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Assessing air quality through citizen science

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Two good practice examples were taken from participants in CleanAir@School, a joint citizen science initiative of the European Network of the Heads of Environmental Protection Agencies (EPA Network) and the EEA.

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Summary

People's awareness of air pollution and the associated risks to their health and that of their children has grown significantly over recent years, often informed by local or national campaigns led by non-governmental organisations (NGOs) as well as by media coverage. In some countries, groups of concerned citizens, often supported by NGOs, have taken authorities to court over air quality issues, and the courts have ruled in favour of the right to clean air in several instances.

As awareness increases, people are more and more interested in the quality of the air that they breathe every day close to their homes and places of work, as well as at their children's schools and playgrounds.

To inform themselves about their local air quality, increasing numbers of people are taking the initiative to measure the level of pollutants in the air themselves. This is particularly common in cities with highly polluted air. In recent years, an increasing number of simple, relatively cheap samplers and sensor monitoring devices have become available on the market. Some NGOs offer measurement kits that people can assemble and deploy themselves. Interested members of the public are also organising themselves in 'citizen science initiatives' to monitor their local air quality and to present their results in a coordinated way on the internet or by using apps.

This report provides a non-technical summary of the types of options and tools now available for citizens to measure their local air quality.

What is citizen science?

Citizen science allows people without professional scientific training to use technical tools to explore questions that concern them. People learn through their engagement, develop ownership of the issue and can then make an informed contribution to public debate. The citizen science concept is not new and includes such past and current activities as bird counting or observing the sky at night. However, nowadays digital technologies and social media mean that citizens can connect, join initiatives and communicate their results in easier and more varied ways than ever before. Alan Irwin, a sociologist at Copenhagen Business School, defines citizen science both as 'science which assists the needs and concerns of citizens' and as 'a form of science developed and enacted by the citizens themselves' (Irwin, 2018).

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The report:

- presents examples of how such devices have been used by citizen science initiatives to answer questions about air quality;
- explains how low-cost passive air pollutant samplers and air quality sensors work;
- considers the reliability of the different devices in measuring air quality;
- summarises how these devices can be used by individuals, within networks and on information service platforms; and
- reflects on how such low-cost devices are stimulating new approaches to addressing air quality issues.

Europe's air quality — an overview

Although emissions of air pollutants have decreased substantially in Europe over recent decades, air quality problems in Europe persist. Air pollution harms human health and the environment (EEA, 2019a), with exposure to air pollution accounting for an estimated 400 000 premature deaths in Europe every year. A significant proportion of Europe's population lives in areas where air pollution poses risks to health (Figure 1). This is especially true for cities, where exposure to particulate matter (PM) and nitrogen dioxide (NO_2) pollution poses health risks. Around 77 % of city dwellers in Europe are exposed to fine particulate matter ($PM_{2.5}$) at levels deemed harmful to health, according to the latest *EEA Air Quality in Europe report* (EEA, 2019a).

Source: EEA.

Figure 1: Percentages of the EU urban population exposed to air pollution concentrations above EU and WHO reference values during the period 2015-2017

	EU Limit/Target Values	WHO Guidelines
$PM_{2.5}$	6-8 %	74-81 %
PM_{10}	13-19 %	42-52 %
O_3	12-29 %	95-98 %
NO_2	7-8%	7-8 %
BaP	17-20 %	83-90 %
SO_2	< 1 %	21-31 %

Source: EEA

Engaging citizens in measuring air quality using low-cost devices

Citizen science initiatives with a focus on air quality commonly use low-cost measuring devices to learn more about local or regional air pollution and its sources. Examples of active public involvement in air quality measurement initiatives, from both a scientific and a political perspective, are growing in scale and becoming more ambitious and better connected.

Citizen science initiatives dealing with air quality can address a variety of objectives, including:

- producing information on local air quality and the exposure of the population to air pollution;
- raising awareness of a local air quality problem to attract the attention of local or national authorities;
- complementing measurements taken by official air quality monitoring networks and helping improve air quality models; and/or
- generating experience of the use of low-cost measuring devices and networks of such devices.

There are numerous examples of citizen science initiatives that have led to concrete improvements in our knowledge about air quality and that involve cooperation between various stakeholders. Several of these have involved collaboration between citizens and the official institutions responsible for air quality monitoring activities. Such initiatives demonstrate how citizens can make positive contributions to our knowledge about air quality issues, particularly in their local areas where they may be exposed to high levels of air pollution. The projects can also help to maintain trust in official air quality measurement results, complementing the information obtained from formal monitoring networks and ultimately helping inform decision-makers by providing additional information on levels of air pollution.

'An air pollution analyser inside an official monitoring station uses a well-defined, standardised and selective principle. Analysers are type approved and tested for interferences and under varying conditions. The environment in official monitoring stations is controlled, their instruments are regularly checked, and the measurements are subject to rigorous quality control and calibration procedures.

Sensors can be sensitive to weather conditions (wind speed, temperature, humidity) or can have difficulties distinguishing pollutants. When using sensors, the measurements should be carefully evaluated and validated.' From: Measuring air pollution with low-cost sensors — thoughts on the quality of data measured by sensors (EC, 2019b).

Types of instruments for measuring air quality

A **passive air pollutant sampler** (or 'diffusion tube') exposes a surface known as a 'plate' to the air for a set period and collects air pollutants that settle onto the plate. After the exposure period, the plate is collected and analysed in a laboratory. The amount of air pollution collected reflects the average concentration of the pollutant in the air over the sampling period.

A **low-cost air pollution sensor** is a device that measures certain pollutants in ambient air. Gas or particle concentrations are typically monitored as electrical signals. The signals are then converted by a software or data acquisition into a concentration value.

An air pollution **sensor system** is the combination of one or several sensors with a power source within an enclosed structure. In some cases, it may include a processor or amplifier to convert the electrical or optical signals into concentration units, as well as data storage and transmission systems. The user can deploy them individually or in groups.

An air pollution **reference instrument** for measuring air pollutants is a monitoring device that has been certified by an official regulating body and is normally operated by a public authority. Such instruments are typically used in official air quality monitoring networks for purposes such as regulatory compliance checking. The cost of such devices is typically high, and they require regular on-site maintenance and calibration.

Source: Based on CEN (2019) and Lewis et al. (2018).

CurieuzeNeuzen Vlaanderen — 'the largest citizen science project on air quality to date'

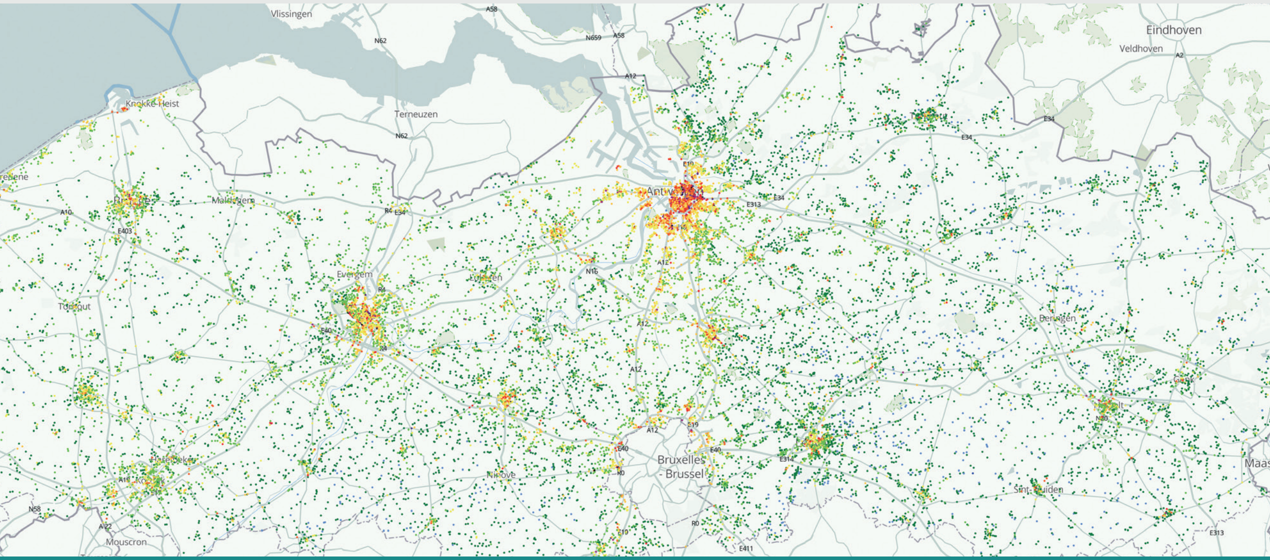
In 2018, the University of Antwerp collaborated with the Flanders Environment Agency, the regional newspaper De Standaard and three research institutions ([i]) to implement the citizen science project CurieuzeNeuzen Vlaanderen (Curious Noses Flanders) in the northern region of Belgium. This initiative has been labelled as 'the largest citizen science project on air quality to date', and it was based on an earlier (2016) project run in the city of Antwerp that used a similar approach.

The aim of the CurieuzeNeuzen Vlaanderen initiative was to provide a detailed map of nitrogen dioxide (NO_2) concentrations in Flanders, both in cities and in the countryside. To meet this objective, Flemish citizens used a simple, standardised measurement device, a **passive sampler**, to measure NO_2.

By developing a reliable spatial mapping of NO_2 concentrations, the project also aimed to improve the predictive capability of the existing air quality model used by the Flanders Environment Agency for assessing the air pollution situation in Flanders. This would provide a better estimate of citizens'

([i]) The Department of Biology and the Institute of Sustainable Development of the University of Antwerp, the Flemish Institute for Technological Research (VITO) and the kariboo parcel service.

Figure 2: Screenshot of the map showing the results of the CurieuzeNeuzen Vlaanderen NO_2 measurements



Note: Information on colour coding and its interpretation is available on the CurieuzeNeuzen map viewer.
Source: CurieuzeNeuzen Vlaanderen (2019).

exposure of NO_2 and the public health effects in all parts of Flanders as a basis for making recommendations to policymakers.

By reaching out through De Standaard, a major Flemish newspaper, the project partners attracted almost 53 000 people interested in participating in the project. Twenty thousand participants covering the whole of Flanders were subsequently selected to measure the air quality near their homes during the month of May 2018. Participants were mostly families, with 967 schools and some companies and organisations also participating (CurieuzeNeuzen Vlaanderen, 2019).

The project successfully mobilised citizens to gather 'big data' on air quality across Flanders and showed that large groups of people can help collect high-quality large-scale data. In addition, CurieuzeNeuzen Vlaanderen raised awareness of air quality issues among the participants. The results were communicated through an online map viewer, in which users can see the overview and zoom in to their local area (Figure 2). The newspaper also helped lead an effective communication campaign, and the results were publicised across Flanders and made national and international news.

Figure 3: Measuring NO_2 using passive samplers in the CurieuzeNeuzen Vlaanderen project

In terms of measuring the air pollutant NO_2, CurieuzeNeuzen Vlaanderen distributed a set of two **passive samplers** to each participant. By following the guidance provided, participants installed the devices themselves on a window in their house, apartment or building that faced the street (Figure 3 shows one example). They attached the samplers to a v-shaped window sign, commonly used to advertise real estate, which served also as housing to protect the device. With these two passive samplers, participants measured NO_2 over a period of 4 weeks in May 2018.

The initial results were calibrated to official reference monitoring stations. In a next step, the May 2018 concentrations were extrapolated to 'the final result': a 12-month average that would allow citizens to compare their measurements to official EU limit values and WHO guidelines.

The University of Antwerp presented the results in the publicly available online map viewer. The large data set collected was then used to test and improve Atmosys (ii), the official regional model used to assess air quality in Flanders. Air quality can vary significantly over short distances, especially as a result of the 'street canyon effect', whereby pollutants accumulate in narrow, poorly ventilated streets with dense traffic. Measurement results from multiple locations provided by CurieuzeNeuzen Vlaanderen helped to assess the accuracy of predicted concentrations of air pollutants emerging from the Atmosys model (iii).

Furthermore, CurieuzeNeuzen Vlaanderen monitored behavioural changes in terms of choice of transport mode in three groups of people. These included the 20 000 participants in the air quality measurement campaign, the approximately 33 000 people who expressed interest in participating but were not selected and a reference group of 1 000 citizens not involved in the project. Interestingly, the majority of people involved *and* interested in the initiative indicated that they now use their cars less, while those not involved in the initiative had not changed their behaviour.

