Community in Action

A COMPREHENSIVE GUIDEBOOK ON AIR QUALITY SENSORS

South Coast AQMD

STi Sonoma Technology

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A Comprehensive Guidebook on Air Quality Sensors

April 2021

Published by South Coast Air Quality Management District
21865 Copley Drive
Diamond Bar, CA 91765

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Citation

Polidori A., Papapostolou V., Collier-Oxandale A., Hafner H., and Blakey T. (2021) Community in Action: A Comprehensive Guidebook on Air Quality Sensors. April.
Available on the South Coast AQMD's AQ-SPEC website:
http://www.aqmd.gov/aq-spec/special-projects/star-grant

Acknowledgments

The Authors (Dr. Andrea Polidori, Contact Principal Investigator; Dr. Vasileios Papapostolou, Project Lead; and, Dr. Ashley Collier-Oxandale, Project Coordinator) would like to thank the following Individuals, Agency partners, and Community Groups and Organizations for their valuable contributions to the project and the development of the Guidebook.

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- Dr. Yifang Zhu and students; Fielding School of Public Health, University of California, Los Angeles (UCLA)

Project Support

- AQ-SPEC staff (Berj Der Boghossian, Dr. Brandon Feenstra, Dr. Michelle Kuang, Randy Lam, Dr. Wilton Mui), South Coast AQMD

Internal and External Agency Partners

- Information Management, South Coast AQMD
- Bay Area AQMD
- San Luis Obispo County APCD
- Santa Barbara County APCD

Communities and Other Partners

- Asian Health Services, Oakland, CA
- Asian Pacific Environmental Network, Richmond, CA
- Comite Civico del Valle, Inc, Imperial County, CA
- Leisure World Club, Seal Beach, CA
- Mazama Science, Seattle, WA
- Pioneer Valley High School, Santa Maria, CA
- Roberts Environmental Center at Claremont McKenna College, Claremont, CA
- Special Service for Groups/Asian Pacific Islander Forward Movement, San Gabriel Valley, CA
- Sycamore Heights Community Action Group, Riverside, CA
- South Gate Community Environmental Health Assessment Team, Los Angeles, CA
- Temescal Valley, Riverside, CA
- University Village Apartments, UCLA, CA

Contents

Glossary

Aerosols Small solid particles or liquid droplets suspended in air

AQI Air quality index, created by EPA

AQ-SPEC The South Coast AQMD's Air Quality Sensor Performance Evaluation Center

BAAQMD Bay Area Air Quality Management District

BAM Beta attenuation monitor, a federal regulatory-grade scientific instrument

BTEX compounds Benzene, toluene, ethylbenzene, and xylenes

CAA Clean Air Act

CAP Criteria air pollutant

CEN European Committee for Standardization

CH_4 Methane

CO Carbon monoxide

CO_2 Carbon dioxide

COPD Chronic obstructive pulmonary disease

DERA Diesel Emissions Reduction Act

EPA U.S. Environmental Protection Agency

GHGs Greenhouse gases

HAPs Hazardous air pollutants

HI-Vog Hawai'i Island Volcanic Smog Sensor Network

H_2S Hydrogen sulfide

HVAC Heating, ventilating, and air conditioning

JRC Joint Research Center, European Commission's science and knowledge service

MAE Mean absolute error

MAPE Mean absolute percent error

MEP People's Republic of China's Ministry of Environmental Protection

NAAQS National Ambient Air Quality Standards

NextGenSS Putting Next Generation Sensors and Scientists in Practice to Reduce Wood Smoke in a Highly Impacted, Multicultural Rural Setting

NGSS Next Generation Science Standards

NH_3 Ammonia

NO Nitric oxide

NO_2 Nitrogen dioxide

NOx Oxides of nitrogen

O_3 Ozone

OEM Original equipment manufacturer

ORD U.S. EPA Office of Research and Development

PAQ Map Pittsburgh Air Quality Map

Pb Lead

PERC Perchloroethylene

POM Personal ozone monitor

PM Particulate matter

PM_{10} Particles less than 10 microns in diameter (coarse particles)

$PM_{2.5}$ Particles less than 2.5 microns in diameter (fine particles)

QAPP Quality Assurance Project Plan

QA/QC Quality assurance/quality control

RETIGO EPA's Real Time Geospatial Data Viewer

RMSE Root-mean-square error

SO_2 Sulfur dioxide

South Coast AQMD South Coast Air Quality Management District

SPEAR initiative Sensor Performance Evaluation and Application Research
STAR program EPA's Science to Achieve Results program

STEM Science, technology, engineering, and math

SVOCs Semivolatile organic compounds

UCLA University of California, Los Angeles

UW University of Washington

VOC Volatile organic compounds

Vog Volcanic smog

Executive Summary

In 2016, the U.S. Environmental Protection Agency awarded the South Coast Air Quality Management District (South Coast AQMD) with a Science to Achieve Results (STAR) grant to work on a project entitled Engage, Educate, and Empower California Communities on the Use and Applications of "Low-Cost" Air Monitoring Sensors. The Air Quality Sensor Performance Evaluation Center (AQ-SPEC) at the South Coast AQMD served as the lead group for the grant. Collaborating principal investigators included Sonoma Technology and UCLA Fielding School of Public Health. The study was intended to provide California communities with the knowledge necessary to appropriately select, use, and maintain low-cost air pollution sensors and correctly interpret sensor data. This work was guided by the following four specific aims:

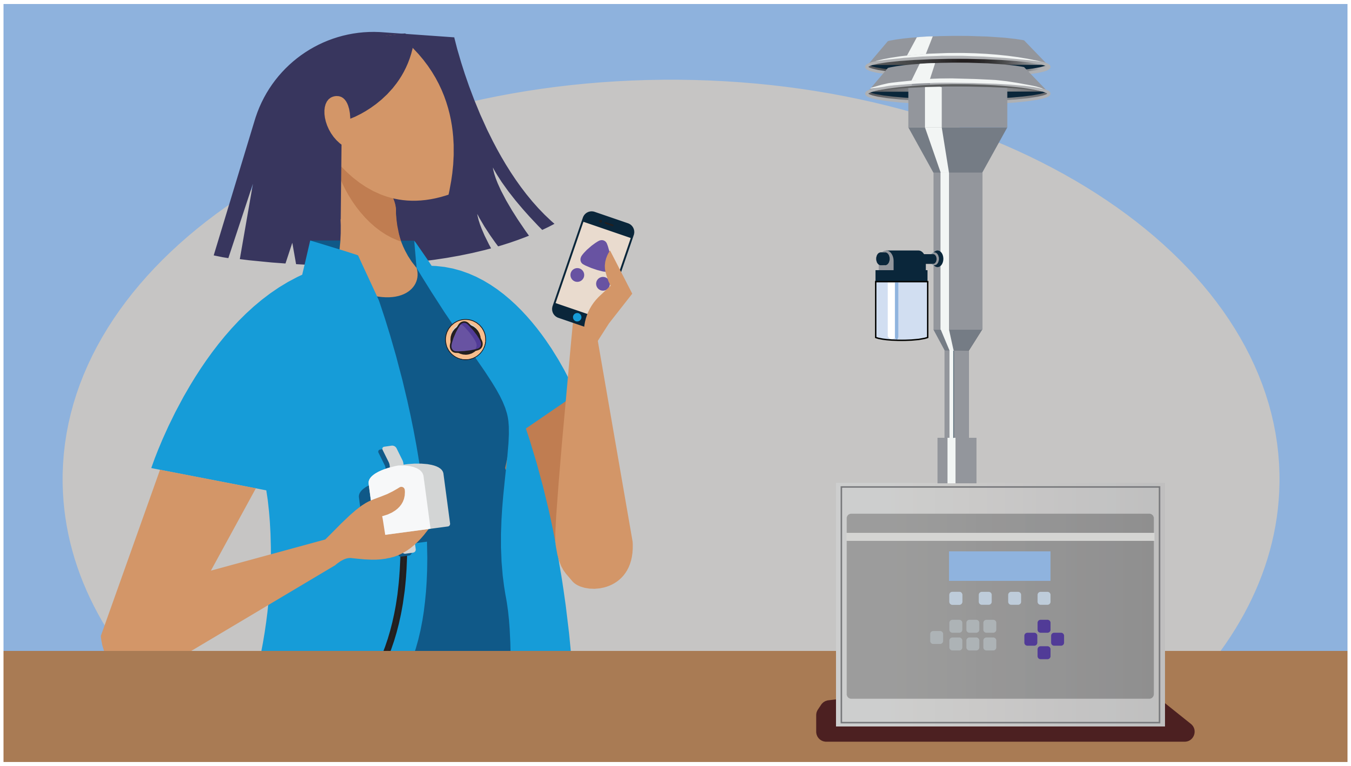
1. Develop new methodologies to educate and engage communities on the use and applications of low-cost sensors;
2. Conduct testing to characterize the performance of commercially available low-cost sensors and identify candidates for field deployment;
3. Deploy the selected sensors in California communities, and interpret the collected data; and
4. Communicate the lessons learned to the public through a series of outreach activities.

Throughout the project, regular public meetings and other outreach activities were conducted to educate the public on the capabilities of commercially available low-cost sensors and their potential applications and limitations. Many sensors were evaluated in the field and in the laboratory according to standard protocols developed by AQ-SPEC. Sensors were selected, and sensor networks were developed in 14 California communities. Workshops were held periodically to discuss participants' experiences and interpret the data collected. This work led to and shaped the development of a comprehensive Educational Toolkit, which includes resources used during this project (e.g., a sensor installation guide based on feedback provided by community participants), and resources developed in response to specific needs identified during the project (e.g., the AirSensor R-package, the DataViewer tool, and other solutions to support sensor data access, processing, analysis, and visualization). This Guidebook is another resource included in the Educational Toolkit, and lessons from this work informed and were reflected in its development.

The Guidebook covers planning (e.g., what to monitor, where to monitor, which sensors to use) and deployment (e.g., how to use and maintain sensors, what factors to consider when taking measurements). It also covers sensor data handling, interpretation, communication, and use. It is intended to build on existing resources and aid community organizations in effectively using low-cost air quality sensors to support citizen science for community monitoring applications. Appropriate use of sensors may enable the public to use sensor data to understand local air quality and take action to reduce pollutant emissions and/or exposure to air pollution. Appropriate use of sensors may also help governmental organizations and other policymakers better understand air quality issues at the community level and make better policy decisions to protect the public from the impacts of air pollution.

01 Introduction

This Guidebook is intended to aid community members and community partners in effectively using low-cost sensors. People can use sensor data to understand local air quality and take action to reduce pollutant emissions and exposure to air pollution.



The large BAM 1020 shown here is a federal regulatory-grade scientific instrument used across the country to measure regional air quality.

Smaller, low-cost air sensors include wearable sensors, home-powered sensors, and field sensors with built-in solar power and cellular service.

Background

Manufacturers have begun marketing "low-cost" air monitoring sensors to measure air pollution in real-time.

Low-Cost Sensors

Because of recent technological advancements in electrical engineering and wireless networking, manufacturers have begun marketing "low-cost" air monitoring sensors to measure air pollution in real-time. This type of technology has been evolving rapidly, and there are many types of sensors available to the consumer. These devices, with "low-cost" defined as prices ranging from about $100 to about $2,000, are often one-tenth or even one-hundredth the cost of the more sophisticated federal reference (or federal equivalent) instruments (FRM, FEM) required for regulatory monitoring. Assuming they produce reliable data, low-cost sensors can significantly augment and improve current ambient air monitoring capabilities that predominantly rely on FRM or FEM instruments operating at fixed sites. Given their low-cost, these sensors are becoming an attractive means for local environmental groups and individuals to independently evaluate air quality.

Air Quality Regulations

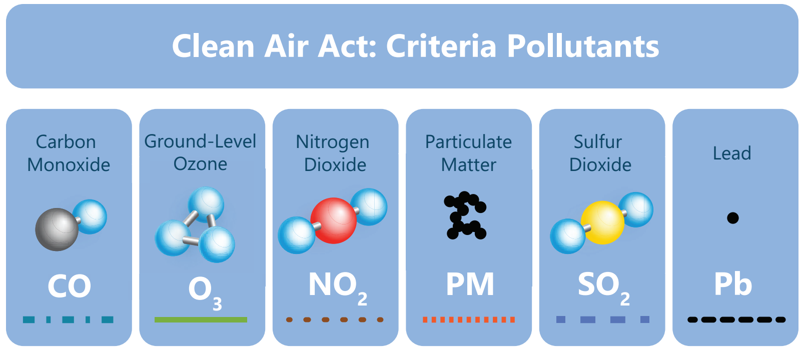
The Clean Air Act (CAA), established in 1970, is the federal law that regulates air emissions from stationary (i.e., fixed emitters of pollutants such as a power plant) and mobile (e.g., cars and trucks) sources. The CAA authorized the U.S. Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS) to protect public health and public welfare and to regulate emissions of hazardous air pollutants. One of the goals of the CAA was to set and achieve NAAQS in every state by 1975 in order to address the public health and welfare risks posed by ubiquitous air pollutants. States were required to develop plans to achieve the NAAQS.

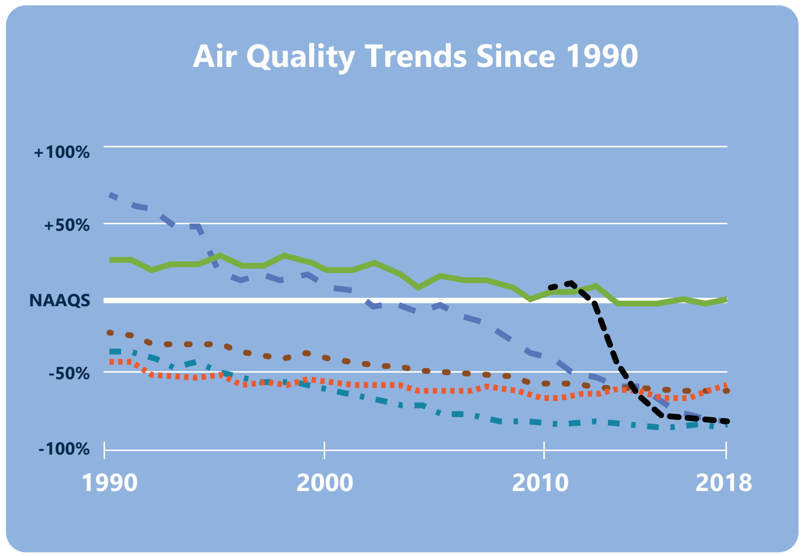
The CAA was amended in 1977 and 1990 primarily to set new goals (and dates) for achieving attainment of NAAQS since many areas of the country had failed to meet the deadlines. The CAA also lays out a schedule that EPA must follow to regularly review the NAAQS and new health and exposure science findings to assess whether changes are warranted.

Data from FRM or FEM instruments, operated by state, local, and tribal air agencies, are used by EPA to assess attainment of the NAAQS; this network is relatively sparse and does not cover all communities. To date, low-cost sensors are not of sufficient quality to meet FEM or FRM standards. However, low-cost sensors can be deployed to enhance understanding of air pollution at a community level.

Community-Based Air Quality Work

Individuals and communities have been measuring air pollution since the mid-1990s. For example, the "Bucket Brigade"[1] measured hydrocarbons, such as benzene, using five-gallon buckets modified to collect air samples along with community observations. These measurements have led to verification testing by government entities and, in some cases, action to reduce pollutants. Historically, community-based efforts have led to a variety of benefits,[2] including increased awareness of air quality issues, new data and forecasts, support for equipment replacement programs, new monitoring sites, and procedures to help the public reduce their exposure to certain pollutants. These measurements are still in use as a method to gain attention about air toxics emissions or odors at a local level.





Criteria pollutant concentrations have declined relative to the most recent NAAQS since 1990.[3] Although concentrations have declined nationally, there are still air districts that have not attained certain NAAQS.

Benefits of Community-Based Science

As individuals use sensor technology, they become more educated and informed about specific air quality issues in their community. This knowledge has the potential to empower them to develop community-based strategies to reduce air pollution exposures to protect their health.

We use the terms community science or community scientist throughout this document because they are inclusive terms. Citizen science or citizen scientists are also commonly accepted terms; however, the word citizen can be misinterpreted to mean U.S. citizen instead of resident or community member.

Given the recent emergence of low-cost sensing, there is a need to create new methodologies for engaging communities and individuals in the appropriate use of air pollution sensors, and to develop a better understanding of how communities respond to different types of data output, data interpretation, and data sharing.

EPA has developed numerous resources for communities, such as the Air Sensor Toolbox,[4] which includes information about how to use air sensors, understand sensor readings, sensor performance evaluations, and sensor loan programs for communities. The California Air Resources Board has developed Community Science Resources.[5] The South Coast Air Quality Management District (South Coast AQMD)'s Air Quality Sensor Performance Evaluation Center, AQ-SPEC,[6] provides information about the performance of low-cost sensors. Other sources for guidance on best practices include citizenscience.gov[7] and the following resources:

- Air Sensor Guidebook[8]
- Low-Cost Air Quality Monitoring Tools: From Research to Practice (A Workshop Summary)[9]
- Air Sensor Study Design: Details Matter[10]
- Tracking California: Guidebook for Developing a Community Air Monitoring Network[11]

Educational resources have been developed by air quality scientists and educators to reach out to interested students and the public. For example, Kids Making Sense®[12] unites STEM (Science, Technology, Engineering, and Math) education and NGSS (Next Generation Science Standards) with an air sensing system to teach students and other community members about air pollution using project-based learning and hands-on activities. EPA has developed educational material such as how to build a particle sensor.[13] The Air Quality InQuiry Program,[14] developed by university researchers, also includes lessons and activities that support project-based learning using sensors. Many local air quality agencies have developed, or are developing, educational material about low-cost sensors, sensor loan programs, and other resources.

EPA STAR Grant

EPA's Science to Achieve Results (STAR) program offers grants and graduate fellowships to scientists for targeted research across several disciplines. STAR research is funded through a competitive solicitation process derived from the EPA Office of Research and Development's Strategic Plan and research plans for specific topics in cooperation with other parts of the Agency. Research is related to EPA's central mission: to protect human health and the environment.

In 2016, the EPA awarded South Coast AQMD and partners with a STAR grant for the project titled *Engage, Educate, and Empower California Communities on the Use and Applications of "Low-Cost" Air Monitoring Sensors*. AQ-SPEC served as the lead for the grant. Collaborating principal investigators included Sonoma Technology and UCLA Fielding School of Public Health.

The study was intended to provide local California communities with the knowledge necessary to appropriately select, use, and maintain low-cost air pollution sensors and to correctly interpret sensor data. The team specifically targeted communities in environmental justice (EJ) areas and near specific sources of air pollution. It is important to note that South Coast AQMD found that "many Basin residents live, work, and play in areas with poorer air quality than others, and are often more economically disadvantaged…" (South Coast AQMD, March 2017 - 2016 AQMP Socioeconomic Report).[15]

Regular public meetings and other outreach activities were conducted to educate the public on the capabilities of commercially available low-cost sensors and their potential applications and limitations. The end points of the research will help governmental organizations and other policy makers better understand air quality issues at the community level and make better policy decisions to protect the public from the impacts of air pollution.

The EPA also awarded grants in 2016 to five other research organizations to work with local communities to explore data quality, durability, and uses of low-cost air pollution sensor technology. These research projects explored how scientific data can be effectively gathered and used by communities to learn about local air quality:

Shared Air/Shared Action (SA2): Community Empowerment through Low-Cost Air Pollution Monitoring led by Kansas State University. The research team engaged with four local community organizations working to improve air quality for citizens of Chicago. The research hypothesis was that people will become more engaged in and with their environment if they are provided with relevant scientific and technical tools, including low-cost portable sensors and appropriate technical assistance. Air pollution monitoring was conducted in four diverse communities, using low-cost portable air pollution sensors. Seminar recordings about lessons learned from this study are available.[19]

Learn More

EPA STAR grant program overview[16]

South Coast AQMD STAR grant overview[17]

South Coast AQMD AQ-SPEC[6]

Environmental justice areas in California[18]

STAR Grant

This sensor guidebook was made possible by an EPA STAR Grant.

The Hawai'i Island Volcanic Smog Sensor Network (HI-Vog): Tracking air quality and community engagement near a major emissions hotspot, led by the Massachusetts Institute of Technology. This project included the assessment of distributed air quality networks based on portable low-cost sensors to measure volcanic smog (vog), comprised of SO_2 and particulate matter, with high spatial and temporal resolution. The majority of the sampling sites were integrated into the Kohala Center's Hawaii Island School Garden Network, which allowed vog measurements to be used as part of the school curriculum and thus enhanced community education and engagement with the air quality data. Real-time data were available to the community through the network website, as well as touchscreen interfaces at community hubs implemented at health centers throughout the island.

Putting Next Generation Sensors and Scientists in Practice to Reduce Wood Smoke in a Highly Impacted, Multicultural Rural Setting (NextGenSS) led by the University of Washington (UW). UW air pollution researchers partnered with Heritage University faculty whose students represent the community's population of predominately Yakama Nation and Latino immigrant families. The project enhanced the EnvironMentors program, which pairs upper-level undergraduates with high school students. Training and guidance equipped students to formulate and test hypotheses on their community's wood smoke exposure using low-cost Alphasense PM sensors. These projects addressed spatial variability, associations with cardiopulmonary health, and impacts of interventions. Students disseminated the findings to their families, elders, and other community members. Evaluation included student experience using sensors, as well as field reliability and validation testing by comparison to a local fixed site and validated field measurement data.

Monitoring the Air in Our Community: Engaging Citizens in Research conducted by Research Triangle Institute, Groundwork Denver, and National Jewish Health. This project explored how community members use low-cost sensors to understand the air quality in their neighborhoods and how their personal exposure to pollutants empowers them to take actions to protect their health. The study identified audience-specific air quality data presentation needs and preferences to support understanding of and interpretation of data. The project also evaluated the effectiveness of different ways of supporting behavior changes to minimize exposure to indoor and outdoor air pollutants. The study focused on an environmental justice community north of downtown Denver. The low-cost sensors deployed were the RTI MicroPEM™ for $PM_{2.5}$ and the Cairpol NO_2 CairClip.

Democratization of Measurement and Modeling Tools for Community Action on Air Quality, and Improved Spatial Resolution of Air Pollutant Concentrations conducted by Carnegie Mellon University. Improving air quality and human health, particularly in environmental justice communities, motivated the University to use distributed air quality monitoring with low-cost sensors and air quality modeling to support community efforts to reduce pollution exposure. Portable bi-pollutant ($PM_{2.5}$/gas) monitors and stationary multipollutant ($PM_{2.5}$, four criteria gases, VOCs) monitors were developed for this study. The reliability of these monitors was tested under a variety of environmental conditions. User surveys and input from a community advisory board informed sensor design and data output. Ambient data with distributed monitors were incorporated into a new, publicly available Pittsburgh Air Quality Map (PAQMap), made with community input.

Similar Efforts

In addition to the STAR grant, recent California legislation and air district rules provide funding for community air quality monitoring or community-based science, including California Assembly Bill (AB) 617,[20] South Coast AQMD Rule 1180,[21] and Bay Area Air Quality Management District Rule 12-15.[22] Other state and local agencies and non-profit groups have been developing resources as well. For example, see the Clean Air Carolina AirKeepers program,[23] the Oregon Department of Environmental Quality,[24] the California Air Resources Board,[25] and the Denver Department of Public Health and Environment's Love My Air program.[26]

Sensors (, ,) can be used to "fill in the gaps" in an air monitoring network (,) to potentially better understand how pollutant concentrations vary locally.

Guidebook Purpose, Content, and User Roadmap

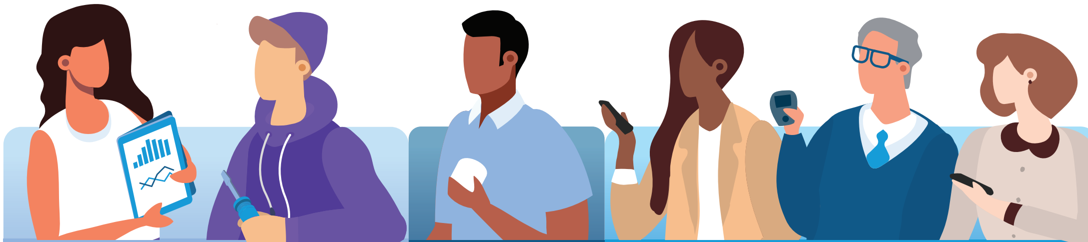
The guidebook covers planning (e.g., what to monitor, where to monitor, which sensors to use) and deployment (e.g., how to use and maintain sensors, what factors to consider when taking measurements). It also covers data handling, interpretation, communication, and use.

Table 1-1 provides a roadmap of the guidebook for users with different responsibilities and interests. Users are not expected to read this document from start to finish – we recommend accessing individual sections on an as-needed basis.

Guidebook Highlights

- Chapter 2, pages 2-20 and 2-21 – Guide to Choosing a Sensor
- Chapter 3, page 3-9 – Guide to Sources and Pollutants
- Chapter 5, page 5-10 – Sharing Your Results and Discussing Your Project

Table 1-1. A roadmap of the guidebook for users with different responsibilities and interests.



Chapters	Organizer Community organizer or project lead for an air quality sensor project	Participant Participant using a sensor in a community led project	Individual Individual member of the public using a sensor	Partner (Academic, Industry, Government Agency) New to using sensors	 New to air quality monitoring	 New to community-based research
2 Learn Valuable information about air quality	●	●	●		●	
3 Plan Plan a successful project	●		●	●	●	●
4 Deploy Deploy and maintain your sensors	●	●	●	●	●	●
5 Act Move from results to action	●	●	●	●	●	●
Appendices						
A Air Quality Index	●	●	●		●	
B FAQs	●		●	●	●	●
C Purple Air Sensor	●	●	●	●	●	
D Data Analysis	●		●	●	●	
E Infographic	●					●
F Install Template				●		
G Project Template	●					●
H Log Notes	●	●	●		●	
I Liability Form	●			●	●	●
J Agency Contacts	●					●
K Sensor Tests	●			●		
L DataViewer	●	●		●	●	●
M Community Reports	●	●		●		●

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02 Understanding Air Quality and Monitoring

Air quality is important because it affects our health and the environment. Poor air quality is linked to a range of health and environmental problems.

