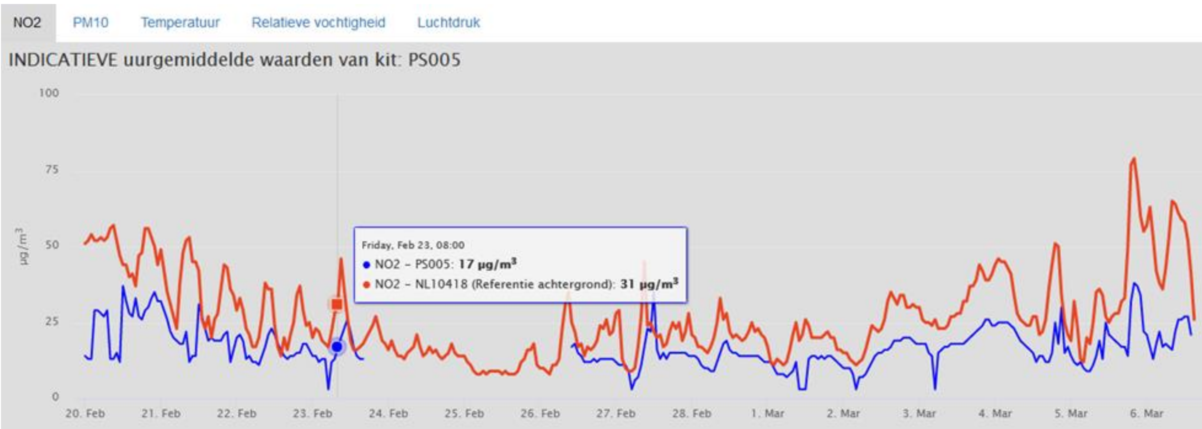

Figure 5.4 Still from https://samenmeten.rivm.nl/dataportaal/

5.3 Data repositories

The architecture of data repositories for air quality data from low cost sensor systems can draw on the experiences from database development for ambient air quality monitoring; the data structures and functionalities are similar in both ambient air quality monitoring and air quality sensor system network, addressing several levels of sensor system and data calibration, and quality control flags. Modern large scale systems with the ability to handle numerous inputs are now routinely being built within the IoT and Smart Cities applications.

An important property of the data repositories is their scalability. They need to be "growing with the network". This requires data flow standardization and an open infrastructure that allows data sharing.

Such data structure requires meticulous attention to metadata collection. The metadata should include also information about how data were processed to convert sensor signal to the desired measurand (e.g., version of the algorithm used), and information about procedures for quality control and quality assurance. Using big data approaches or machine learning to improve the data quality is gaining a lot of interest as it offers the advantages of sophisticated statistical routines. Information about such processing should also be part of the metadata on the measurand.

5.4 Sharing data between different users

Nowadays, society asks for open data and governments are increasingly providing them. Via API's, large amounts of data can be retrieved for automated use of data in other applications (e.g. smartphone visualization). These are preferred by developers from governments and commercial enterprises. API's can also be used to exchange sensor data between platforms. In this way data from sensor networks owned or organized by for example local governments can be transported to national or even international data platforms.

The Sensor Observation Service REST API (which is used for data exchange of official air quality data between member states and the EEA) has been implemented in the data platform of the Smart Emission project in Nijmegen, the Netherlands. It provides the latest actual sensor values. Since the SOS API turned out quite complex, actually too complex for regular developers, recently the Sensor Things API, an OCG standard for IoT, has been implemented. The Sensor Observation Service complies also with the INSPIRE Directive.

Citizens, students and local governments may want to analyze the data for their own purpose. If users have very specific wishes for visualization, they can be referred to data download and have their own analyses. Still, reference institutes might help at this stage by providing data analysis tools (see for example the US EPA tool for evaluating low cost sensors: https://www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-evaluating-low cost-air-sensors-collocation).

For educational purposes, lesson programs might be developed and provided to schools in which students are challenged to analyze their own data.

The air quality data are increasingly used also by commercial actors. An example is the Weather Company that is currently including information on air quality in their information services (Menard 2018).