New Year's Eve fireworks — using low-cost sensors to detect peaks in particulate matter

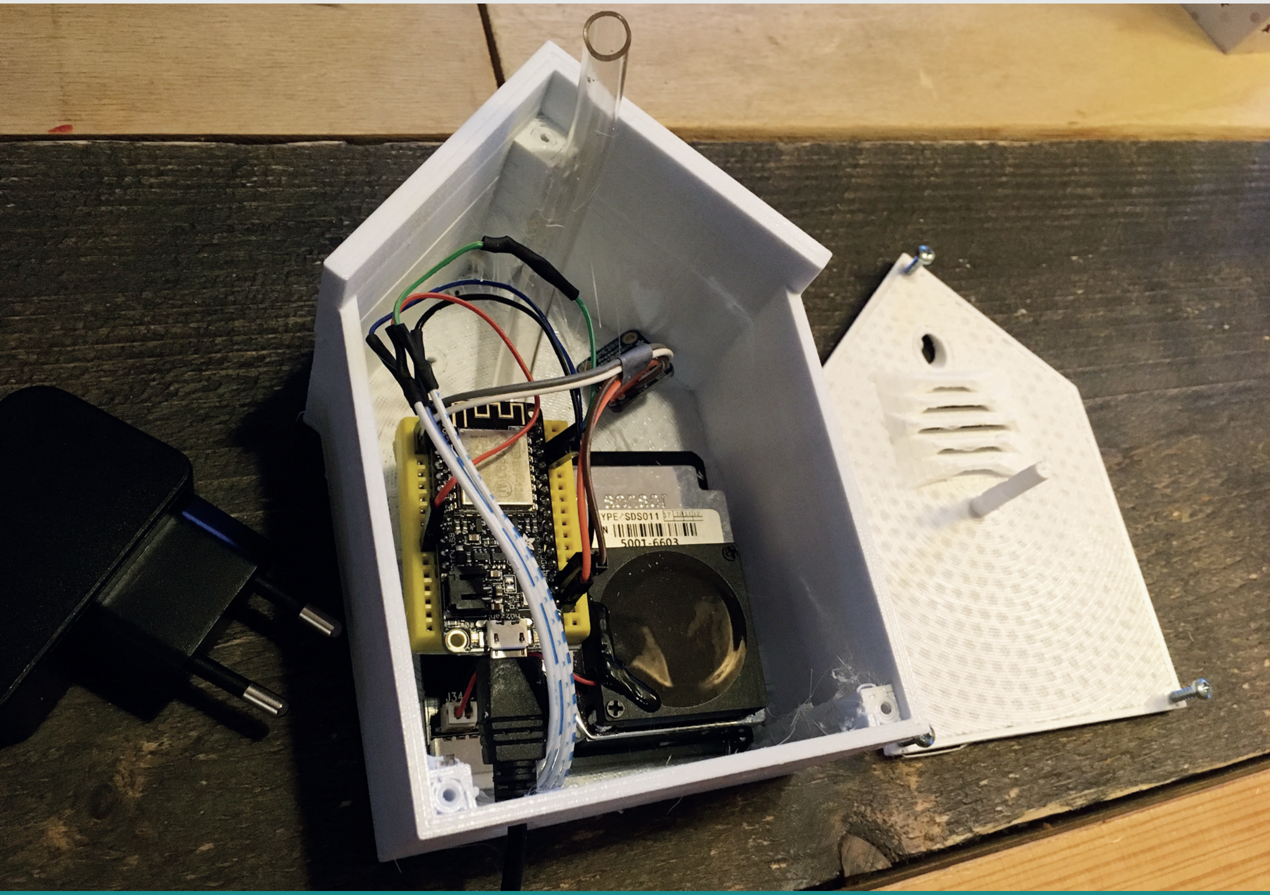
Concentrations of particulate matter with a diameter equal to or smaller than 10 microns (PM_{10}) are routinely measured using official **reference instruments** at around 40 locations in the Netherlands. According to the National Institute for Public Health and the Environment (RIVM), the average PM_{10} levels monitored in 2017 were in the order of 18-24 $\mu g/m^3$.

Setting off fireworks releases significant amounts of particulate matter, and on New Year's Eve, when people celebrate with fireworks, PM concentrations can be 50 to 100 times higher than average in some locations. In 2016, RIVM designed a project to test how accurately 80 simple **low-cost sensors** measure particulate matter when concentrations are at a peak on New Year's Eve. The experiment was repeated over the following years.

In 2017, the project raised a lot of public interest. RIVM distributed 55 more advanced sensor kits, and on the eve of 2018 around 130 Dutch citizens used these sensors to measure particulate matter in the air around their homes. They then shared the results of the measurements through a data portal developed by RIVM. To foster ownership, participants were also asked to build a creative, weatherproofed housing for the sensor devices themselves, leading to creative results (Figure 4). The data were wirelessly transmitted to the RIVM data

(ii) Atmosys was developed for the Flanders Environment Agency by VITO, an independent Flemish research organisation.
(iii) Users can also apply this model at high resolution to simulate the situation in street canyons.

Figure 4: Example of home-made weatherproof housing for a sensor device



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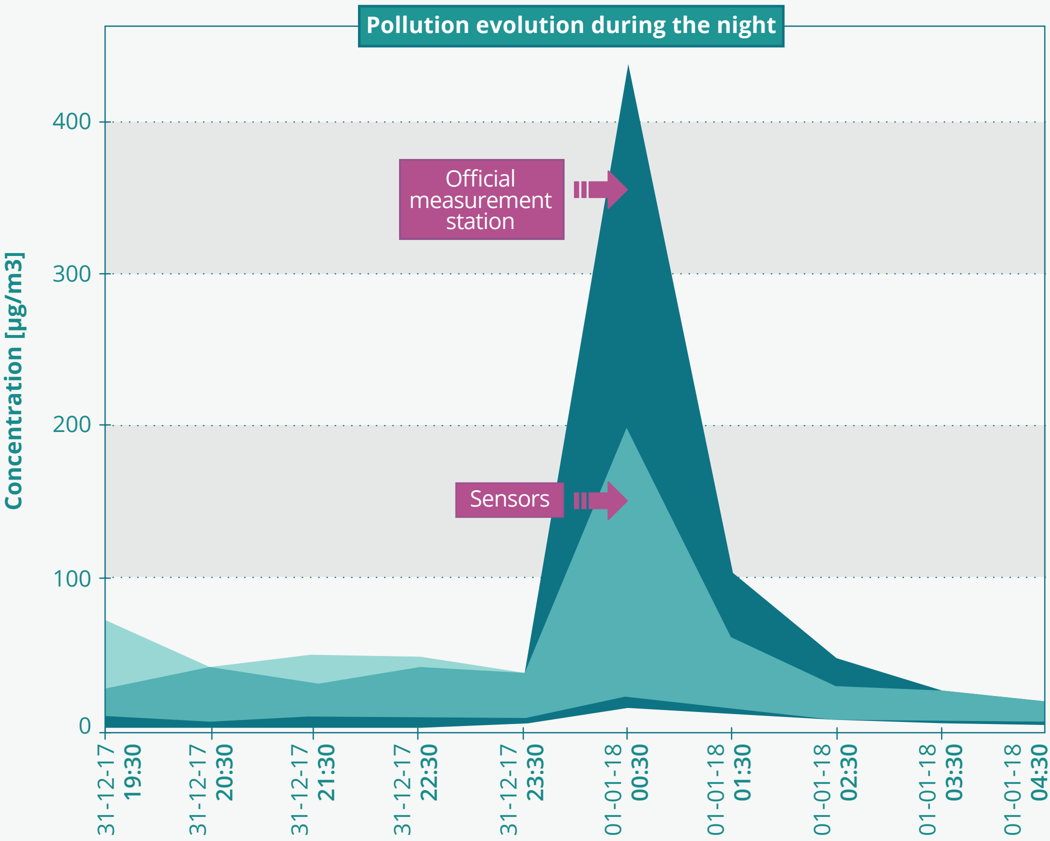
portal. To protect the participants' privacy, the data portal displayed data collection points within a radius of 100 metres.

In addition to the sensors distributed by RIVM, data were harvested from other projects using, for example, sensors provided by the German luftdaten.info initiative (luftdaten.info, 2019, now known as Sensor.Community, 2020) and sensor projects in cities.

Figure 5: Hourly particulate matter measurements during New Year's Eve 2017/2018 from a Dutch citizen science campaign



Note: The official data are available only on an hourly average basis, while the sensors report every minute. Comparing the concentration ranges between the 10th and 90th percentiles, i.e. the range where 80 % of the data are located, showed that the hourly average values of the official measurements were higher.

Source: RIVM, the Netherlands, 2018.

The average concentration of particulate matter in the air increased by a factor of 17 (compared to the afternoon) while the fireworks were being set off. The Dutch National Air Quality Monitoring Network's official measurements showed an even larger increase (Figure 5). Although the magnitude of the increase was different, the shape of the signal from the two instruments was the same.

The increases were short lived across the Netherlands, and the level of particulate matter in the air rapidly returned to average.

In cooperation with citizens, RIVM is carrying out further research to better calibrate sensor data by comparing them with official monitoring stations (RIVM, 2018 and RIVM 2020).

Joint EPA Network/EEA CleanAir@School initiative

CleanAir@School is a joint initiative of the European Network of the Heads of Environmental Protection Agencies and the EEA. Under the initiative, which ran from 2018 to early 2020, participants are monitoring air quality around schools across Europe using a common approach (EEA, 2019b).

The initiative uses citizen science campaigns to better understand children's exposure to a key air pollutant, NO_2, in the school environment. Children at participating schools learn about air pollution and the resulting health effects, while both pupils and their parents see how road transport affects air quality. A key question is whether, in the light of this knowledge, parents move away from bringing their children to school by car. As part of the project, participating environmental protection agencies explain their work to improve air quality to local communities.

To ensure a degree of comparability across the campaigns, each includes common elements:

- Environmental protection agencies identify the participating schools and implement the initiative at local level.
- The schools monitor air quality using **NO_2 passive samplers**, with at least two sampling points located at each school.
- The schools monitor the effects of road transport emissions at the schools in 'low-traffic' and 'high-traffic' situations. To do so, one passive sampler is placed on the road at the front of the school and one in a less polluted area such as a school backyard.
- In terms of timing, when using passive samplers, NO_2 should be measured for at least 4 weeks, ideally in the spring and/or autumn.

Environmental protection agencies from Flanders in Belgium, Estonia, Ireland, Italy, Malta, the Netherlands, Slovakia, Spain and from Scotland in the United Kingdom are involved in running measurement campaigns as part of the project, and several other agencies are participating as observers (EEA, 2019b). One organisation, the Scottish Environment Protection Agency, used **NO_2 low-cost sensors** instead of passive samplers to identify peak NO_2 levels during the day when parents dropped off and picked up their children by car or when school buses running on diesel fuel delivered the pupils.

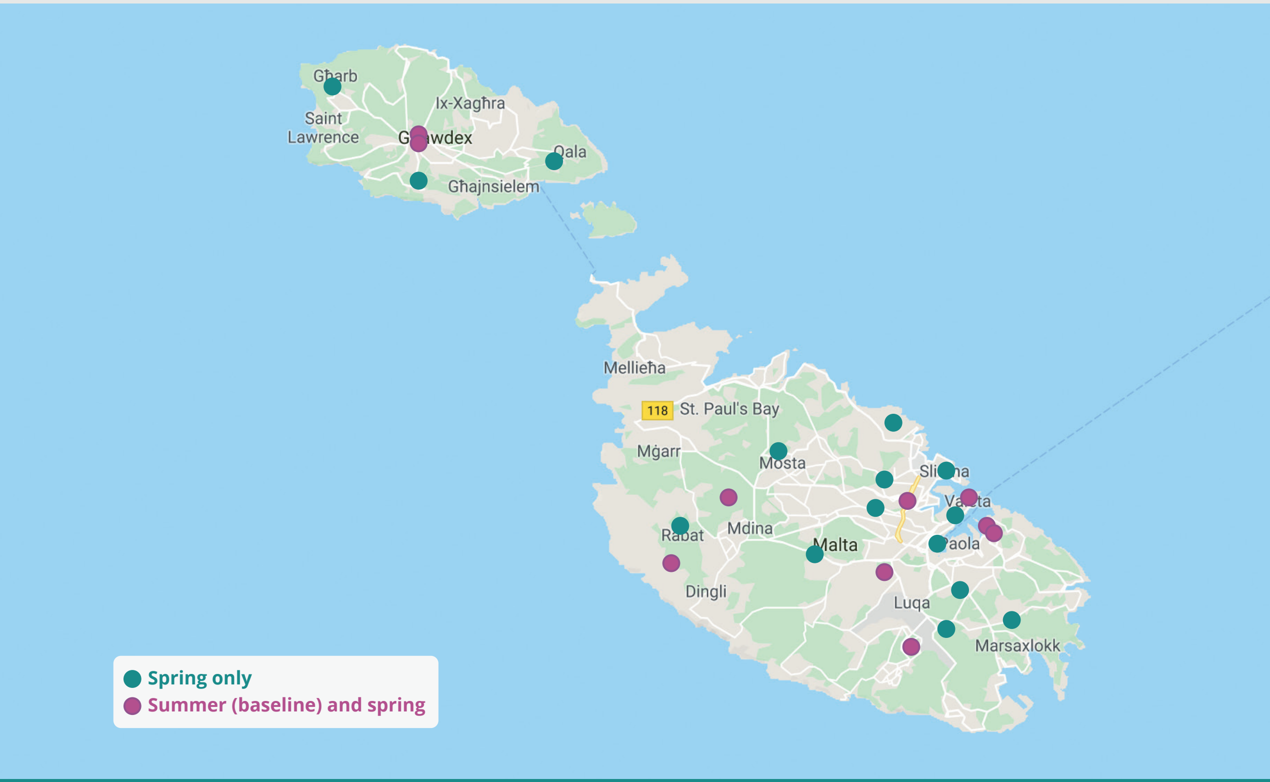
To raise awareness of air pollution issues, pupils, teachers and parents are actively engaged in implementing the project. Once the measurement campaigns are complete, the agencies explain the results and run surveys at each school to assess changes in awareness and in the modes of transport used by parents and older pupils.

Two examples of the activities undertaken by participating agencies are illustrated below.

CleanAir@School initiative in Malta

The Environment and Resources Authority of Malta contributed to CleanAir@School with its Fair with Air project, supported by the country's Ministry for Education. The project ran from November 2018 to November 2019 with the slogan 'Do you know what the air quality is like at your school? You're about to find out!' (ERA, 2019).

Figure 6: Schools involved in summer 2018 and spring 2019 air quality measurement campaigns in Malta



Source: Environment and Resources Authority, Malta.

As a first step and with the aim of establishing baseline measurements, the Environment and Resources Authority measured NO_2 using passive samplers at ten schools during the summer holiday period in August and September 2018 when traffic would not be generated from school activities. The result of this monitoring campaign served as a baseline for measurements taken during the school year in 2019.

The Environment and Resources Authority then selected an additional 15 schools out of 43, which had expressed their interest, to measure air quality during the school year. The selection was based on location , to ensure a good spatial coverage of the country, the environment type (i.e. urban, semi-urban or rural) and the age of the schoolchildren (i.e. primary, middle or secondary). The map above shows the schools involved in this initiative (Figure 6).

