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Low-cost sensors and networks

Overview of current status by the Norwegian Reference Laboratory for Air Quality

Núria Castell

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ABSTRACT

The increase of the commercial availability of low-cost sensor technology to monitor atmospheric composition is contributing to the rapid adoption of such technology by both public authorities and self-organized initiatives (e.g. grass root movements, citizen science, etc.). Low-cost sensors (LCS) can provide real time measurements, in principle at lower cost than traditional monitoring reference stations, allowing higher spatial coverage than the current reference methods. However, data quality from LCS is lower than the one provided by reference methods. Also, the total cost of deploying a dense sensor network needs to consider the costs associated not only to the sensor platforms but also the costs associated for instance with deployment, maintenance and data transmission.

This report aims to give an overview of the current status of LCS technology in relation to commercialization, measuring capabilities and data quality, with especial emphasis on the challenges associated to the use of this novel technology, and the opportunities they open when correctly used.

NORWEGIAN TITLE

Mikrosensorer og målenett

KEYWORDS

Low cost sensors | Air quality | Sensor procurement

ABSTRACT (in Norwegian)

Denne rapporten går igjennom status innen mikrosensorteknologien. Den vurderer tilgjengelighet av produkter på markedet, målte parametere og datakvalitet, samt hvilke muligheter sensorene åpner for når de blir brukt riktig.

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Preface

The increase of the commercial availability of low-cost sensor technology to monitor atmospheric composition is contributing to the rapid adoption of such technology by both public authorities and self-organized initiatives (e.g. grass root movements, citizen science, etc.). Low-cost sensors (LCS) can provide real time measurements, in principle at lower cost than traditional reference monitoring stations, allowing higher spatial coverage than the current reference methods. However, data quality from LCS is lower than the one provided by reference methods. Also, the total cost of deploying a dense sensor network needs to consider the costs associated not only with the sensor platforms but also the costs associated for instance with deployment, maintenance and data transmission.

This report aims to give an overview of the current status of LCS technology in relation to commercialization, measuring capabilities and data quality, with especial emphasis on the challenges associated with the use of this novel technology, and the opportunities they open when correctly used.

Many organizations in charge of air quality monitoring for regulatory purposes, including public authorities, are considering including low-cost sensor systems among their routine methods of measurements to supplement monitoring with reference measurements or provide measurements in places that are currently not being monitored. However, the lack of exhaustive and accessible information in order to compare the performance of low-cost sensors and the wide commercial offerings make the task of selecting appropriate LCS very difficult.

The information in this document aims to help organizations and individuals interested in monitoring air quality using low-cost sensor systems to make informed decisions before purchasing sensor systems or establishing a sensor network.

This report was written by NILU in the capacity of the Norwegian Reference Laboratory for Air Quality. The Reference Laboratory is financed by the Norwegian Environment Agency.

Contents

Summary

Air pollution is regarded as an on-going threat to public health and is linked to an estimated number of 400.000 premature deaths in the EU each year. In the Nordic countries, air pollution causes around 4000 deaths in both Denmark and Sweden and around 2000 deaths in both Finland and Norway every year (Im et al., 2019). The external costs related to these health effects caused by air pollution amounts to 8-13 billion Euros per year (Geels, C. et al, 2015).

Authorities have to provide healthy and pollution-free neighbourhoods. High temporal and spatial air quality data would help to improve air quality mitigation strategies and also to answer citizen's demand of personalized information. Existing regulatory monitoring networks are generally strictly regulated and based on a limited number of quality-assured reference instruments. Regulatory monitoring networks need to be run by experts and are subject to rigorous calibration and quality control routines. In result, the spatial density of air pollution data is usually low.

As novel technologies, data communication protocols and Internet of Things (IoT) become more prevalent, low-cost sensors may enable wide-scale monitoring in dense, supplementary networks (Wesseling, et al., 2019). The use of low-cost sensors for air quality measurements is expanding rapidly, with an associated rise of air quality pilot studies in the framework of smart city projects and also an increase in the number of citizens measuring air quality themselves.

Low-cost sensor technologies are compact and easy to use, allowing deployment of many units, bringing the opportunity for ubiquitous monitoring, potentially at a fraction of current costs. However, the generated data are often of questionable quality. Low-cost devices tend to be less sensitive, less precise and less chemically-specific to the compound or variable of interest than reference methods. Nevertheless, the application of advanced calibration and intelligent corrections has been shown to improve significantly the sensor data quality.

This report describes the current state-of-the-art of sensor systems, provides advice on key considerations for users before purchasing a sensor system and looks at the challenges and opportunities of this novel technology.

The report highlights that low-cost sensors are not currently a direct substitute for reference instruments, especially for regulatory purposes. They are, however, an important complementary source of information on air quality, provided that the appropriate sensor is used, and that calibration and quality control routines are in place.

Low-cost sensors and networks. Overview of current status by the Norwegian Reference Laboratory for Air Quality

1 Sensor systems

A growing number of companies have started commercializing low-cost sensors (LCS) that are said to be able to monitor atmospheric composition in outdoor air. The benefit of the use of LCS is the increased spatial coverage when monitoring air quality in cities, and the possibility to monitor in remote locations where traditional technology cannot be employed.

Today, there are hundreds of LCS commercially available on the market with cost ranging from several hundred to several thousand euros. The price difference is not always directly related to their performance. Usually, the LCS in the lower price range require more expert knowledge from the user, for example on assembling the sensor system or programming the data communication protocols, while the LCS from the higher price range might offer web services to visualize the data or a help-desk for the user.