5.5 Expectation management and disclaimers

Providing download options and API's for sensor data means that depending e.g., on type of open data license, third parties can use the data for its own purpose. It is extremely important to describe the can do's and can't do's with air quality sensor data. However, metadata, disclaimers and guidelines are easily overlooked and this may lead to inappropriate use of data. An example is when citizens measure air quality themselves and want to use the data for demanding action from governments to act against local sources. The way this might work is when governments and citizens seek the dialogue based on open data and open minds. It will not work when citizens want to use the data in court against governments. Sensor data simply do not have a legal status. The question is how to explain this to citizens that distrust the government in the first place. Practice shows that citizens can successfully teach each other based on their own experience. For example, in the Netherlands, RIVM facilitates regular meetings between groups of citizens that measure air quality themselves, and citizens are invited to bring their sensors to a reference station to learn about the quality of their sensor directly.

Commercial enterprises are constantly seeking for data to use in their products. They are especially interested in real time data. Real time data for air quality, either from reference monitors of from sensors, are often not validated. (Experimental) data validation and calibration techniques might have been applied, but still data quality will often be unknown. This should be acknowledged and communicated when providing real time sensor data as open data.

5.6 Respecting privacy and ownership

When sensor data are plotted on digital maps, location details of sensors at citizens properties should be dealt with care. Laws and regulations for the use of personal data should be followed, for example, non-disclosure of information that makes an individual identifiable such as home addresses or other personal data. For example, in the data platform of Luftdaten, sensor data cannot be traced back to individual home addresses due to the limited zooming function. The RIVM data portal applies a randomizer with a margin of 100 meters. However, when data are provided through API's, location details may still be shared. It is important that participants know what kind of measures are taken to protect their privacy, and give their permission.

Citizens sharing their data should receive detailed explanations how their personal data will be treated and be asked for permission. When data are provided as open data, citizens should be made aware what license is being used, and what consequences such data sharing could have (e.g. use for commercial purposes). According to European legislation, participants have the right to withdraw their permission to share data they have generated, meaning that from that moment on the data stream must be stopped. They also have the right of "being forgotten". Their historic data should then be removed from the database. However, when their data have been provided as open data, they should acknowledge the fact that these data cannot be made unavailable.

One could question whether air quality data themselves can raise privacy issues. For example, when high concentrations of particulate matter are measured on a regular basis, these might for example be traced back to individual wood burning. When all of a sudden the signal changes, it might be an indication of absence human activity over a longer period, indicating an empty residence

Ownership of data shared through central platforms is an additional challenge. It is necessary to consider the relevant legal provisions before implementing solutions, but there may still be questions. When data are edited by the owner of the database (for example, when a sensor system manufacturer or provider of an internet access to data employs on-the-fly calibration algorithm to improve data quality) will the person who has purchased the sensor system still hold the right or is it transferred to the database owner?

6 Implementation of low cost sensor systems

Using the new technologies is an opportunity to add new data types to existing monitoring and data gathering, opening the way for new products and services and to enhancements of existing products. Utilizing this new source of information however may require that actors acquire new skills and capacities, for example, master technologies such as big data analytics.

The task flows related to low cost sensor systems and their use are similar to those of conventional monitoring, but more demanding due to the large number of heterogeneous systems that need to be connected. There are however rapid developments, merging together advances in Internet of Things (IOT)/communication technologies and sensor systems. There seems no doubt that future applications using sensor system networks have the potential to provide new scientific and technical insights, and will enable new ways to inform the public on air quality.

Sensor systems seem attractive for both existing and emerging applications including monitoring and management of air quality and public information, or exposure assessments. Not all of these areas have well defined requirements for data quality, and in some situation, existence of such criteria is not considered, and available infrastructure does not support quality assurance and control. Thus, ensuring that data is fit for purpose remains a major challenge. Further insight is needed on data quality standards for these applications.