Air quality experts helped the schools to set up the passive NO_2 samplers. A questionnaire based on the CurieuseNeuzen Vlaanderen

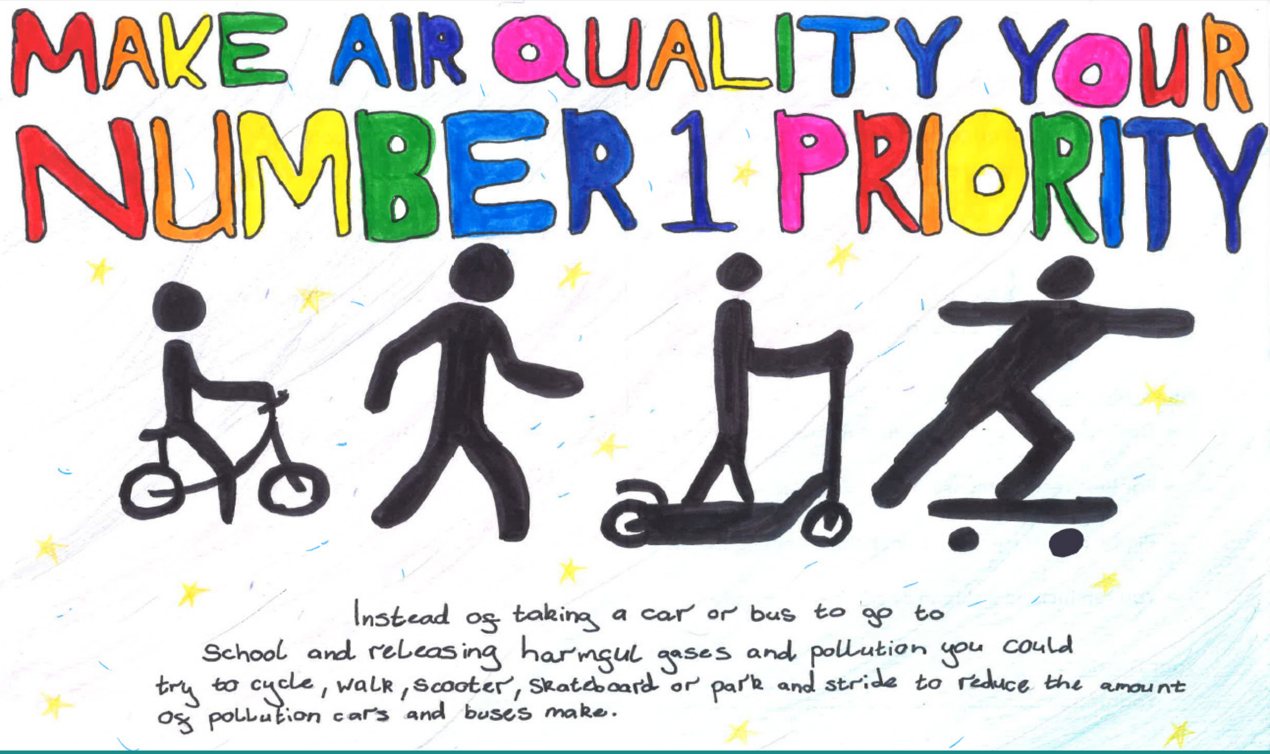
Figure 7: Promoting Fair with Air at the Valletta Green Festival in May 2019

project was distributed to parents and teachers to assess the in relation to perceptions on air quality and mobility behaviour.

In terms of outreach, a promotional video was used to describe the project and explain the approach to monitoring air quality. The project received extensive media coverage in Malta. In 2018, the Environment and Resources Authority raised awareness on air quality issues by showcasing a selection of posters created by schoolchildren on the theme "air quality: our environment and our role". Fair with Air was also presented as a side event during the EU Green Week in May 2019.

After monitoring and analyses were completed a closing conference was held in November 2019. Students from each participating school were invited to this conference during which an overview of the results from the initiative was given. Schools received also a certificate to recognize that they had participated.

Figure 8: Winning poster from a school competition in Scotland (designed by Misha Biswas)



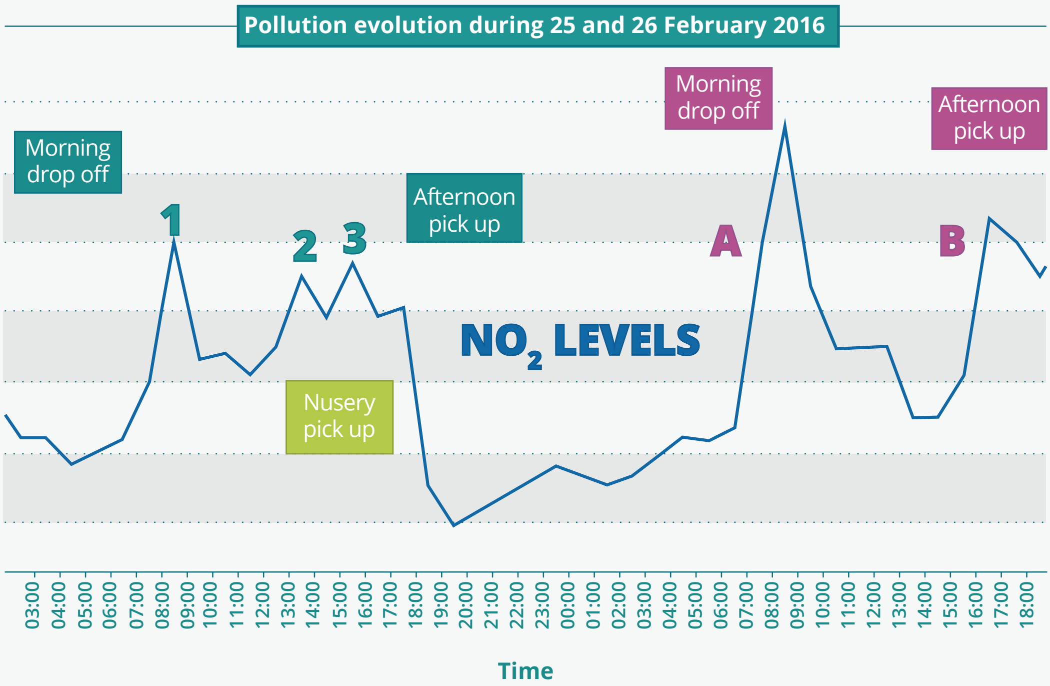
CleanAir@School initiative in Scotland, United Kingdom

In its citizen science initiative, the Scottish Environment Protection Agency teamed up with local authorities and environment officers to raise awareness of clean air among schoolchildren using the agency's 'Learning about Air Quality' package (SEPA, 2019).

Schools in Edinburgh, Glasgow and Dundee were involved in monitoring air quality and ran a competition for the best banner on air quality produced by the schoolchildren. The competition engaged children's creativity and stimulated their thinking about air quality (Figure 8). Three banners were chosen and the winning pupils presented them at an event held to mark the 2019 Scottish Clean Air Day.

In terms of measuring air quality, the schools used low-cost sensors, provided by the Scottish Environment Protection Agency or by the local authority, to measure NO_2 concentrations during the day. Given the limitations of low-cost sensors in terms of accuracy, the Scottish

Figure 9: Changes in NO_2 levels during drop off and pick up of school children at the St Clare's Primary School in Scotland

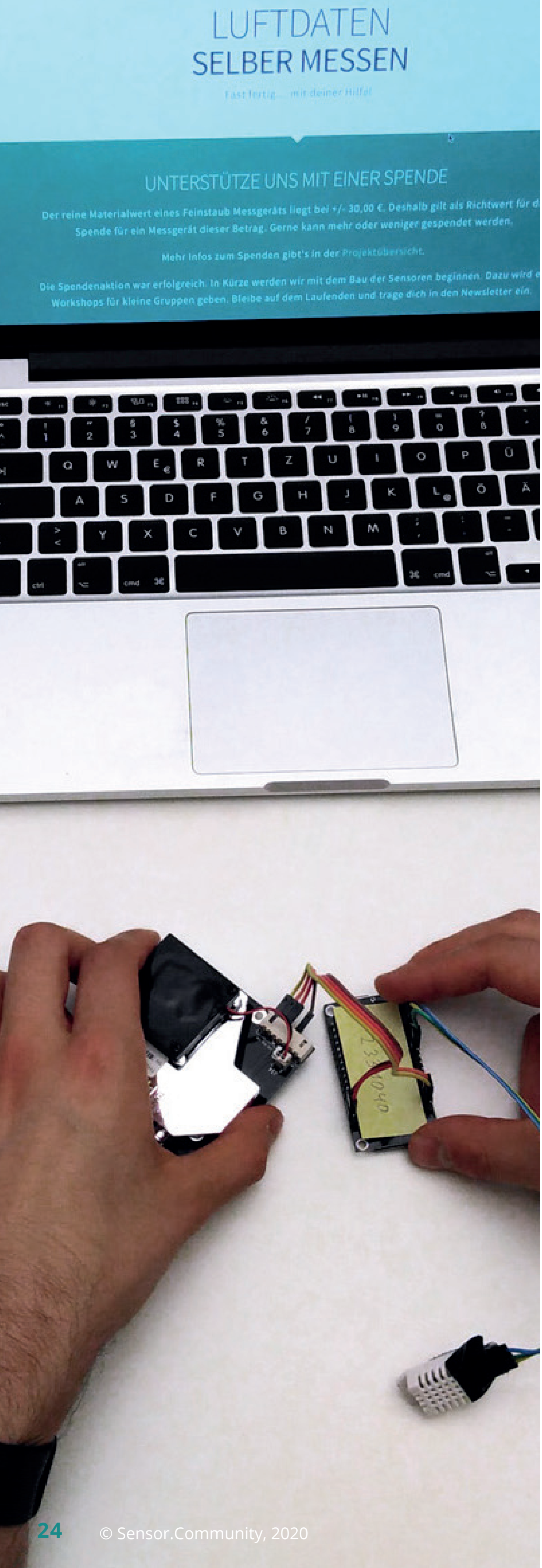


Source: East Renfrewshire Council, Scotland, United Kingdom.

initiative was less interested in absolute concentrations but instead focused on peaks in NO_2 levels when parents dropped off and picked up their children. Figure 9 shows how peaks at drop-off and pick-up times were clearly detected by the sensors.

NO_2 sensors were also placed by a bus stop, where children get off buses and which they walk past on their way into school. Measurement results showed peaks in the morning and the afternoon corresponding to the bus timetable. In the afternoon, buses waited for the children with their engines running, contributing to the peak in NO_2 concentrations.

In terms of follow-up action, the city council in charge of operating the relatively old buses was encouraged to look into possible alternatives, including promoting walking, scooting and cycling. One of the schools ran a successful campaign by closing a street to vehicles during school hours. The Scottish Environment Protection Agency linked the initiative to active travel campaigns, with organisations such as Cycling Scotland and Living Streets Scotland



as well as a Beat the Street initiative, which promotes daily exercise, such as walking and biking, to improve people's heath (Intelligent Health, 2019).

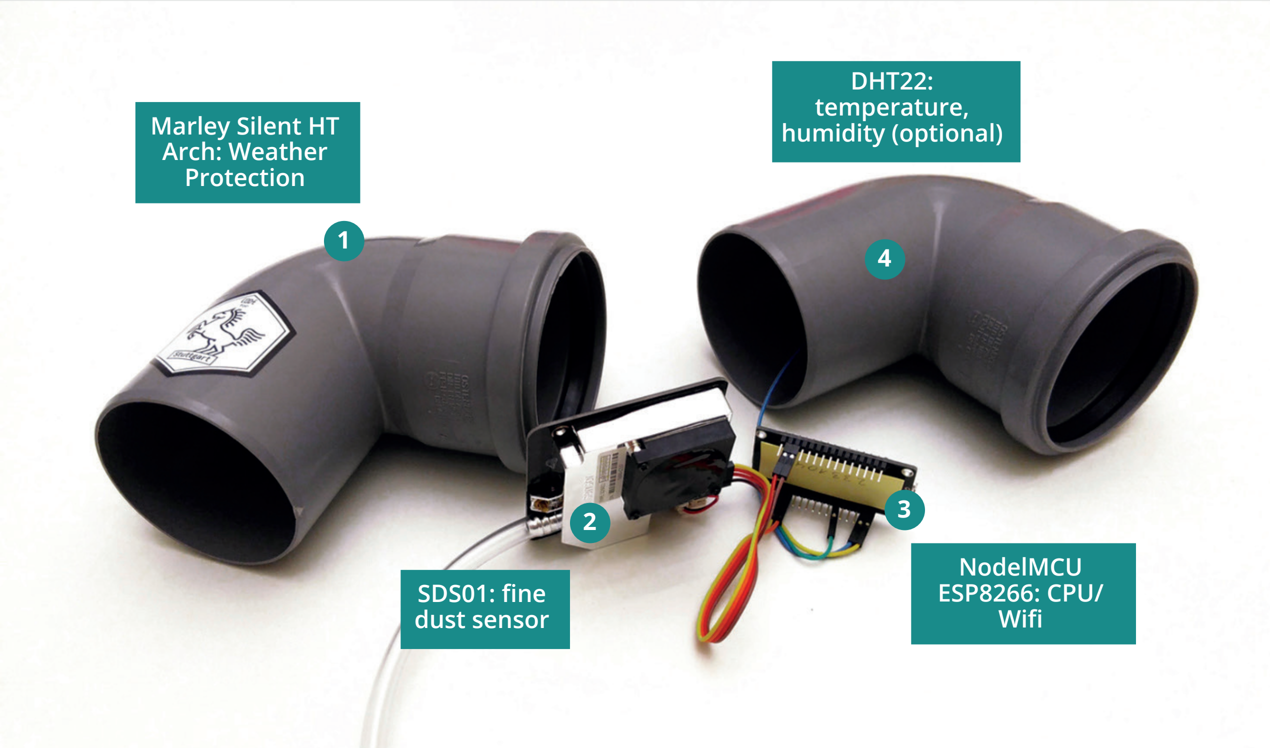
Mijn lucht, mijn school — examples of NGO citizen science campaigns with schoolchildren

In 2018, Greenpeace published the results of a campaign run at 222 schools in Belgium, Mijn lucht, mijn school (My air, my school). In late 2017, the pupils used passive samplers to measure NO_2 around their schools. The general conclusion was that at many of the schools (61 %) air quality was worryingly poor.

The Health and Environment Alliance (HEAL) monitored involved 50 schools in Berlin, London, Madrid, Paris, Sofia and Warsaw as part of their Healthy air, healthier children campaign (results published in 2019). Using passive samplers, the schoolchildren measured NO_2 levels outside and inside their schools.

Both initiatives stressed that children are more vulnerable to air pollution and that — being closer to vehicle exhausts than adults — they are more exposed to air pollutants.

Figure 10: The Sensor.Community particulate matter sensor kit



Source: Sensor.Community, 2020

Sensor.Community: a 'grass roots' air quality initiative

The collection and dissemination which are known as 'open data' using digital tools is a rapidly developing phenomenon in Europe. Every second week, citizens, including programmers, designers, developers and journalists, meet across Germany.