Regarding LCS-performance, the scientific literature currently reports independent evaluation of the performance of LCS against reference measurements for a wide range of commercial platforms. These studies report that LCS suffer from interferences with atmospheric conditions (temperature and relative humidity) and cross-sensitivities from interfering compounds (e.g. presence of ozone might alter nitrogen dioxide readings). Moreover, LCS-performance might change depending on site location (i.e. background vs traffic) and over time (i.e. sensor degradation).

Although there are reviews published in the scientific literature and reports from independent institutes, there is still not a standard protocol for comparing and evaluating the agreement between LCS and reference data. There are protocols developed by research institutes and national standardization institutes, like for instance AQMD (http://www.aqmd.gov/aq-spec) and US-EPA. There is also a European joint effort to create a standard method for evaluating LCS (CEN/TC 264 Air quality-Performance evaluation of air quality sensors-Part 1: gaseous pollutants in ambient air and Part 2: Performance evaluation of sensors for the determination of concentrations of particulate matter in ambient air). These protocols set different requirements, including sensor data treatment, levels and duration of tests, seasonality of tests, sensor averaging time, and type of reference measurements to which sensor data are compared to (WMO, 2018).

1.1 Main components and detection principles of sensor systems

Low-cost sensor systems contain a number of common components in addition to the basic sensing/analytical element that is used for atmospheric composition detection. Additional components within a sensor system may include: sampling capability (e.g. pump), power system (e.g. batteries), sensor signal processing (e.g. signal amplification), local data storage, data transmission capability (e.g. WiFi, 4G), housing and weatherproofing (e.g. IP65). Many commercial sensor systems combine multiple air pollutant sensors in one system and often include sensors for non-pollutant parameters such as humidity and temperature. In addition, some sensor systems also offer data post-processing and data visualization “in the cloud”. Sensor systems are usually the most interesting for the end user, as they can be used as stand-alone measuring device. The price of sensor systems can vary depending on the number of sensors included (i.e. pollutants measured), the quality of the electronics and housing, and also the extended services (e.g. web visualization, data treatment, user support). Despite all units on the market are sold for significantly lower prices than reference analysers, there are large price differences (see Table 1).

Karagulian et al., (2019) shows that there is no linear relation between the price of the sensor (the sensing element) and the precision (r^2). However, there is a slight linear increase between the price of sensor systems and their precision, meaning that sensor systems with higher price tend to offer better precision. Nevertheless, the results also show a high scattering of r^2 at the low end of the price range (< 500 euro), meaning that some sensor systems in the lower price range can also offer a high precision.

Table 1: Price classes for low-cost sensor systems

Price class	Price range [EUR]	Comment
Low	<500	Usually only available for particulate matter (PM) measurements
Medium	500 -2000	
High	2000 -5000	
Very high	> 5000	

The sensors included in the sensor systems, i.e. the detection element, use different physical and chemical principles to measure the atmospheric composition. For gases, there are three main principles: electrochemical, metal-oxides and photoionization detector.

For particles, there are two main principles: nephelometry and optical particle counting; both use a LED or laser and a photo detection device, and consider the concentration is proportional to the scattered light intensity, while particle density and size distribution is assumed.

Regarding gas monitoring, electrochemical sensors are the most employed ones in sensor systems. For PM-monitoring, although optical particle counting is expected to be more reliable, due to the technological limitations and costs, most current sensor systems employ nephelometry based sensors instead. There are also sensors in the market to monitor greenhouse gases. Table 2 gives an overview of the different detection principles and their main limitations reported in the scientific literature. More detailed information can be found in Baron and Saffell (2017) and WMO (2018).

Table 2: Review of detection principles for gases and particles and current limitations of the sensor technology.

Type	**Principle**	**Compounds**	**Limitations**
Electrochemical sensors (EC)	An electrochemical reaction results in a signal (current) that is related to the concentration of the target gas in the air	NO, NO_2, O_3, SO_2, CO	Interferences with relative humidity and temperature. Cross-sensitivity with other gases.
Metal oxide sensors (MOS)	A surface film absorbs the gas, resulting in a change in conductivity or resistance.	NO, NO_2, O_3	Non-linear response. Interferences with environmental conditions and with other gases.
Photoionization detectors (PID)	Ultraviolet light to break organic molecules apart; as they are ionized, a small current is induced and measured by the sensors.	VOCs	It does not ionize VOCs with equal efficiency across different compounds. The values for total VOC are influenced by the actual VOC mixture.
Nephelometry	Measures particle light scattering of the total aerosol.	PM	Interferences with high relative humidity (>80%). Limits of detection, that makes them not suitable for ultrafine particles and course particles. No control of particle flow.
Optical particle counting (OPC)	Detects particle size and number of individual particles.	PM	Not enough studies with OPC.
Optical absorption (NDIR)	Infrared light is absorbed by the gas, and that is proportional to the concentration.	CO_2	Not many studies. Interferences with temperature and relative humidity.

1.2 Metrics to consider when purchasing a sensor system

In the absence of an internationally or European accepted standard protocol for testing LCS, there is a lack of harmonization of the tests being carried out. Consequently, the conditions of tests and the metrics reported are generally diverse, making it difficult to compare the performance of LCS in different evaluation studies.