As an example, to support health/medical decision-making, data quality requirements may be:

- a 'reasonable' degree of agreement with measurements by reference instruments
- a 'substantial' degree of confidence since it is part of policy decision making
- quantitative or qualitative measurements to capture behaviour
- some degree of data quality standard and reliability

In the case of public information the following might be adequate:

- quantitative or qualitative measurement
- flexibility in how the levels of measurand are reported
- data quality objectives similar to "indicative measurements" as prescribed by EC, 2008
- methods not legally prescribed, but conflict with air quality data generated from compliance/regulatory applications should be avoided

Services enabled by sensor systems are emerging by concept and in trial experiments. It is inevitable that supporting infrastructure (e.g. data quality approaches, calibration, maintenance and so on) will take time to develop the new applications as consensus is reached on best practice. For those interested in 'new science' the responsibility will be placed largely on users to demonstrate that data meets an appropriate quality threshold. Over time, methods may rely to a larger extent on computational procedures, but a certain level of physical/manual quality assessment and quality control procedures will be necessary to ensure that the resulting systems reflect well the physical and chemical conditions they are supposed to describe.

6.1 Connecting sensor systems in networks

One of the advantages of the "low cost" sensor systems is the low investment cost of an individual device. This affordability has led scientists to study the outputs of the sensor systems, mostly from the point of view of quality of individual measurements. It has motivated scientific groups to develop also non-commercial devices, such as the AirSensEUr, https://airsenseur.org/website/, with the eye on providing an open infrastructure consisting of devices, communication solutions and basic applications that would enable affordable yet good quality measurements to interested amateurs.

Low cost sensor systems are however still used more often as individual instruments, rather than in networks, though a number of such networks is growing. Establishing a network of sensors requires communication infrastructure, which poses many challenges related to connectivity of the devices and data traffic. But advantages of exploiting the properties of the network rather than focusing on individual instruments seem to be more and more obvious, as exponentially growing literature on the subject shows.

To begin with, research done by the air quality community seems to have focused on improving the capabilities of individual sensor systems. A few early examples exist that instead of focusing of an individual sensor system unit address the properties of the whole network. They include Kizel et al., 2017, or work done by Schneider et al. 2017.

Kizel et al (2017) addressed sensor output calibration by developing a “node-to-node” calibration procedure, calibrating (or correcting data) in sequence using the calibration/correction information from the previous sensor system. Other authors have shown how to use the sensor systems network data for calibration and correction purposes. The corresponding box in Figure 2.4, “Machine learning”, is subject to quickly developing research (Esposito et al., 2017). However, such procedures raise important questions, such as when do data stop to be measurement data and become model data (Hagler et al, 2018).

Schneider et al. (2017) have used sensor systems output and combined this with a base map that describes spatial gradients of air pollution in an urban area. They showed that by using a simple data assimilation technique, the sensor data will enable to provide up-to-date or nearly real time highly spatially resolved map (in this case on hourly basis), that when tested for agreement with reference instruments nearly reaches data quality objectives required for an equivalent instrumentation. This work is continuing: providing high resolution maps of pollution “now” is not possible using other current techniques such as dispersion modelling, as they generally are computationally demanding, unlike the proposed statistical technique.

These early examples are now followed by numerous authors that demonstrate how machine learning can be used to improve data quality, and for other purposes including short term prediction of air quality. The large number of research papers that have been published only in 2018 testifies to the rapid development of both, the networks of sensor systems, and methods that use statistical properties of data provided by these networks. This development is enabled by advances in the information and communication technologies including smart cities applications.

The potential of the low cost sensor system technologies is likely to be fully utilized only when larger amounts of sensor systems are deployed simultaneously in one region. Such applications are already planned or operational in several areas in China and Asia. They are enabled by the development of information technologies such as Internet-of-Things or Smart Cities connectivity. The requirements on systems scalability bring about the need to develop complex data systems, with high degree of standardization of e.g., data protocols and other elements. Such systems are already on offer e.g., from the Open Geospatial Consortium, but are not well known to the air quality community. Connecting the ICT and the air quality communities is thus one of the imperative near-future tasks.

An easy scalability of the deployment seems an essential requirement. It can be understood in the following way. One individual can purchase a sensor system and follow their own data – and sometimes data from other users - using a proprietary web portal (such as, e.g., the purple air web portal, www.purpleair.com). For a municipality or a group of interested citizens who wish to combine several technologies or several types of sensor systems, it may be necessary to “scale up” the system, i.e. to connect a larger number of devices in one information system so that data can be viewed simultaneously.

Such a system can comprise of devices from different manufacturers and models, or combine municipal air quality monitoring with the citizen's own measurements.