The Sensor.Community uses citizen science to gather large air quality data sets. The aim of Sensor.Community is to make "Feinstaub" (particulate matter) visible — by monitoring its concentrations in air in locations where it is not officially measured and by visualising the results in online viewers. Having started at the local level in Stuttgart, the project has since grown to capture measurements from over 10 500 unique locations around the world (in 71 countries).

Sensor.Community (2020) provides links to equipment that can be purchased, downloadable software and a guide showing how to assemble a low-cost sensor and start measuring particular matter (Figure 10).

Ensuring the quality of sensor data — cooperating with the research community

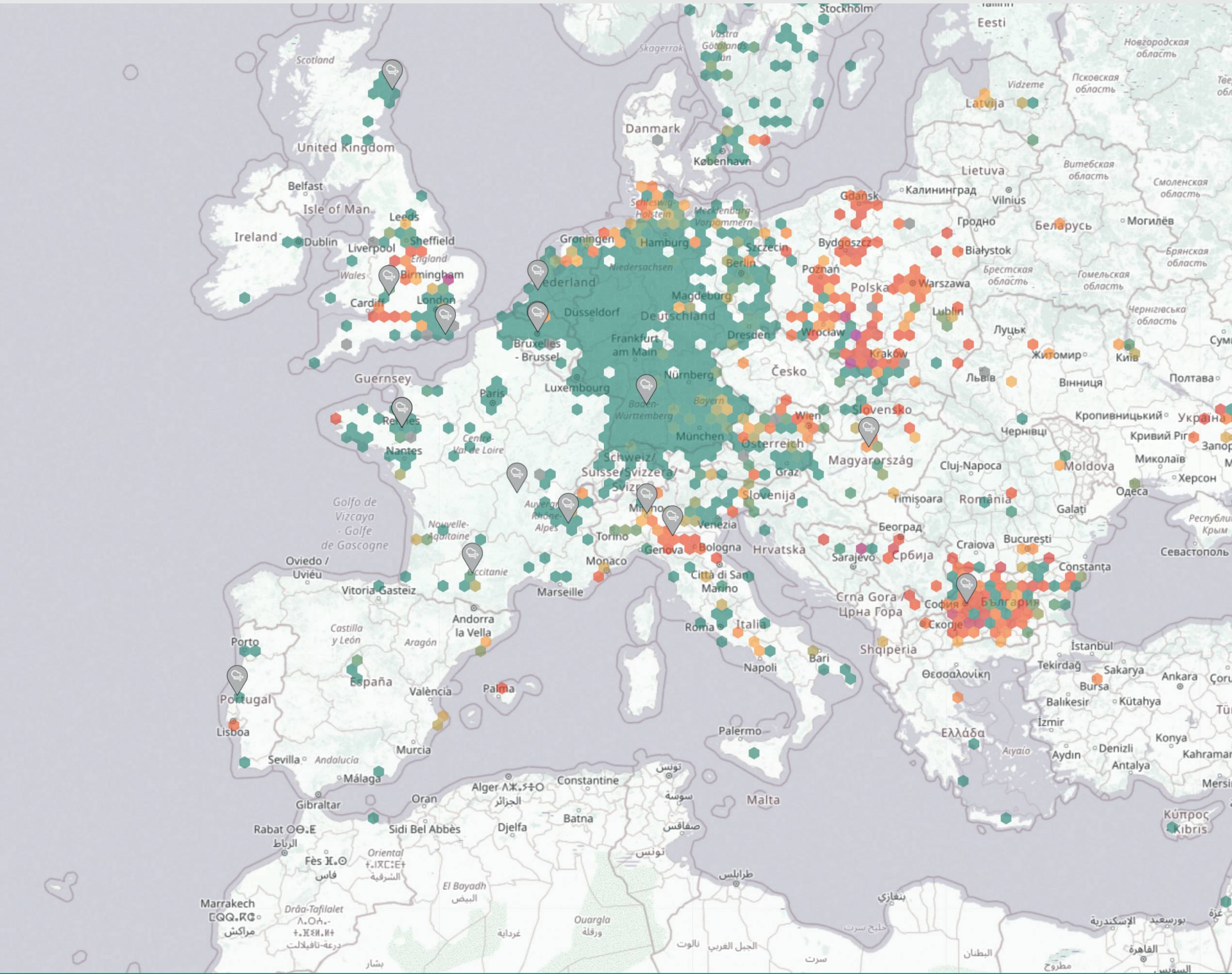
Sensor.Community acknowledges some issues with the accuracy of the data provided by its sensors. Co-location measurements using the sensor and comparing the results with those from a more advanced optical monitor have shown that the results obtained are robust under typical conditions, i.e. when humidity is in the range of 20-50 % and particulate matter (PM_{10}) ([iv]) mass concentrations are below 20 $\mu g/m^3$ (Budde et al., 2018). However, when humidity is very high, for example when it is foggy, the sensors can deliver incorrect values. Co-location studies with official reference instruments in the German federal state of Baden-Württemberg showed good relative agreement, for example when comparing trends in concentrations. At the same time, there were discrepancies between absolute values (Blon, 2017).

Sensor.Community project members are therefore looking for algorithms that can be used to minimise the impact of high humidity on particulate matter readings. They are working with research institutions, such as RIVM, to continuously improve the sensors.

Like many initiatives, Sensor.Community displays the results of measurement of particulate matter on an online map. They show the air quality in hexagons with colour coding to indicate the level of air pollution. Either one or more sensors feed data into each hexagon. This means that signals of 'bad air quality' can result from readings from only one sensor measuring very high particulate matter concentrations. Such readings might be strongly influenced by, for example, humidity or the location of the sampling point. To protect privacy, the location of individual sensors is not given (Figure 11).

([iv]) Particulate matter with a diameter of 10 μm or less.

Figure 11: Screenshot of the Sensor.Community map displaying results of measurements results of particulate matter.



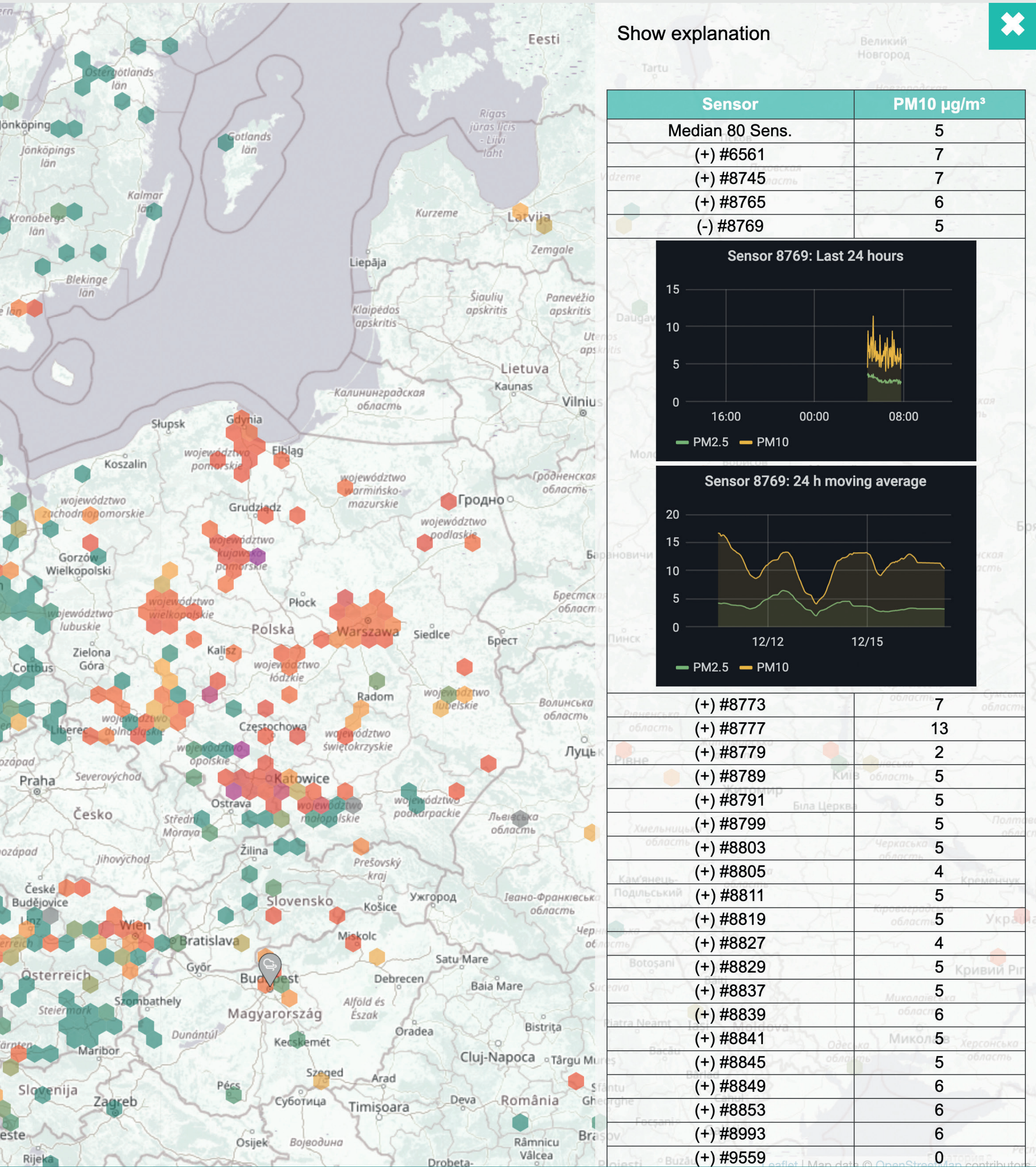
Source: Sensor.Community (2020).

Note: Information on colour coding and its interpretation is available on the Sensor.Community map viewer. When individuals contribute their measurements to open data networks, privacy issues have to be considered. On Sensor. Community's data platform, sensor data cannot be traced back to the precise within each hexagon (because of the limited zooming function).

Users can click on a hexagon and then on the identification code for specific sensors to find information on the 24-hour average concentrations of two particulate matter fractions (PM_{10} and $PM_{2.5}$) (7) and how they have changed over the past 24 hours (Figure 12).

(7) Particulate matter with a diameter of 2.5 μm or less.

Figure 12: Screenshot showing results from individual sensors available on Sensor.Community



Source: Sensor.Community, 2020.

In addition, Sensor.Community has developed a 'PM alarm' app that provides people with an overview of the air quality near their homes, their workplaces or in their city. Users can choose to receive a text when local levels of particulate matter are very high ([vi]).

Several NGOs working on air pollution issues are encouraging people to engage with projects to monitor air quality using the low-cost sensor sets supplied by Sensor.Cummunity. One example is a citizen science project, run in Brussels by the NGO Transport & Environment.

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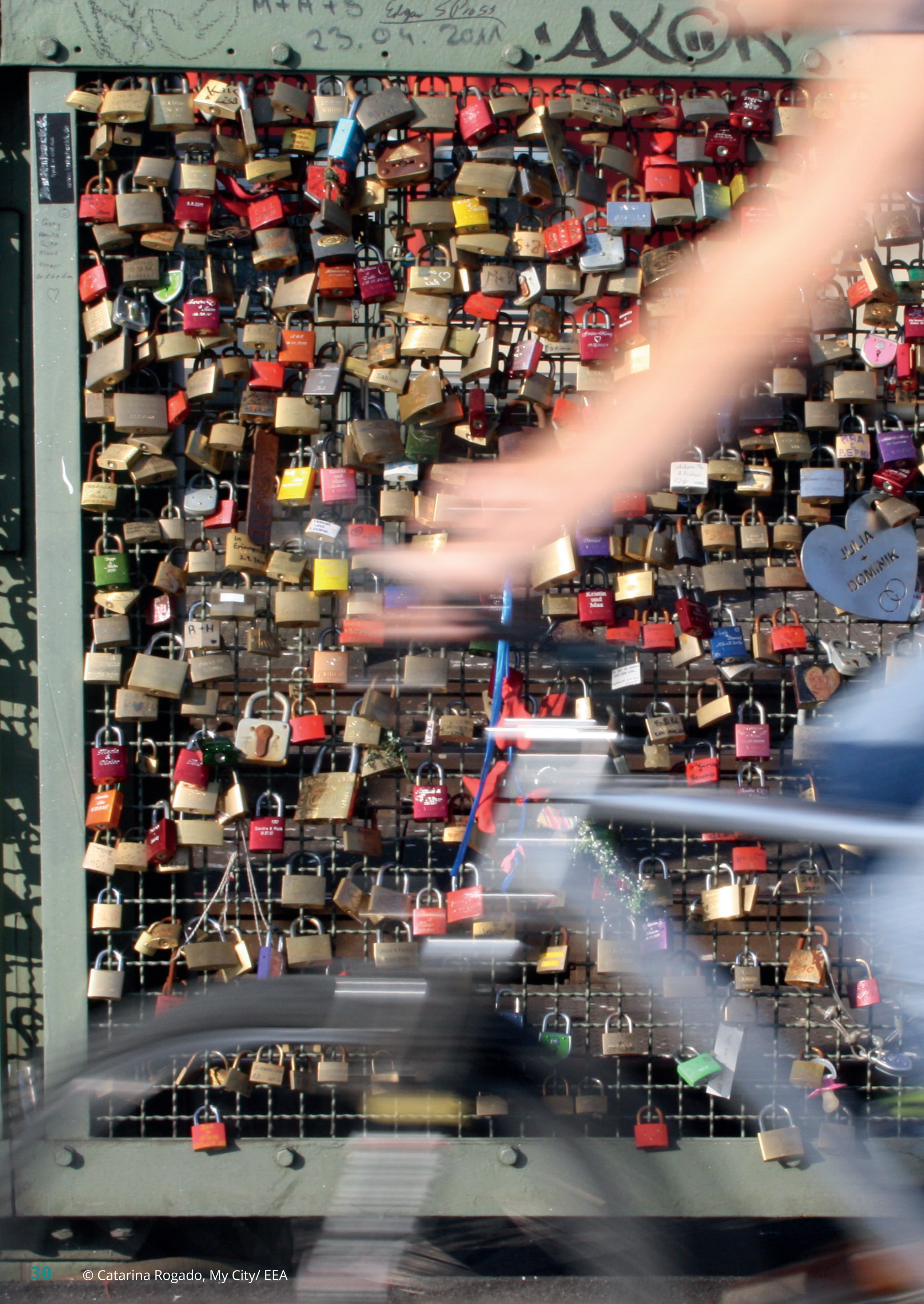
([vi]) The German Federal Ministry of Education and Research, funded the development of this app.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+
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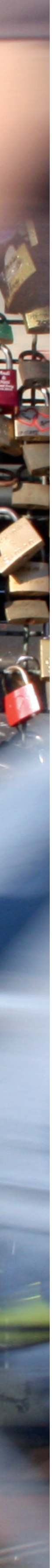
Kristin und Max
In Erinnerung
R+H
Sabine



Low-cost measuring devices — how do they work?