In the framework of the iFLINK project (http://iflink.nilu.no), it has been published a technical report providing recommendations and requirements in connection with preparation of tenders (Dauge et al., 2019). It offers an overview of the key metrological terms and the necessary knowledge to interpret instrument specifications. Some of the crucial parameters to consider when purchasing a sensor system are:

1. Limit of Detection (LOD). This is the lowest value that can be reliably detected by the sensor. Table 3 offers a summary of the recommended and the maximum LOD.
2. Measuring range. This is the range (for gas of particle concentrations) that can be detected by the sensor. Table 4 offers the recommended measuring range for sensor systems.
3. Response time. This indicates how fast the sensor responds to a stimulus, i.e. how quickly it responds to a change in gas or particle concentration. Commonly it is used the value t_{90}, which represents the time it takes for the sensor to generate 90% of the end signal. Table 5 shows the recommended response time for sensor systems measuring gas or particles.
4. Precision. This is a measure of how similar the sensor measures the same concentration each time. This is usually assessed by comparing the signal from the sensor to a reference instrument. A coefficient of determination (r^2) of 1 or close to 1 indicates good precision. Note that a sensor can have good precision but still have large measurement errors (e.g. if the instrument always underestimate concentrations). Table 6 shows the recommended precision for gas and particle sensor systems.

Table 3: Recommended and maximum limit of detection (LOD) for gas and particle sensor systems.

Component	**Recommended LOD** [µg/m³]	**Maximum LOD** [µg/m³]
NO, NO_2	<19	<28
O_3	<20	<30
CO	<300	<500
SO_2	<40	<80
PM_{10} and $PM_{2.5}$	<2	<5

Table 4: Recommended measuring range for sensor systems.

Component	Recommended range	Comment
NO [µg/m^3]	[0 - 1000]	Conversion factor from ppb to µg/m^3: 1,25
NO_2 [µg/m^3]	[0 - 1000]	Conversion factor from ppb to µg/m^3: 1,91
O_3 [µg/m^3]	[0 - 1000]	Conversion factor from ppb to µg/m^3: 2
SO_2 [µg/m^3]	[0 - 1000]	Conversion factor from ppb to µg/m^3: 2,66
CO [mg/m^3]	[0 - 10]	Conversion factor from ppb to mg/m^3: 1,16
$PM_{2.5}$ [µg/m^3]	[0 - 500]	
PM_{10} [µg/m^3]	[0 - 1000]	
Atmospheric pressure [hPa]	900 - 1200	
Relative humidity [%]	0 - 100	
Temperature [° C]	[-30 - 40]	

Table 5: Recommended and maximum response time expressed as t_{90} in minutes.

Type of sensors	Recommended t_{90} [min]	Max. t_{90} [min]
Gas (NO, NO_2, O_3, SO_2, CO)	6	15
PM_{10} and $PM_{2.5}$	10	15

Table 6: Recommended and minimum required precision for sensor systems

Component	Recommended R^2	Minimum R^2
NO_2	0.8	0.6
O_3	0.8	0.6
SO_2	0.7	0.6
CO	0.8	0.6
PM_{10}	0.7	0.6
$PM_{2.5}$	0.8	0.6

2 Calibration, performance assessment and quality control of sensor systems

Data quality is a key issue determining the usability of a low-cost sensor system, and the necessary level of data quality will be dictated by the user and application. For example, users interested in the technological aspect of hobby (do-it-yourself) will have lower expectations than organizations interested in operational air pollution management. Nevertheless, independently of the different requirements for accuracy, there is a critical need to establish a cohesive approach for the evaluation and performance assessment of LCS prior to their large-scale adoption in atmospheric science (Lewis and Edwards, 2016).

Most of the published studies using low-cost sensors have focused on the characterization of the sensor performance from comparison against reference instruments under laboratory or field conditions. In general, the performance of low cost sensor systems is evaluated by assessing a number of parameters, including:

1. Sensitivity/Measuring range (their ability to reach high or low concentrations)
2. Selectivity (the lack of interferences with weather or other pollutants)
3. Reproducibility (comparability between different units of the same monitor)
4. Response time
5. Precision, accuracy and uncertainty
6. Stability over time

As any other analytical instrument, including reference instruments, low-cost sensor systems will require regular calibration and will show long-term changes in drift and sensitivity. Usually, calibration of LCS is performed by establishing a relationship between the output of the LCS and the output of a standard measurement (i.e. reference instrument or equivalent). The model extracted by comparing the measurement from the LCS and the standard measurement is called calibration model.

An initial calibration is performed by the sensor manufacturer, this is a factory calibration that provides a model that can be used to convert between the measurement parameter (e.g. voltage, light absorption) and the desired output variable (e.g. ppb, µg/m^3). Despite many sensor system manufacturers continue to rely on these factory calibration settings as the main calibration model, there is evidence that this is not sufficient to provide accurate data across the possible environments in which the sensor might be used. In order to assess if the factory calibration is sufficient, it is necessary to validate (quality assurance) the sensor data against reference data in an environment similar to the one in which the LCS will be used. This can be done using co-location, this is, compare the sensor data to a reference instrument output closely located (preferably within 10 meters) for a period of 3 weeks (or longer), to ensure we capture variations in weather and pollutant concentrations.

Laboratory calibration against reference instruments has also been explored in the scientific literature (e.g. Spinelle et al., 2015). Laboratory calibration involves the same approaches employed to calibrate reference instruments. With this approach, the sensor system is subjected to a series of known concentrations of pollutant in a controlled environment. Laboratory experiments are very useful for determining how LCS behave under very specific, controlled conditions which contribute to our fundamental understanding of how they work. However, using a laboratory test as a primary calibration approach is not sufficient, as usually laboratory conditions cannot reproduce the full range of conditions encountered in an ambient environment (Castell et al., 2017).

Field calibration, using co-location against reference monitors seems to be, for now, an effective method to calibrate LCS. However, it can be difficult to experience the entire dynamic range of environmental conditions in a short period of time. For that reason, comprehensive field calibrations can be rather time intensive. Because of changing environmental conditions and drifts in sensor performance over time, a common recommendation in the scientific literature, is to carry co-location comparisons on a regular basis (to cover all the seasons, before-after a campaign) and use a period about 3 weeks (Castell et al., 2017). Important factors to consider to obtain a good field calibration model are temperature, relative humidity, and cross-sensitive pollutants for gas sensors, and relative humidity, composition, density, size distribution and optical properties for particle sensors (WMO, 2018).