Los Angeles on a clear day

Air quality is often displayed on a color scale.

The term air quality relates to the amount of pollution in the air.

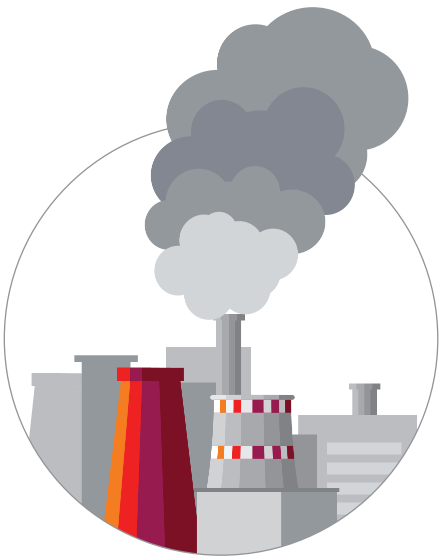
Good air quality means there is less air pollution.

Poor air quality means there is more air pollution.

Air pollution is a complex mixture of chemical compounds which are caused by human activity, such as cars and power plants, as well as by natural events such as wildfires, volcanoes, and lightning. Pollutants of concern are present as gases or particles.

Air pollution is caused by both human activity as well as natural events.

Cars, Buses, Trucks, Planes, Trains

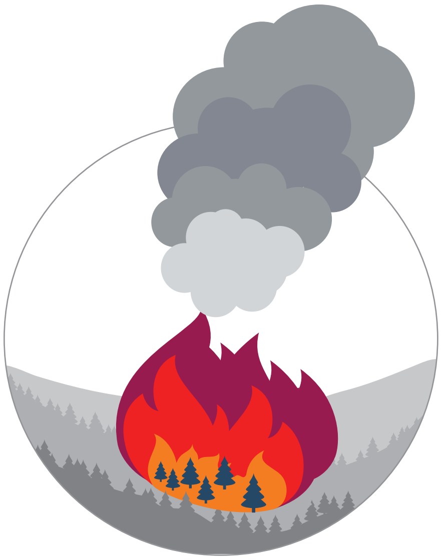


Power Plants, Factories, Incinerators

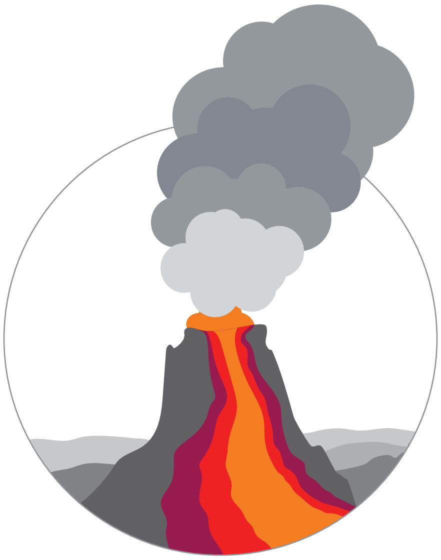
Los Angeles
on a smoggy day

Particle pollution is a key contributor to reduced visual air quality, also called visibility, haze, or smog. However, existing air quality standards for particle pollution are based on potential health impacts, not on visual air quality. Visual perception of air quality is subjective, and different individuals might categorize the pollution on the same day differently. Visual perception studies[1] of air quality consistently show that improvements to reduce the number of poor visibility days and increase the number of excellent visibility days are both important.

The two photos above show the same area of Los Angeles on days with good and poor air quality.



Wildfires, Prescribed Burns, Residential Wood Burning



Natural Emissions such as Volcanoes, Hot Springs, Marshes

Particle Pollution

Particle pollution is a general term for a mixture of solid particles and liquid droplets in the air.

Some particles are large enough to be seen as dust or dirt; others are so small that they can only be detected with an electron microscope. Particles are both directly emitted into the air and can be formed in the air from other pollutants.

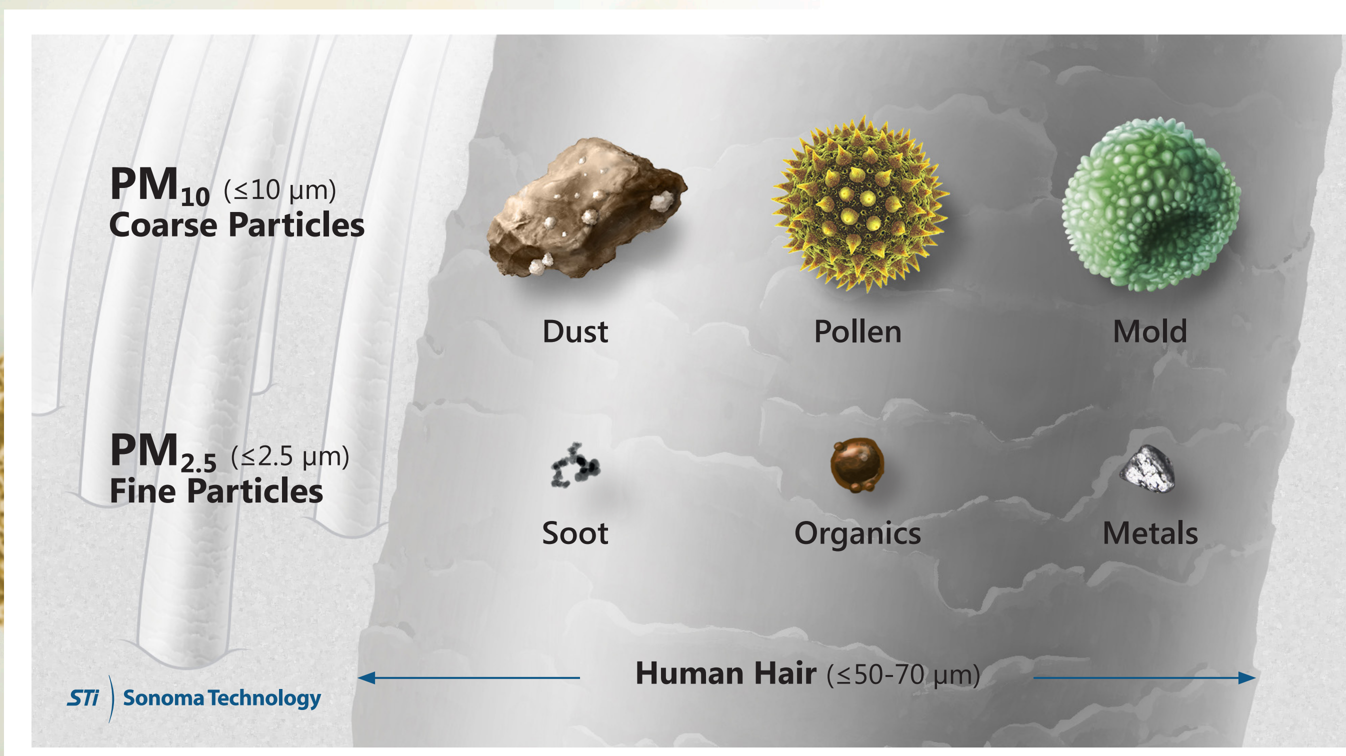
Particle Size

Particles in the air are referred to as particulate matter, or PM. Another term used in atmospheric science is aerosols which are small solid particles or liquid droplets suspended in air. Particles range in size and composition. Most commonly, measurements focus on two size ranges – particles less than 10 microns in diameter (coarse particles, PM_{10}) [or micrometers (µm) in aerodynamic diameter] and particles less than 2.5 microns in diameter (fine particles, $PM_{2.5}$) [or, micrometers (µm) in aerodynamic diameter]. Particle size refers to particle diameter (i.e., spherical particles) or "equivalent" diameter for odd-shaped particles. The fine and coarse particles have different sources, properties, and effects. **Figure 2-1** puts particle size in perspective.

Linking Particles and Health Effects

Health research has primarily focused on PM mass because those measurements were the most common data available with a long measurement history of sampling conducted at many sites across the country. PM has been shown to cause premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma,

Figure 2-1. *$PM_{2.5}$ and PM_{10} particle sizes compared to a human hair.*



decreased lung function, and increased respiratory symptoms, such as irritation of the airways, coughing, or difficulty breathing. Particle size is directly linked to the potential for causing respiratory problems. Larger particles impact the upper respiratory tract, while smaller particles can enter the lower respiratory tract and even enter the bloodstream (**Figure 2-2**).

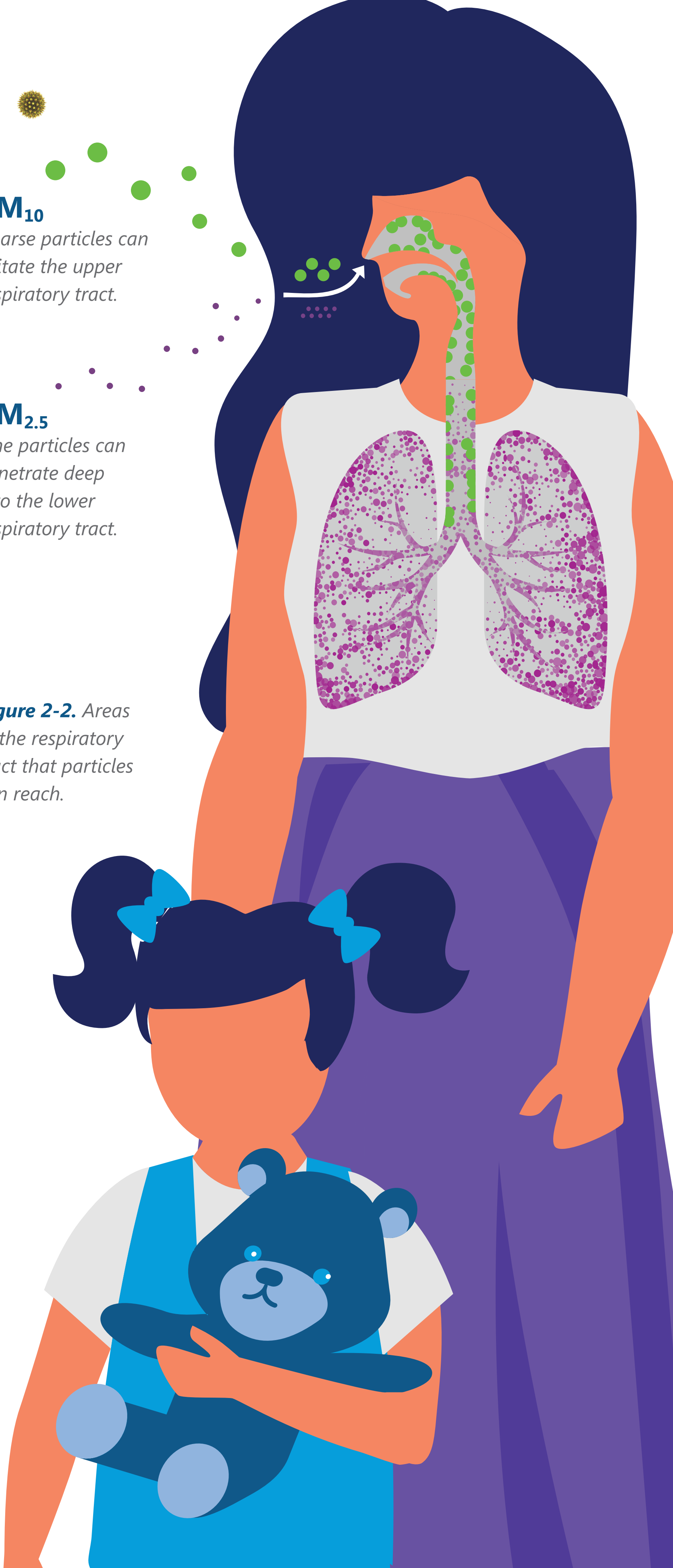


Figure 2-2. *Areas of the respiratory tract that particles can reach.*

The U.S. Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) to protect human health (see Appendix A). The 24-hr standards for $PM_{2.5}$ and PM_{10} are shown in **Table 2-1**. These standards stipulate that the average PM mass concentration in the outdoor air over a 24-hour time-period should not exceed a certain threshold, based on the findings of health and risk assessments. More details about the NAAQS are available on the EPA website.[2]

Table 2-1. *NAAQS (2012) for $PM_{2.5}$ and PM_{10}.*

Pollutant	Averaging time	Level
$PM_{2.5}$	24 hours	35 µg/m^3
PM_{10}	24 hours	150 µg/m^3

There are currently no EPA standards for $PM_{2.5}$ and PM_{10} at shorter time periods such as 1-minute or 1-hour. EPA reports the air quality index (AQI), based on several criteria pollutants, to inform the public about how clean or polluted the air is and what associated health effects might be a concern (see Appendix A).

WORLD HEALTH ORGANIZATION ESTIMATED WORLDWIDE DEATHS FROM AMBIENT AIR POLLUTION IN 2016

16% of lung cancer deaths

25% of COPD deaths

17% of ischemic heart disease and strokes

26% of respiratory infection deaths

People with compromised health and vulnerable populations (i.e., children, pregnant women, and the elderly) are more susceptible to the effects of air pollution.

Worldwide, the World Health Organization[4] estimated that in 2016, ambient air pollution caused about 16% of lung cancer deaths, 25% of chronic obstructive pulmonary disease (COPD) deaths, about 17% of ischemic heart disease and stroke, and about 26% of respiratory infection deaths. A 2019 paper published in the European Heart Journal[3] estimated that air pollution could be causing double the number of excess deaths a year in Europe than had been estimated previously. The researchers found that air pollution caused an estimated 8.8 million extra deaths globally. Similarly, a 2018 study[5] estimated that 8.9 million deaths were associated with long-term exposure to outdoor $PM_{2.5}$.

8.8 million extra deaths globally
European Heart Journal, 2019[3]

For Further Reading

If you would like more information on the overall burden of PM on human health nationally and globally, check out the following:

HealthData.org Global Burden of Disease Study 2017.[6]

World Health Organization Ambient Air Pollution.[4]

If you would like more information on the different ways in which PM exposure impacts human health, check out the following:

An association between air pollution and mortality in six U.S. cities.[7]

Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution.[8]

The effect of air pollution on lung development from 10 to 18 years of age.[9]






Sources of particle pollution include, clockwise from upper left, wildfires, vehicle exhaust, geothermal emissions, pollen, brake wear, and resuspended dust.

Sources Contributing to Particle Pollution Outdoors

Particles can be directly emitted into the air, formed in the air from other pollutants, or created through some combination of both processes. Directly emitted (or primary) particles include suspended dust, sea salt, organic carbon (e.g., hydrocarbons), elemental carbon (e.g., graphite), and metals from combustion. Directly emitted gases that form particles in the atmosphere include sulfur dioxide (SO_2, which forms sulfates), nitrogen oxides (NO_x, which forms nitrates), ammonia (NH_3, which forms ammonium compounds), and volatile organic compounds (VOCs, which are organic carbon compounds, that can become a gas at normal indoor and outdoor temperatures).

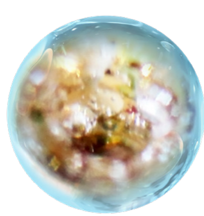
Fine particles are emitted primarily by combustion—of coal, oil, gasoline, diesel, and wood—and formed through gas-to-particle conversion of NO_x, SO_2, and VOCs under the influence of sunlight. These particles can stay in the air for days to weeks and travel long distances.

The larger particles (also called coarse particles) are emitted into the air by resuspension of dust, biological sources (pollen, spores), construction, and ocean spray. Coarse particles are more readily removed from the air and thus are present from minutes to days and typically do not travel far.

Particles of any size stay in the air until one of three things happen: sedimentation, condensation, or coagulation.

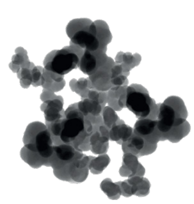
Sedimentation

Particles settle on a surface



Condensation

Water or other gases collect on particles to form larger particles



Coagulation

Particles collide and form larger particles

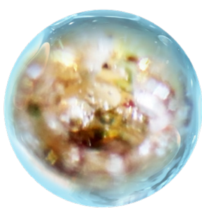
Complexity of Particles

The chemical make-up of particle pollution is complex and varies with particle size (see **Table 2-2**). Soot, organic compounds, and trace metals tend to form fine particles. Sea salt components typically occur in coarse particles. Windblown and fugitive dust are also found mainly in coarse particles. Nitrates may occur in both fine and coarse particles.

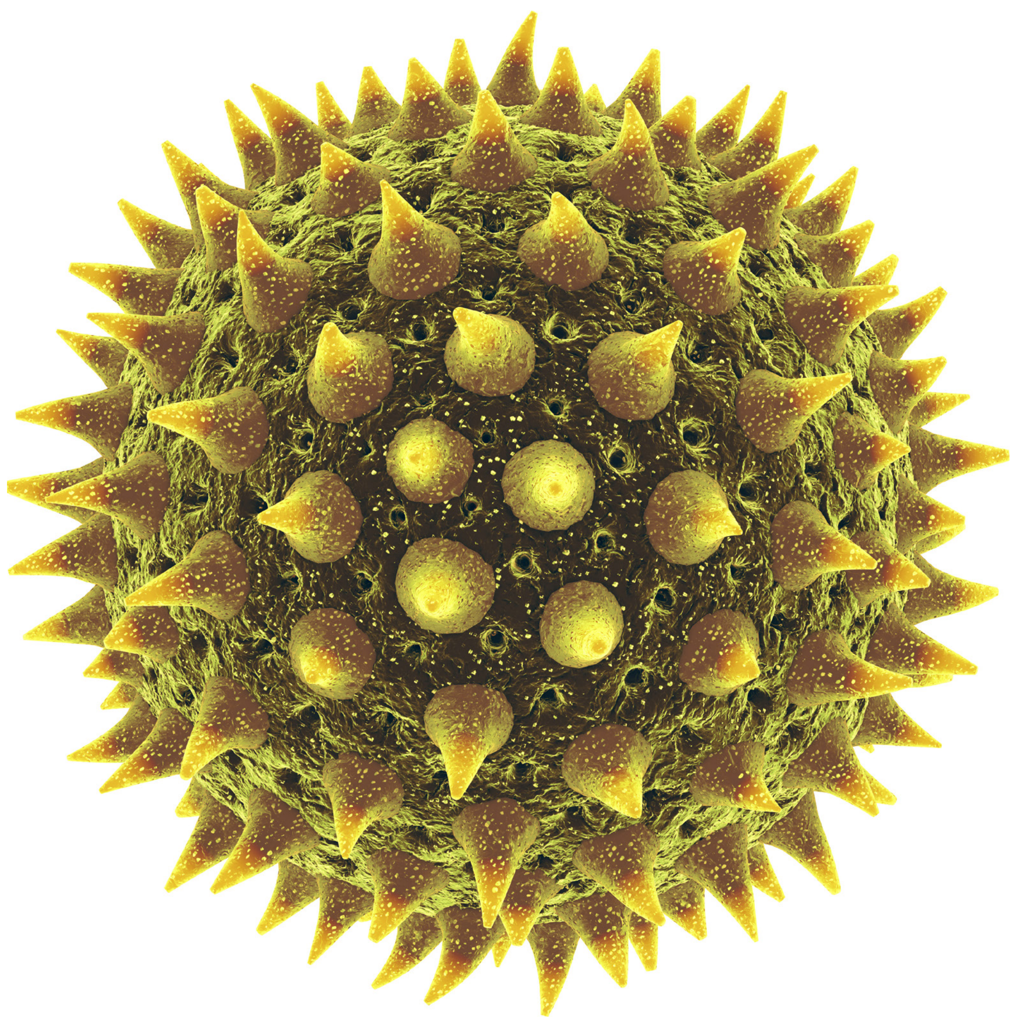
Particles may be oddly shaped, of different colors, or be dry or wet. Size, shape, chemical composition, color, and other factors affect how particles are measured, how far they travel, and how they impact human health. The chemical composition of particles helps researchers understand the sources contributing to particle pollution.

Light scattering and absorption by particles in a sensor are impacted by the difference in particle composition. For example, organic materials (e.g., pollen) tend to absorb a higher proportion of light compared to inorganic materials (e.g., metals, dust). In this case, the optical sensor would report a higher concentration[10] when measuring organic-containing particles than inorganic particles. One implication of this is the importance of performing collocation and calibration in the vicinity of the project in order to expose the sensors to the particle composition expected during the project.

Because of the complexity of particles, it is challenging to measure them in ambient air.



Particles can be dry, slightly wet, or dissolved/suspended in liquid droplets.



Particles often have complex shapes, like this illustration of a pollen spore, even though they are sometimes depicted as being perfect spheres.

Table 2-2. *Summary of characteristics of fine and coarse particulate matter (adapted from Seinfeld and Pandis, 1998).*[11]

$PM_{2.5}$ Fine Particles	PM_{10} Coarse Particles
Chemical Process *How the particles are formed*	
Reaction, nucleation, condensation, coagulation, cloud/fog processing	Suspension of dust or sea salt, mechanical process
Sources *Where the particles come from*	
Coal Combustion, Gasoline Combustion, Diesel Combustion, Wood Combustion, Motor Vehicles, Industry, Fires, Gas to Particle Conversion	Industrial Dust, Farming Dust, Mining Dust, Unpaved Roads, Biological Sources, Construction/ Demolition, Ocean Spray, Road Salt
Composition *What the particles are made of*	
Sulfates and Nitrates, Elemental Carbon, Other Organics, Water, Metals	Crustal Elements, Salt, Pollen, Mold, Plant and Animal Debris
Formation *When the particles are formed*	
Primary (directly emitted) and Secondary (formed in the atmosphere)	Primary (directly emitted)
Atmospheric Lifetime *How long the particles stay in the air*	
Days to Weeks	Minutes to Days
Travel Distance *How far the particles travel*	
100 to 1000+ km (about 60 to over 600 miles)	Generally < 100 km (< about 60 miles)

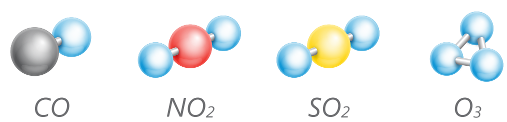
Gas-Phase Pollutants

Gas-phase pollutants refer to compounds in the air that negatively affect human or environmental health.

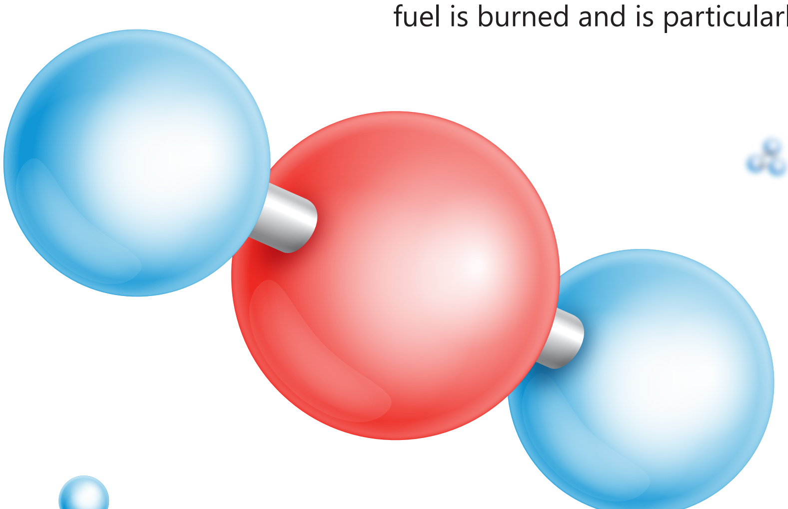
Common gas-phase pollutants that may be of concern to you or your community are organized into the following categories: criteria pollutants, hazardous air pollutants (HAPs)/air toxics, greenhouse gases (GHGs), and radon.

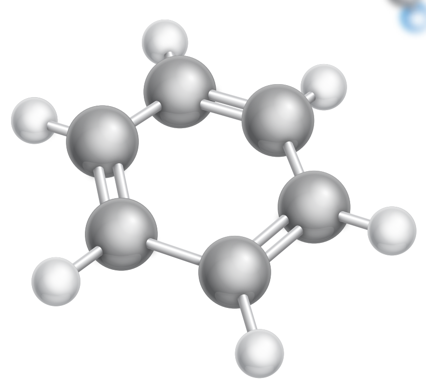
Criteria Pollutants

Four of the six criteria pollutants designated by EPA are gaseous pollutants that are currently regulated through the Clean Air Act:



carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ground-level ozone (O_3). CO is released when a carbon-containing fuel is burned and is particularly dangerous to human health if large amounts are allowed to accumulate indoors where it may be inhaled. NO_2 is typically generated when fuel is burned (for example, diesel trucks). In addition to being a respiratory irritant, NO_2 helps form another harmful pollutant – ground-level ozone. SO_2 is released when materials containing sulfur or sulfur itself is burned, and in addition to being a danger to human health, SO_2 is key to forming acid rain in the environment. Finally, ground-level ozone is formed in the air by other compounds (specifically, volatile organic compounds [VOCs] and oxides of nitrogen [NO_x]) interacting in the presence of sunlight. Because it is not directly emitted, ozone is considered a secondary pollutant because it is formed in the atmosphere. While ozone at high altitudes (i.e., 6 to 30 miles above the earth's surface) protects us from harmful ultraviolet radiation, ozone at the ground level, where it can be inhaled, poses a variety of respiratory health risks. An effective way to remember this is that O_3 is "good up high, bad nearby."