Citizen science initiatives that focus on air quality often use low-cost passive samplers or sensors to measure concentrations of different pollutants. Although low-cost devices offer a means of measuring air pollution at significantly lower cost than conventional instruments, the various types now available on the market have different benefits and disadvantages in terms of their performance that users should be aware of.

The many types of low-cost samplers and sensors now commercially available provide different mechanisms and opportunities for citizens to monitor their local air quality. In turn, such measurements, especially when conducted as part of a larger campaign, can help to inform and raise the awareness of both citizens' groups and decision-makers about local air quality levels.

The air pollutants that are most typically measured by low cost measuring devices are particulate matter, nitrogen dioxide (NO_2) and, to a more limited extent, ozone (O_3), sulphur dioxide (SO_2), carbon monoxide (CO) and volatile organic compounds (VOCs).

This chapter provides an overview of the main types of devices currently available on the market and describes the different benefits and disadvantages of each of the different types.

Passive air pollutant samplers

Passive samplers, otherwise often referred to as diffusion tubes, are low-cost measuring devices that are relatively easy to use and can be placed in nearly any location. Thus, it is possible to detect differences in air quality at a local or regional scale. After a sampling period of, for example, 4 weeks, the devices are then removed and analysed in a laboratory with the necessary equipment.

The passive samplers themselves are small tubes, which include reactive substances that adsorb and accumulate air pollutants without the need for any power supply. The tubes are small, often less than 15 cm long, light and are usually placed inside a small fender to protect them from the elements (Figure 13).

The samplers can, if used and located correctly, meet the formal data quality criteria set out in the EU Ambient Air Quality Directive (EU, 2008). 'A Member State may use any other method which it can demonstrate gives results equivalent to any of the methods' ([vii]), defined as reference methods in the Directive. Finland and Germany, for example, officially report passive sampler results to the EEA. Further, many local authorities already use passive samplers to supplement reference equipment, see for example the city of Berlin (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2018).

([vii]) See Annex VI of the 2008 Ambient Air Quality Directive, B. Demonstration of equivalence.

Passive samplers are particularly useful for measuring the influence of NO_2 emissions from road transport and benzene (C_6H_6) levels in ambient air. Member States are required to monitor both of these pollutants under the EU Ambient Air Quality Directive (EU, 2008). The main disadvantage of this type of sensor is that it cannot deliver 'real-time' information on local air quality, as measurements require a sampling period of at least several weeks followed by analysis of the sampler in a laboratory. The cost of a passive NO_2 sampling unit, including handling and analysis, is 50 Euro (Alena Bartonova, NILU, personal communication, November 2019).

Figure 13: Passive sampler for measuring NO_2 at Brückenstraße, Berlin Mitte, Germany

© Paul Herenz, Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin.

Electronic and optical sensors for measuring air pollutants

Many sensors or simple sensor systems are relatively inexpensive. Such sensors offer important new opportunities in terms of measuring air quality in different areas and may complement information obtained from traditional air quality monitoring networks. They are, however, relatively new technologies, typically developed by small- and medium-sized companies, and their reliability and performance needs to be understood in order to have confidence in the results they generate (Lewis and Edwards, 2016). Air quality sensors generally monitor gas or particulate matter in the air. They produce electrical signals that are correlated with pollutant concentrations. The development of these new sensor technologies has therefore required scientists and the air quality community to focus on testing the quality of sensor measurements and improving their functionalities (e.g. Spinelle et al., 2017a; Karagulian et al., 2019).

A user might assume that **low-cost sensors** are small versions of the high-quality reference instruments used to measure air quality by public authorities. However, they are not. The levels of many air pollutants change during the different seasons of the year as a result of variations in emission patterns, as well as changing weather conditions. Temperature and humidity can significantly affect measurements from low-cost sensors. In addition, gas sensors can gradually lose their responsiveness over longer measurement periods, such as a year. Users should therefore be aware of, and consider, the different pros and cons of low-cost measuring devices when deciding whether they can help to answer questions about local air quality (see summary in Figure 18).

What does 'low-cost' mean?

The part in the sensor unit that is dedicated to sensing an air pollutant can be relatively cheap. However, for meaningful measurements, the user will need a full sensor system with housing, data storage units, etc. Such sensor systems can be used as stand-alone measuring devices and their price 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 visualisation, data treatment, user support). Although all units on the market are sold for significantly lower prices than official reference equipment, there are large price differences (Table 1).

Table 1: A simple classification based on the purchase price of sensor systems

Price class	Indicative costs (EUR)
Low	< 500 ([a])
Medium	500-2 000
High	2 000-5 000
Very high	> 5 000

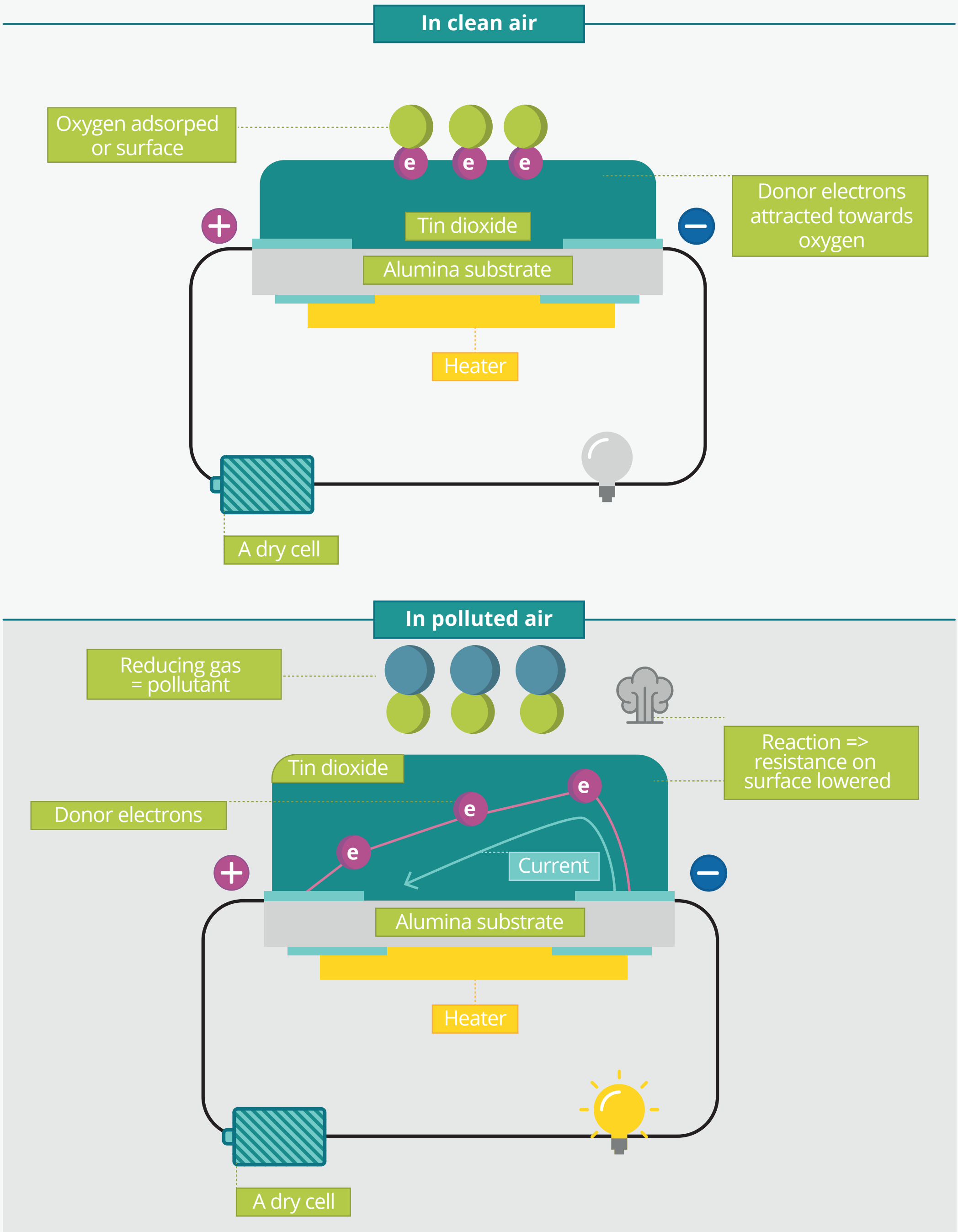
Note: ([a]) Usually only available for particulate matter measurements.
Source: Castell (forthcoming).

Metal oxide gas sensors

Metal-oxide sensors are sensitive to gaseous air pollutant concentrations based on the reaction of air with the sensor surface. Pollutants in the air react on the metal and modify its resistance. Electrons are then released, allowing current to flow freely through the sensor (Figure 14). This current is correlated to the pollutant's concentration. Using this kind of sensor, the user can measure NO_2, O_3 and CO.

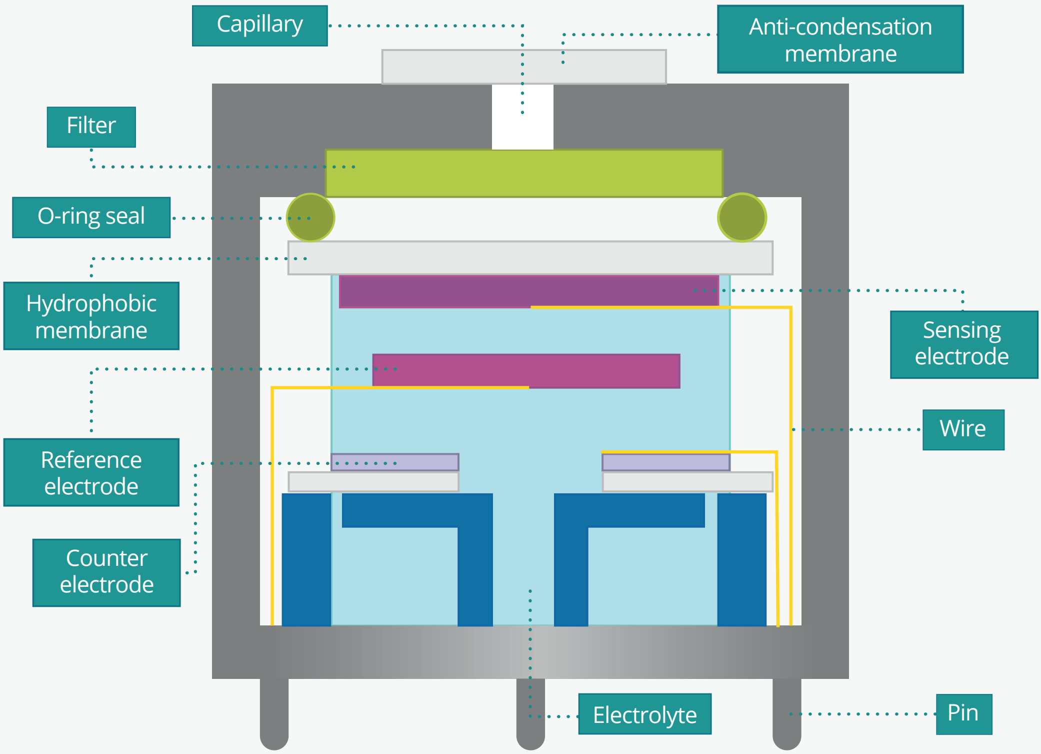
One disadvantage of metal oxide sensors is that their response is often limited to high concentrations of the targeted gaseous pollutant and that they can suffer from interference from other non-target gases present in the atmosphere. Furthermore, variations in temperature and humidity affect the results of measurements and they can have long response times from a few minutes up to almost an hour.

Figure 14: Schematic showing the operation of metal oxide sensors



Based on: © FIGARO Engineering Inc., Japan.
Note: Low-cost; around 10 to 15 Euro for a sensor (EC, 2019b).

Figure 15: Schematic showing the operation of electrochemical sensors



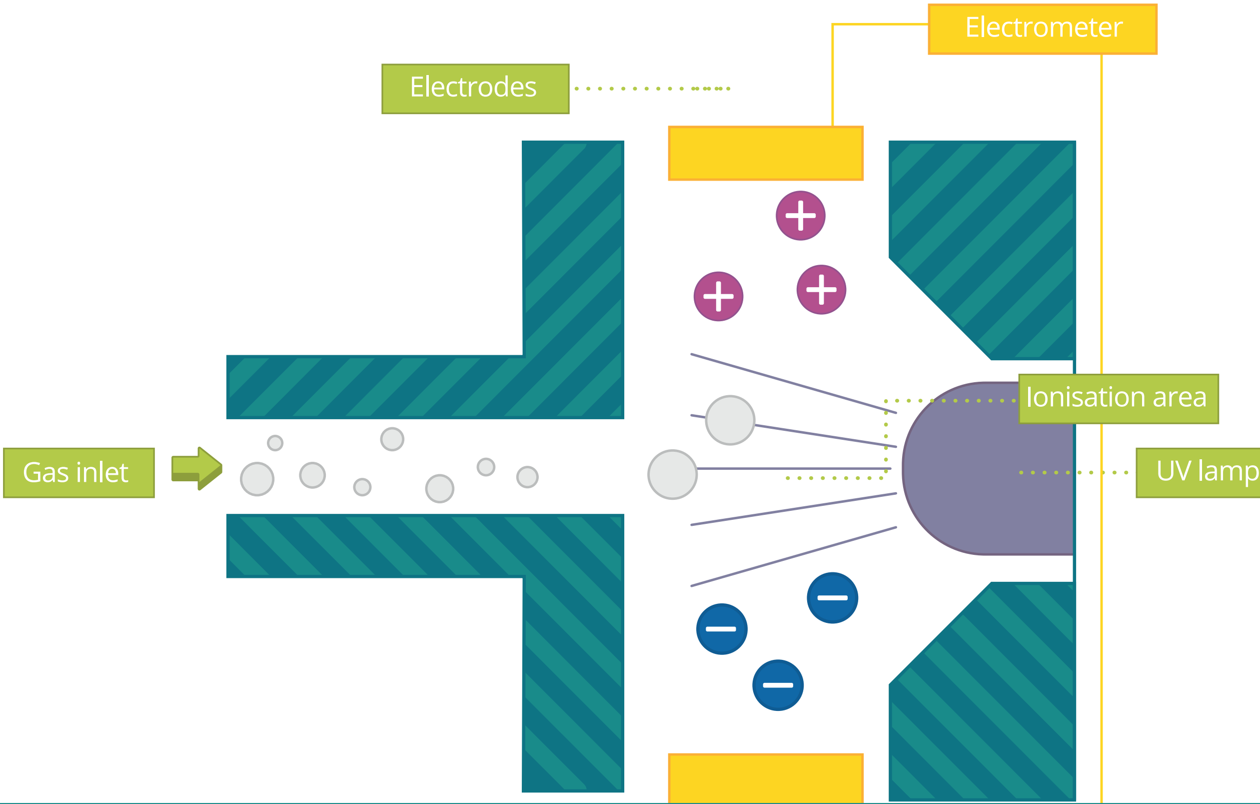
Source: EEA.
Note: Medium-cost; around 50 to 150 Euro for a sensor (EC, 2019b).