Determining the optimal calibration model to transform the raw data from the sensor to a usable format, or to improve the quality of sensor data, is an active field of research (Spinelle et al., 2015, 2017). The most employed options are variations of a parametric regression using multiple parameters (e.g. multilinear regression) and nonparametric/nonlinear/machine learning approaches. Machine learning approaches seem to give better results than parametric regression approaches, as they account for less obvious environmental effects and interference with cross-sensitive species (Topalovic, et al., 2019). However, both calibration approaches are limited by the data employed to derive the model. For instance, if the sensor is calibrated during summer, the model might not perform well during winter.

Regardless of the extraction of a calibration model, the comparison between sensor data and reference data is useful to evaluate in a standardized way the quality of the data from the LCS. Usual parameters employed to describe the sensor performance against reference instrumentation, are: coefficient of determination (r^2), root mean squared error (RMSE) and mean absolute error (MAE). Fishbain et al (2016) provide an integrated performance index (IPI) for LCS evaluation, accounting for correlation, bias, failure, source apportionment with LCS, accuracy and time series variability of LCS and reference measurements.

In Europe, the EU Directive on Ambient Air (2008/50/EC) uses the expanded uncertainty as a metric to assess if a monitoring method can be used as an official method to report data. If low-cost sensors comply with the data quality objectives documented in the framework of the Indicative Measurements, such application would be possible. The regulatory standard for indicative measurements is less stringent than the fixed measurements of the directive, and at present, fixed measurements can only be addressed by reference instruments.

Aside of the quality assessment, another important aspect is the quality control of the LCS. Quality control is the act of systematically monitoring the performance of the LCS during deployment (i.e. not co-located with a reference station) to ensure it remains in calibration. Quality control should advice the user when the LCS needs re-calibration (e.g. when the bias exceeds the measurement uncertainty), maintenance and reparation as well as when the life of the sensor has ended. There are several parameters that need to be monitored over time: baseline drift (i.e. change in intercept), changes in sensitivity (i.e. change is slope), spikes, interferences with weather conditions, etc. Several approaches on how to conduct quality control have been proposed, but this is still an active field of research. Some of the approaches suggest to compare the values obtained with a LCS to a nearby (but not co-located) reference station (Mueller et al., 2017), or a node-to-node calibration, where only one sensor in each chain is directly calibrated against the reference measurements and the rest of the sensors are calibrated sequentially one against the other (Kizel et al., 2018). Another approach is to use knowledge of regional atmospheric chemistry in combination with a small number of anchor point (reference stations) to perform remote calibrations (Kim et al., 2107).

Automated quality control approaches, become essential to increase consistency of data, save time and effort, and support quality checks on large number of sensors, especially as sensor networks move from tens to thousands of sensor systems. Developing, optimizing, and refining advanced techniques for sensor calibration, validation and quality control is an important area of ongoing research and is absolutely central to obtaining reliable and meaningful data from low-cost air quality sensors (WMO, 2018).

2.1 Processing levels for low-cost sensors

Improving the quality of the data from low-cost sensors using field calibration is very common. As mentioned above, the methods range from (multi)linear regression to more complex statistical techniques as machine learning, often using additional predictor variables such as air temperature or relative humidity, and in some occasions, data not actually measured by the sensor system itself (e.g., reference observations or model output). Hagler et al. (2018) warned that some systems may use predictor variables for calibration in such a way that a line is crossed from justifiable and empirical correction of a known artefact (e.g. cross-sensitivity) to a methods that is essentially a predictive statistical model. Schneider et al. (2019), proposes a unified terminology of processing levels for low-cost air quality sensor systems, to add clarity regarding the level of sensor data processing and thus provide a correct use and interpretation of its data. The proposed processing levels range from Level-0, indicating output from the electronically interfaced raw sensor signal, to Level-4, representing a spatially continuous map of concentrations derived from a network of sensor systems, for example using spatial interpolation or data assimilation into a chemical transport model. Table 7 shows the proposed processing levels for low-cost sensor systems for air quality. A more detailed description can be found on Schneider et al. (2019).

Table 7: Summary of the proposed processing levels for low-cost sensor systems by Schneider et al. (2019)

Level	Name	Definition
Level-0	Raw measurements	Original measurand produced by sensor system
Level-1	Intermediate geophysical quantities	Estimate derived from corresponding Level-0 data, using basic physical principles or simple calibration equations, and no compensation schemes.
Level-2A	Standard geophysical quantities	Estimate using sensor plus other on-board sensors demonstrated as appropriate for artifact correction and directly related to measurement principle (Hagler et al., 2018)
Level-2B	Standard geophysical quantities-extended	As Level-2A but using external data demonstrated as appropriate for artifact correction and directly related to measurement principle (Hagler et al., 2018)
Measurement/prediction boundary		
Level-3	Advanced geophysical quantities	Estimate using sensor plus internal/external inputs, not constrained to data proven as causes of measurement bias or related to measurement principle (Hagler et al., 2018)
Level-4	Spatially continuous geophysical quantities	Spatially continuous maps derived from network of sensor systems

Currently, many sensor systems operate as black boxes, and the calibration, validation and quality control methods offered by manufacturers are proprietary and non-transparent (i.e. commercially confidential). However, it is essential that the type and amount of processing performed on sensor systems is communicated transparently so that the users can make informed decisions. This is particularly important for scientific, operational, and policy applications where methods have to be thoroughly documented and their fitness for purpose demonstrated.