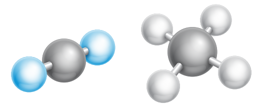
Hazardous Air Pollutants / Air Toxics

There are hundreds of VOCs ranging from naturally occurring to man-made, and from harmless to harmful.

HAPs are compounds that are known to cause serious health effects, such as cancer. There are 187 toxic air pollutants recognized by the EPA, and many of these are gas-phase pollutants. Some of the gases categorized as HAPs include benzene which is found in gasoline and known to cause cancer. All BTEX compounds (i.e., benzene, toluene, ethylbenzene, and xylenes) are considered HAPs and are emitted by vehicles, other industrial sources, and oil and gas extraction or processing activities. Another common HAP is formaldehyde, which may be emitted by a variety of sources from building materials to cigarette smoke and is also formed in the atmosphere through reactions of other VOCs. Perchloroethylene (PERC) is the chemical used by dry cleaners using older processes.

In addition to the gases, metals such as arsenic, mercury, chromium, and lead are HAPs, and these metals are emitted, for example, from metal processing operations. There are also semivolatile organic compounds (SVOCs) such as naphthalene, which is emitted in petroleum refining, fossil fuels and wood combustion. These compounds exist in gas, liquid, or particle form under typical atmospheric conditions, may be present in extremely low concentrations, and are difficult to measure. No single measurement technique can capture all HAPs.

Greenhouse Gases



CO_2 CH_4

Human greenhouse gas emissions include CO_2 and methane.

GHGs are gases that trap and heat the atmosphere. The main GHGs of concern in terms of human emissions are carbon dioxide (CO_2) and methane (CH_4). Neither of these gases pose a direct threat to human health (for example, as a toxin) except in extreme circumstances. For example, at extremely high CO_2 concentrations there is a risk of suffocation, and at high concentrations of methane there is a risk of suffocation as well as explosion. In 2016, roughly 80% of CO_2 emissions in the U.S. were from human activity,[12] and globally it is estimated that more than

60% of methane emissions were from human activity. CO_2 comes primarily from electricity generation, transportation, and industrial sources. Methane comes primarily from natural gas and petroleum systems, ranching/agriculture, and landfills. Additionally, methane is the primary component in natural gas, typically making up ~70-90% of the mixture. Measuring these pollutants assists in addressing climate change.

CO_2 comes primarily from electricity generation, transportation, and industrial sources.

Radon is the leading cause of lung cancer in the U.S. among non-smokers.

Radon

Radon is a naturally occurring, radioactive gas that can seep through the foundation of your home and accumulate to dangerous levels. It is an indoor air pollutant that is not currently regulated. Nonetheless, it is the leading cause of lung cancer in the U.S. among non-smokers and the EPA recommends testing your home. A simple $10-$20 short-term test kit from a hardware or online store can be used to self-test radon. See the U.S. EPA's Citizen's Guide to Radon[13] if you are concerned about this particular airborne pollutant.

Gas-Phase Pollutant Impacts on Human Health

Gases can impact human health. Depending on the pollutant, the concentration, and the length of exposure, gas-phase pollutants can affect our respiratory systems, neurological systems, immune systems, or reproductive health and development. The NAAQS for the four gas-phase criteria pollutants can be found in **Table 2-3**. These standards are based on the findings of health and risk assessment and intended to protect public health.

HAPs are not regulated in the same way as criteria pollutants. EPA is required to develop standards for controlling air toxics emissions from some source categories (a technology-based approach). EPA also must determine whether more health-protective standards are necessary using a risk-based approach. EPA periodically assesses the remaining health risks from each source category to determine whether the control standards protect public health with an ample margin of safety and protect against adverse environmental effects.

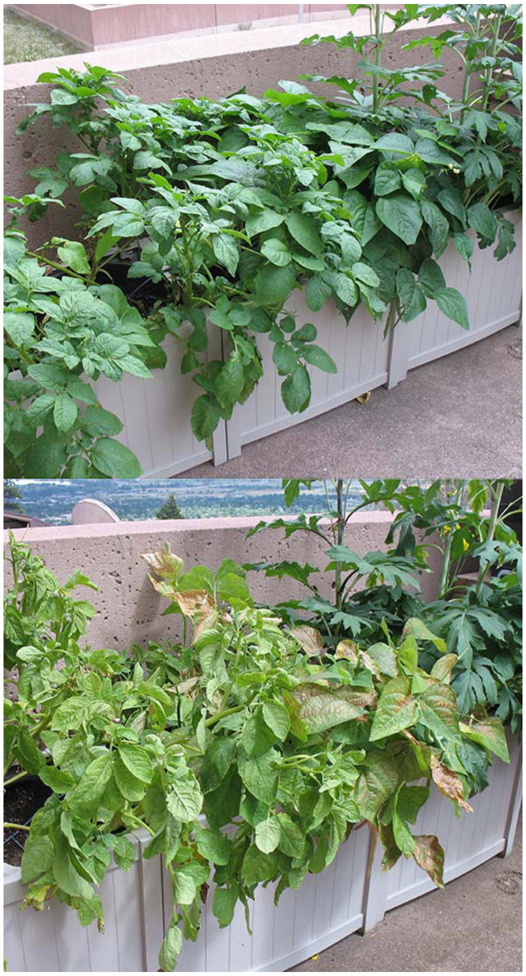
Table 2-3. *Gas-Phase Criteria Pollutants Regulated by the Clean Air Act.*

Pollutant (Year of Last Revision)	Averaging Time	Level
CO (2011)	1 hour 8 hours	35 ppm 9 ppm
NO_2 (2012)	1 hour	100 ppb
SO_2 (2012)	1 hour	75 ppb
O_3 (2015)	8 hours	70 ppb

Impact of Gas-Phase Pollutants on Environmental Health

In addition to hazards to human health, air pollution also damages our environment. As previously mentioned, SO_2 and NO_2 can form acid rain, which can harm ecosystems. While acid deposition can damage trees directly, it more commonly stresses trees by changing the chemical and physical characteristics of the soil. In lakes, acid deposition can kill fish and other aquatic life. Ground-level ozone also can damage vegetation and adversely impact the growth of plants and trees. This damage can result in crop loss in agricultural areas. Indirectly, the increase of GHGs in the air exacerbates the negative environmental impacts of climate change. Visibility is reduced by particles in the air that scatter and absorb light.

EPA has set secondary standards[2] to provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings. EPA also has the Regional Haze Rule[14] that is focused on improving visibility in protected areas such as national parks.



Above: *Effects of acid rain, woods, Jizera Mountains, Czech Republic. Credit: commons.wikimedia.org.*[15]

Left: *Before and after photographs of ozone damage on potato and bean plants. Credit: Danica Lombardozzi, National Center for Atmosperic Research.*[16]

Upper left: *Ozone damage to a leaf. Credit: Danica Lombardozzi, National Center for Atmosperic Research.*[16]

Gaseous pollutant sources, clockwise from top left: oil production, oil refining, gasoline transportation, diesel engines, paints and solvents, and dry cleaning.

Sources Contributing to Gaseous Pollutants

Gases may be emitted by sources directly (primary) or they may be the product of atmospheric chemistry and/or the aging of compounds (secondary). The general processes by which compounds are emitted include combustion (burning) or volatilization (the release of compounds that exist as gases at normal temperatures).

Complete combustion results when a carbon-based fuel (such as gasoline, natural gas, coal, or a biofuel) is burned at the right temperature with plenty of oxygen; these byproducts include CO_2 and water. Incomplete combustion results when the temperature is too low and/or there is not enough oxygen; these byproducts include CO_2, CO, and VOCs, as well as water. For incomplete combustion, the particular VOCs vary in part by what type of fuel is burned. High temperature combustion or the burning of certain fuels can also result in NO_2 production (e.g., diesel vehicles). Similarly, SO_2 is generated as a result of burning specific fuels (e.g., coal with a high sulfur content).

Volatilized or leaked emissions result from a gas-phase pollutant being intentionally or unintentionally released. Some industries may release compounds through venting, such as dry cleaners (e.g., perchloroethylene) or auto body shops (e.g., VOCs released from the drying paints and solvents used). Gas-phase pollutants may also be released throughout the oil and gas production chain. For example, VOCs in petroleum, such as benzene, may be vented from a well pad or leak during transport/storage. There have also been instances of processed natural gas (composed primarily of methane) leaking from distribution systems in cities.[17]

Finally, some pollutants transform as they age in the atmosphere and interact with other gases. An important example of a pollutant formed by other emissions is formaldehyde, an

air toxic and known carcinogen. As freshly emitted chemicals transform in the atmosphere, they become formaldehyde. While formaldehyde is also removed by these same processes, a continuous supply of fresh emissions results in the continual presence of formaldehyde above delectable levels.

Understanding Air Pollution Source Contributions to Air Quality

Air quality is complex. The air contains a mixture of old and new emissions, which are aging and interacting in the atmosphere, all while meteorological phenomena (e.g., temperature, humidity, wind or rain) are also affecting the mixture. By learning more about what these mixtures are made of, we can begin to understand which sources influence our air quality and to what extent. In the earlier example of smog in Los Angeles (shown in the first photo of this chapter), the pollutants that contribute to smog are typically ozone, NO_x, VOCs, and $PM_{2.5}$. On roadways, heavy duty diesel trucks tend to be responsible for a larger proportion of NO_x emissions than passenger vehicles.[18] Furthermore, measuring and comparing the amounts of two pollutants like CO_2 and CO can indicate whether pollution is more likely originating from a roadway or a forest fire. As you learn more about air quality by taking measurements, consider how measuring multiple pollutants might help you understand your local air quality.

Understanding the link between air pollutants and their sources is sometimes undertaken in regulatory settings or academic research. One method to understand this link is source apportionment (also called receptor modeling). Source apportionment tools use ambient pollutant measurements to infer the source types and contributions that led to measured pollutant concentrations. To conduct this analysis, a comprehensive air quality data set is processed to sort all of the emissions into likely source types. EPA's receptor modeling tools are available here.[19]
If the analysis is correct, these source types will have a recognizable chemical composition (emission profile) and can be identified, for example, as diesel traffic or wood burning.

We can sometimes determine what are the likely sources of pollutants by analyzing information from a few different pollutants. This can be done without relying on very high quality comprehensive data sets required for source apportionment. Check out Figure 3-2 in Chapter 3 for more information on the types of pollutants emitted by different sources.

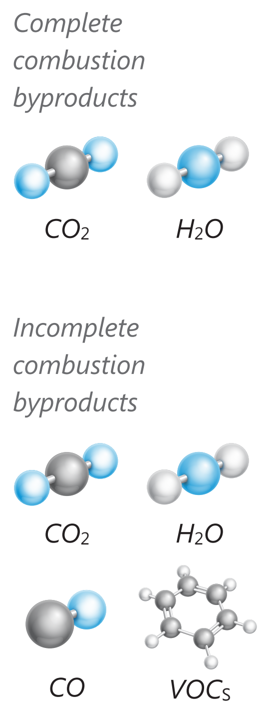


Figure 2-3. *Example of a regulatory ambient monitoring station (South Coast AQMD Riverside-Rubidoux site).*

Monitoring Air Quality

Air quality is monitored by local, state, and federal governments as part of air quality management programs that provide consistent, long-term assessment of pollutant levels in outdoor air. These programs typically use traditional, approved, regulatory-grade monitoring methods that comply with EPA guidance for the design and operation of these networks. Requirements are provided in the Code of Federal Regulations Title 40.[20]

Air pollution measurements are also made using research-grade instruments to explore less commonly measured pollutants, measure common pollutants at different sampling intervals (e.g., 1-minute), or measure criteria pollutants using new technology. And, as discussed in this document, air pollution measurements can be made using newer, low-cost sensors.

Air pollution measurements are often made at stationary monitoring locations. However, many air pollution instruments and sensors can be adapted to be portable.

Regulatory Monitoring

As discussed earlier, the EPA tracks six criteria pollutants because of their impacts on health and the environment: ozone, PM (i.e., $PM_{2.5}$ and PM_{10}), CO, NO_2, SO_2, and lead (Pb). Air agencies measure these pollutants in the air and if an area does not meet one or more of the NAAQS, it is designated as a nonattainment area and the air agency must design a plan to meet the standard. There are strict and detailed rules for monitoring the concentrations of these pollutants in the air. Regulatory monitoring generally requires very sophisticated and proven instruments that have been tested and qualify[21] as Federal Reference Methods (FRM) or Federal Equivalent Methods (FEM). These measurement methods must meet EPA's accuracy requirements. An extensive list of procedures[22] is followed to ensure data quality is adequate including instrument calibration, maintenance, operating conditions, audits, and strict data quality control.

Instruments approved for regulatory level measurements typically cost thousands of dollars to purchase and require trained technicians to operate and maintain them. The strict requirements for regulatory monitoring ensure that the data quality is sufficient for supporting the important decisions made based on the data. For example, South Coast AQMD operates a network of over 40 regulatory monitoring sites. **Figure 2-3** shows an example of a regulatory monitoring site in Southern California. **Figure 2-4** shows a map of the $PM_{2.5}$ regulatory ambient monitoring stations operated across the U.S.

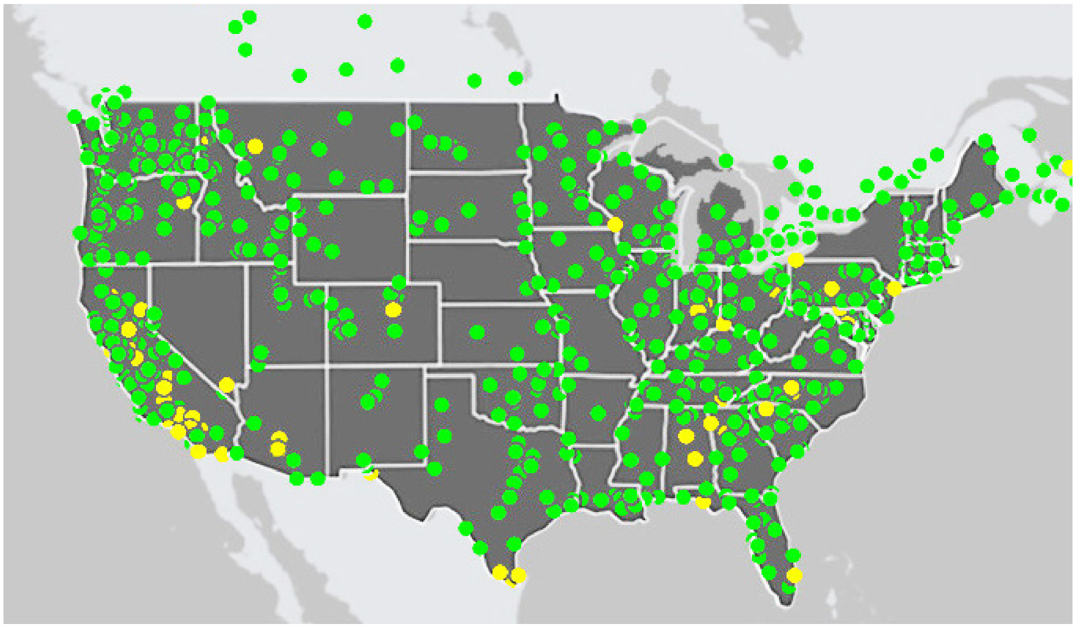


Figure 2-4. *$PM_{2.5}$ regulatory ambient monitoring stations operated across the U.S. (Source: AirNowTech.org,[23] September 2019).*

Research Monitoring

Researchers use similar or sometimes the same instruments as those used in regulatory monitoring to conduct their studies. Air quality monitoring for research purposes often supports regulatory monitoring by answering related questions (such as providing more insight into the atmospheric chemistry that results in the formation of a pollutant). This type of monitoring can also provide information on pollutants other than criteria pollutants (such as monitoring important greenhouse gases like carbon dioxide and methane).

While regulatory monitoring must adhere to strict siting and instrument maintenance guidelines, monitoring for research purposes allows for greater flexibility in study design. For example, research can include air monitoring conducted using mobile vehicle or aircraft platforms. This category may also include air monitoring conducted using satellites, or remote sensing, which can provide a picture of what is happening across the globe. While the methods used and objectives of air quality monitoring for research may be broader and more varied than monitoring for regulatory purposes, this type of monitoring is still subject to rigorous standards in terms of data quality resulting in trustworthy data.

Researchers will sometimes have people wear several sensors to measure their personal exposure to different pollutants.

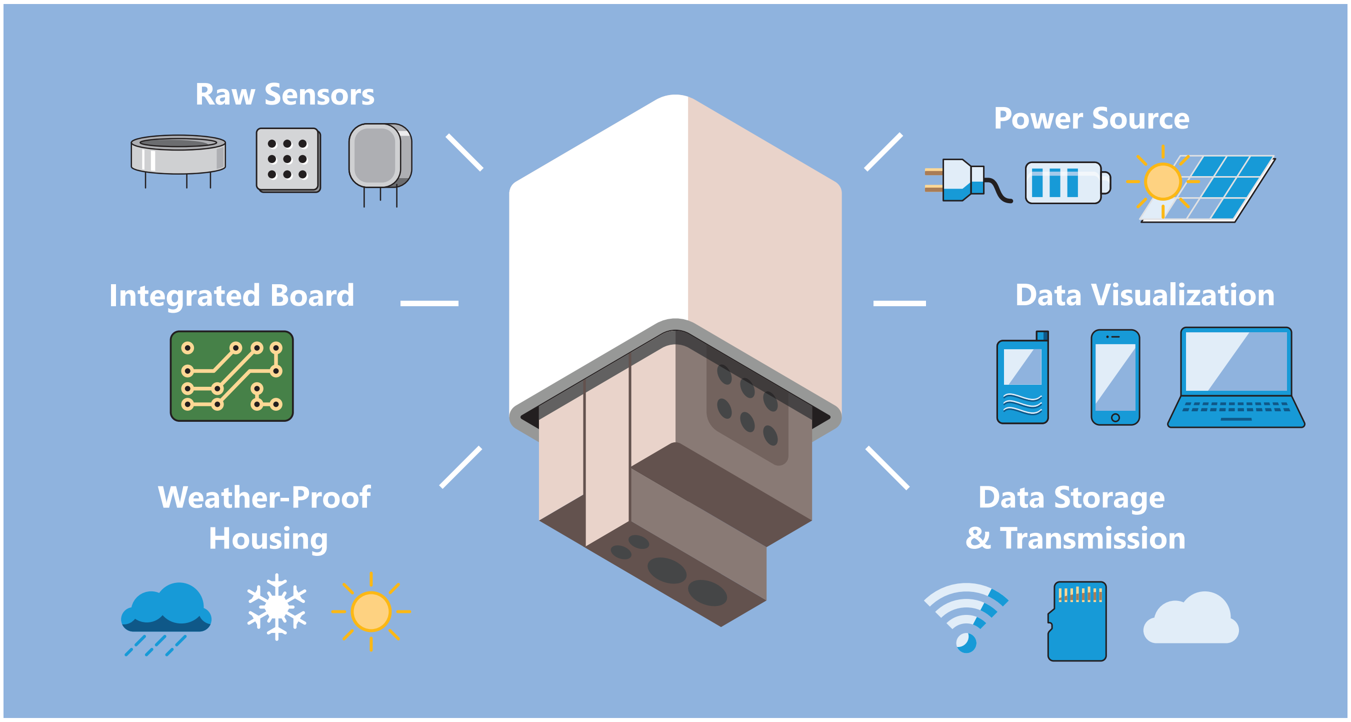


Figure 2-5. *Basic components of a sensor system.*

What Is a Sensor System?

A sensor (or sensor unit) is part of an entire system comprised of packaging (e.g., weather protection for an outdoor sensor), the pollutant sensor or sensors, data storage, data communication, data visualization, location and time information, and power. **Figure 2-5** shows an illustration of basic components of a sensor system – original equipment manufacturer (OEM) sensors (sometimes referred to as raw sensors), integrated circuit board, power, and data storage and transmission. All the components are important and the packaging of the sensor system is a key consideration for a project as it will be an indicator of sensor durability and ease-of-use.

In recent years, low-cost air quality sensors have provided another method to measure pollutants in the air and have opened the exploration of air quality to a much broader audience including community members, educators, students, etc. These devices are typically not approved measurement methods for regulatory purposes (i.e., not FEM or FRM). But, low-cost sensors can complement the existing regulatory air monitoring network instruments, they are accessible to the general public due to their low purchasing price, and they require little maintenance. There are many differences between low-cost sensors and regulatory-grade instruments.

Cost. Low-cost sensors are typically far less expensive than regulatory monitors, ranging in price from a few hundred dollars to a few thousand, and often less for OEM sensors.

Time resolution. Sensors may collect and report data with higher time resolution (e.g., 1-second or 1-minute) than regulatory monitors (typically 1-hr).

Data quality. To date, almost none of the measurement methods used in these sensors have been approved by the EPA for regulatory monitoring, with the exception of an ozone sensor (i.e., Personal ozone Monitor [POM] by 2B Technologies) that uses a federally approved instrument but costs around $5,000.

Operation and maintenance. Sensors typically require much less maintenance than a regulatory monitor; however, this also means that data quality can be affected.

Measurement technique. The way low-cost sensors measure pollutants is sometimes a simpler version of how regulatory-grade instruments work – but some also work completely differently from regulatory-grade instruments. This makes comparisons to regulatory data difficult. These low-cost sensors provide new opportunities, but they need to be used appropriately. For example, many more sensors can be deployed in an area for much less cost than regulatory monitors. For non-regulatory use, selection of a low-cost sensor appropriate to a project will depend on what types of questions are being asked. Some examples of commonly used low-cost sensors are shown in **Figure 2-6** (on page 2-22).

Many of these sensors have been evaluated to determine their precision, accuracy and other characteristics under a variety of circumstances. One testing facility is operated by the South Coast AQMD, called the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) program.[24] The AQ-SPEC program evaluates currently available low-cost sensors under ambient and controlled environmental conditions. The program also aims to "provide guidance and clarity for the ever-evolving sensor technology and data interpretation and to catalyze the successful evolution,

development, and use of sensor technology." Sensors tested in the program are selected as follows:

- The sensor is commercially available.
- The sensor provides real- or near-real-time measurements with the time resolution of one reading every 5 minutes or less.
- The sensor measures one or more of the NAAQS criteria pollutants, air toxics, pollutants of concern and non-air toxics. Examples of the targeted gases and particles are CO, ozone, NO_x, PM, VOCs, hydrogen sulfide (H_2S), and methane.
- The market cost of the sensor is less than $2,000 total for single pollutant devices or <$2,000 per parameter for multi-pollutant devices.

Programs like AQ-SPEC, provide an objective way to evaluate the performance of sensors and to better understand the precision and overall data quality. Poor quality data obtained from unreliable sensors may not only lead to confusion but also jeopardize the successful evolution of low-cost sensor technology.

HOW TO CHOOSE AN

AIR QUALITY SENSOR

1 WHY? FRAME THE PROBLEM

What nearby pollution sources concern you?

DISTURBED SOIL
- Dirt Roads
- Farming
- Construction
- Windblown Dust

WOOD COMBUSTION
- Fireplaces
- Restaurants
- Wildfires

SMALL-SCALE TRANSPORT
- Passenger Vehicles
- Small Engines

LARGE-SCALE TRANSPORT
- Diesel Trucks
- Shipping
- Airplanes
- Trains

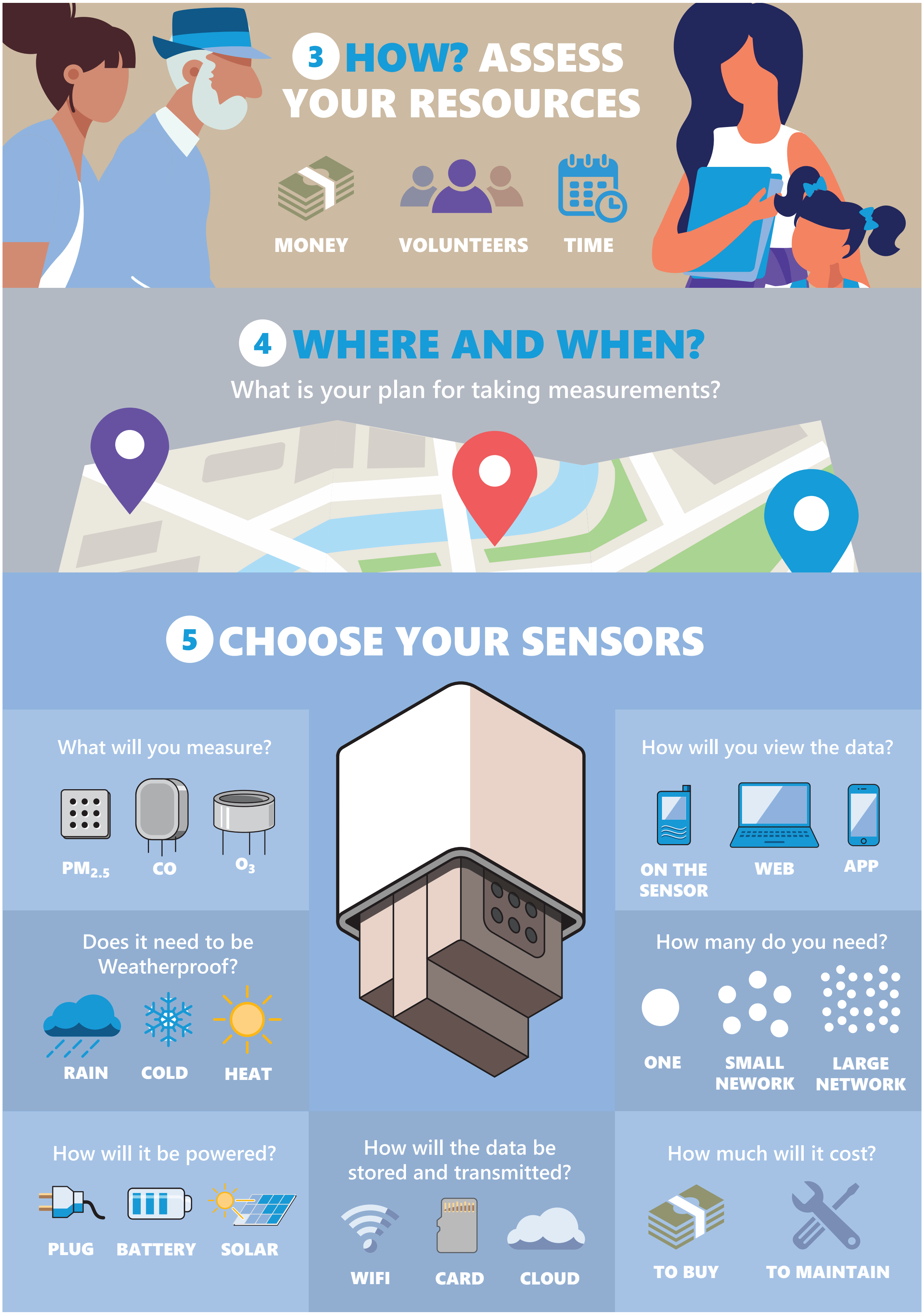
LIGHT INDUSTRY
- Dry Cleaner
- Auto Shop
- Fabrication

HEAVY INDUSTRY
- Extraction
- Refining
- Factories
- Distribution

2 WHAT? IDENTIFY THE POLLUTANTS

What pollutants are being created by those sources?