For example, our goal can be to develop a network of affordable sensor systems for measuring air pollution that will provide real time information on air quality with high timely and spatial resolution, allow automatic traffic control, or give guidance to bicyclists as to which path through the city will lead to least exposure to air pollutants. To achieve this goal, a typical project can consist of the following components includes (Morawska et al., 2018):

- Deployment of (large number of heterogeneous) sensor systems
- Ensuring communication and data harvesting
- Ensuring quality of data, including correctness of observations
- Ensuring access to data and their connectivity
- Providing information in an appropriate way
- Developing appropriate action on the information.

Not all the above elements need to be the responsibility of the project owner. For example, the ongoing work on calibration of sensor systems under the auspices of the CEN/TG 264 WG42 may eventually lead to a standardization and approval system for sensor systems. This will then pose requirements on the manufacturer, and will likely facilitate use of the products and improve data quality.

New ways to deploy sensor networks are piloted by the numerous citizen science activities, as Chapter 3 illustrates. This includes also possibility for crowd-funding or alternative funding methods, in addition to public funding. Technical and logistical support of such networks is however likely to be an issue with time, as most of the sensors have limited life time and faulty sensor systems may need to be identified and replaced.

Internet of Things will bring about changes in communication protocols and will enable deployment of low cost sensor systems for air quality as its integral part. At the moment, however, the number of communication protocols and system architecture designs in IoT may make it difficult to develop truly generic systems.

6.2 Supporting Citizen Science and citizens' contribution to monitoring10

Citizens' contribution to maintaining or improving environmental quality will be of paramount importance. The new thinking for future users will enable new insights and perspectives on pollution data, and will contribute to applications such as city air pollution management or public information. Sensor system data requirements have yet to be firmly established and methods of exploiting sensor data are only in their infancy, but it would seem wise if the authorities on all levels supported these complex efforts: the first examples are only young, but undoubtedly will be evaluated and the best experiences brought forward.

Administrations have already expressed their concerns as to how to respond to citizens reporting data from sensor systems while information on data quality is unavailable. Citizens that want to measure the air quality themselves should prepare themselves by getting information about the can do's and cannot do's. Sensor systems data quality is a key issue. Guidance documents and advice on sensor system use and

[10] Freely based on Volten et al 2018.

data interpretation are essential to help communities and individuals to take advantage of this new technology. Information can come from EPA's or other citizen scientist that have more experience.

The concept of citizen science evolves closely with the development of new sensor technologies. Sensor systems deliver real time information at affordable costs to citizens. Real time information has added value over monthly information by passive samplers, another low cost measurement technique applied by citizens. They give insight in temporal variations allowing better understanding of air quality by citizens. Citizens start to measure air quality in their own backyard, form their own neighbour watch, and reach out to Environmental Protection Agencies (EPAs) for knowledge and guidance. For EPAs, supporting and participating in citizen science projects allows for a two-way knowledge exchange.

Experts at EPAs receive high spatial-temporal resolution data, information on local perspectives on air quality, and learn to communicate their methods and findings in a way that appeals to their citizen audience. The process of inquiring air quality issues advances into a method that still roots in the scientific paradigm, but grows in reflexivity, meaning researchers become more aware of the potential societal impacts of their research. Hence, they shape their topic of choice, methods and approaches more according to citizen views and needs. This will increase the accountability, quality, effectiveness and legitimacy of scientific expertise in society.

Citizens may become more involved in air quality issues and potentially gain more understanding of causes and consequences. Because of the possibility to perform measurements, the often highly technical and highly scientific work becomes more understandable for non-professionals, which contributes to a better comprehension of air quality measurements and better acceptance of policy measures.

Most importantly, citizens may become aware of their own behaviour. Combined with localized data availability, citizen empowerment increases, enhancing their motivation and possibilities to make changes in their local environment. Sensor data may facilitate more dialogue between citizens and governments at all levels. An example is the Smart Emission project in the city of Nijmegen (The Netherlands). Besides a large source of environmental data, democratization of data and knowledge is a significant benefits of citizen science projects.