Electrochemical gas sensors

Electrochemical sensors are composed of electrodes in contact with an electrolyte, usually an aqueous solution of strong inorganic acids. The reaction of a gas molecule, such as NO_2, with the sensing electrode in the liquid generates a small current proportional to the concentration of the gas (Figure 15). Electrochemical sensors can be used to measure NO_2, SO_2, O_3, NO and CO.

Performance issues with this kind of sensor are that they are highly sensitive to variations in relative humidity in the air as well as temperature. As with metal oxide gas sensors, they also suffer from interference from other non-targeted gases in the atmosphere (Cross et al., 2017; Wei et al., 2018). However, some newer NO_2 sensors, for example, include a filter to reduce such interference (Castell et al., 2017).

Figure 16: Schematic showing the operation of photoionisation detectors



Source: EEA.

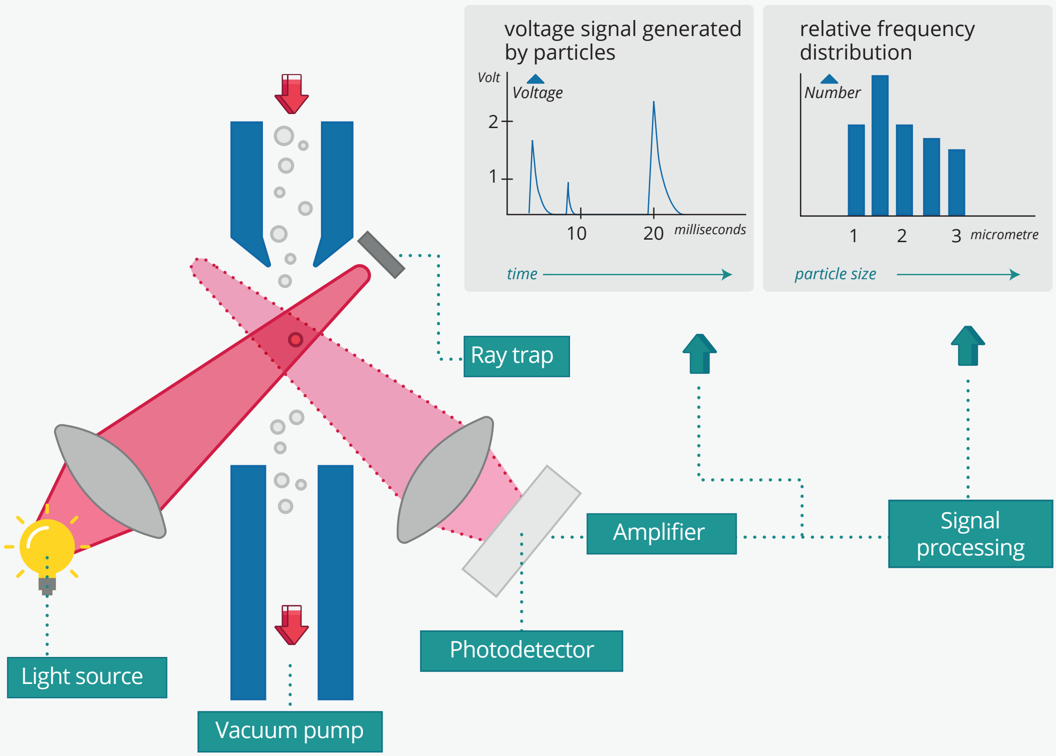
Note: Moderate cost; 400 Euro for a sensor to 5000 Euro for a handled device, i.e. a hand-held technology that can include mobile telephone and computer functionalities (EC, 2019b).

Photoionisation detectors

Photoionisation detectors measure a group of chemicals categorised as volatile organic compounds (VOCs) in the air. The energy of ultraviolet light provided by a lamp excites the neutrally charged VOC molecule and removes a negatively charged electron (e.g. Szulczynski and Gebicki, 2017). The VOC molecule is now a 'positive' charged molecule. The different charges of the electron (negative) and the VOC molecule (positive) results in a flow of current, which is directly proportional to the concentration of the VOC. The measurements are, however, not selective to specific VOCs (Figure 16).

Photoionisation detectors are more sensitive to larger VOC molecules. They are not significantly affected by humidity and temperature.

Figure 17: Schematic of the operation of optical particle counters



Source: EEA.

Note: Moderate cost; 300 Euro for a sensor to 2000 Euro for a handled device, i.e. a hand-held technology that can include mobile telephone and computer functionalities (EC, 2019b).

Particulate matter sensors

Sensors measuring particulate matter most commonly rely on optical measurements, typically the scattering of light. Air enters the sensor by means of a small pump or an induced temperature gradient. Light is shone onto the particulate matter in the airstream, causing the light to be scattered, which is detected by a monitoring device (e.g. Wang et al., 2015). The particulate matter concentration is therefore proportional to the scattered light intensity. A photodetector then transfers the scattered light into electrical signals. Finally, an in-line device counts the particulate matter signals and, based on the signal amplitudes, a particle size distribution is created (Figure 17).

In contrast to optical sensors, reference instruments used for official air quality measurements often employ a ‘gravimetric’ method to establish the concentration of particulate matter, i.e. the mass of particles collected on a filter at a monitoring location is subsequently analysed in a laboratory.

Particulate matter optical sensors calculate mass concentrations indirectly, based on a theoretical model: the optical measurements as described above assume a certain particulate matter density and then convert particle numbers and size distributions into mass concentrations.

Low-cost particulate matter sensors suffer from interference from relative humidity, as they do not include any system to dry the particles. This is particularly critical when relative humidity is high, i.e. above 80-90 %.

Particulate matter characteristics such as colour and shape have an influence on the signal measured, too. For this kind of optical sensor, it is essential to establish, through a calibration procedure, the relation between the scattering capability of a particle in a measurement volume and the particle size.

The results derived from optical particulate matter sensors are considered much more uncertain than those obtained by the official reference instruments.

Figure 18: Pros and cons of the different types of measuring devices

	Advantages	Disadvantages
Passive samplers (diffusion tubes)	Usually cheap Easy to handle Reliable Good for large-scale data collection Good for setting up measurement networks	No continuous measurements, cannot link to near real-time monitoring systems Need to be analysed in a laboratory Not for all main air pollutants
Gas sensors	Can be relatively cheap Can measure time series Good for large-scale data collection Good for setting up measurement networks Rapidly evolving technology	Sensitive to temperature Sensitive to humidity Interference from other gases Not easy to process data Not always reliable Can lose responsiveness over time
Particle sensors	Can be relatively cheap Can measure time series Good for large-scale data collection Good for setting up measurement networks Rapidly evolving technology	Particulate matter mass not measured directly Sensitive to humidity Not always reliable Not easy to process data Can lose responsiveness over time

Source: EEA, 2020.


saba

Ensuring the quality and reliability of low-cost measuring devices

Data quality is a key issue determining the use or interpretation of information generated by low-cost measuring devices. Data quality refers to the performance of a passive sampler, sensor or sensor system in terms of its stability and accuracy when compared with high-quality reference instruments. However, performance also includes aspects such as the ability of a sensor system 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 device, the second is related to the data processing and transmission systems.

Although passive samplers are relatively reliable and deliver good-quality results, they cannot deliver results in real time. Understanding the potential performance limitations of low-cost sensors that, in contrast, can provide real-time information but not always of high quality is equally important. In considering performance, a number of elements need assessing, including (Lewis et al., 2018):

- sensitivity (the ability of a sensor to measure high and low concentrations);
- selectivity (the lack of interference from other pollutants);
- temporal resolution (how often measurements are taken);
- reproducibility (comparability and consistency over time).

Tests and calibrations by manufacturers

Manufacturers test their passive samplers, or low-cost sensors, mainly to ensure operational performance and to understand technical malfunctions. The manufacturer or a research institution calibrates the devices in the laboratory using measurements of known mixes of gases and particulate matter concentrations. However, the 'real world' mixes of gases to be measured in local environments are much more varied than control conditions in the laboratory, and meteorological conditions, such as humidity and temperature, can also significantly influence measurements made under real conditions (Castell et al., 2017; Jayaratne et al., 2018).

Calibration against official air quality monitoring stations

A common way of calibrating a low-cost sensor device is to compare the data it produces with that of an official reference instrument situated not more than 10 metres away (Lewis et al., 2018). Known as 'collocation', this approach allows users to compare the data obtained to understand the performance of the low-cost device (Figure 19). Users are often advised to repeat this exercise during each season of the year, undertaking a minimum of 2 weeks of continuous measurements (Castell et al., 2017; Spinelle et al., 2017b; Ripoll et al., 2019).

If it is not possible for users to check the performance of their low-cost sensor, then some information and guidance is available in sensor evaluation reports based on co-location studies (e.g. Spinelle et al., 2017b; Karagulian et al., 2019). The European Committee for Standardization (CEN) is currently developing a protocol to evaluate sensors (EC, 2019b).

Figure 19: Options for calibrating sensor systems

1 Individual sensor testing
During manufacture.

2 Laboratory calibration
Understanding main influencing factors on sensor response.

3 Sensor system collocation
Comparison with reference instrument, closely located and under field conditions. Should be performed at regular intervals.

4 Machine learning
Based on learning across sensor systems in a network. Requires collocation of a number of the sensor systems with reference instruments. Currently being developed.

Source: EEA.

Whenever possible, citizens are encouraged to contact their local air quality network and take part in calibration exercises that are increasingly being offered to owners of low-cost devices for use in citizen science initiatives.

Calibration exercises provided by national research institutions

Often ensuring the quality of the data collected by comparing them with an official monitoring station is not possible. In some countries, national institutions provide support to calibration exercises. For example, the National Institute for Public Health and the Environment (RIVM) in the Netherlands offers support to interested parties wishing to calibrate NO_2 sensors. They use nightly concentration values to perform calibration, correcting for unexpected results or drift (Wesseling, 2019; Wesseling et al., 2019). During the night, there are only small variations in NO_2 concentrations due to low traffic intensity. Sensors are calibrated against the data collected the previous night by a nearby official monitoring station. This can enhance the quality of the data produced by sensors that could not be collocated with reference stations.

Artificial intelligence — machine learning

Machine learning is an approach used in the rapidly developing field of artificial intelligence. Instead of explicitly programming a computer, machine learning makes use of algorithms that automatically learn and improve performance based on experience. Algorithms are a sequence of instructions and rules designed to solve a certain problem. Machine learning can range from sophisticated statistical models to artificial neural networks ([viii]).

Machine learning is currently being applied to the calibration of networks of low-cost sensor devices. This technique considers several variables, including temperature, relative humidity and the overall composition of gases in the air, i.e. not only the gas to be measured (e.g. Spinelle et al., 2017b). This enables the system to account for the impacts of meteorology on sensor measurements, as well as interference from other gases. In this case, machine learning is based on statistical analysis of data from across sensor systems, whereby sensors are calibrated against each other. The results are also always compared against data from official monitoring stations equipped with reference instruments.

Representativeness in space and time

The spatial representativeness of monitoring results requires attention. This concerns how well the values measured by low-cost devices at a specific point relate to the area around that point. Measurement values are affected by how the pollutant to be measured behaves in the air, the proximity to emission sources and the characteristics of the surrounding environment.

In addition, if users wish to understand how air quality in their area changes throughout the day and over the year, then a time series of air quality data is needed. This provides a much more robust understanding of air quality than a single measurement. Users will then need to ensure that their device can collect data over time, without major gaps in recording the concentration of the pollutant of interest.

([viii]) Artificial neural networks are computing systems that are inspired by the biological neural networks that constitute animals' brains.

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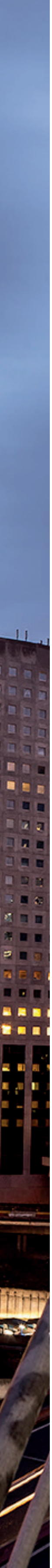


Connecting sensors in networks and communicating results

People usually use low-cost sensor systems as individual instruments, rather than as part of a connected network. However, the number of such networks in Europe is growing. Establishing a network of sensors requires a communication infrastructure, which can pose challenges related to the connectivity of the devices and data traffic. There are a number of important steps to consider when sensors are connected in a network and the results are communicated to the target audience.

Deploying low-cost sensors

The generic steps involved in deploying low-cost sensor technology to measure air pollutants are illustrated in Figure 20. How users implement these steps depends on the objective of monitoring air quality.