- PM_{10} Coarse Particles
- $PM_{2.5}$ Fine Particles
- VOCs Volatile Organic Compounds
- CO_2 Carbon Dioxide
- CO Carbon Monoxide
- NO Nitrogen Oxide
- NO_2 Nitrogen Dioxide
- O_3 Ozone
- SO_2 Sulfer Dioxide


3 HOW? ASSESS YOUR RESOURCES
MONEY
VOLUNTEERS
TIME
4 WHERE AND WHEN?
What is your plan for taking measurements?
5 CHOOSE YOUR SENSORS
What will you measure?
$PM_{2.5}$
CO
O_3
How will you view the data?
ON THE SENSOR
WEB
APP
Does it need to be Weatherproof?
RAIN
COLD
HEAT
How many do you need?
ONE
SMALL NEWORK
LARGE NETWORK
How will it be powered?
PLUG
BATTERY
SOLAR
How will the data be stored and transmitted?
WIFI
CARD
CLOUD
How much will it cost?
TO BUY
TO MAINTAIN

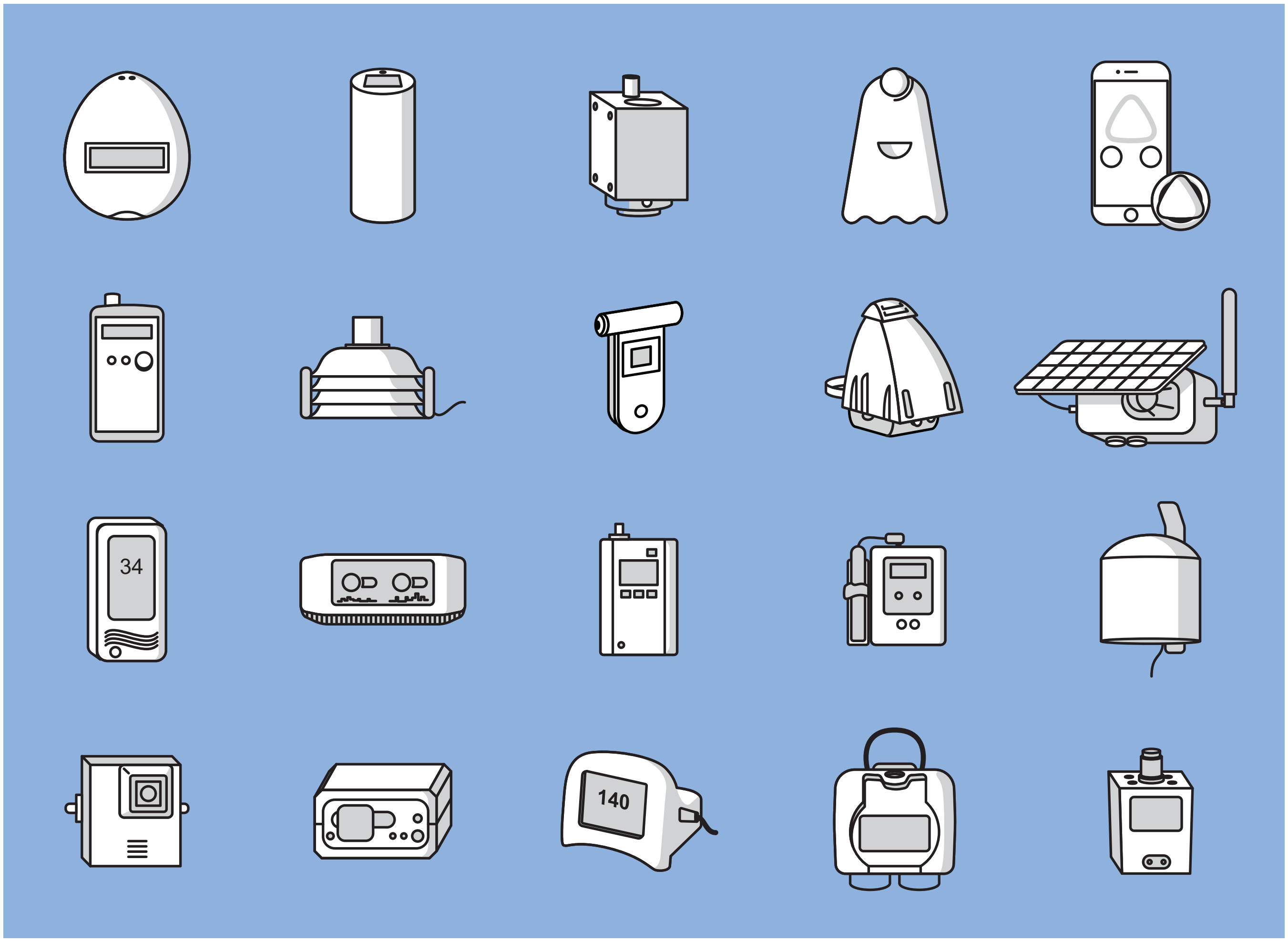


Figure 2-6. *Some of the many low-cost sensors available on the market.*

The EPA also conducts research on sensors through its Sensor Performance Evaluation and Application Research (SPEAR) initiative. Through SPEAR, EPA is evaluating and testing[25] commercial devices, as well as developing new instruments using OEM sensors and other technologies. SPEAR evaluations of commercially-available devices are occurring at EPA laboratories and several field locations throughout the United States. The goals of these performance evaluations are to:

- Develop a better understanding of basic sensor performance characteristics.
- Provide results to sensor manufacturers that encourage improvements in sensor performance.
- Communicate findings to stakeholders to improve outcomes of sensor applications.

The results of the sensor evaluations are being shared with the public through the publication of reports and journal articles.

For Further Reading

Perspectives on low-cost sensors[26]

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03 Planning Your Project

To develop a monitoring strategy and design you will need to frame the problem to be studied, identify pollutants of interest, determine where and when to make measurements, assess your resources, and then select a sensor system.

Planning Is a Process

Project goals may need to be revised to make them achievable.

Planning is often an iterative process. Once you have initial goals, you will need to assess them in terms of what can be accomplished given the project realities (especially resources). To design and develop a monitoring strategy, you will need to frame the problem to be studied, identify the pollutants of interest, determine where and when to make measurements, assess your resources, and then select a sensor system.

A monitoring strategy is developed according to project objectives, size of the area to be assessed, number and distribution of emission sources, presence/absence of existing air quality monitoring, number and types of pollutants of interest, specificity and sensitivity of a sensor system, monitoring frequency and duration, magnitude of concentrations expected, and available resources including funds, manpower, and schedules. It's also advantageous at this stage of your project to consider how you plan to use the data and potential follow-up actions based on particular results. This will help ensure you collect data that meet your needs.

Figure 3-1 emphasizes the iterative nature of planning. This section will guide you through addressing the why, what, where, when, and how questions that will shape an ideal plan. Often this cycle needs to be repeated to respond to realities such as budget limitations.

Figure 3-1. *Project planning is a process that may need to be repeated to adjust for realities such as budget limitations.*

Why Does My Community Want to Take Air Quality Measurements?

Frame the Problem

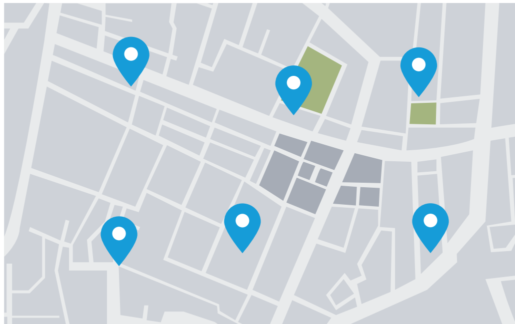
To frame the problem to be studied, you will need to identify issues of concern to the community by considering emission sources, pollutants, pollution transport, vulnerable populations (e.g., children, pregnant women, the elderly, and people with pre-existing health conditions), and proximity to emission sources in your study area.

Engage the Community

For community-based projects, authentic engagement and participation can help ensure that the collected data is meaningful and relevant to the members of that community. This can include involving the community in the decision-making process, supporting active participation in project activities, communicating the science, incorporating local knowledge and expertise, and building relationships to increase community trust and understanding of the data.

For research partners, it may be helpful to work with established community groups with valuable knowledge and experience. Projects should consider forming a Community Steering Committee that includes a range of community members and other stakeholders. Also, consider forming a Technical Advisory Group that includes air quality and monitoring experts. Strong community partnerships and engagement is the foundation for success and can lead to increased knowledge and awareness of air quality issues for community members.

Begin by considering what questions you would like answered.



Are You Concerned About Your Community's Air Quality?

Suggestions for characterizing community air quality: Think about how you can gauge the results. You could compare your local air quality to other communities. You could compare data from the same location across different times of days or seasons. You could compare your community's air quality to state (e.g., California) or federal air quality standards.

Recommended Approach: Design a network of sensors placed relatively evenly throughout the community, consider how you will analyze this data, and identify to what data you will compare.

Case Study: *Combining Community Engagement and Scientific Approaches in Next-Generation Monitor Siting: The Case of the Imperial County Community Air Network*[1]
This case study illustrates a collaborative, community-engaged process to develop a community air monitoring network to produce high quality data. Community residents were engaged in the project design, monitor siting processes, data dissemination, and other key activities which increased their understanding and trust in the data.

Are You Concerned About a Specific Source of Pollution?

Suggestions for characterizing community air quality: You could assess when the source has an impact or the level of the impact. You could assess a new or future emission source by capturing the current (also called "baseline") conditions before the new source is added.

Recommended Approach: Place sensors near the source and also place sensors at varying distances from the source that will help you understand transport and/or the possible impact on nearby residents. For this application, it is important to have sensors to characterize background air pollutant levels.

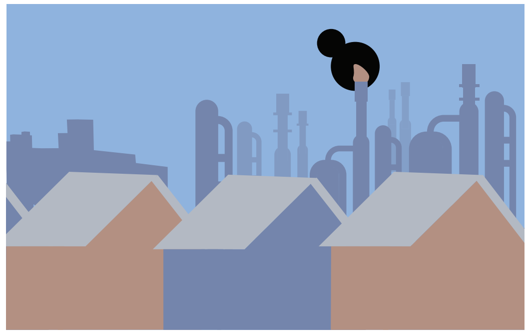
Case Study: *South Philadelphia passive sampler and sensor study to characterize background air pollutant levels*[2]
This study deployed a network of passive samplers (collecting benzene from the air for a period of 2 weeks) to understand the spatial distribution of benzene near industrial facilities. The study also included high time resolution sampling at higher cost. A decreasing gradient in benzene concentrations moving away from the industrial facilities was observed, as was a significant period-to-period variation.

Are You Concerned About the Air You Breathe – Your Personal Exposure?

Suggestions for characterizing community air quality: You could explore air quality during various activities or at different locations and times.

Recommended Approach: Consider both wearable sensors and a small network of stationary sensors throughout the community to serve as a basis for comparison or to provide additional context.

Case Study: *Validating novel air pollution sensors to improve exposure estimates for epidemiological analyses and citizen science*[3]
This case study illustrates an application of low-cost sensors to measure personal exposure to carbon monoxide (CO), nitric oxide (NO), and nitrogen dioxide (NO_2). The sensors were able to detect high and low air pollution levels in agreement with expectations (e.g., high levels on or near busy roadways and lower levels in background residential areas and parks). Data were used to augment two ongoing exposure studies.



Other Considerations

For community projects, typically the focus is on the local scale – that is, within a community or neighborhood. However, a community may wish to understand the impact of transported air pollution from farther away. Larger particles (PM_{10}), such as dust from construction or industrial activities, do not travel far from the source, while smaller particles ($PM_{2.5}$) can travel up to hundreds of kilometers. You may also want to consider other communities or areas that could serve as good comparisons to help you understand your data. For example, a project may contrast pollutant concentrations in environmental justice (EJ) areas relative to non-EJ areas.

Environmental Justice

Environmental justice (EJ) is defined[4] as the fair treatment of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. Fair treatment means no group of people should bear a disproportionate share of the negative environmental consequences resulting from industrial, governmental, and commercial operations or policies.

It is important to consider the population of concern – that is, who is impacted? Consider also how you define your community. For example, is it defined as a particular neighborhood, or are there geographical boundaries? Alternatively, is your community defined by a certain demographic or group of people who share a common concern or need, but may span a large area? Who else may be affected by or interested in your project? For example, you may want to investigate pollutant concentrations in locations with sensitive populations such as the elderly, people whose health is impaired, or the young. Thinking through your definition of community will help you consider who to include in your project as participants, partners, and stakeholders.

In addition to considering who to include, you should also consider how your project will be organized. These types of projects are often led by or involve the public, and there are different governance structures available to help shape participation:[7] contributory, collaborative, and co-created or transformative. Typically, contributory projects are designed and led by researchers, and participants help by contributing data. While in collaborative projects, in addition to contributing data, the participating members of the public might provide feedback on project design or data analysis. In co-created or transformative projects, at least some of the participating members of the public are involved in all phases of the research from determining the guiding questions to discussing next steps based on the results.

A project is more likely to result in useful and relevant information when there is greater participation and engagement by the community. They will shape the project according to the needs, concerns, and local knowledge of community members.

For more information before you get started

The following resource provides overviews of various community-based air quality monitoring projects, including project outcomes. Consider using these as examples or models as you plan your project:

Community-based participatory research for the study of air pollution: a review of motivations, approaches, and outcomes[5]

The following resource provides a comprehensive list of questions to consider when planning an environmental assessment, such as research into local air quality. Additionally, this resource includes an assessment of an air quality research project that used low-cost air quality sensors.

Advice and Frequently Asked Questions (FAQs) for citizen-science environmental health assessments[6]

Set Project Goals

In setting project goals, be specific and focused. To make goals achievable, use the SMART principle presented in [*There's a S.M.A.R.T. way to write management's goals and objectives*](#).[8]

Building on experience from other community projects, also consider:

- Manage expectations – keep in mind the limitations of sensor technology and the nature of the scientific process. Be open to taking extra or different measurements in case the data are of insufficient quality or do not answer your question.

- Plan on having spare sensors to replace those that are malfunctioning.

- Discuss how you intend to use the data, and work with your partners to outline potential next steps for the various results you may see (refer to Section 5 to assist with this discussion).

- Write a project question that will help you better understand your concerns about your local air quality if it were to be answered. For example,

"How is emission source ________ impacting air quality in our community?"

"How do the $PM_{2.5}$ concentrations measured by my low-cost sensor compare to those reported by other monitoring equipment such as the regulatory monitor representing the area?"

- Continually assess whether the data you plan to collect address your project question, and revise your plan as necessary.

- Consider holding some amount of funding in reserve to expand data collection as necessary (this may involve purchasing additional sensors, adding a different type of sensor, or collecting another type of data such as health surveys or more air quality data using time-integrated passive samplers). Include a budget for routine preventative maintenance and troubleshooting of the sensors and for general oversight.

- Factor the cost of community meetings into your budget (e.g., room rental, refreshments/meals, office supplies, photocopies, translation services, and childcare) as well as adequate support for community partners and compensation/incentives for participants and sensor users for their time.

- Keep the project focused; for example, don't take on too many pollutants at once.

- More data increases the statistical power of your results: Take measurements at multiple locations for extended periods of time to maximize data collection. Take extra measurements if possible (e.g., more sites, more time). If you are able to, place duplicate or triplicate sensors at some locations to support later assessments of data quality.

Project plans should include goals that are specific, measurable, achievable, relevant, and timebound.

Explore emission types by pollutant in your area using free online tools.

Figure 3-2. *(Opposite page) Emission processes and pollutants, their sources, and air quality concerns.*

What Does My Community Want to Measure?

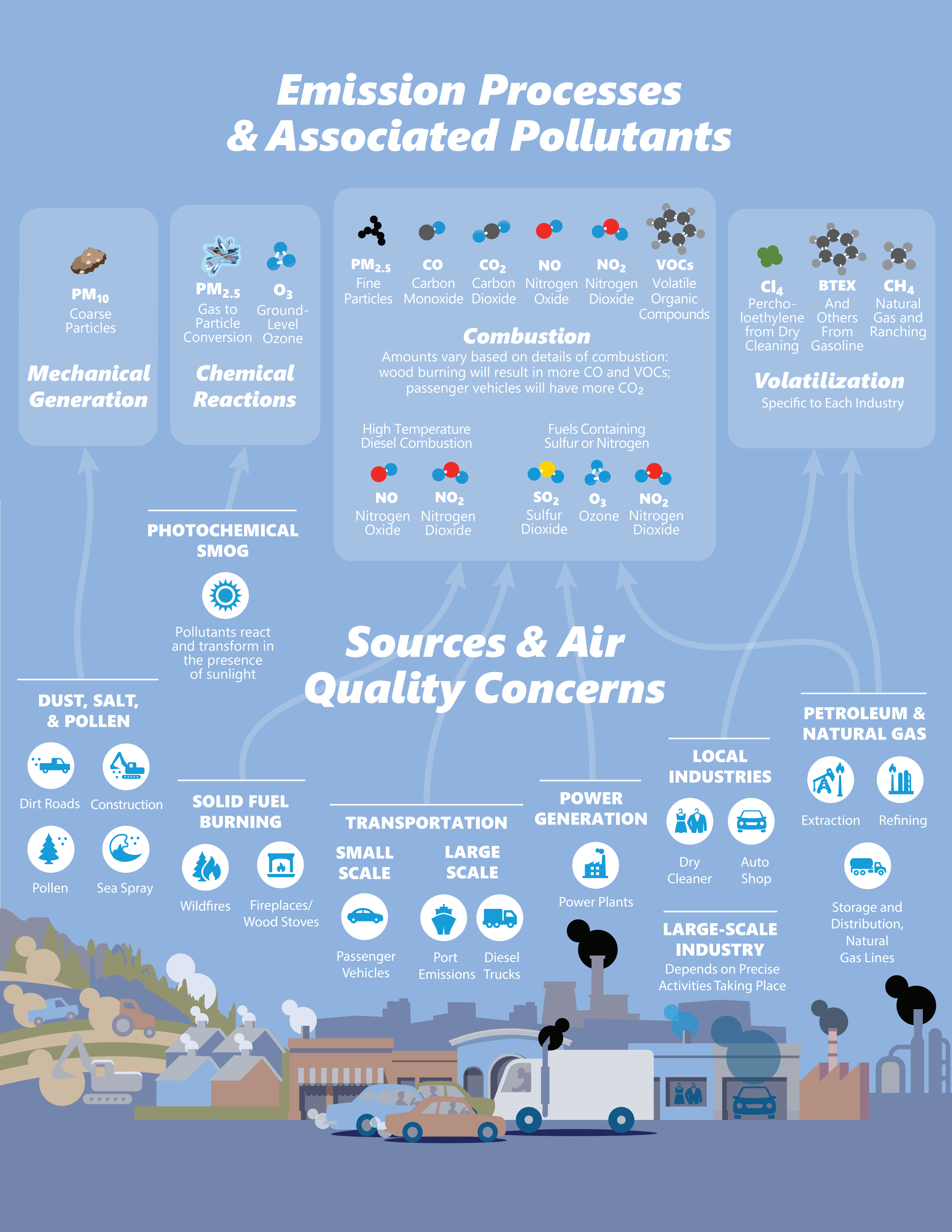
The pollutants of interest will be defined by project goals (e.g., sources of concern). Sensor options are limited to a short list of pollutants at this time. There are many pollutants which cannot yet be reliably measured with low-cost sensors, or cannot be measured at all because the appropriate sensor technology does not exist. In addition to selecting the pollutant, you will need to understand the concentration ranges expected, concentrations measurable by the sensor, and sensor accuracy and precision needed to meet project goals.

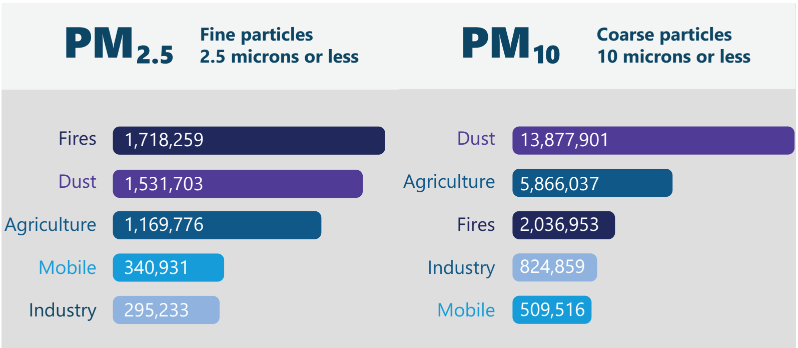
Link Your Source(s) to Pollutants

Sources often emit more than one pollutant; **Figure 3-2** provides an overview of the pollutants potentially emitted by different source types, including transportation and the energy sector. Pollutant emission and formation processes are also shown. These processes include combustion (e.g., diesel fuel), volatilization (e.g., fuel evaporation), mechanical generation (e.g., windblown dust), and chemical reactions (e.g., ozone).

Once you have determined the pollutants likely to be emitted by the source you are concerned about, you should also make note of the other sources in your study area that may release these same pollutants. If possible, try to choose a pollutant/pollutants to measure that will provide the most useful information on the source of interest.

Resources to better understand specific sources or pollutants in your area include the National Emissions Inventory Report,[9] California's CalEnviroScreen,[10] and the U.S. EPA's EJScreen tool.[11]


Emission Processes & Associated Pollutants
PM_{10}
Coarse Particles
Mechanical Generation
$PM_{2.5}$
Gas to Particle Conversion
O_3
Ground-Level Ozone
Chemical Reactions
$PM_{2.5}$
Fine Particles
CO
Carbon Monoxide
CO_2
Carbon Dioxide
NO
Nitrogen Oxide
NO_2
Nitrogen Dioxide
VOCs
Volatile Organic Compounds
Combustion
Amounts vary based on details of combustion: wood burning will result in more CO and VOCs; passenger vehicles will have more CO_2
High Temperature Diesel Combustion
NO
Nitrogen Oxide
NO_2
Nitrogen Dioxide
Fuels Containing Sulfur or Nitrogen
SO_2
Sulfur Dioxide
O_3
Ozone
NO_2
Nitrogen Dioxide
Cl_4
Percho-loethylene from Dry Cleaning
BTEX
And Others From Gasoline
CH_4
Natural Gas and Ranching
Volatilization
Specific to Each Industry
PHOTOCHEMICAL SMOG
Pollutants react and transform in the presence of sunlight
Sources & Air Quality Concerns
DUST, SALT, & POLLEN
Dirt Roads
Construction
Pollen
Sea Spray
SOLID FUEL BURNING
Wildfires
Fireplaces/ Wood Stoves
TRANSPORTATION
SMALL SCALE
Passenger Vehicles
LARGE SCALE
Port Emissions
Diesel Trucks
POWER GENERATION
Power Plants
LOCAL INDUSTRIES
Dry Cleaner
Auto Shop
LARGE-SCALE INDUSTRY
Depends on Precise Activities Taking Place
PETROLEUM & NATURAL GAS
Extraction
Refining
Storage and Distribution, Natural Gas Lines



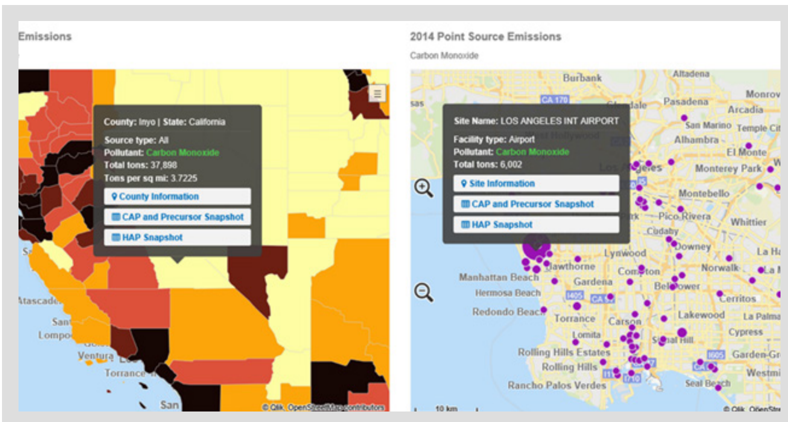
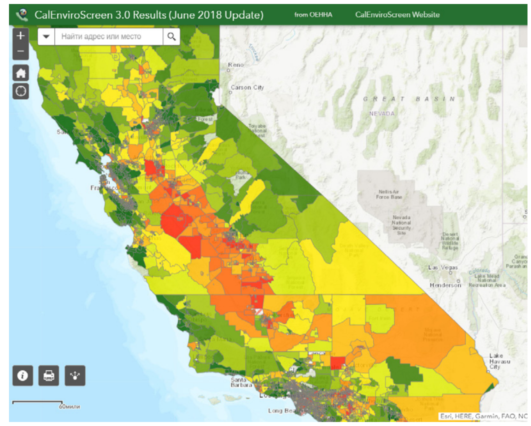


Figure 3-3. *2014 national emissions inventory for $PM_{2.5}$ (upper left) and PM_{10} (upper right) by source type in tons* *(Source: EPA).*[12]

Figure 3-4. *Total CO emitted by county (bottom left), and point sources emitting CO (bottom right). CAP = criteria air pollutant and HAP = hazardous air pollutant* *(Source: EPA).*[12]

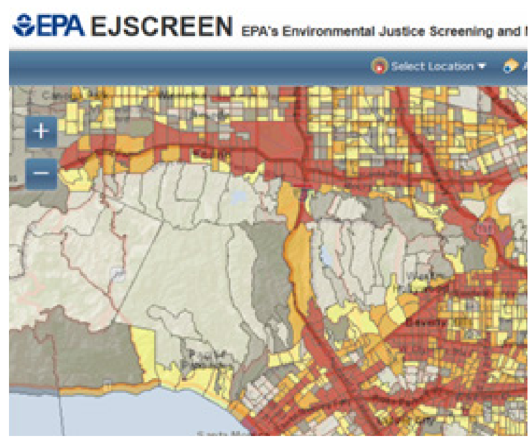
National Emissions Inventory Report

EPA documents the emissions inventory by state.[12] At this website, you can explore emission types by pollutant in your area using EPA's tools and Google Earth.[13] A summary of 2014 emissions for $PM_{2.5}$ and PM_{10} nationwide is shown in **Figure 3-3**. You can also explore the total emissions of individual pollutants by county or even individual point sources, as shown in **Figure 3-4**. To use this resource, once it is open, scroll down to use the different tools available: the "Trends" section provides overall summaries of emissions, the "Source Contributions" section provides information on emissions in map form by state and by county, and the "Point Source Contributions" allows you to explore individual point (localized and stationary) sources on a map.