The combination of sensor systems and citizen science has also proven to be a great tool for community building. At the level of cities and neighbourhoods, but also in rural areas, citizens that have an interest in or concern about local air quality, team up to perform measurements, collect data, and can interpret results. Emerging IT concepts, such as big data and IoT, offer state of the art tools for sharing data, experiences, and applications. Likewise, developments in sensor technology are well applicable in education. Students of all ages can learn about air quality and its effects, how to take measurements and experiment with sensor technologies. Schools can choose to participate in local or regional sensor systems networks, stimulating self-learning experiences, and contribute to high resolution air quality measurements. Besides, measuring air quality has become an interest within technical communities. For example, The Things Network is building a network for the IoT by creating abundant data connectivity, so applications and businesses can flourish. They use LoRaWAN technology that allows for things to talk to the internet without 3G or WiFi. Measuring air quality with low cost sensor systems seem a perfect way to test the technology. For example in the Netherlands, some local groups participated in measuring particulate matter from New Year's Eve fireworks.

Following the fit-for-purpose principle, sensor systems that do not meet requirements for accurately measuring particulate matter mass concentration, can be of great value to citizen science. One way to deal with data from optical particle counters is to use the raw particle number concentration, which can be measured quite well with these sensor systems rather than the conversion to mass concentration. Citizens might go and look for differences in time and space (outdoor as well as indoor) and seek for the lowest number concentrations. This can lead to increased understanding that might influence their behaviour.

The involvement of citizens with sensor systems measurements has the potential to generate much data and increase knowledge. The resulting benefits, however, are dependent on how we address several challenges. Examples are:

- Extent of interactions at the local level: is a sensor project initiated top-down or bottom-up?
- Extent of citizen involvement: are they just an extended sensor, or do they actively contribute to the research set-up
- The way collected data are made available to participant: raw data or maps with adequate explanation
- Facilitation of citizen science sensor projects by experts in air quality, measurements and/or data interpretation
- Information about sensor technology is available to citizen scientists in an understandable format.

In way of an example of institutionalized support to citizen science, we can mention a Dutch initiative (Figure 6.1). In December 2017, RIVM has launched an experimental sensor data portal. The goal is to make environmental sensor data from citizens, local governments and others in the Netherlands available through a central database. In this experimental phase RIVM uses the data for several research topics, for example developing on the fly calibration algorithms, assimilating sensor data in hourly air quality maps and testing data visualizations for citizen scientists. In the near future, RIVM aims for a monitoring network in which third parties, including citizens, can actively take part.

Figure 6.1 Still from the Dutch portal samenmeten.rivm.nl.

7 Concluding remarks

For a successful use of low cost sensor systems, we need to recognize that an individual sensor system (one monitoring device) is not equivalent to reference monitors (at the moment), and perhaps should not be thought of as such. Evidence begins to emerge that data from a large ensemble of low cost sensor systems, when employed in e.g. statistical or machine learning procedures, enable providing information that matches data quality objectives in terms of precision and accuracy. Data from a network of sensor systems can thus support providing up-to-date or real time information products that are sought after by the public. They can also contribute to other applications such as health impact assessments, or validation of emission estimates.

To make sensor systems operational, we thus need to connect two kinds of infrastructures:

Sensor systems network infrastructure

- Heterogeneous sensor system deployment
- ICT infrastructure for data harvesting

Data processing infrastructure

- On-the-fly calibration and correction
- Connectivity to other systems
- Real time products

Both the necessary infrastructures (communication infrastructure and sensing infrastructure) will incur substantial investment as well operational costs, and thus require funding, host organizations, and technical competence.

Sensing techniques are rapidly evolving and are frequently updated by manufacturers. It is important to keep in mind that this 'ever' improving capability implies that there is currently no traceable method of evaluation that can be referred to. Despite the efforts of numerous groups, including within the European standardization system, a certification system will take some time to develop. Fitness for purpose will be paramount.

We hope that this report provides enough information for those considering developing such infrastructures to aid their planning and successful implementation. We feel that the new technologies, while a disruptive change, provide many exciting opportunities, and we hope that this report will contribute to promote their use alongside with other assessment methods. We believe that increased understanding of technical issues we discuss will ultimately lead to better communication on air quality, and in its consequence, will lead to further improvements in this environmental domain.

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