2.2 Independent evaluation of low-cost sensor systems

As mentioned earlier, 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 commercializing a sensor system. This makes it very difficult for authorities and the public to know if a sensor system will be fit-for-purpose. Moreover, technology is changing so fast that often when independent institutes or research centres publish the evaluation results of a given sensor system, a new version might already be on the market (Bartonova et al., 2019).

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://db-airmontech.jrc.ec.europa.eu/), the EDUCEO project (www.snuffle.org) and the AQ-SPEC (http://www.aqmd.gov/aq-spec).

There are also national initiatives, as for instance in the Netherlands (https://www.samenmetenaanluchtkwaliteit.nl) that provide information about sensor performance as well as references to national projects in the local language. This type of initiatives might contribute to increase the uptake of the technology as well as the understanding of their possibilities and limitations.

3 Sensor networks

One of the primary applications of low-cost sensor systems is to build dense sensor networks, capable to provide air quality data with high temporal and spatial resolution. Low-cost sensor technologies have significantly lower investment costs than traditional instrumentation. They are compact and easy to use, allowing deployment of many units. However, as described previously, the data generated are often of questionable quality. In order to benefit from the sensor monitoring technologies, their deployment requires new ICT infrastructures, including sophisticated algorithm-based methods for calibration and quality assurance and data fusion methods for merging sensor data with other already existing data. In Norway, the iFLINK project, lead by NILU, is developing an open scalable infrastructure, containing smart calibration techniques and automated quality routines, allowing municipalities and other actors to develop data-driven and visualization solutions (see Figure 1).

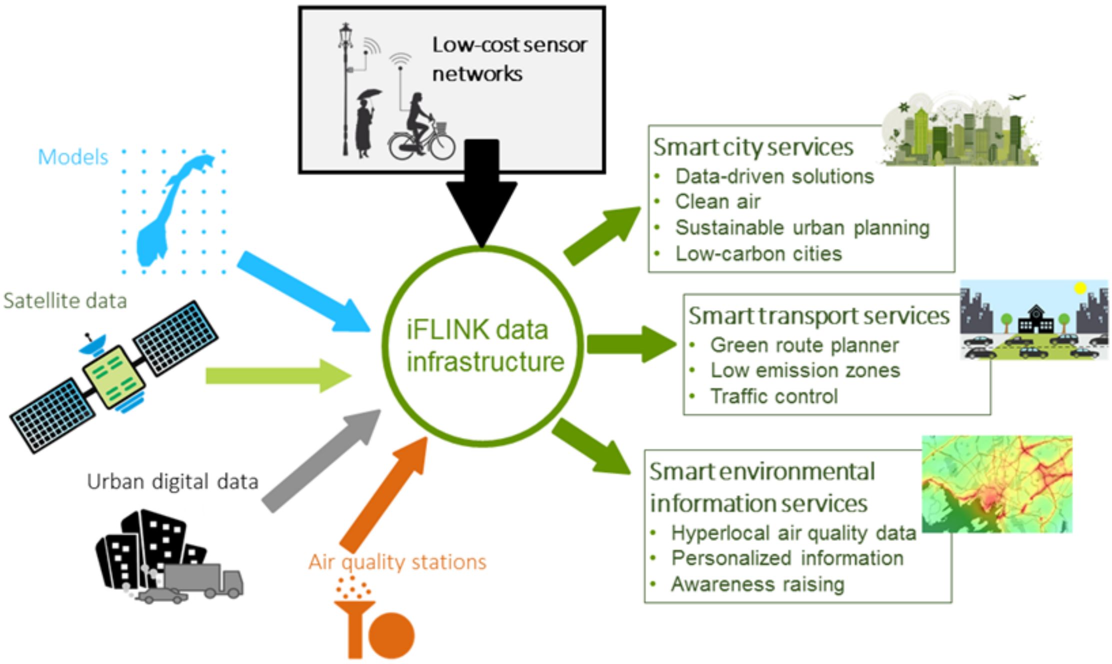

Figure 1: Schematic overview of the iFLINK idea. Source: NILU. iFLINK project.

Low-cost sensor technologies for monitoring air quality bring the opportunity for ubiquitous monitoring and high spatial and temporal air quality mapping (see Figure 2). However, the quality of the sensor data prior to significant processing does not meet the requirements for operational air quality management. Moreover, the total cost of the sensor network solution can reach high costs due to data communication, data storage and sensor network maintenance. Actors interested in air quality management have the following shared experiences:

1. the (poor) quality of data from low-cost sensors severely limits the usefulness of a network,
2. the infrastructure and connectivity needs related to low-cost sensor solutions are substantial, and
3. the costs of the operation of the low-cost system as a whole can be significant, due for instance to short sensor lifetime (1-3 years) and cost associated to deployment and calibration.

In order to take full advantage of the potential of this advanced monitoring technology, it is crucial to develop advanced calibration models, automated quality control algorithms, and use state-of-the-art statistic methods to combine sensor data with a variety of other relevant data for air quality (Schneider et al., 2017).

In the same way as with reference stations, due to the complexity of the technology, it is recommended that sensor networks are operated and maintained in collaboration with qualified experts with recognized experience in air quality and sensor technology.