CalEnviroScreen

CalEnviroScreen[10] provides an interactive map that identifies communities disproportionately burdened by or vulnerable to various pollutants, including a breakdown of relative risk from individual pollutants. Above is a screenshot of the site.



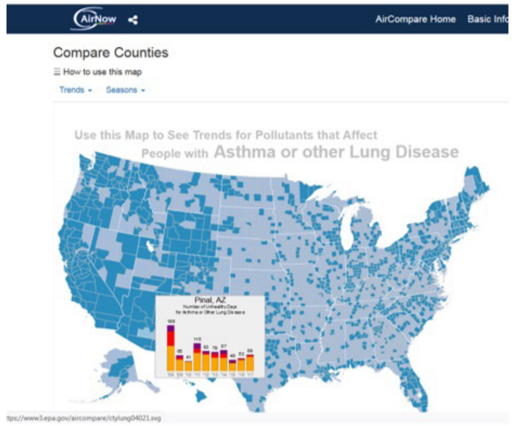
U.S. EPA EJScreen

The EPA's EJScreen tool[11] provides another way to explore EJ and demographic data, as well as examine individual emission sources reporting to the EPA. Once you open the map, select "Add Maps" to either add "EJSCREEN Maps" or "Additional Maps" and then "Sites Reporting to the EPA" to examine individual pollution sources (see above for an example).

Determine Relevant Concentrations of Pollutant(s)

It is important to understand the concentration ranges that might be expected for pollutants of concern. For example, for fine particles, a concentration range to expect might be 0-40 μg/m^3 (24-hr average) with 1-minute values potentially much higher than this. In this case, a desirable lower detection limit for a sensor would be about 5 μg/m^3. A lower detection limit is the lowest pollutant concentration that the sensor can detect. For coarse particles, expect a concentration range of 0 to 100 μg/m^3 (24-hr average) and a useful lower detection limit of 10 μg/m^3. For ozone, a 1-hr average concentration range to expect is 0-150 ppb. A desirable lower detection limit for a sensor would be about 10 ppb. (Source: EPA Air Sensor Guidebook[14]).

There are many available resources to understand typical/normal concentrations in your area, concentrations that are exceptional (e.g., very high), and how concentrations vary across different time scales (e.g., seasonally, daily). To understand typical pollutant concentrations on a regional scale in your area, you can explore air quality data summaries.

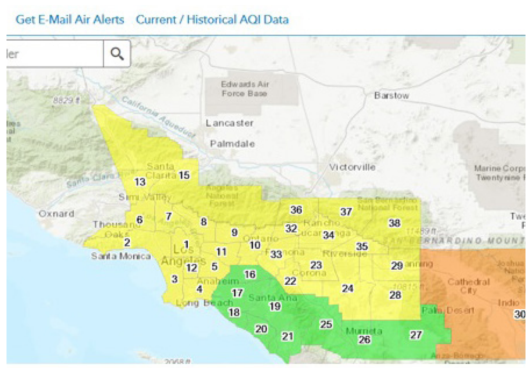


Air Compare

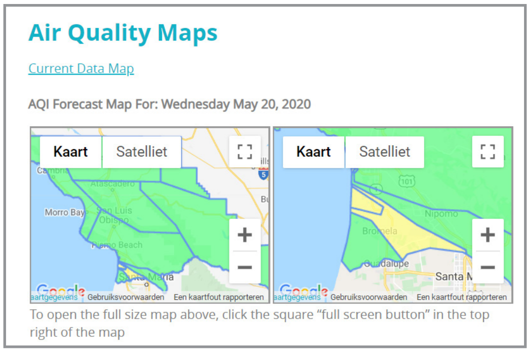
Air Compare[15] allows you to explore pollutant conditions in your area with respect to the number of unhealthy days in your county compared to others. See screenshot above.

Local Air Quality Agencies

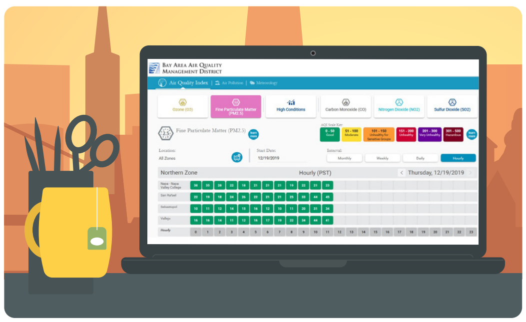
Local air agencies offer information on air quality and emissions.



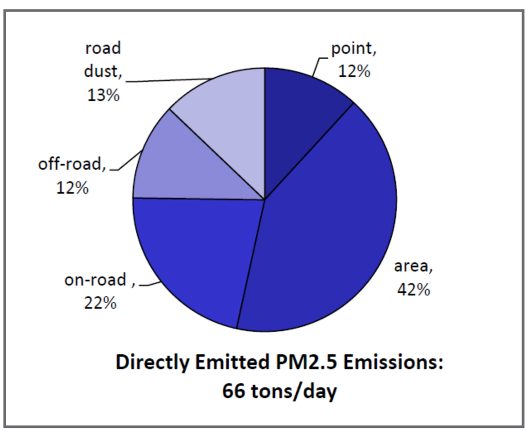
South Coast AQMD air quality.[16] See screenshot above.



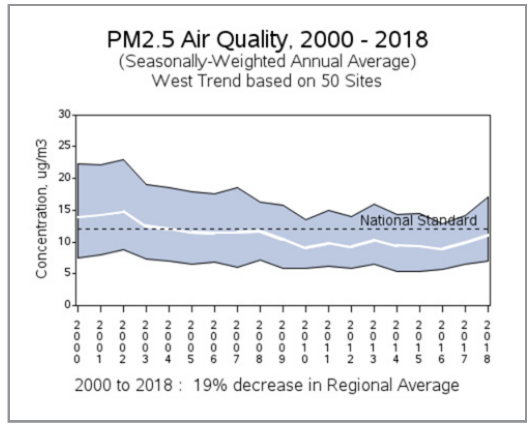
[San Luis Obispo Air Pollution Control District air quality][17] See screenshot above.



[Bay Area Air Quality Management District (BAAQMD) air quality][18] See screenshot above.



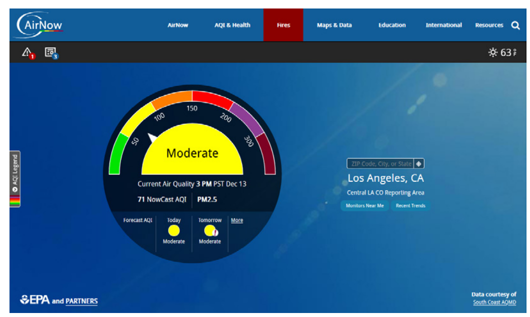
[Air Quality Management Plans][19] See screenshot above.



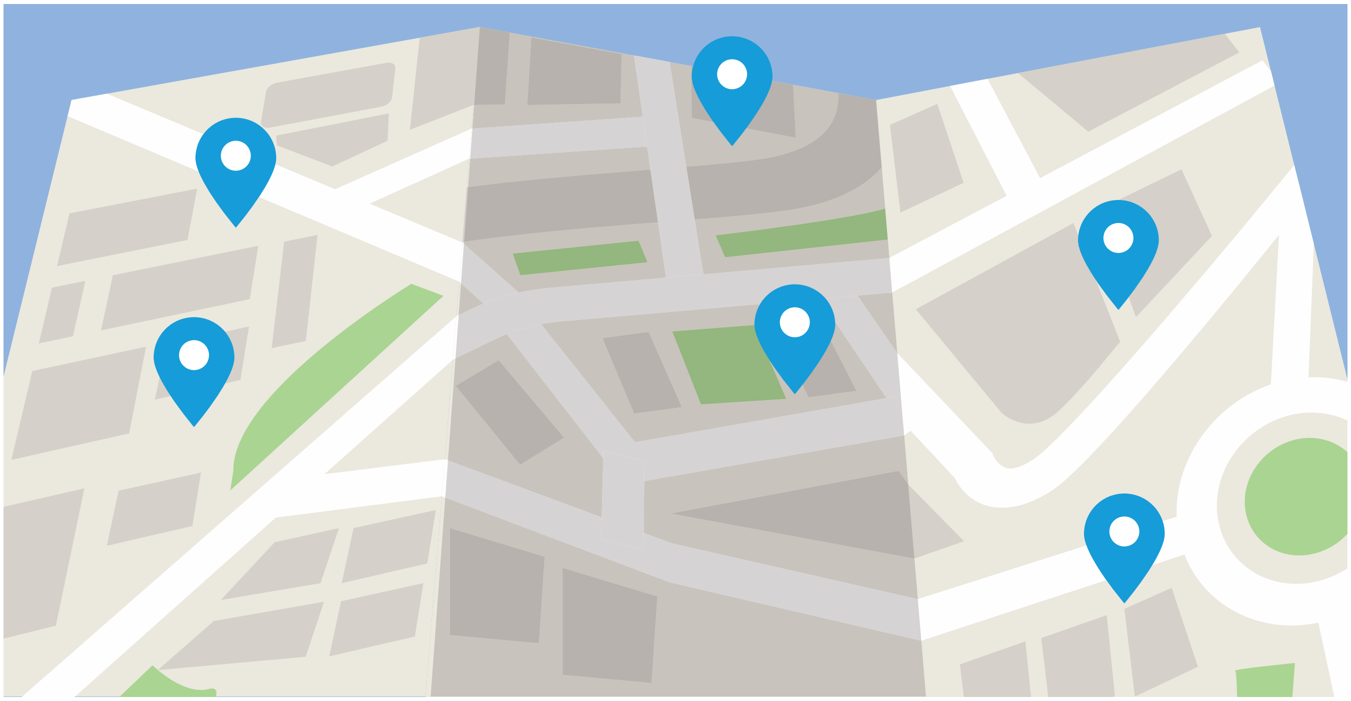
U.S. EPA Air Trends

[Regional $PM_{2.5}$ or PM_{10} concentration trends relative to NAAQS][20] See screenshot above.

AirNow.gov



For current conditions across the U.S., AirNow.gov[21] provides the Air Quality Index (AQI) (see Appendix A). The higher the AQI value, the greater the level of air pollution and the greater the health concern. An AQI value of 100 generally corresponds to the NAAQS for the pollutant, which is the level EPA has set to protect public health. AQI values below 100 are generally thought of as satisfactory. When AQI values are above 100, air quality is considered to be unhealthy for certain sensitive groups of people, and then for everyone as AQI values get higher. See screenshot above.



Where & When Does My Community Want to Take Measurements

When assessing where and when to make measurements, consider the geophysical setting (e.g., terrain), meteorology (e.g., predominant winds), types and characteristics of sources (e.g., operating schedule), and availability of existing monitoring data. Pollutant concentrations may be highly variable over both short- and long-distances. Typically, concentrations will be highest near a source and may decrease rapidly as you move away. In this phase of project planning, it is useful to explore your area, look at detailed maps, define community boundaries and talk to local air quality experts to get an overall understanding of meteorology, emission sources, sites of existing monitors, and other details.

The number of sites in your network will be a function of resources (available funds and staff/volunteers); the size of the area to be assessed including the distance between source(s) and location(s) of concern; the need (or not) for background measurements; and expected gradients in concentrations from source(s) to location(s) of concern (due to wind direction, wind speed, geography, etc.). The planning process is typically iterative.

Select Locations

Table 3-2 shows monitoring scale and what the measurements at these scales represent; this can help you think about the size and coverage of your sensor network. Measurements are typically considered to be collocated (i.e., measuring the same air) when they are placed 1 to 10 meters (i.e., about 3 to 30 feet) apart. Near-source measurements are typically made 10 to 100 meters (i.e., about 30 to 300 feet) away from a source depending on the height of the emissions. If emissions are

Type of Monitoring	Scale	Example Monitoring Goals
Collocated	1 - 10 m *3.3 - 33 ft*	Precision, accuracy, bias
Microsale (i.e., near-source)	10 - 100 m *33 ft - 330 ft*	Highest concentration, source impact
Middle-scale (i.e., changes in concentration [gradients] from sources such as roadways)	100 - 500 m *109 yd - 547 yd*	Highest concentration, source impact
Neighborhood-scale	500 m - 4 km *0.3 mi - 2.5 mi*	Highest concentration, source impact, population impact
Urban-scale (citywide conditions)	4 - 100 km *2.5 mi - 62 mi*	Highest concentration, population impact, background, secondary standard
Regional-scale (typically rural areas)	100 - 1,000 km *62 mi - 621 mi*	Background, secondary standard

Table 3-2.
Monitoring scale.[22]

sent high into the air, you may want to include sampling downwind. Consider also what the sampling height implies about your data; if you are looking to understand the impact on residents of a community, you will want to sample in the breathing zone (defined as between 3 and 72 inches from the floor in ANSI/ ASHRAE Standard 62.1-2010)[23] at homes.

The size of a monitoring network needed to capture air quality characteristics varies by monitoring scale. For middle-scale, for example, a few sensors placed at varying distances from the source are likely adequate to capture a concentration gradient. For a neighborhood, additional sensors may be needed to adequately cover the area.

Site selection can be difficult because there are many considerations including logistics. Some selection ideas include:

- **Ask your local partners** for recommendations on what sites they are interested in learning more about
- **Consider proximity** to existing air monitoring sites
- Consider **under-served/under-resourced areas** or areas designated as EJ
  - Using CalEnviroScreen[10] with default selections or modified to include air quality factors only
  - Applying South Coast AQMD Rule 1309.1[24] (10% of population below poverty line; census 2000)
  - Outside of California, you can use EPA's EJSCREEN[11]

- **Identify "newly" affected areas** such as areas with recent demographic changes or infrastructure development

- Place sensors near **facilities** that hold permit(s) with regulatory agencies

- Place sensors near or at **public spaces** (e.g., schools, hospitals, public parks)

- Place sensors near **relevant pollution sources** (e.g., freeway, port, refineries)

- **Review IVAN** (Identifying Violations Affecting Neighborhoods),[25] for locations of potential concern

- Develop and apply a **scoring system to rank sites** by relevance. Evaluate factors including:

  - Proximity to sensitive receptors (e.g., schools and hospitals)
  - Proximity to potential confounding sources (for community monitoring), or proximity to a source of interest (for near-source monitoring)
  - Site safety, power availability, Wi-Fi, security, accessibility, and other factors

- Plan for **background measurements** or control sites in locations not expected to be impacted by source(s) you are interested in.

- Maximize **data collection to increase the statistical power** of your results by taking measurements at multiple locations for extended periods of time. Take extra measurements if possible (e.g., more sites, more times).

- If possible, place **duplicate or triplicate sensors** at some locations to support later assessments of data quality.

- Be willing to **adjust where you place your sensors.** It's possible that your network of sensors will be denser than necessary (if this is the case, there might be very little difference across sensors). Or your network might not be well placed to pick up pollutant transport.

When asking community members or local businesses to host or maintain sensors, you may want to consider having them sign a release of liability form. See Appendix I for a template.

Figure 3-5. *Predominant winds at Los Angeles Airport are from the west. (Source: [AirNow-Tech](#).[26] Wind rose for December 2018-2019).*

Consider Factors Impacting Emissions

Daily, weekly, and seasonal variations need to be considered when designing a project. To assess when to take a measurement, consider whether emissions are continuous (e.g., 24-hr /7-days per week operations) or follow a pattern, such as vehicle traffic during rush hours. Some emissions sources will be seasonal. For example, if you are studying residential wood smoke, you are more likely to see impacts on cold nights and winter holidays than on mild-temperature nights. To assess how often you need to make measurements and with how many sensors, consider that if source emissions are intermittent, you may need more sampling locations and to run the sensors for a longer period of time to capture an event (i.e., the impact of source emissions on a particular sensor). Also, to capture a quickly changing or short-lived pollutant plume, a sensor will need to be able to take measurements on a very short time interval, on the order of seconds. For less variable air quality conditions, sampling at time scales of minutes or hours is likely adequate.

The height at which pollutants are emitted impacts transport and thus exposure. Emissions can be near ground level, such as car exhaust, or from taller sources, such as industrial stacks. For elevated emissions, it is harder to determine where to measure because of the complexity of meteorology and predicting where the emission plume will travel.

Air quality and weather are linked. Weather can affect both pollutant concentrations and sensor performance. Meteorology is important, particularly winds. Select locations downwind of the source, and note that depending on local meteorology and terrain, “downwind” may encompass multiple directions. Upwind measurements are also useful as they may provide an idea of the background levels of pollutants before the air reaches a particular source. A pre-project analysis of winds is useful to

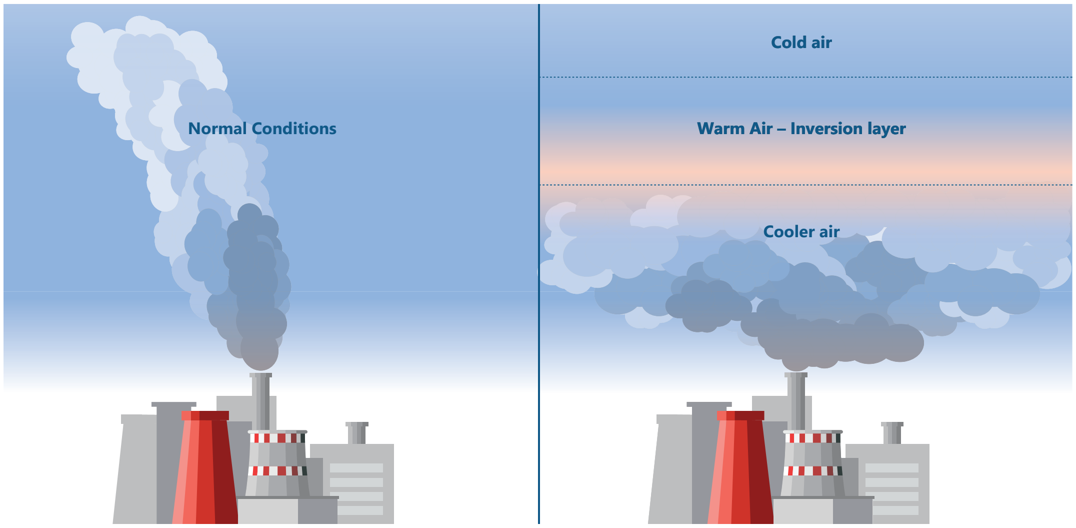


Figure 3-6a. *An inversion layer can lead to high pollutant concentrations by trapping the air pollution closer to the ground.*

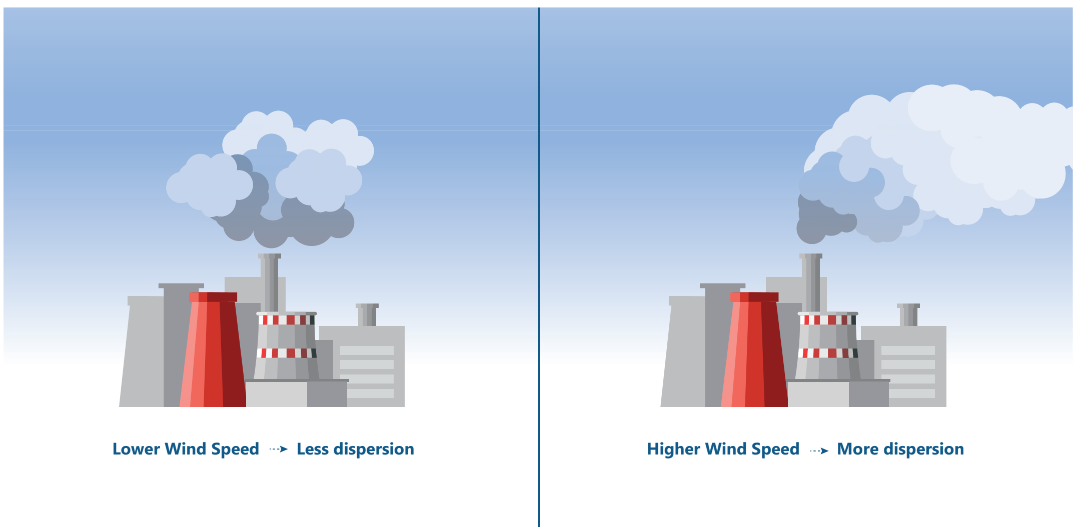


Figure 3-6b. *Winds aid in dispersing the pollutants.*

help determine where to sample relative to the sources of interest. Real-time local wind data are available through websites such as WunderMap.com.[26] To understand predominant winds, one practical method is to look at the position of the runway at an airport near or in your community. Most of the time, the runway is aligned with predominant winds (see **Figure 3-5** on page 3-16).

Winds and mixing height are key meteorological parameters that help explain pollutant concentrations. Mixing height is the height above ground to which pollutants can reach. Generally, higher mixing heights are associated with the lower pollutant concentrations. A low mixing height, such as an inversion, can lead to high pollutant concentrations. In an inversion, the normal decrease in air temperature with increasing altitude is reversed, and the air above the ground is warmer than the air below it – causing stable conditions that trap pollution (**Figure 3-6a**).

Similarly, pollutant concentrations decrease with increasing wind speed by increased dispersion (**Figure 3-6b**). Winds aid in dispersing the pollutants with concentrations proportional to the source emissions divided by the wind speed. Concentrations are also proportional to the source emissions divided by the mixing height.

A project team can include a project leader, participants, sensor users, and academic or regulatory partners.

List Your Resources

To maximize your resources, consider leveraging other work being done or that has been done. For example, be familiar with previous pollution measurement studies or other ongoing research in the area. Findings from these studies may provide important details to improve your measurement plan and provide important lessons about what worked and what did not. It is helpful to obtain regulatory data from your area. You can find out where this monitoring is conducted by going to your local air district's website and looking at the air quality monitoring page. In addition to researching past and current monitoring efforts and studies, speak with your local partners and community members regarding their observations of typical air quality trends and patterns related to local sources.

Some other specifics to consider once you have completed your background research are:

- Budget for sensors and accessories, data handling, technical personnel, participants' time, supporting project partners' time, communicating results, and extras like printing costs or refreshments for public meetings.
- Time constraints, especially if your project is grant funded.

- Technical abilities, knowledge, and skills of all those involved in the project (project leader, participants, sensor users, academic or regulatory partners, etc.). For example, consider whether any participants have:
  - Programming skills that can support data analysis and visualization.
  - Communication skills that can support outreach and keep participants updated and engaged throughout the deployment and build capacity within your community.
- Support for sensors at your desired monitoring sites such as power (e.g., electrical outlet, battery, or solar power), data communication (e.g., Wi-Fi, cellular, Bluetooth), security, access for installation, routine preventive maintenance, and servicing.
- What supplementary data you have or would like, and how to access it (e.g., meteorological data, such as wind speed and direction).

It will be important to allocate adequate time and resources to the project and include contingency planning to address problems that arise. With measurement projects, you will definitely face challenges. The structure of the project and the nature of the public's participation should also guide the allocation of funding and resources. For example, building local capacity, knowledge, and skills may take more time and resources upfront, but it is also likely to result in a stronger and more successful project due to the increased ability and ownership on the part of the partners. Finally, it is important to keep in mind that while low-cost air quality sensors are simpler to operate than conventional monitoring equipment, they are still a new technology for most members of the public.

Consider the technical abilities, knowledge, and skill of all those involved in the project.

Project Manager

Skills include planning, leading a team, budgeting, scheduling, and communication.

Field Technician

Skills include installing and maintaining the hardware, as well as technical support for wifi connections.

Data Scientist

Programming skills are very useful for performing data analysis and visualizing data.