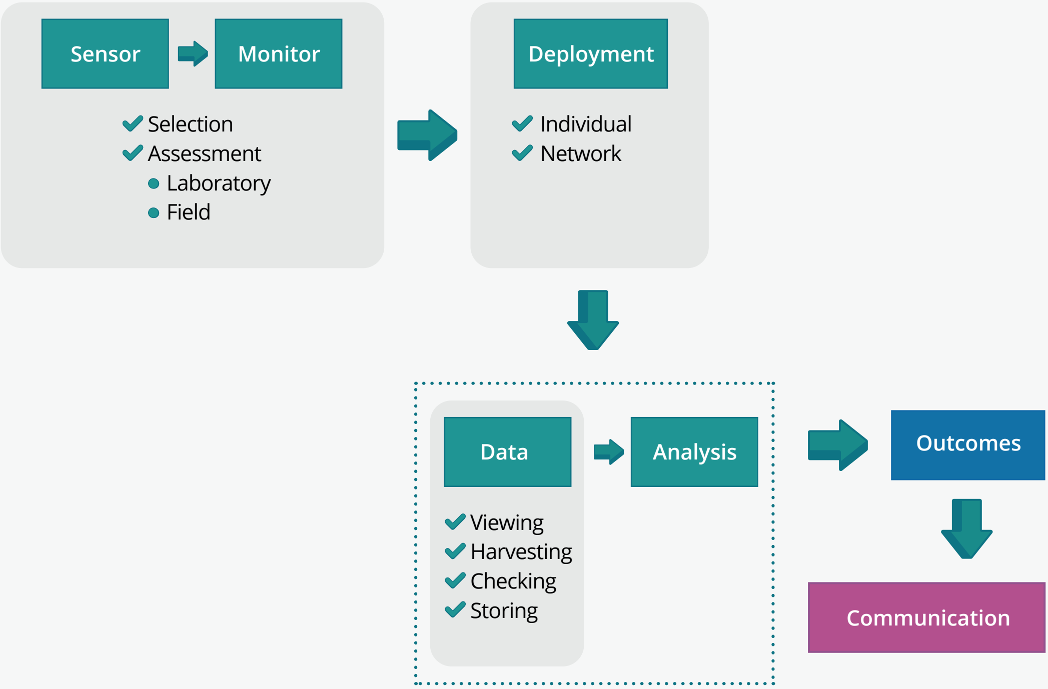
The data produced by low-cost sensors can be real-time pollutant concentrations or average levels measured over time. For internet-connected sensors, individual users can typically view the readings on a computer screen or through an app and can, for example, compare their data with the air quality standards set by national authorities or the World Health Organization guidelines to understand whether there may be health implications arising from exposure to the concentrations observed (WHO, 2006). Users also need to decide whether they wish to communicate their results of their measurements and how best to do this.

Joining a network and sharing data

People using sensors to measure local air pollution levels can often join a network, allowing air quality data to be collected over a larger area and/or a longer period and shared. A number of citizen science initiatives are exploring ways to best gather data from networks of sensors. Such initiatives have been supported by crowdfunding ([ix]), as well as by public funding. Data gathered from sensor networks are often presented through live air quality maps that display the measurements recorded by stationary or mobile sensors, which are accessible online and through mobile phone apps. Examples include the PurpleAir (PurpleAir, 2019) or the Sensor.Community web portal.

([ix]) Crowdfunding is the practice of funding a project or venture by raising small amounts of money from a large number of people, typically using the internet.

Figure 20: Steps for deploying low-cost sensors



Source: Based on Morawska et al. (2018).

Establishing a network of sensors requires the establishment of a communication infrastructure, allowing the data from a number of devices to be pooled and stored. Scientists and citizen groups have developed non-commercial devices, such as the AirSensEUR (AirSensEUR, 2019), that facilitate the development of an open infrastructure consisting of a network of low-cost sensors, as well as communication solutions.

The need for technical and logistical support to increasingly sophisticated sensor networks is likely to become an issue over time, as most sensors have a limited lifetime, and faulty sensors need to be identified and replaced.

Combining data from a larger number of measuring devices

Individuals or public authorities may wish to connect a larger number of devices to one information system or network. Such a network might include different types of devices, and it may combine official air quality monitoring data with measurements taken by citizens.

The potential of low-cost sensor technologies is only likely to be fully realised when large numbers of sensors are simultaneously deployed in one region. This requires that networks of sensors should have the potential to grow and include new users, sensor technologies and data exchange protocols as they become available. Connecting the information technology and the air quality communities is one of the near-future challenges.

As an example of institutional engagement with a sensor network, in December 2017 RIVM launched an experimental sensor data portal (Samen Meten) collating data in the Netherlands and making it available to citizens, local governments and other interested partners through a central database. RIVM is using the data to develop sensor calibration algorithms and to complement data from reference instruments in hourly air quality maps, as well as to explore options for data visualisation for the public. In the near future, RIVM aims to support a sensor network in which third parties, including members of the public, can actively take part (RIVM, 2019).

Issues to consider when setting up an air quality project using a network of monitoring devices

The use of networks installed and operated by citizens to monitor air quality has the potential to generate large data sets and increase the shared understanding of air quality issues. To achieve these benefits, a number of questions must be addressed:

- Citizens generally engage at the local level, while data from a large network may feed into a project coordinated and delivered on a broader scale. How to strike a balance between bottom-up initiatives and top-down coordination?
- To what extent can individuals get involved? Do they just contribute data from their sensors? Or can they actively contribute to setting the project's objective?
- How should data be made available to project participants? As raw data sets or as final communication products, such as maps?
- What role might air quality experts play in facilitating citizen science projects using low-cost devices to monitor air quality?
- How might project coordinators make information about the latest sensor technology available to citizen scientists in a user-friendly way?

When designing an effective air quality project that uses a network of low-cost devices to monitor air pollution, both the project objective and the steps towards achieving it should be clearly defined. The box on the opposite page provides an example of a project objective and its related implementation steps.

Not all of the steps necessarily need to be implemented. For example, ongoing work on the calibration of sensor systems led by the European Committee for Standardization (CEN) ([x]) could lead to a standardisation and approval procedure for sensor systems. This may then be translated into requirements for manufacturers that can lead to improvements in data quality.

([x]) CEN/TG 264 — Air Quality, WG42 — Gas Sensors.

To be successful, the project design needs to consider in the planning stages the questions and objectives to be addressed. This can be as simple as ensuring that a chosen measuring device can produce data on the relevant pollutant over a particular period of time. The project outcomes should answer the questions defined and the results should be able to be clearly communicated to the target audience ([xi]).

Example of the design of a citizen science air quality project using a sensor network

Project objective

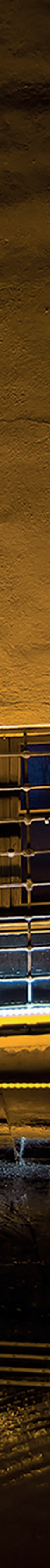
To provide real-time information on air quality with high spatial resolution. This will feed into the local traffic control system and provide guidance to cyclists on which path through the city will minimise their exposure to air pollutants.

Project steps

1. Deploying a large number of heterogeneous sensors.
2. Establishing an infrastructure for communicating and harvesting data from the sensors.
3. Ensuring data quality.
4. Collating data and providing access.
5. Transforming raw data into information products that convey key messages to citizens.
6. Planning and implementing actions based on the information produced by the sensor network.

Source: Adapted from Morawska et al. (2018).

([xi]) The European Commission is currently working on guidelines on the use of citizen science in environmental monitoring. The development of the guidelines is coordinated by the Environmental Knowledge Community (EKC), a collaboration between various services of the Commission and the EEA. The guidelines are expected to be published as a Commission Staff Working Document in 2020.



How is air quality officially monitored in Europe?

The EU Air Quality Directives require that every Member State establishes a network of air quality monitoring stations in accordance with a set of criteria. Quality criteria specify both technical requirements for instruments and the types of locations where stations should be situated, including at traffic, industrial, urban, suburban and rural sites. These basic provisions aim to ensure that measurements are representative for a defined area and ensure the delivery of harmonised, comparable air quality data across Europe.

The EU has been working over recent decades to continually improve air quality by controlling emissions of harmful substances into the atmosphere, improving fuel quality and integrating environmental protection requirements into the transport, industrial and energy sectors.

The EU's clean air policy is based on three pillars addressing different aspects of air quality (EC, 2018); for details, see EEA (2019a):

1. ambient air quality standards set out in the Ambient Air Quality Directives (i.e. EU, 2004, 2008);
2. national emission reduction targets established in the National Emission Ceilings Directive (EU, 2016); and
3. emission and energy efficiency standards for key sources of air pollution (Figure 22), from vehicle emissions to products and industry.

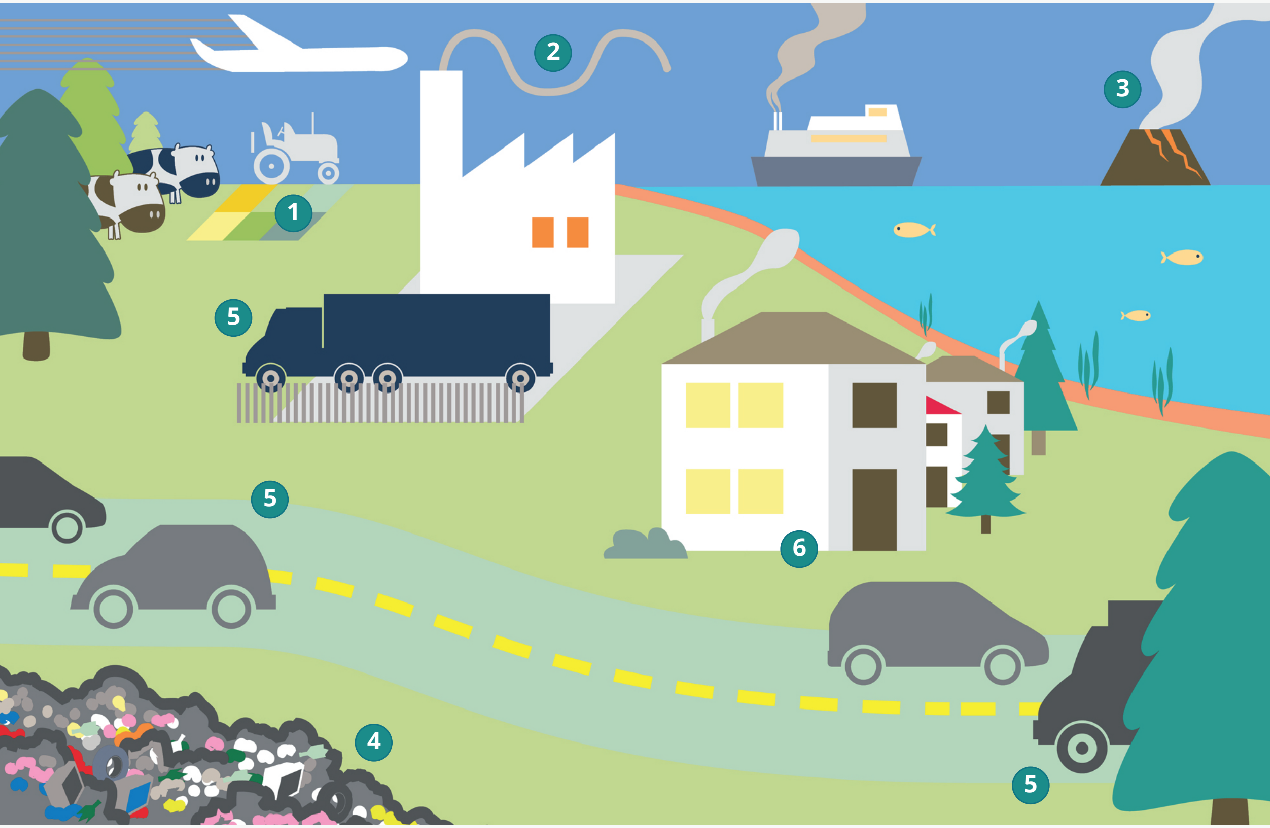
Following measurement, compilation and checking of air quality data by Member States and other European countries, it is sent to the EEA which further checks the quality of information before its public dissemination and use to support the European Commission and countries to implement air quality legislation.

The EEA holds, inter alia, air quality monitoring data and supporting information from Europe's official air quality networks and individual stations monitoring ambient air pollution. Official validated measurement data as well as preliminary up-to-date results are made available through online data viewers (e.g. EEA, 2019c, 2019d). The data reported are used by the EEA and many other organisations to underpin assessments of air quality in Europe, such as the EEA's series of annual *Air quality in Europe reports* (EEA, 2019a).

The Air Quality Directives set threshold concentrations for the main air pollutants that shall not be exceeded in a given period and/or a certain number of times over a given period. These thresholds, called limit values, cover the following air pollutants: particulate matter (PM), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), benzene (C_6H_6) and lead (Pb). In the event of exceedances of the limit values, the competent authorities are required to develop and implement air quality plans. These plans should be designed to bring concentrations of air pollutants below the limit values set for the protection of human health and the environment as fast as possible (EEA, 2018, 2019a).

Figure 22: Sources of air pollutant emissions in Europe

Air pollution is not the same everywhere. Different pollutants are released into the atmosphere from a wide range of sources, including industry, transport, agriculture, waste management and households. Certain air pollutants are also released from natural sources.



1/ Around 90% of ammonia emissions and 80% of methane emissions come from **agriculture activities.**

2/ Some 60% of sulphur oxides come from **energy production and distribution.**

3/ Many **natural phenomena,** including volcanic eruptions and sand storms, release air pollutants into the atmosphere.

4/ Waste (landfills), coal mining and long-distance gas transmission are sources of methane.

5/ More than 40% of emissions of nitrogen oxides come from **road transport.**

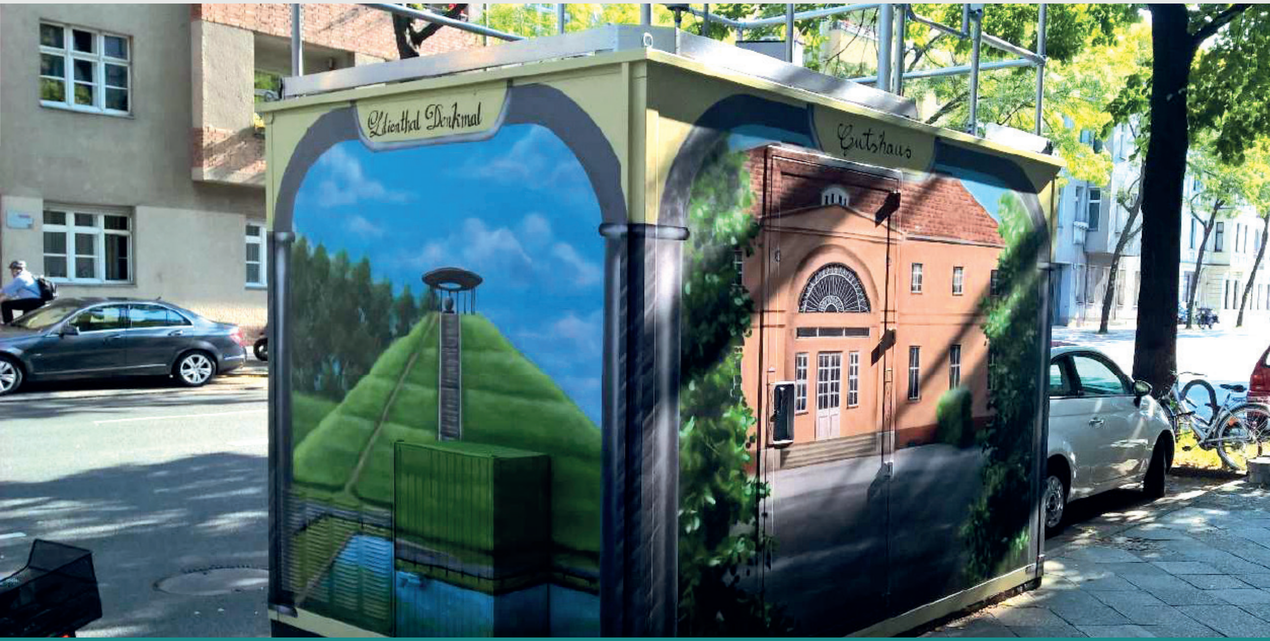
Almost 40% of primary $PM_{2.5}$ emissions come from transport.