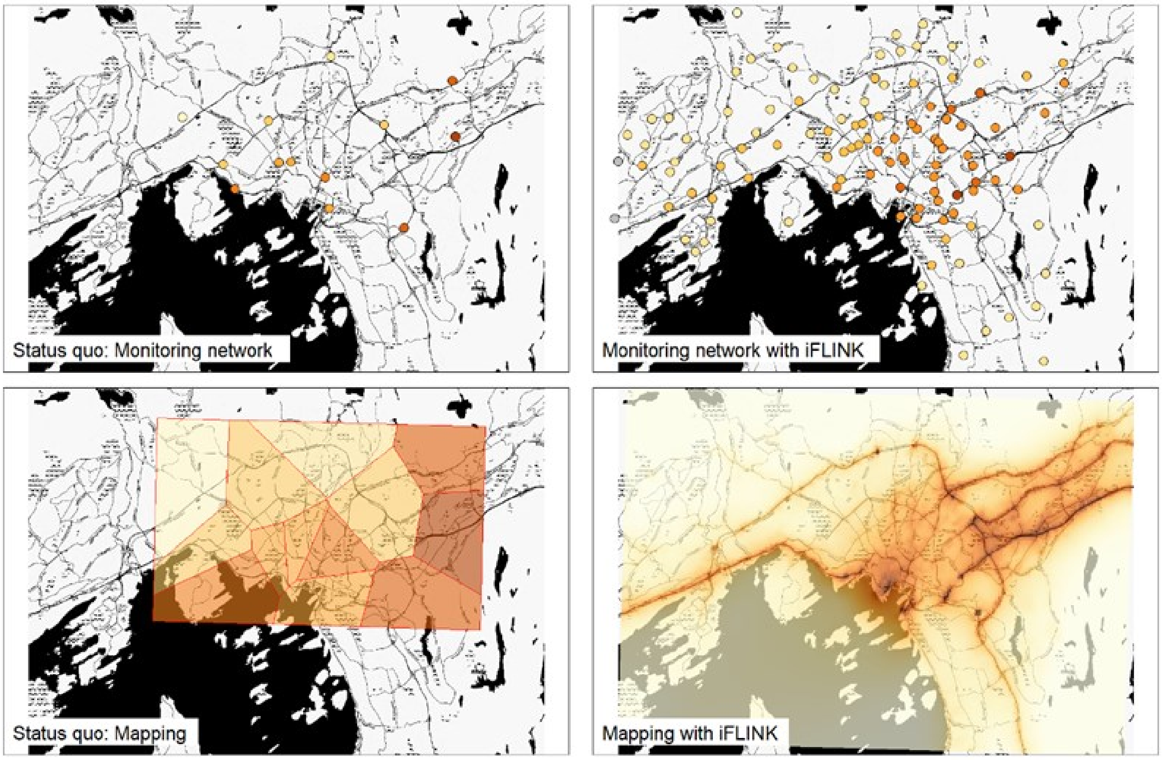

Figure 2: Current status quo of air quality mapping (Oslo, with 12 reference stations) and potential information service derived from a dense LCS network for air quality with the help of machine learning and data fusion techniques. Source: NILU. iFLINK project.

4 Examples of low-cost sensor demonstration projects

The rapid product development, and the wide range of opportunities that low-cost sensor systems open, are resulting in deployment of distributed sensor networks to demonstrate the value and usefulness of sensor systems to monitor air quality. Current projects do not always aim to necessarily provide precise side-by-side comparison data with reference monitors but instead show how a sensor-based approach may give additional insight into atmospheric composition. Demonstration projects have engaged both traditional users and new communities. Newer users are often interested in using sensor networks to understand local air quality conditions, identify local sources and implement educational programmes. LCS represent a clear opportunity to support citizen science initiatives, and make new measurements in low and middle income cities and countries.

In this section we provide a short list of examples of projects using LCS, from self-organized communities and from research organizations. These list aims only to provide examples of existing projects, and it is not an exhaustive project list covering all the current projects neither all possible applications.

An example of self-organized monitoring community is **Sensor.Community** (Measure air quality yourself). The project started in Stuttgart (Germany) by an Open Knowledge Lab, with the aim of making particulate matter visible in places where it is not officially measured. The project is now supported in eight languages and has participants from all over the world (see Figure 3). The current sensor system employs the Nova Sensor SDS011 for measuring particles (PM10 and PM2.5) and the instructions on shopping list and how to assemble the sensor are available on their website (https://sensor.community/en/sensors/). However, there is no information to the users on calibration or data quality. For example, it is well known that particle sensors overestimate particle concentration when the relative humidity is high, giving peak values that are not real. This information is not conveyed to sensor.community users, what might results in misleading information. Moreover, sensor.community does not have any automated routines for quality control, and it is often not possible to fully discern the quality of the data collected (e.g. sensors deterioration over time is not highlighted).

Another example of community-driven air monitoring network is **CITYOS AIR**. The project started in Sarajevo (Bosnia &Herzegovina). They have developed their own sensor system to monitor particle matter (PM10 and PM2.5). The sensor is designed so it changes colour depending on the pollution level, and the information can also be consulted using a mobile app. A web tutorial shows people how they can build their own sensor system (https://cityos.io/air#toolkit). Similar to sensor.community, there is no information available to the user on data quality and data quality control.