Research Assistant

Understanding the pollutants in your area requires skills in research and planning.

Outreach Manager

Communication skills can support community outreach and keep team members updated and engaged.

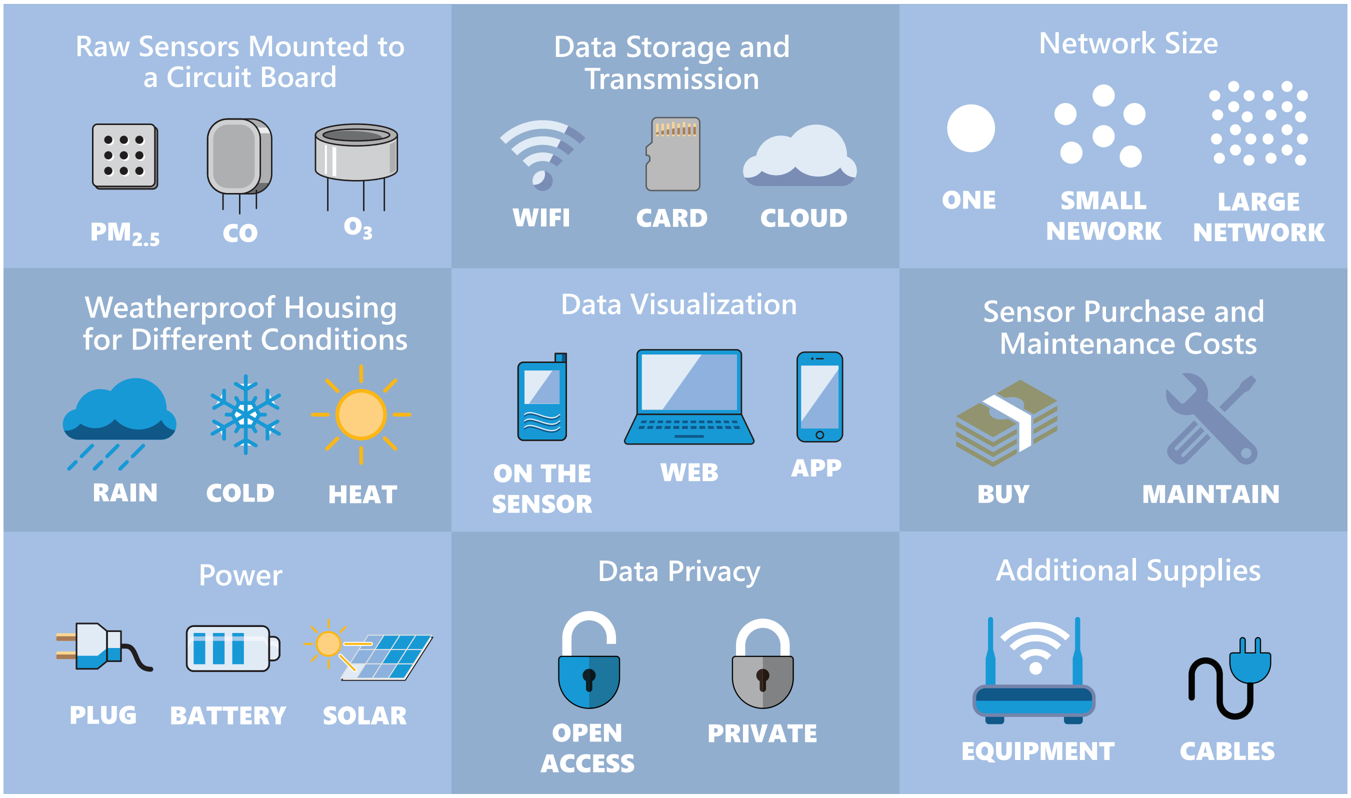


Figure 3-7. *Choose the right features for your sensors.*

How to Select a Sensor System

Overview

Selecting a sensor is probably the most critical step in your project. **Figure 3-7** shows sensor options to be considered. Key steps include choosing a sensor that can reliably measure your pollutant(s) of interest, at the level of concentrations you expect to see, with the level of accuracy and precision needed to address the research question, selecting the features you need for data communication/ processing/display, and fitting your budget and available resources.

For record-keeping, many community groups have found it useful to create a spreadsheet to summarize these key features and considerations of potential sensors for easier comparison and ranking.

Selecting a Sensor for the Pollutant(s) and Expected Concentrations

You can further narrow the sensor options based on other measures, such as sensor detection limit and accuracy/ precision.

In order for measurements to provide meaningful, and potentially actionable, information, it is important to understand measurement metrics such as precision, accuracy, and bias for the sensors you plan to use. Accuracy is the overall agreement of a sensor's measurement to the true concentration, typically as measured by a reference monitor. Precision is how well the sensor reproduces a measurement under identical circumstances—or the agreement among repeat measurements. Bias is measurement error such as consistently reporting higher or lower values than the true value. These metrics—accuracy, precision, and bias—are important to understand for achieving data goals and interpreting the data. These metrics can change over time and under different meteorological conditions. **Figure 3-8** shows a visual description of accuracy and precision. **Figure 3-9** shows an excerpt of a field evaluation of the PurpleAir PA-II showing results for accuracy.

The measurement metrics needed will vary from project to project. You need to make sure that the sensors are accurate enough and have low enough detection limits to provide data that will answer your project questions. Appendix K provides discussion of application-specific considerations regarding sensor performance and several examples of relevant pollutant concentrations based on past studies.

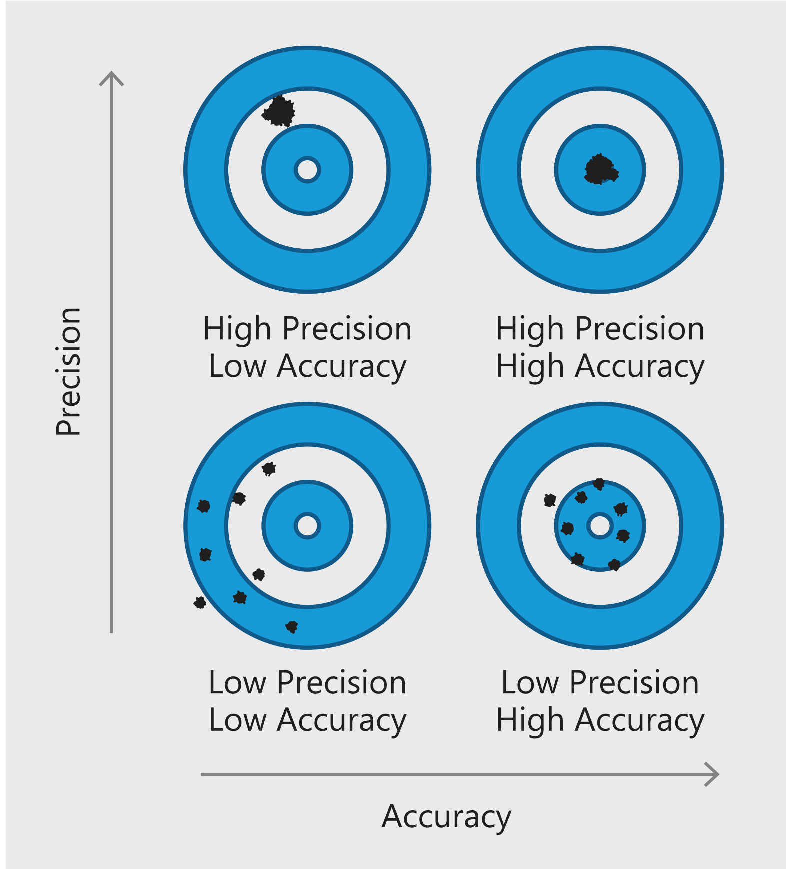


Figure 38. *Illustration of accuracy and precision. An example of bias is in the top left depiction.*

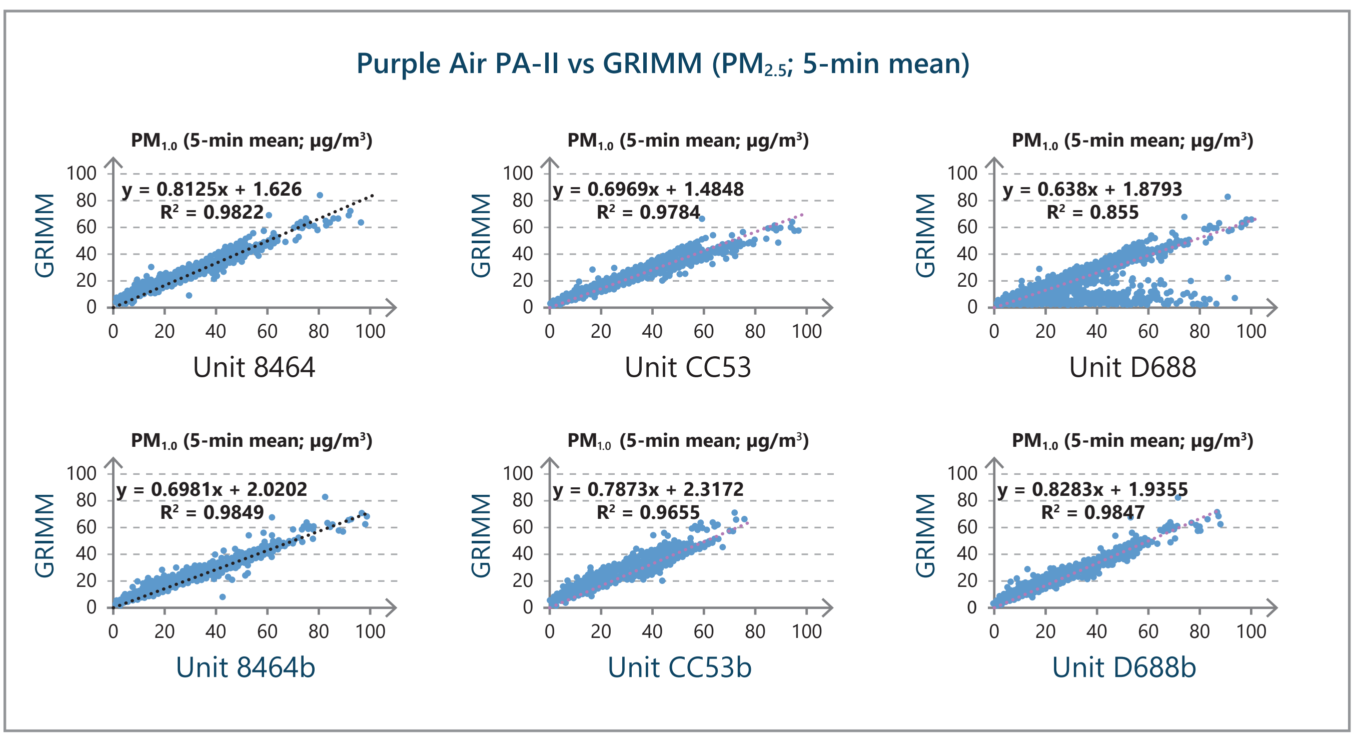


Figure 3-9. *Excerpt of an AQ-SPEC field evaluation of the PurpleAir PA-II. See Chapter 4 for discussion of scatter plots and linear regression.*

Sensor Evaluations

Sensors are being developed rapidly and there are dozens on the market. Sensor evaluations – for non-regulatory use – are being conducted and may be useful resources when considering whether a sensor might meet the needs of your project.

Detection Limit
A detection limit is the lowest concentration of a pollutant in the environment that a particular sensor or other instrument can routinely detect.

- South Coast AQMD's Air Quality Sensor Performance Evaluation Center (AQ-SPEC)[28]
- U.S. EPA Office of Research and Development (ORD)[29]
- People's Republic of China's Ministry of Environmental Protection (MEP)[30]
- European Committee for Standardization (CEN) Technical Committee 264, Working Group 42[31]

South Coast AQMD's AQ-SPEC program tests low-cost sensors according to protocols in order to both inform the public about the performance of commercially available sensors and to catalyze the successful evolution, development, and use of this technology. Sensors are evaluated in the field under ambient conditions and in the laboratory under controlled environmental conditions. In the field, sensors are tested at an existing air monitoring station using traditional FRM or FEM instruments to gauge overall performance. Sensors demonstrating acceptable performance in the field are then brought to the AQ-SPEC laboratory for more detailed testing in an environmental chamber under controlled conditions and alongside FEM, FRM, and/or best available technology instruments. AQ-SPEC has tested both particle and gaseous sensors.

EPA ORD conducts "research to advance the development and application of next generation air monitoring through its Sensor Performance Evaluation and Application Research (SPEAR) initiative." EPA is evaluating and testing commercial devices and developing and testing new instruments using miniaturized sensors and other technologies. The EPA prepared a summary of the sensors that have been tested.[32] EPA has tested both particle and gaseous sensors.

In 2017, the People's Republic of China's MEP developed performance standards for particle and gas sensor systems including criteria for laboratory and field evaluations (Environmental Protection Department of Hebei Province [China]). The standards also cover the methods to compare sensor data to reference instrument data, network design, technical requirements and testing methods, monitoring system quality assurance/quality control (QA/QC) and operation, and network installation and acceptance.

The CEN Technical Committee 264, Working Group 42 is developing technical specifications for performance requirements and test methods for low-cost sensors under prescribed laboratory and field conditions. The specifications will describe test procedures and requirements for performance evaluations of low-cost air sensor systems with a focus on gaseous compounds. Evaluations will include sensor sensitivity, selectivity, and stability.

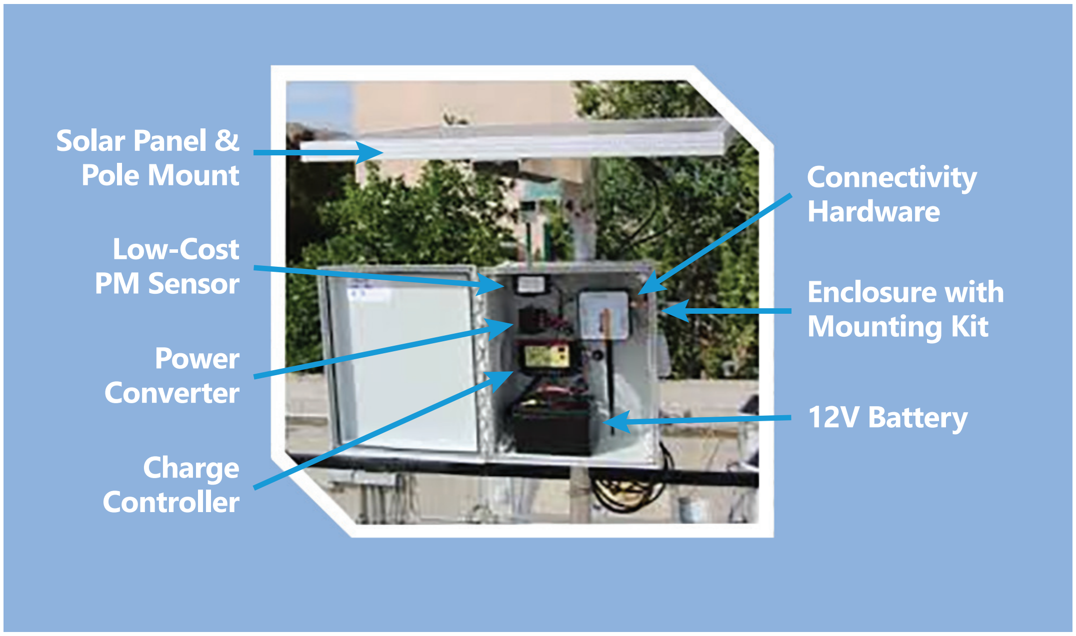


Figure 3-10. *An example of a sensor system.*

The Joint Research Centre (JRC) is the European Commission's science and knowledge service. In addition, the JRC published an evaluation of gaseous sensors.[33]

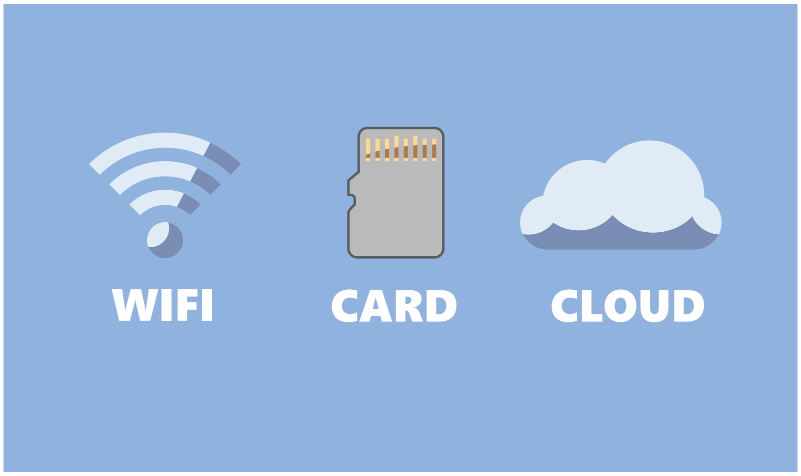
Experience has shown that commercially available sensors are preferred in community work because of their availability and technical support. However, there have been very successful partnerships between academia and community groups that worked together to deploy custom-made systems.

Ease of Use

A key criterion for sensor selection is usability – is the sensor system easy to use? For community involvement using a wide range of participants, intuitive and easy-to-use sensors are likely more desirable. Consider questions like: How complicated is the sensor to install? Is it easy to check if the sensor is still collecting data? Does the sensor include any features that sustain engagement (e.g., sending automatic notifications or offering a readily viewable screen)? If possible, it is useful to test various sensors with a community focus group to obtain feedback from the potential users based on hands-on experience.

Power Requirements

Depending on where you plan to deploy your sensors, you will be faced with how to power the sensors. Line power is a preferred option but is not always available. Some sensor systems can be set up with or come equipped with the option of solar panels. **Figure 3-10** shows an example of a sensor system.



Consider how the data are stored and accessed.

Access to Data and Data Handling

Another important consideration is the process of accessing data. Where are data stored and processed, and how are data transmitted? How important is having raw data versus final values? With regard to sensors, raw data often refers to the data taken from the sensor before any corrections, calibrations, or conversion equations have been applied. Raw data may refer to the electronic signal (e.g., voltage values) from the sensor, which is then corrected and converted into concentrations values. Or, raw may refer to minimally processed concentration values from a commercial sensor – sometimes data are available before a more complex correction algorithm(s) is applied to the data.

A user may want to use less-processed data (or raw data) if they intend to develop their own calibration equations or sensor data corrections. Or, a user may trust the correction algorithms developed by the manufacturer and prefer to use the processed and corrected data. In either case, it is useful to have an idea of the level of processing the data has undergone when selecting a sensor.

In addition to the type of data available, consider how the data are stored and accessed. Some sensors store data "locally" (i.e., on the sensor), for example on an SD card, and will need to be manually uploaded to a website or data analysis tool. Alternatively, many sensors automatically transmit data to a virtual computer server (i.e., cloud) for storage; however, these often require that the sensor be continuously linked to a Wi-Fi or cellular connection. Some sensors also transmit the data using cellular networks, which do not require Wi-Fi. However, an important consideration is that linking a sensor to a web service (using Wi-Fi or cellular networks) can be difficult and/or troublesome and not all participants may be equipped with internet access or Wi-Fi. A weak cellular signal can also lead to missing data because of connectivity issues. Also note that some sensors have monthly or annual data access subscriptions or cellular provider fees.

Be sure to consider the level of comfort with technology for everyone who will be using a sensor or interpreting the sensor data and the project's budget.

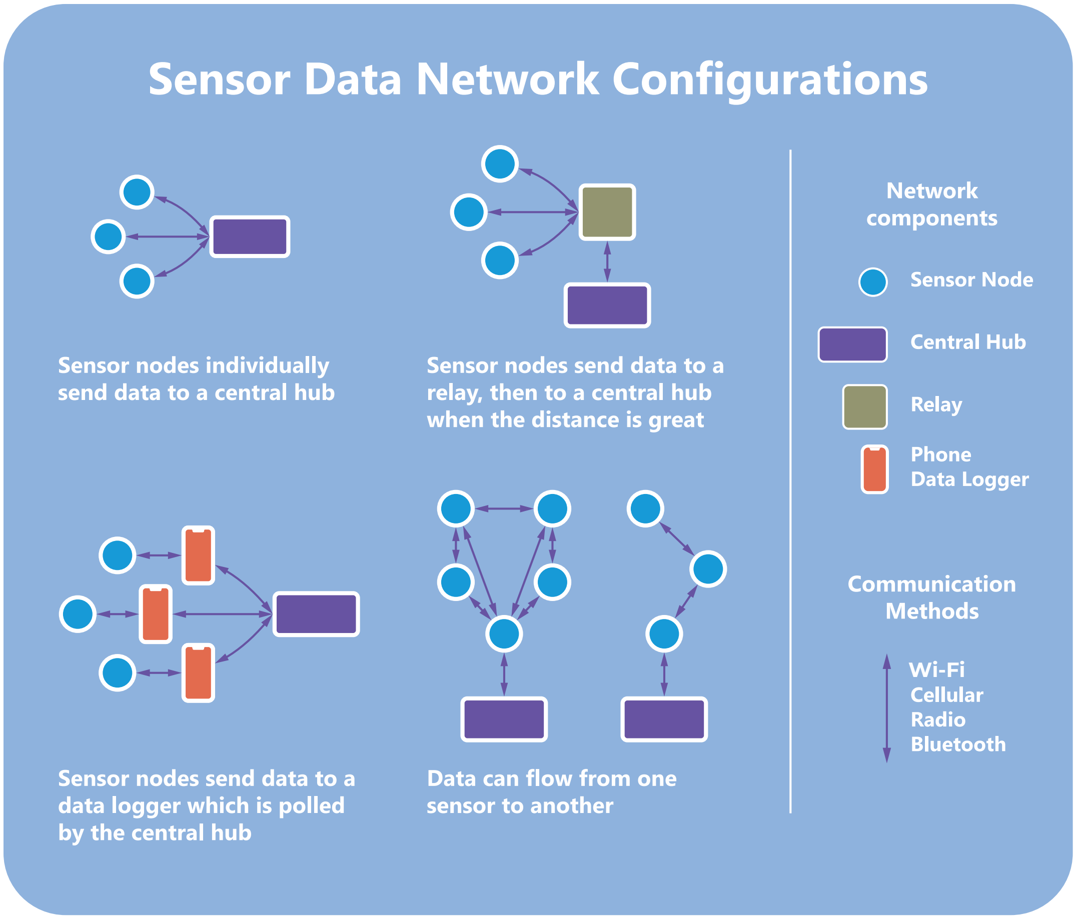
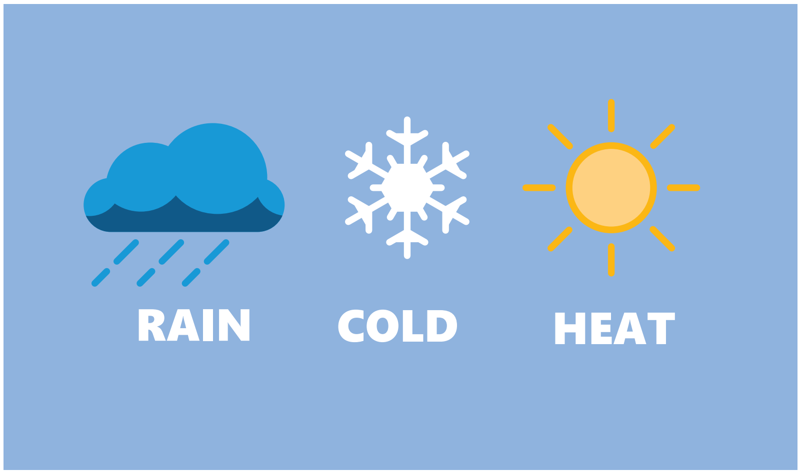


Figure 3-11. *Various sensor data network configurations.*

Figure 3-11 shows various sensor data network configurations. Sensor nodes could (1) individually send data to a central hub or (2) send data to relay to central hub (when the distance between the sensors and the central hub is greater than the transmission capabilities). Sensors also can send data to a data logger, which then is polled by the central hub. Data can also flow from one sensor to another.

Note that there are also differences in how the data are managed and communicated from one manufacturer to another. Some take an open access approach, while others use private cloud data processing, storage, and communication. Communities have expressed concerns about where data are kept and whether sensor manufacturers may go out of business and lose the sensor's data.

As further discussed in Chapter 4, it is important to watch your data during collection. Therefore, it is vital to have a way to visualize your data through maps, time series, and other graphics. Watching your data helps to ensure that problems are identified and solved early to maximize data capture. Also, by looking at data regularly, you can build an understanding of what you are seeing. Past projects have also found that while you may have provided training to a community, few sensors may have been deployed. Identifying this early helps you assess and readjust your outreach plans.



Sensors deployed outside will be exposed to the elements.

Durability

For any project, it is important to consider the sensor system durability. Durability refers to the sensor system's ability to endure wear and tear and continue to perform well. Sensors deployed outside will be exposed to heat, winds, moisture, and dust. Sensors will likely be jostled, shaken, and dropped. Sensors with strong, waterproof packaging will likely be more durable. For gas-phase sensors, the sensor can be poisoned over time and cease to work properly. Researchers and air quality agencies are learning more about sensor durability as deployments have gotten longer and more types/manufacturers of sensors are deployed.

Costs and Cost Effectiveness

Costs for sensor systems vary widely. Cost is always a significant consideration in project design. Individual sensors typically range from a few to several hundreds of dollars, while multi-sensor units range from a few hundred to a few thousands of dollars. You also may need to consider buying or renting a more sophisticated measurement method, such as an FEM, in order to meet your project goals. The size and composition of your sensor network can affect feasibility. It is easier to work with a small network (e.g., 1 to 10) consisting of the same type of sensor and manufacturer than it is to have a large network (e.g., more than 50) consisting of multiple types of sensors and/or sensor manufacturers. You will need to consider the entire sensor system, including data communication and access, replacement parts, how the system will be deployed (e.g., mounted, carried), and power requirements.