6/ Fuel combustion is a key contributor to air pollution - from road transport, households to energy use and production.

Businesses, public buildings and households contribute to around half of the $PM_{2.5}$ and carbon monoxide emissions.

Source: EEA.

Figure 23: Official traffic monitoring station in Berlin, Germany



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When measuring air quality, Member States must meet rigorous quality standards for accuracy and reliability. They are supported by AQUILA — the EU-wide network of air quality reference laboratories (see the text box below). Figure 23 shows a street-side station measuring air quality in Berlin, Germany.

AQUILA — the EU-wide network of air quality reference laboratories

AQUILA was established in 2002, chaired by the Joint Research Centre (JRC) of the European Commission (EC, 2019a). AQUILA's objectives include:

- providing expert information on equipment measuring air quality;
- promoting the harmonisation of air quality measurements among European countries;
- coordinating quality assurance and control initiatives;
- participating in activities related to standardising air quality measurement methodologies; and
- providing a forum for information exchange between countries.


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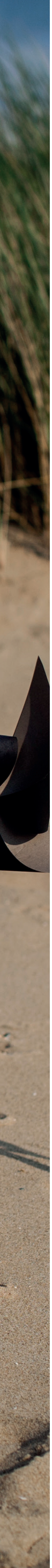

New thinking on air quality — what is the future for low-cost measuring devices?

Small cheap devices for measuring air pollution are now widely available, and people are increasingly using them to monitor local air quality where they live, work, study, exercise and travel. Using readily available information technology, people can collect, store and visualise their results on internet platforms or through mobile phone apps.

Citizen science initiatives on air quality can help raise public awareness of air quality issues in communities and trigger behavioural changes to reduce emissions. Sharing results through digital platforms contributes to the democratisation of data, with visualisation tools used to turn data into knowledge about local air quality.

Using low-cost measuring devices to complement official measurements

An important shift is playing out in the field of air pollution monitoring. Until recently, typically only government-operated or research networks of reference instruments measured air quality. There is now a shift towards networks that combine data from reference equipment and low-cost-sensors or passive samplers. This raises the question of to what extent data from low-cost devices can supplement official data.

Passive air pollutant samplers can, if handled correctly, meet the data quality objectives for stationary equipment according to the Ambient Air Quality Directive (EU, 2008). Many city authorities already use such samplers to supplement information from static local official monitoring locations. For example, the city of Berlin has placed 23 passive nitrogen dioxide (NO_2) samplers along busy streets, supplementing the 16 official traffic monitoring stations. In 2018, most of them showed exceedances of the EU annual limit value for NO_2 (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2018).

With ongoing improvements in the performance of low-cost air quality sensors, the resulting measurements will also increasingly provide a significantly cheaper option for complementing official measurements. According to the Joint Research Centre, sensors may meet the quality objectives for ‘indicative measurements at fixed stations’ ([xii]) set in the Air Quality Directive in the future if calibration procedures are improved (Karagulian et al., 2019). Equally, however, it may not always be necessary for sensors to deliver the exact same technical performance as more expensive

([xii]) ‘Information from fixed measurements may be supplemented by modelling techniques and/or indicative measurements to enable point data to be interpreted in terms of geographical distribution of concentrations.’ (EU, 2008).

instrumentation to still deliver useful and policy-relevant air quality data. In the future, exchanging a limited number of expensive monitoring stations with numerous low-cost sensors might provide the same or even better information on the air quality situation (Volten et al., 2018).

Towards the future

The increasing number of citizen science initiatives focused on air pollution may represent a paradigm shift in the way that air quality is monitored. The rapid development and deployment of low-cost sensors will enable air quality monitoring at many more locations than provided by the official network. Air quality data will increasingly be decentralised and not managed through a single database maintained by a local or government authority. In response to this development, many authorities involved in monitoring air quality are reflecting on how this emerging stream of air quality data might best be accessed and used to supplement official air quality monitoring. The principal challenge is ensuring data quality.

'There needs to be some type of acceptance and institutionalization of citizen science,' says Steffen Fritz, a specialist in Earth observation and citizen science at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. 'It needs to be not just bottom-up — it needs also to be accepted as some kind of official data stream.' (Irwin, 2018)

Clear, step-by-step guidance can help people to effectively use low-cost measuring devices to better understand their local air quality. Setting up a sensor and communicating results requires upfront investment and operational costs, access to a network and digital platform to host results and a degree of technical competence. Collaboration between citizens and competent authorities can help to ensure that sensors are correctly deployed and produce reliable data sets. Assistance from competent authorities in calibrating measuring devices can help to maintain public confidence in the results of official measurements.

Many low-cost passive air pollutant samplers already deliver sound results when correctly used. However, it is important to recognise that, generally speaking, low-cost sensors are presently at an early stage of development, and their application requires caution and good planning if users are to produce reliable answers that address their questions.

Most sensors currently on the market do not meet the requirements set for official monitoring stations under the Ambient Air Quality Directives. This means that they are not yet suitable for replacing official air quality monitoring networks and instruments. The successful deployment of low-cost sensor systems should recognise that an individual sensor device is not equivalent to an official reference station.

Nevertheless, sensing techniques are rapidly evolving. This dynamic situation means that there also is currently no clear standard against which to evaluate performance. Despite ongoing efforts, including within the European standardisation system, a certification system will take some time to develop. Ensuring that a device is fit for purpose will continue to be important.

At the same time, emerging evidence suggests that data from a large network of low-cost sensors, subject to statistical analysis or machine learning, could in the future provide information of a precision and accuracy that matches current quality criteria for official data. In the near future, a network of sensor systems could provide the kind of real-time information on air quality sought by the public.

References

AirSensEUR, 2019, 'Air Quality Monitoring Open Framework', AirSensEUR — Open framework for air quality monitoring (https://airsenseur.org/website/airsenseur-air-quality-monitoring-open-framework/).

Blon, M., 2017, *Untersuchungen zur Messung von Feinstaub — Das Citizen Science Project luftdaten.info*, Masterarbeit, Masterstudiengang Umweltschutz, Hochschulen Esslingen, Nürtingen, Reutlingen, Stuttgart.

Budde, M., et al., 2018, 'Suitability of the low-cost SD011 particle sensor for urban PM monitoring', *Atmospheric Dust* 8, p. 11.

Castell, N., et al., 2017, 'Can commercial low cost sensor platforms contribute to air quality monitoring and exposure estimates?', *Environment International* 99, pp. 293-302.

Castell, N., *Low-cost sensors and networks — Overview of current status, challenges and opportunities*, Norwegian Institute for Air Research (forthcoming).

CEN, 2019, 'European Committee for Standardization', CEN/TC 264/WG 42 — Ambient air — Air quality sensors (https://standards.cen.eu/dyn/www/f?p=CENWEB:7:0::::FSP_ORG_ID:2012773&cs=1FD71819F25D74834BB38751B78ACE16D).

Cross, E. S., et al., 2017, 'Use of electrochemical sensors for measurement of air pollution: correcting interference response and validating measurements', *Atmospheric Measurement Techniques* 10, pp. 3575-3588.

CurieuzeNeuzen Vlaanderen, 2019, 'Home page', CurieuzeNeuzen Vlaanderen (https://curieuzeneuzen.be/).

EC, 2018, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — A Europe that protects (COM(2018)330 final).

EC, 2019a, 'About AQUILA', EU Science Hub — The European Commission's science and knowledge service (https://ec.europa.eu/jrc/en/aquila).

EC, 2019b, 'Measuring air pollution with low-cost sensors — Thoughts on the quality of data measured by sensors', EU Science Hub — The European Commission's science and knowledge service (https://ec.europa.eu/jrc/en/publication/brochures-leaflets/measuring-air-pollution-low-cost-sensors).

EEA, 2018, *Europe's urban air quality — Re-assessing implementation challenges for cities*, EEA Report No 24/2018, European Environment Agency.

EEA, 2019a, *Air quality in Europe — 2019 report*, EEA Report No 10/2019, European Environment Agency.

EEA, 2019b, 'Citizen science initiative CleanAir@School', European Environment Agency (https://www.eea.europa.eu/themes/air/cleanair-at-school).

EEA, 2019c, ‘European Air Quality Index’, European Environment Agency (https://www.eea.europa.eu/themes/air/air-quality-index/index).

EEA, 2019d, ‘Up-to-date air quality data’, European Environment Agency (https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/up-to-date-air-quality-data).

ERA, 2019, ‘Fair with Air at Schools’, Environment and Resources Authority, Malta, and ŻiguŻajg Project (https://www.ziguzajg.org/project/fair-with-air-at-schools/).

EU, 2004, Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (OJ L 23, 26.1.2005, p. 3-16).

EU, 2008, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (OJ L 152, 11.6.2008, p. 1-44).

EU, 2016, Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC (OJ L 344, 17.12.2016, p. 1-31).

Intelligent Health, 2019, ‘Beat the Street — The physical activity challenge that works!’, Beat the Street (https://www.beatthestreet.me/UserPortal/Default).

Irwin, A., 2018, ‘Citizen science comes of age — Efforts to engage the public in research are bigger and more diverse than ever. But how much more room is there to grow?’, *Nature* 562, pp. 480-482.

Jayaratne, R., et al., 2018, ‘The influence of humidity on the performance of a low-cost air particle mass sensor and the effect of atmospheric fog’, *Atmospheric Measuring Techniques* 11, pp. 4883-4890.

Karagulian, F., et al., 2019, *Review of sensors for air quality monitoring*, JRC Technical Report, Publications Office of the European Union, Luxembourg.

Lewis, A. C., et al., 2018, *Low-cost sensors for the measurement of atmospheric composition: Overview of topic and future applications*, Report No WMO 1215, World Meteorological Organization, Geneva.

Lewis, A. and Edwards, P., 2016, ‘Validate personal air-pollution sensors’, *Nature* 535, pp. 29-31.

luftdaten.info, 2019, ‘Measure air quality yourself’, lufdaten.info (https://luftdaten.info/en/home-en/).

Morawska, L., et al., 2018, ‘Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: how far have they gone?’, *Environment International* 116, pp. 286-299.

PurpleAir, 2019, 'PurpleAir: Real time air quality monitoring', PurpleAir (https://www2.purpleair.com/).

Ripoll, A., et al., 2019, 'Testing the performance of sensors for ozone pollution monitoring in a citizen science approach', *Science of the Total Environment* 651, pp. 1166-1179.

RIVM, 2018, 'RIVM Fireworks experiment', National Institute for Public Health and the Environment, Netherlands (https://www.samenmetenaanluchtkwaliteit.nl/vuurwerkexperiment-20172018).

RIVM, 2019, 'Samen Meten', National Institute for Public Health and the Environment, Netherlands (https://samenmeten.rivm.nl/dataportaal-v1.5/).

RIVM, 2020, 'RIVM fireworks experiment 2018-2019, National Institute for Public Health and Environment, Netherlands (https://www.samenmetenaanluchtkwaliteit.nl/vuurwerkexperiment-2018-2019 and https://www.samenmetenaanluchtkwaliteit.nl/vuurwerkexperiment-2019-2020).

Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2018, *Luftgütemessdaten — Jahresbericht 2018*, Senatsverwaltung für Umwelt, Verkehr und Klimaschutz.

Sensor.Community, 2020, 'Help us to grow the community, by spreading the word!' (https://sensor.community/).

SEPA, 2019, 'Clear the Air', Air Quality in Scotland — Scottish Environment Protection Agency (http://cleartheair.scottishairquality.scot/citizen-science).

Spinelle, L., et al., 2017a, *Evaluation of low-cost sensors for air pollution monitoring — Effects of interfering compounds and meteorological conditions*, JRC Technical Report, Publications Office of the European Union, Luxembourg.

Spinelle, L., et al., 2017b, 'Field calibration of a cluster of low-cost commercially available sensors for air quality monitoring. Part B: NO, CO and CO_2', *Sensors Actuators B Chemical* 238, pp. 706-715.

Szulczynski, B. and Gebicki, J., 2017, 'Currently commercially available chemical sensors employed for detection of volatile organic compounds in outdoor and indoor air', *Environments*, pp. 1-15.

Volten, H., et al., 2018, 'Enhancing national environmental monitoring through local citizen science', in: Hecker, S. et al. (eds), *Citizien science — Innovation in open science, society and policy*, UCL Press, London.

Wang, Y., et al., 2015, 'Laboratory evaluation and calibration of three low cost particle sensors for particulate matter measurement', *Aerosol Science and Technology* 49(11), pp. 1063-1077.

Wei, P., et al., 2018, 'Impact analysis of temperature and humidity conditions on electrochemical sensor response in ambient air quality monitoring', *Sensors* 18(2), p. 59.

Wesseling, J., et al., 2019, 'Development and implementation of a platform for public information on air quality, sensor measurements, and citizen science', *Atmosphere* 10(8), p. 445.

Wesseling, J., 2019, *Results of SDS-11 sensors in Amsterdam during 2018*, Concept paper April 2019, National Institute for Health and Welfare.

WHO, 2006, *WHO air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide*, World Health Organization, Geneva.

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