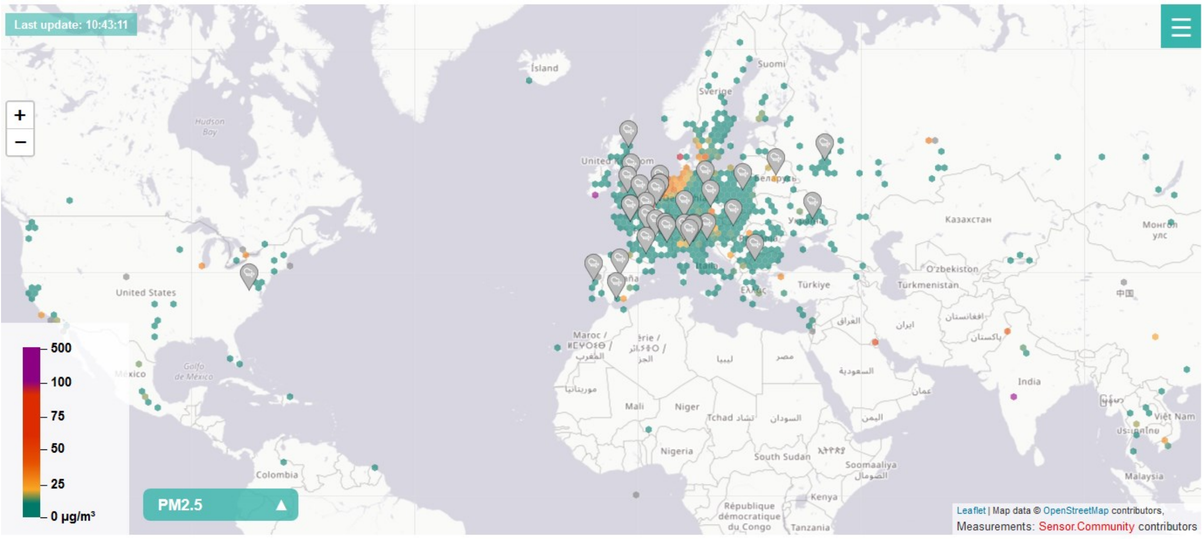

Figure 3: Sensor.Community sensor network over the world. Source: https://sensor.community/en/

The **AIR Network** in Nairobi (Kenya), is an example of how low-cost sensor networks can be used in development countries. It is an interdisciplinary research partnership of African and European researchers and African community members (https://airnetworkafrica.com/).

The EU funded **hackAIR** project (www.hackair.eu) is an example of top-down citizen science project, where research institutes engaged with local citizens in monitoring air quality. The project finished in 2018, and had pilots in Norway, Germany, Belgium and Greece. The data quality of the sensor was checked against reference instrumentation using co-location over a period of three months (Liu et al., 2018). The results showed that the sensor had a good performance for PM2.5, with correlations over 0.7, but suffer from interference with relative humidity, especially when the relative humidity was higher than 70-80%.

Figure 4: hackAIR stationary sensor system components (left), sensor casing (middle, modified from sensor.community sensor casing), and sensor co-located at one official air quality monitoring station in Oslo, Norway.

The **iFLINK** project (http://iflink.nilu.no), financed by the Norwegian Research Council, is an example of public innovation research and application. The project owner is Oslo Municipality and the project leader is NILU-Norwegian Institute for Air Research. The project will finish in September 2021. iFLINK utilizes low-cost sensor solutions to develop a geographically distributed network of environmental sensors for Norwegian municipalities. The project is developing the necessary data infrastructure to support practical uptake of the technologies by municipalities, and enable upscaling and exploitation of the sensor network systems. Currently, municipalities and other interested actors can connect their sensors to the iFLINK infrastructure and benefit from smart on-line calibration and real-time automated quality control. The data is accessible through API, allowing other parties to develop environmental services.

The **LoV-IoT** project (https://loviot.se/) in Gothenburg (Sweden) aims to compile a low-cost, flexible platform for monitoring, data quality control and standardization, and communication of urban air quality. The project provides a test bed for exploring the usability of sensor systems to provide real-time information about air pollution concentration on construction sites.

In the **London Heathrow Airport** project (Popoola, et al., 2018), measurements from the sensor network were used to unequivocally distinguish airport emissions from long range transport, and then to infer emission indices from the various airport activities. These were used to constrain an air quality model (ADMS-Airport), creating a powerful predictive tool for modelling pollutant concentrations. The authors comment that the sensor network approached employed for the airport emissions, has general applicability for a wide range of environmental monitoring studies and air pollution interventions.

The **NordicPATH** project (http://nordicpath.nilu.no), is a research and innovation project funded under NordForsk's Sustainable Urban Development and Smart Cities programme. It runs from April 2020 to March 2023. NordicPATH's overall objective is to establish a new model for citizens' participation and collaborative planning in Nordic countries to create healthy and people-centred cities. The project will engage citizens to monitor air quality using low-cost sensor technologies. The data will be pushed to the iFLINK infrastructure, where data quality is checked in real time.

5 Future opportunities

The field of low-cost sensors is advancing fast, and both sensors and sensor systems are rapidly evolving. An advantage of sensor systems is their intrinsic modularity that allows new sensor components to be introduced very fast. This is not the case for many existing reference methods.

The general trajectory for LCS is one of ever-improving capability, with new sensors outperforming older versions, and sensor systems that are more reliable. However, the lack of a traceable method for sensor evaluation, still makes it very difficult to distinguish good performing sensor systems from the ones that do not offer trustable data.

With a growing interest from municipalities, and other public and private actors in using low-cost sensor systems and networks, it will be compulsive to create a national platform of sensor users aimed at sharing experiences and learning from each other. A similar initiative was initiated by the city of Gothenburg in 2019, organizing annual meetings where municipalities and experts are invited to present their recent work related to air quality monitoring using low-cost sensors.

At present, low-cost sensor systems are particularly attractive for areas that have less stringent requirement for data quality, as, for instance, public information and citizen science activities aimed at engaging people and creating awareness. Nevertheless, also in such applications it is important to ensure that the data is fit for purpose. As commented in the beginning of this report, data of unknown quality is less useful than no data.