Project Description	Individual Sensor Cost	Additional Costs	Total for the First Year
An individual obtains a single sensor for personal monitoring, and the selected sensor provides open access to the data.	$200	$0	**$200**
A community network of 20 sensors that are fairly easy to set up and include open access to the data.	$150	$0	**$3,000**
Setting up a network of 12 sensors for fenceline monitoring around a source of potential concern, in this instance additional housing is needed to protect the sensors from weather as well as a system for data logging and communications.	$400	$1,000 (for housing, per sensor) $650 (for data logging and cellular communications, per month for network)	**$24,600**
A community network utilizing fewer (five), but more complex multi-pollutant devices that also require a subscription to access the data.	$3,000	$500 (per unit, per year)	**$17,500**

Table 3-4. *Examples of costs for various project sizes.*

Table 3-4 provides an example of sensor system costs for a project. Planning for replacing some systems with new ones because of system failure, vandalism, or theft is prudent as well.

If you are concerned about funding, consider starting with a pilot project, or a smaller and more preliminary version of the project you envision, the results of which could help you obtain more funding for future iterations of the project. Also, check into Sensor Libraries and Sensor Loan Programs; a program such as this may meet your project needs in terms of access to sensors or it may be a good way to conduct a pilot project. Information about available loan programs is listed on the EPA's website.[34]

Technical Support

Another key part of a project, and project plan, is to include adequate people and funds for technical support to the community. Technical support includes training on how to use sensors, troubleshooting sensor issues with community members (throughout the entire deployment), creating videos about various aspects of a project (e.g., sensor installation, sensor siting), and creating installation guides or checklists (e.g., see Appendix C of this document). Some communities have found it effective to engage students in their projects to help with technology (e.g., the sensors, Wi-Fi) questions from other community members.

Sensor Project Tips

Key tips from community and research monitoring studies are summarized below:

Schedule
Build adequate time into your plan to acquire and assemble equipment. Sometimes sensor systems can be in scarce supply, particularly if the sensor manufacturer is relatively new to the business.

Training
Obtain and provide adequate training for equipment. Training is key to helping your participants obtain useful data. Having people available to help participants troubleshoot their sensors and answer questions throughout the deployment of the sensors helps ensure a smoother project and limit participant frustration.

Pre-project testing
Perform tests to ensure the equipment operates as expected. Initial testing of sensor systems for your particular use is important. You will need to ensure that participants can easily use the systems as intended.

Data quality
Include quality assurance in your planning. A project with poor quality data can be less useful than no data collected at all.

One common issue with community low-cost sensor projects is confusion over what emissions are of interest versus what the sensor can actually measure. Often, a participant will be concerned with gaseous emissions, say from a gasoline station, but the sensor is measuring particles which are not emitted from gasoline evaporation. Make sure that community expectations are understood, managed, and reconciled with what is feasible during the planning process to minimize confusion and dissatisfaction later in the project.

For Further Reading

- Air Sensor Guidebook[35]
- Guidebook for Developing a Community Monitoring Network[36]

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35. https://www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook

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04 Deploying Your Sensors

Key components to successfully deploying a sensor network include:

1. Using and troubleshooting your sensor
2. Collecting useful, useable data
3. Understanding your data

Sensor hosts will need training if they will be installing and maintaining their own sensors.

Using and Troubleshooting Sensors

Training

How will the sensors be installed or who will install them?

To begin, the project leads should decide how to approach sensor installation. For example, sensors can be provided to individuals who can then install them on their own, or the project can rely on a single installer or small team of installers. To make this decision, consider project resources, scope, objectives, and the technical abilities of participants. Project leads may wish to use resources to support the work of the installer or installation team. A benefit of this approach is that using a single installer or small team of installers may result in more uniform installations of the sensors and thus more reliable data. However, the project scope (i.e., the size of the planned sensor network) or available resources may necessitate installation by sensor hosts.

Installation by a single installer or team of installers

To ensure installation is consistent and as directed, it is important to develop an SOP (standard operating procedure) or set of instructions to guide the installers. See Appendix C for installation guidance for the PurpleAir sensor. Best practices include holding in-person training sessions where the installers can familiarize themselves with the sensors, practice installation, and have the opportunity to ask questions. To document installation, it is important to implement a system for installers to record notes. These notes may include the time and date of the installation, the location, and photographs or descriptions of the area surrounding the sensor.

Installation by participants or sensor hosts

For installation by sensor hosts, all participants will need training on how to install and use their sensor. Depending on the size of the deployment, it is common practice to "train the trainer," when an expert trains a few project members who then lead a larger training for the community. Training includes providing information about the project goals, requirements for the sensors (such as the need for Wi-Fi), where to install the sensor (siting criteria), how to minimize your impact on the measurements, how to look at the data being collected, basic troubleshooting of the sensing system, and how the data will be used.

Clear, brief, laminated instructions describing the sensor system installation, configuration, and data access are useful for participants. The Star Grant project found that installation guides should limit text and rely on visual aids (i.e., images, diagrams, etc.). Appendix B has some useful frequently asked questions (and answers). Appendix C provides installation information for the PurpleAir PA-II sensor. Appendix F provides a template to assist with the development of guides for new/different sensors based on lessons learned developing the PurpleAir Installation Guide.

It is important to consider whether a partner community may need resources translated. When information needs to be translated, it is useful to create instructions that rely heavily on photos and diagrams with fewer words to ease translation. **Figure 4-1** shows an example excerpt of a community-produced "how-to" guide that greatly reduced the use of words to facilitate easier translation.

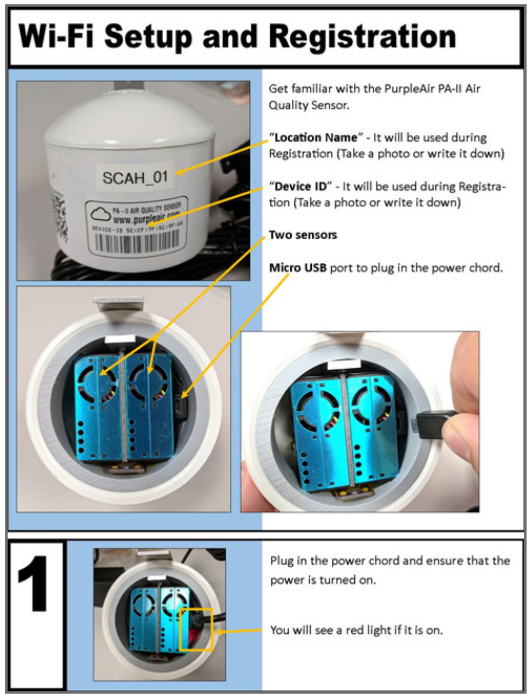


Figure 4-1. *Excerpt of PurpleAir PA-II installation instructions produced by the Bay Area Air Quality Management District in collaboration with the Oakland, CA, community partner, Asian Health Services. Less text and more images were used to facilitate translation into seven languages used in the community.*

In working with communities, it is important to remember that people have different ways of learning, so multiple approaches are useful, if not necessary. For example, a combination of hands-on training, handouts, presentations, and videos may be optimum. Communities should also note that training may need to be conducted at different times of day, on different days of the week, and at different locations to reach more community members. In some communities, translation during meetings may be needed.

The key to identifying sensor problems is to frequently look at the data being collected.

Maintaining the Sensor

Maintaining sensor performance over the project period may require some action (preventative maintenance), such as cleaning a part of the system, replacing a battery, or simply turning the system off and on. Sensor degradation is an important consideration because an entire sensor may need to be replaced in a multi-unit device.

It is important to provide simple troubleshooting and maintenance instructions for participants so that they can address basic issues. Common sensor issues include sensor failure, fouling from dusty conditions, and insect nests or spider webs in the air inlet. Consider making a maintenance schedule and sending reminders to the sensor hosts if there is anything that will need to be completed throughout the deployment.

Identifying Sensor Problems

The key to identifying sensor problems is to frequently look at the data being collected. If the data stops being shown, the sensor may have lost power, lost connection with Wi-Fi, or have some other problem that needs to be addressed. Observe how the data change with the time of day and the day of week to see if there are regular patterns. It is important to watch your data across weeks and months of collection to see if the lowest values (baseline) or highest values are changing significantly. A gradual change over time, also referred to as drift, could indicate degradation of the sensor. It is also useful to look at data from other sensors or measurements made nearby and compare these to your sensor. If your sensor is consistently showing very different readings, it may be malfunctioning or need some troubleshooting. More details are discussed and shown in the next section.

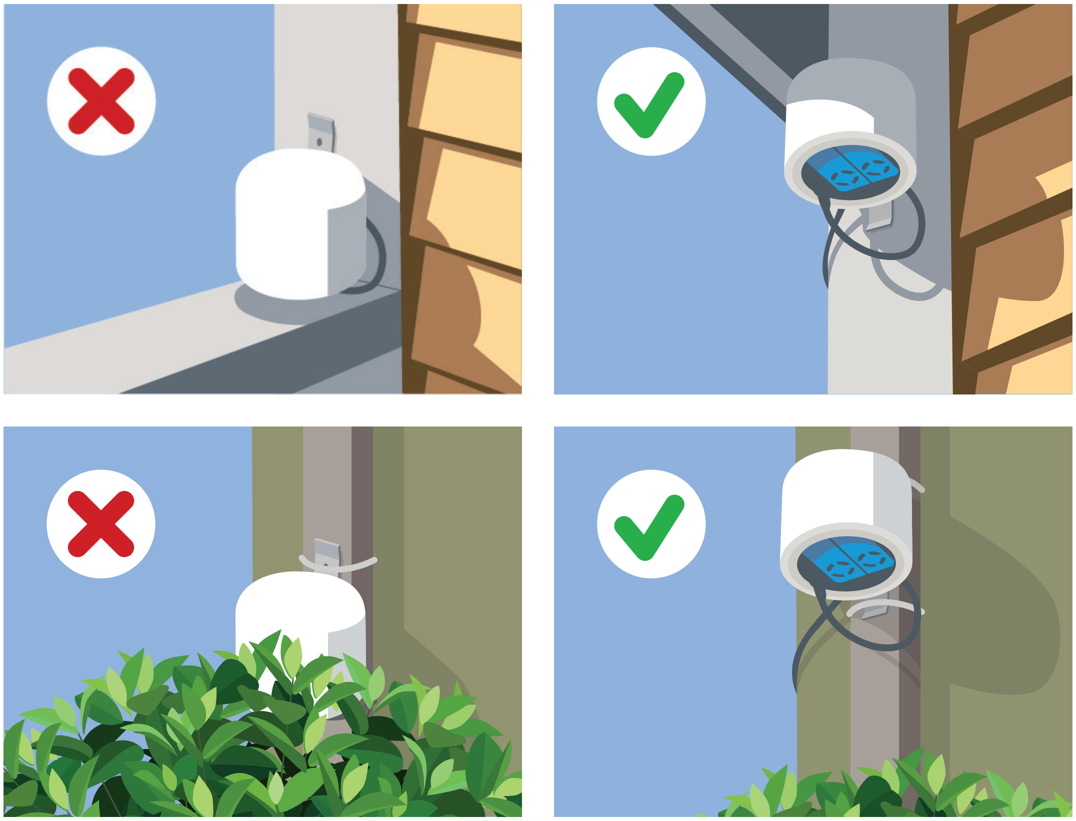


Figure 4-2. Proper and improper examples of sensor siting.

Collecting Useful Data

A project's goals cannot be met unless the data collected are of sufficient quality to answer the project questions.

Key aspects of data quality are:

1. Understanding (and controlling) participant's impact on measurements,
2. Maintaining sufficient quality control throughout the project, and
3. Collocating sensors before and after the project to understand precision.

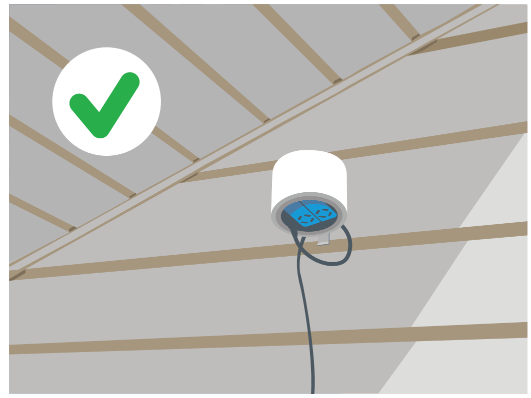
Siting Criteria

It is very important to, if possible, place sensors at breathing height and in a position with unobstructed airflow. Some sensors need protection from direct sunlight. **Figure 4-2** shows proper and improper examples of placement of a PurpleAir sensor. The not-so-good examples show that the PurpleAir is placed too close to a surface or foliage, which would impede airflow.

It is also very important to minimize your personal impact on a sensor – such as not smoking in the vicinity of the sensor and not placing it next to a grill or fireplace or near your vehicle tailpipe. Installation tips are provided in Appendices B and C.

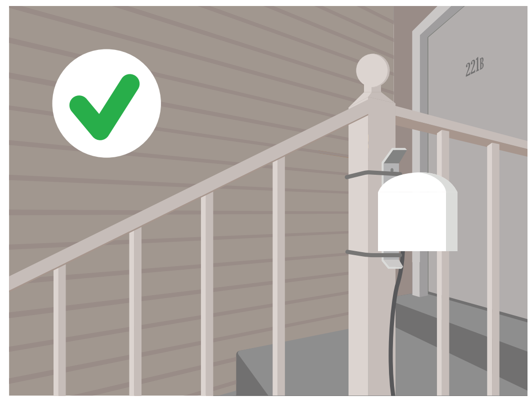
Place sensors at breathing height, with unobstructed air flow, and away from sources of emissions.

Poor location: *The sensor is placed too close to a source of emissions that will affect measurements.*



Good location: *The sensor has good air flow and is sheltered from the elements.*

Poor location: *Think about how the location will change if, for example, a car is idling near your sensor.*



Good location: *Breathing height can be higher off the ground, such as outside this second-story apartment.*

For Further Reading

For more information on what researchers have learned about siting sensors, you can check out the EPA's Air Sensor Guidebook[1] and these academic papers:

Low-cost sensors and crowd-sourced data: Observations of siting impacts on a network of air-quality instruments.[2]

Combining Community Engagement and Scientific Approaches in Next-Generation Monitor Siting: The Case of the Imperial County Community Air Network.[3]

Comparing Building and Neighborhood-Scale Variability of CO_2 and O_3 to Inform Deployment Considerations for Low-Cost Sensor System Use.[4]

Quality Control While Collecting Data

For ongoing quality control, there are several recommended key actions.

Follow guidelines on sensor use. Provide sensor users with simple lists of dos and don'ts. Some examples include:

- Do follow provided instructions on sensor placement and use.
- Don't place your sensor near sources such as a BBQ, air conditioning unit, or dryer vent.
- Do make sure there is unrestricted airflow to your sensor.
- Do take notes about weather and pollution observations – these will come in handy during data analysis.

Regularly review data. While you will more fully address data quality during the analysis phase, quick checks to make sure a sensor is working properly can help to ensure you are collecting usable data and keeping data gaps to a minimum. Also, by watching the data, you are learning about how pollutant concentrations change from day to day and hour to hour, which will be important in later analysis. It's helpful to establish a schedule for reviewing data and some simple benchmarks to quickly check. For examples, see **Table 4-1.**

Table 4-1. *Common data quality checks (assuming 1-minute sample frequency), what to look for, and how to interpret the finding.*

Check	What to look for	Action/Interpretation
Low values	Long periods (10s of minutes) of a zero concentration or negative values.	The sensor may be malfunctioning.
Missing data	Data gaps or no signal at all.	The sensor may have lost power, lost connection to the Internet, or may be malfunctioning.
Sticking	Four or more minutes with exactly the same, non-zero concentration.	The sensor may be malfunctioning.
Sensor-to-sensor	One sensor over a period of time is reporting much higher or lower concentrations than nearby sensors.	Check to see if one of the sensors is located near a source because higher concentrations near a source might be expected. A series of unusual readings in an area at just one sensor may indicate a problem with that sensor.
Very high values	Very high, possibly erratic, concentrations.	This behavior may be seen during start up periods for sensors that need time to warm up. For particle measurements, this could indicate high humidity interference. This could also indicate the sensor is operating in weather conditions beyond those recommended by the sensor manufacturer (e.g., extreme cold).

Use a Log Sheet to keep track of what's happening near where you are sampling.

Keep track of what's happening near where you are sampling. For example, community members can use the Log Sheet in Appendix H or a similar tool to record weather conditions, nearby emissions or activities, presence of smoke or odors, and the local Air Quality Index.

Calibrate sensors before, during, and at the end of sampling (ideally). One method is to collocate the sensors with an FEM operated by a university or air quality agency in or near your community. More information about collocation is provided on page 4-9. If this method is not available to you, you will need to establish another way to assess the quality of your data, possibly with the assistance of a scientific partner.

If your project's objectives involve sharing data and results with outside groups (e.g., local/regional/state government agencies or local industry), consider using the Quality Assurance Handbook and Guidance Documents for Citizen Science Projects[5] developed by the U.S. EPA. This resource includes a Handbook to guide the development of a QAPP (Quality Assurance Project Plan), examples of QAPPs for citizen science projects, and template documents that you can use. Developing and using a QAPP for your project will enable groups outside of the project to understand and assess the quality of the data collected, which may strengthen any conclusions drawn from the data.

Supplementing Your Data

Supplementary data can be very valuable when analyzing and interpreting the data from your sensor(s). Keeping track of any events that you believe may affect your local air quality (as mentioned in the previous section) will give you the opportunity to compare your observations to the sensor data and assess whether or not your perceptions and the sensor data agree and why this might be the case. Appendix H contains a blank copy of a log sheet that can be copied and used

Figure 4-3. PurpleAir PA-II sensors collocated with regulatory monitors at the South Coast AQMD Ambient Monitoring Station site in Rubidoux, California

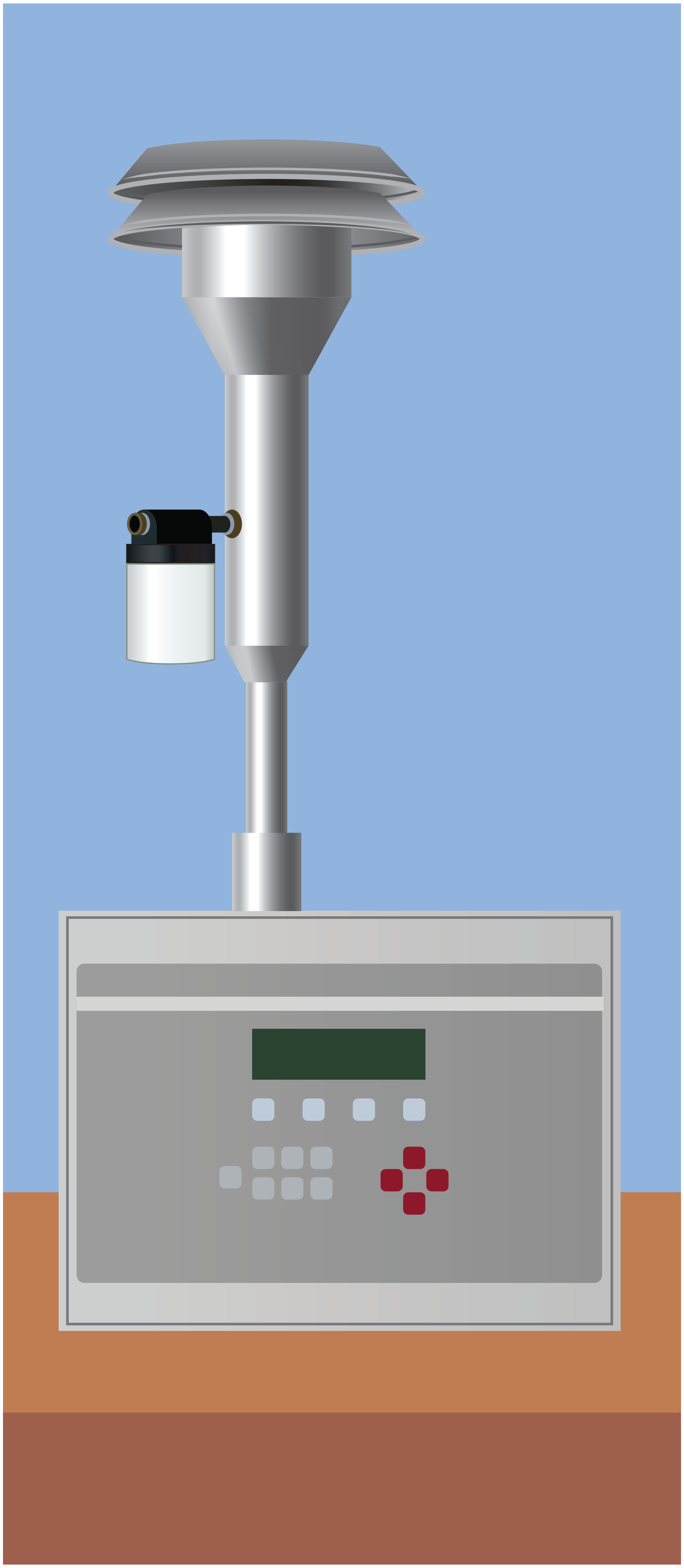
to effectively note these observations. Other supplementary data that can be helpful during data analysis and interpretation include maps showing the locations of pollution sources and wind speed and direction. Wind data can help indicate likely sources by showing the direction from which pollution may have come.

Collocating Your Sensors Pre- and Post-Deployment

Collocation means operating the sensors (all or a subset) in one location at the beginning of a project, prior to the deployment. Ideally, this will occur at a site with high-quality reliable reference monitors (e.g., a regulatory air monitoring station). This provides an opportunity to understand any differences between the sensors (bias, intra-model variability for a network of the same type of sensor, inter-model variability for a network of more than one type of sensors). If you also have data from a reference monitor, you can develop a calibration model or a correction algorithm for the sensor data to improve the accuracy of the data. A post-deployment collocation is key as well to see if the relationship among the sensors has changed. If possible, add a way to check sensor performance during the deployment. This could include placing duplicate or triplicate sensors at some sites, moving sensors for a temporary collocation during the deployment, or bringing a reliable monitor to a sensor's location. An example collocation of sensors at a regulatory monitoring site is shown in **Figure 4-3**. With multiple collocations:

- Bias between sensors can be corrected.
- Drift of sensor readings over time can be caught and corrected.
- Sensor accuracy can be determined and possibly improved if the collocation includes a reference monitor.

If you would like to conduct a field collocation, the next section lists some



steps to help guide you through this process. An important consideration is how many sensors you intend to deploy. If you are deploying only a few, it is reasonable to collocate all of them. However, if you are deploying a large network, then collocating all of the sensors may not be feasible. In the latter case, you can try collocating a portion of your sensors and developing a general calibration model or correction algorithm that can be applied to all of your sensors. Or, you can simply use the collocation to quantify the expected average error from your sensors.

How to Conduct a Collocation

1. **Find a local FEM or FRM.** Contact your local regulatory agency to find which site you may access for collocation that has the appropriate reference instruments for comparison. Work with them to schedule a time for the collocations and coordinate your access. The agency will likely request basic information about your project and the sensors you are using for their records; use the template in Appendix G to draft this document. Appendix J contains guidance on how to contact your local agency.

2. **Collect your collocated data.** Review your collocated data to ensure you have all the data you need and to determine whether there were any sensor malfunctions. In How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors,[6] EPA suggests a collocation period of a week for 5-minute data. Though the collocation duration should be adjusted as needed, ideally you want your sensors to experience pollutant concentration ranges and environmental conditions similar to what they will experience during the deployment.

3. **Obtain data from the reference instruments to compare and use to correct your sensor data.** If you would like minute-resolution data, speak with your site contact about obtaining this data. If you would like hourly averaged data and your project is in California, this data set is available publicly at the California Air Resources Board website,[7] by selecting your monitoring station and pollutant of interest.

4. **Analyze your data.** You are now ready for the data analysis phase – either follow an existing plan to compare data or use the reference data to correct your sensor data. Or you can use a guide and tool developed by the EPA called the Macro Analysis Tool, or MAT.[8]

Researchers are continually developing and testing methods for sensor network calibrations and different calibration models. Consider finding an academic partner to assist with sensor performance and calibration issues.