As interest in the use of sensor networks is increasing, and as new standards are created, more manufacturers are becoming aware of the importance of validation and calibration. We expect that the areas of application of sensors will expand. Some interesting and emerging applications of low-cost sensors are:

1. Research in atmospheric sciences. Short and long-term observations of atmospheric composition and analysis of trends and behaviour. Data quality and long-term sensor behaviour need to be carefully considered.
2. Estimation of emissions (pollutants and greenhouse gas emissions). There have been recent papers using LCS to estimate emissions from airports and also to map urban CO2 emissions. Sensors tend to perform well when used in short monitoring campaigns.
3. Air quality compliance and regulation. Observations of air pollution concentrations and support to decision-making. Data quality and long-term sensor behaviour need to be carefully considered.
4. Public information and citizen involvement. Support public information and awareness, citizen science activities, education, data for advocacy and local empowerment. Need of less precise data as it is possible to use data classes: low, medium, high. Data quality and interferences should be considered and communicated.
5. Health. Provide exposure data of a population or individuals in specific areas or buildings. Current portable instrumentation is very expensive which limits the number of participants. Low-cost sensors provide a new opportunity in this field but due to the low accuracy of these sensors and their cross-sensitivities, they need to be use with caution.
6. Indoor monitoring. Provide information on indoor air quality, increasing information about the exposure to different sources like cooking or wood burning, or the effectiveness of different type of ventilation systems. However, indoor environments require the measurement of different compounds like VOC, for which the currently available sensors are not selective enough. Other compounds like CO2 and PM can be monitored.

7. Industrial monitoring. In relation with health protection of workers in industrial plants (indoor) as well as diffuse emissions from industries, harbours and construction sites, and punctual emissions like chimneys or ships.
8. Conservation (buildings, art). Currently historical buildings and art conservation are using sensors to control the ambient conditions. This can be complemented with air quality sensors.

6 Recommendations

Low-cost sensors and networks will likely continue to grow in Norway across research institutes, municipalities, citizens and organizations. Both the sensing technology and the post-processing methods are rapidly improving facilitating the adoption of the technology and increasing the number of applications. However, low cost sensors should not be viewed as fully operational replacements for reference measurements, and caution is still warranted (Lewis, A. C. et al., 2018).

Users of low cost sensors should have a clearly-defined application scope for the use of sensors, that will guide them through the appropriate use of measuring techniques, and evaluate if sensors and what type of sensors are fit-for-purpose.

As low-cost sensor systems still require firm evaluation, calibration and continuous quality control, it is crucial that the user answers the question: Do we have infrastructure and capacity to appropriately evaluate/calibrate low-cost sensor systems in place? In order to help municipalities, NILU has created a sensor data infrastructure that from 2021 will be available for the municipalities to connect their sensors and networks providing support on evaluation of sensor performance and automated quality control. NILU has also the possibility to help municipalities to characterize low-cost sensor units against reference instrumentation and offer advice if they are or not fit-for-purpose. As mentioned in the report, there are on-line reports on sensor performance, but it is always recommended to assess the performance under local meteorological conditions. This is especially important in Norway during winter conditions.

Low-cost sensor systems can provide meaningful data, but not yet at a level of robustness in which reference monitoring will not be required. Low-cost sensor systems need to have a routine of calibration and quality control in place before they are used.

We advise to create a set of national reference monitoring platforms for providing low-cost sensor systems evaluation performance. Current monitoring stations can be prepared to allow the co-location of sensor units and their comparison against reference data. Such stations should include the following pollutants: NO2, O3, PM10, PM2.5, PM1, and when possible also particulate matter filter garret and particle counts and meteorology.

We advise to create a Norwegian knowledge hub for municipalities and other actors using or interested in using sensor networks. This will be a meeting place where lessons learnt and best practices are shared among practitioners.

7 Conclusions

The scientific literature supports the use of low-cost sensors and sensor networks with caution and always with a careful consideration of their data quality. When the application requires accurate data, it is highly encouraged that the user cooperates with qualified experts with experience in both atmospheric composition and sensor use. It is important for prospective users to identify their specific application needs firsts, examine examples of studies with similar characteristics, evaluate the challenges and limitations associated with the use of LCS, and select the proper technology that meets the data quality needs.

Previous studies have shown that data quality from sensor systems are highly variable. There is currently no simple answer to the question: are low-cost sensor systems reliable? Different sensor systems using the same sensor (sensing device) might have very different performance depending on the manufacturer, as the sensor units might use different electronics or calibration algorithms. The lack of an international or European standard for performance evaluation makes it difficult to compare the quality of the different sensor systems in the market. Also, manufacturers do not currently need to provide any specifications on data quality when commercializing a product. This can make the task of understanding sensor data accuracy very challenging for the users. There is a need to develop harmonized standards and guidelines for sensor performance evaluation.

Low-cost sensor systems, as any other analytical instrument, require regular calibration, and will be affected by changes in behaviour over long-term as for instance drift and changes in sensitivity and selectivity. Moreover, LCS suffer from interferences with temperature and relative humidity and some have cross-sensitivity issues with other gas species. There is an active field of research on smart calibrations, data correction and automated quality control. Results are promising, but there is still not an optimal method that can be used for all sensor systems and networks.

Nowadays, the application of LCS for regulatory activities is limited. The legislation (e.g. EU Directive 2008/50/EC) requires air quality data to meet established uncertainty levels. However, there is currently no official certification for LCS, and sensor uncertainty is rarely being provided by manufacturers. Nevertheless, there are already many applications where it is not necessary to meet certified standards and LCS can be used when considering their measurement limitations, and when proper data quality and data control routines are in place. Examples of such uses are personalized information to the public, high-resolution data for improved urban management or citizen science activities. There is a rapidly-growing scientific literature in the field of low-cost sensor applications. Post-processing data techniques, as machine learning or data assimilation, are likely to play an increasingly important role in improving LCS data quality and diversifying sensor applications.

Adoption of open access and open data policies to further facilitate the development, applications, and use of LCS data is essential. Such practices would facilitate exchange of information among the wide range of interested communities including national/local government, research, policy, industry and public, and encourage accountability for data quality and any resulting advice derived from LCS data.

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