For Further Reading

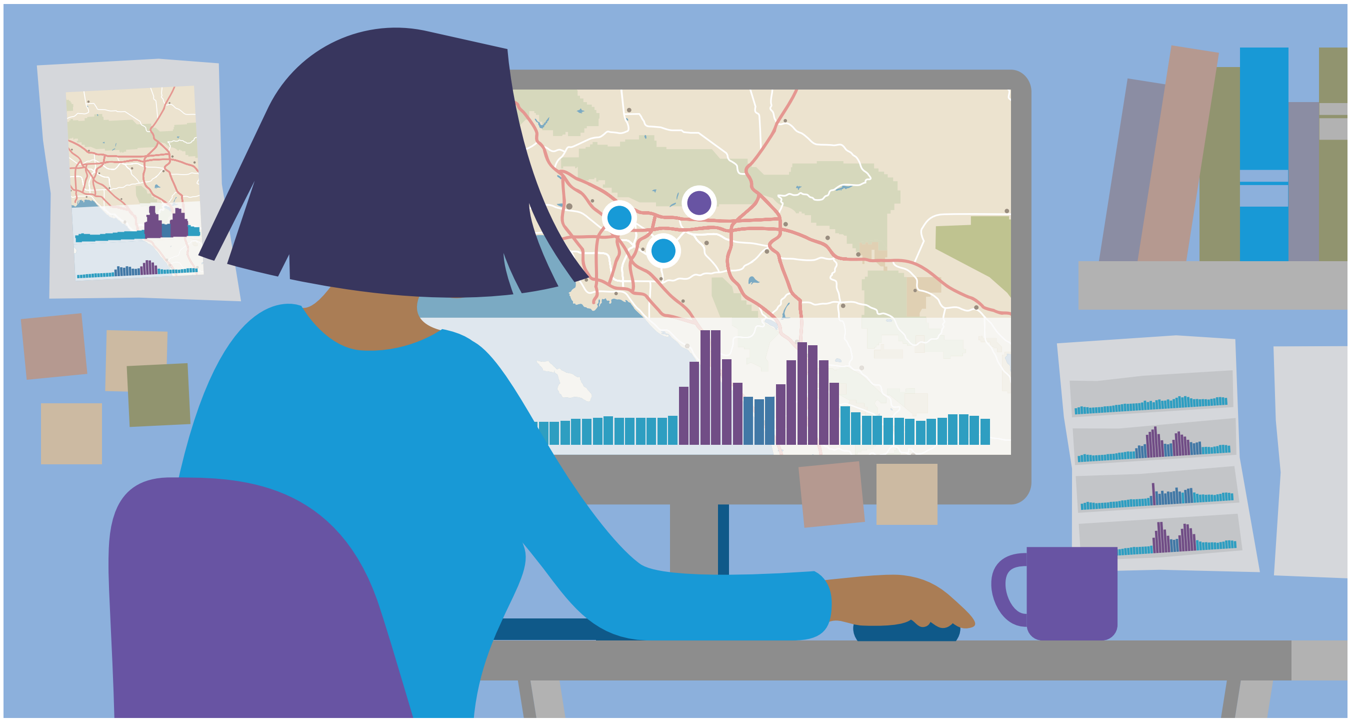
The following journal articles provide examples of low-cost sensor studies that used a collocation to either develop a calibration model or a correction algorithm. The articles can be used to learn more about how they are typically conducted, how to use collocated data, and lessons learned.

How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors.[6]

Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?[9]

A Survey on Sensor Calibration in Air Pollution Monitoring Deployments.[10]

Development of a General Calibration Model and Long-Term Performance Evaluation of Low-Cost Sensors for Air Pollutant Gas Monitoring.[11]



Visualizing your data is key. Visual data review is focused on patterns to verify that data are reasonable.

Understanding Your Data

Interacting with Your Data

The first step to successful data analysis and interpretation is identifying tools or a platform to support your analysis and get your data into a format that you can work with. Some sensors provide a data management and exploration platform that is web-based and allows you to view and assess the data. However, if this is not the case, it is recommended that you briefly explore what tools are available and choose a method appropriate to your comfort and skill levels.

A few tools and platforms for data exploration and analysis are listed in this section; for other advice, speak with an academic or regulatory partner on your project. For more information on these tools and platforms, as well as tips for accessing sensor data and getting it into the correct format, see the Data Analysis Guide in Appendix D and the PurpleAir Sensor Data Processing Guides in Appendix C.

Spreadsheets (e.g., Excel): Microsoft Excel is fairly easy to use for basic data analysis and assessment, and online help and tutorials are widely available. Additionally, the EPA's Macro Analysis tool[8] for assessing collocated sensor data was designed for Microsoft Excel. The tool helps users compare data from low-cost sensors to data from regulatory monitors and interpret their results. The tool allows input of data from low-cost and regulatory monitors for comparison, even if measurements weren't recorded at precisely the same time, or were collected at different time intervals, such as 1-minute versus 5-minute intervals. Microsoft Excel can also complement the tools already provided by some sensor manufacturers. For example, if a manufacturer already offers a real-time map, you can use Microsoft Excel to make other types of plots (such as time series plots) throughout the deployment

– providing another way of viewing and understanding your data. At the end of your deployment, you can download the complete data and open it in Microsoft Excel to analyze and assess the full data set. Microsoft Excel can handle up to about 1 million records. One consideration is that Excel lacks mapping capabilities.

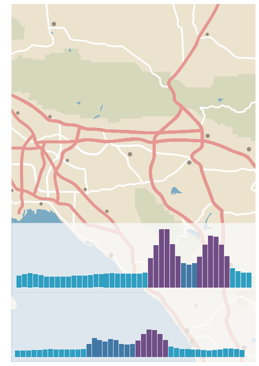
Real Time Geospatial Data Viewer (RETIGO): This tool developed by EPA provides a relatively easy way to upload and visualize air quality data on maps and through other types of plots. In addition, the tool allows you to study changes in concentration relative to specific points (e.g., a source) or lines (e.g., a road). The EPA provides training documentation and tutorials[12] to help you with this process. This tool can handle large data sets and is free.

RStudio & the OpenAir package: If you or a project member have good programming skills or experience coding in R (an open-source language for statistical computing and graphics), RStudio (open-source environment) is a great option. Tools in the OpenAir package[13] make formatting, processing, and plotting air quality data simple and powerful. R has a steep learning curve but is free and has a large user community that shares code. R can handle very large data sets.

RStudio & the AirSensor package: This is another package available for use with RStudio. This package enables easy access to, processing of, and the analysis/visualization of low-cost sensor data. Currently this package supports interaction with data from PurpleAir PA-II sensors (i.e., $PM_{2.5}$ mass concentration data in µg/m^3). Again, if you or a project member has experience with the R programming language, the AirSensor package[14] is well-suited to support ongoing monitoring of the data from your sensor network, with the help of sensor "state-of-health" metrics. This package also supports the final processing and analysis of data from the completed deployment, with the help of QA/QC algorithms and other functions enabling analysis and powerful visualizations of the data.

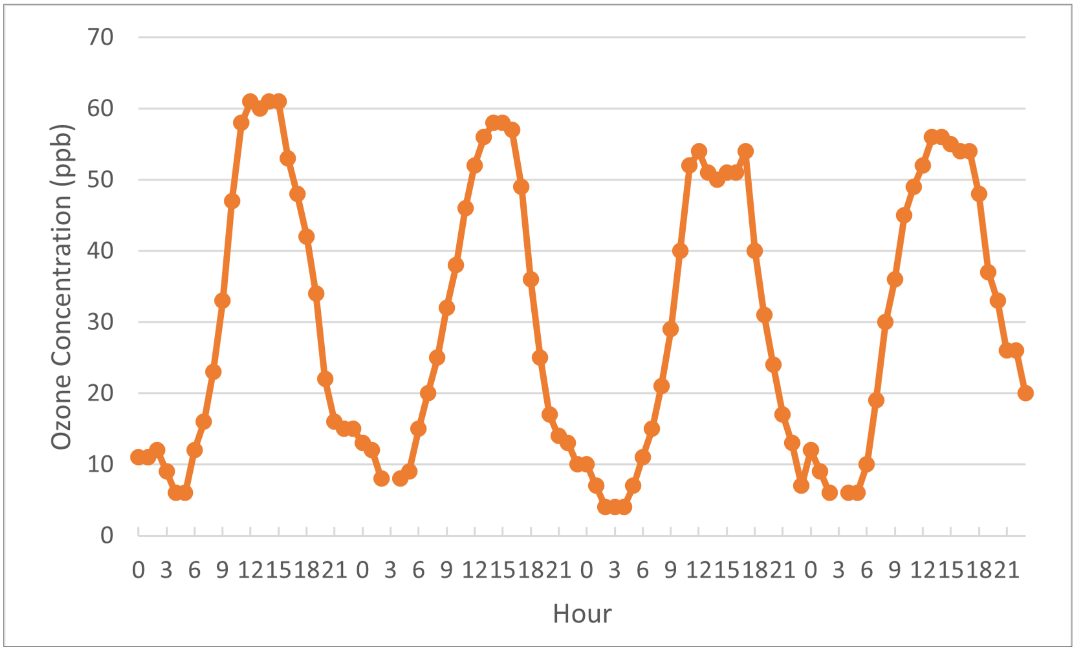
AirSensor DataViewer: The AirSensor DataViewer is a web-based data visualization tool that leverages the AirSensor package to provide access to, processing of, and visualizations of low-cost sensor data. This tool requires no programming experience and has a user-friendly and engaging interface that allows users to explore their data using a variety of different plots. Currently this tool is limited to providing data from PurpleAir PA-II sensors used in the EPA funded STAR Grant project, titled "Engage, Educate and Empower California Communities on the Use and Applications of Low-cost Air Monitoring Sensors."[15] However, as the package is open source, this resource could be replicated and adapted to provide access to sensors belonging to a different project. South Coast AQMD has posted this tool as part of their AQ-SPEC website.[16] A user guide for this tool is available in Appendix L.

Other options: Custom solutions to data handling and analysis can be built to meet project needs; however, this is typically very costly. Some air quality agencies, including the California Air Resources Board, are developing data management and analysis platforms for community-collected data. Finally, there are other commercial options such as Microsoft Power BI, Google Earth, and ArcGIS. Similar to R, these options can have a steep learning curve and vary widely in graphing ability, cost, and ability to share visuals with others.



South Coast AQMD's AirSensor DataViewer is a free, web-based tool that allows users to explore their data using a variety of different plots.

Figure 4-4. *Example of a time series plot of preliminary 1-hr ozone data (ppb) retrieved from [AirNow-Tech][17] for Elk Grove, California (July 8-11, 2020).*



Validating Your Sensor Data

Data validation is the process of determining the quality and validity of observations. The purpose is to detect any data values that may not represent the actual physical and chemical conditions at the sampling location. During your project, it is important to look at data early and often to correct problems before the project is over. It is also very helpful to keep notes or a log about weather, air quality conditions, and unusual events (e.g., "concentrations increased when neighbor was grilling outdoors") that could affect your data. This information is useful in data interpretation and assessing validity. Problems with the data may look like those listed in **Table 4-1**, and they may require some simple filtering.

Generally, the more data (of sufficient quality) that you have, the more confidence you can have in your results. As you prepare your valid data set, being able to visualize your data is key. Visual data review is focused on patterns – diurnal (i.e., time of day) and spatial – to verify that data are reasonable. Consider the following data visualizations (and see the Data Analysis Guide in Appendix D):

Time-series plots: Are concentrations consistent with the time of day, the day of the week, the season, and other pollutant concentrations? Are peak or low concentrations occurring where and when they are expected? Do concentration spikes or dips correspond with those of other pollutants? Are they consistent with meteorology (e.g., changes in wind direction or wind speed)? Do baseline concentrations remain stable over time? **Figure 4-4** shows a time series of 1-hr ozone concentrations at a monitoring site in California. Ozone concentrations typically peak in the afternoon.

Scatter plots: Are pollutant concentration relationships as expected? Do concentrations at some sites correlate while others do not? Scatter plots can be a quick way to determine major sensor malfunctions, especially when you expect sensors to exhibit similar behavior overall. **Figure 4-5** shows a comparison of two sensors during collocation. The sensors compared well, which gives us confidence that differences found between sites during the project were real.

Maps: Do concentrations vary throughout the community in the way you expected (e.g., do the sites where you expected higher concentrations typically show higher concentrations)? Are concentrations higher near known sources? **Figure 4-6** shows a sample map from PurpleAir in the Los Angeles area. Higher concentrations are seen in heavily trafficked areas and downwind near the mountains, as expected when winds are onshore and weather conditions are conducive to pollution formation and transport.

A good way to validate data throughout the deployment is to define a set of "state-of-health" metrics and then oversee sensors closely to understand/confirm how well they adhere to these metrics. Metrics may include data completeness, whether sensor data are within expected ranges, the degree of correlation between different sensors in a single device, and regression statistics from comparisons to nearby reference instruments or other sensors.

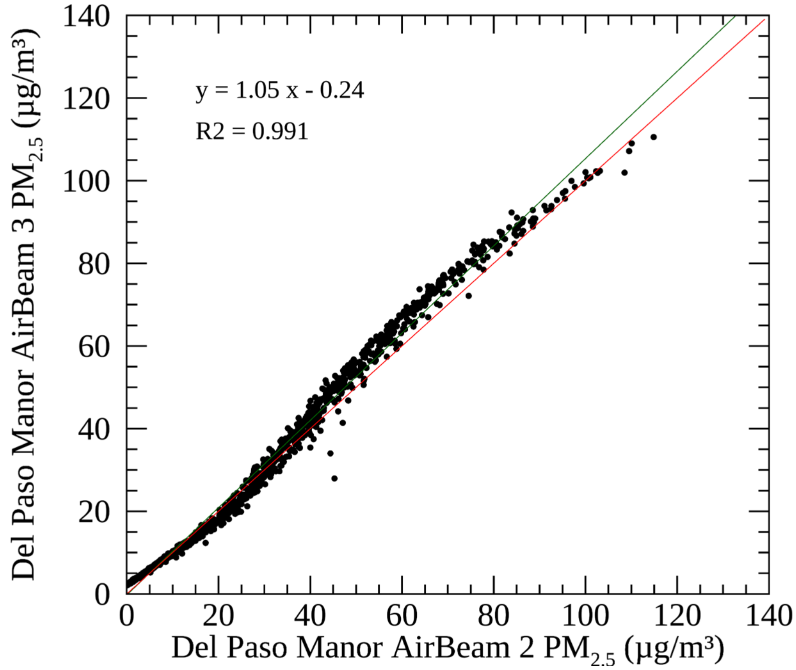


__Figure 4-5.__ Sample sensor versus sensor comparison[18] from a low-cost sensor study in Sacramento, CA.

Figure 4-7 on the following page shows an example of a plot summarizing how well the specified sensor is adhering to the predefined "state-of-health" metrics. This example was created using metrics and plotting functions available in the AirSensor package.

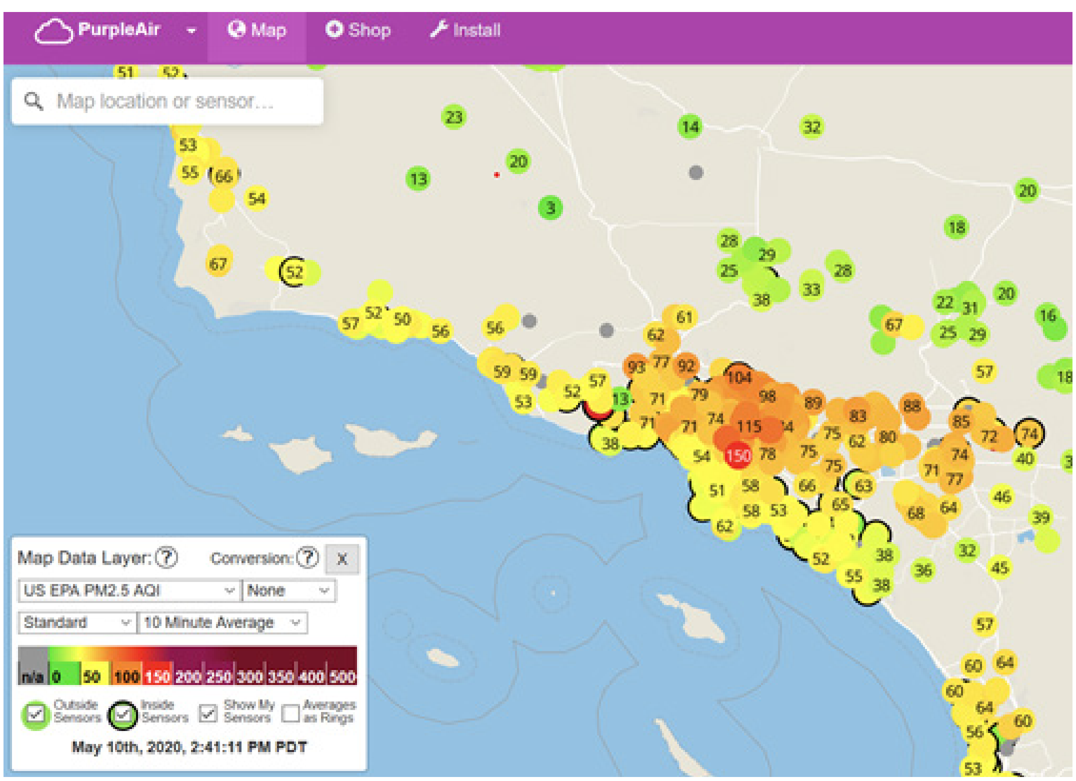


__Figure 4-6.__ PurpleAir map showing levels of $PM_{2.5}$ using a color gradient and numbers.

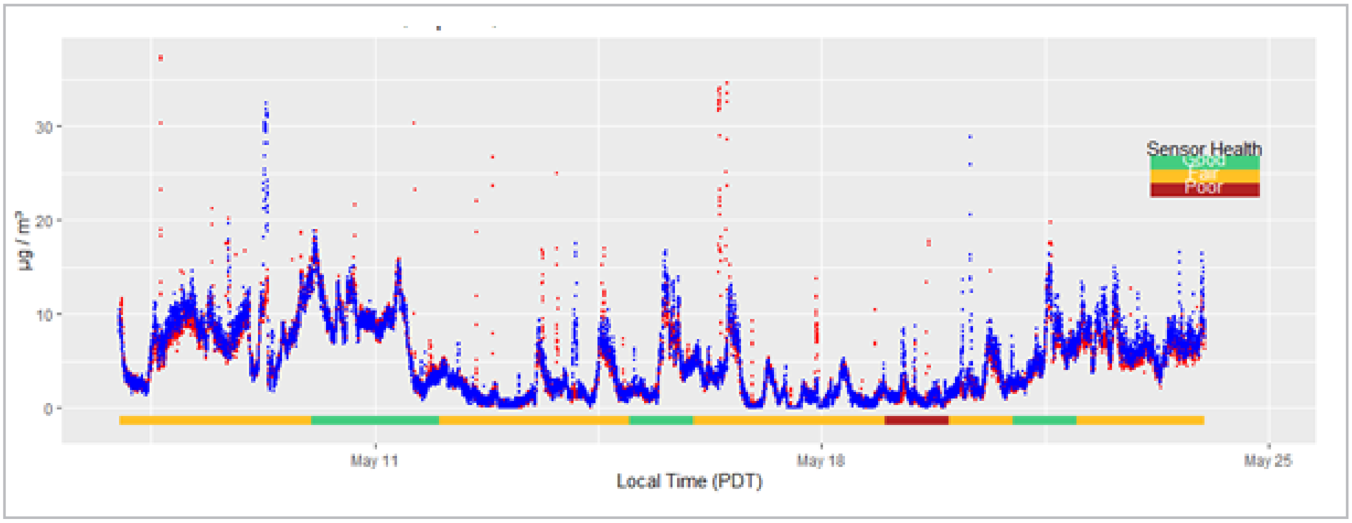


Figure 4-7. *Sample plot created using the function 'pat_dailySoHIndexPlot()' in the AirSensor package.*

The blue line is $PM_{2.5}$ (in µg/m³) data from Channel A and the red line is $PM_{2.5}$ (in µg/m³) data from Channel B.

How well the data adheres to the defined state-of-health metrics each day is indicated by the color in the bar at the bottom.

As discussed earlier in this chapter, collocation of your sensors with a reference instrument allows you to assess the precision and accuracy of your data. And, as discussed in Chapter 3, accuracy is the overall agreement of a sensor's measurement with the true concentration. Precision is how well the sensor reproduces a measurement under identical circumstances – or the agreement among repeat measurements. Accuracy is often assessed by linear regression of the sensor and reference data with the equation $y = mx + b$. In this equation, we are looking for a slope (m) of the slope-intercept line close to 1, an intercept (b) close to 0, and a coefficient of determination, R^2, close to 1. R^2, which ranges from 0 to 1, is a statistical measure of how close the data are to the slope-intercept line or, in other words, how much scatter is in the data. The closer R^2 is to 1, the better the agreement between the sensor and the reference data. The closer b is to zero, the less bias there is in the sensor data.

Precision is quantified by statistical metrics such as standard deviation and variance. Standard deviation describes how much the data are spread out. A low standard deviation indicates that values are close to the mean (also called the average) of the data set. A high standard deviation indicates that the values are spread out over a wider range. Variance is the average of the squared differences from the mean, and it measures how far a set of numbers are spread out from their average value.

Other metrics that are applied to comparisons of sensor and reference instrument measurements are mean absolute error (MAE), mean absolute percent error (MAPE), and root-mean-square error (RMSE). MAE is the average of the absolute of the difference between the sensor and the reference. A smaller MAE indicates better accuracy. MAPE is the average of the absolute of the difference between the sensor and the reference measurement divided by the reference measurement. Similar to MAE, a smaller value indicates better accuracy. RMSE is the square root of the average of the square of the difference between the sensor and the reference data. This provides a result similar to MAE, but is more sensitive to outliers. The statistical metrics for accuracy and precision, described above, can be calculated with tools such as MAT, R, or Microsoft Excel. Medium.com[19] provides more information on the differences and similarities between these statistical metrics, while Duke University[20] provides a technical deep dive into these metrics.

In addition to visually checking your data, using state-of-health metrics, or exploring accuracy and precision, you can implement QA/QC (Quality Assurance/Quality Control) procedures to help you process your data prior to analysis. Below is an example of QA/QC procedures available in the AirSensor R-package. Again, this package currently works with data from PurpleAir PA-II sensors, and this particular sensor includes two raw/OEM particle sensors in each unit (referred to as Channel A and Channel B). Thus, the QA/QC algorithm uses these duplicate sensor to assess the quality of the data.

1. Remove values that are outside of the manufacturer specifications. This initial filter is intended to remove unrealistic or impossible values that may be the result of sensor malfunction. For example, the range for the humidity values could be set to 0-100% since values outside of that range are not possible. For a PM sensor, PM mass concentration values may be set between 0-1000 $\mu g/m^3$ if the manufacturer states that 1,000 $\mu g/m^3$ (or 1 mg/m^3) is the highest concentration the sensor can reliably record.

2. Check for data completeness. If you are aggregating or averaging data for specific time frames (e.g., if you have sub-minute data and wish to use 1-minute averages, or if you plan to aggregate your data to hourly averages), you can implement a check to ensure that at least a certain portion of the possible data are present for each minute or hour. This will allow you to exclude periods where the data are incomplete from your analysis.

Collocation of your sensors with a reference instrument allows you to assess the precision and accuracy of your data.

3. Compare values from duplicate sensors in a single unit, if possible, or duplicate sensors at a single site. For a device like the PurpleAir PA-II sensor, with duplicate raw sensors in each unit, you can choose an aggregation period and compare the average values from each sensor for that period. Different methods can then be used to determine whether the data should be included in or excluded from the processed dataset. One algorithm in the AirSensor package uses a student's t-test and the mean difference to determine whether or not the values from the two raw sensors are significantly different.

When determining the appropriate QA/QC procedures for your project, consider the technical principles behind your sensor's operation, the target pollutant, and any scenarios that might cause the sensors to record poor quality falsely or questionable data. For sensors that do not have duplicates in each individual unit, you can consider comparing sensors to their nearest neighboring sensors in the network. You can also consider comparing the sensor data to data from the nearest reference site. When trying to identify malfunctioning sensors or poor-quality data, you can also consider the typical behavior of the pollutant you are interested in and if there are major deviations from the typical behavior – flag the data for closer

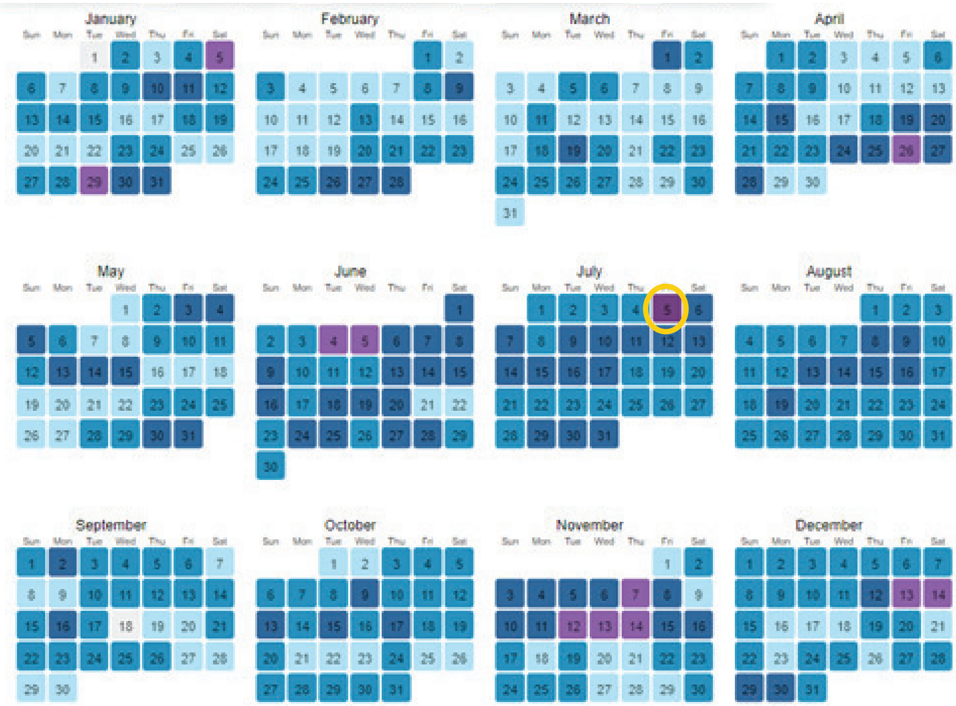


Figure 4-8. *Calendar plot of $PM_{2.5}$ sensor data showing high concentrations following 4th of July fireworks.*

inspection. Defining and implementing a QA/QC procedure can help you to identify and remove questionable data in a systematic and repeatable way, which can save you time and help you more effectively work with large quantities of data.

Analyzing Your Sensor Data

It is good practice to try a wide range of approaches to analyze your data. Try calculating different statistics, making different plots, mapping the data, and grouping the data by time or certain meteorological conditions. Then, look for observations or patterns that are consistent across all the different types of analyses. From this basis of exploration, you can begin to try and interpret your results.

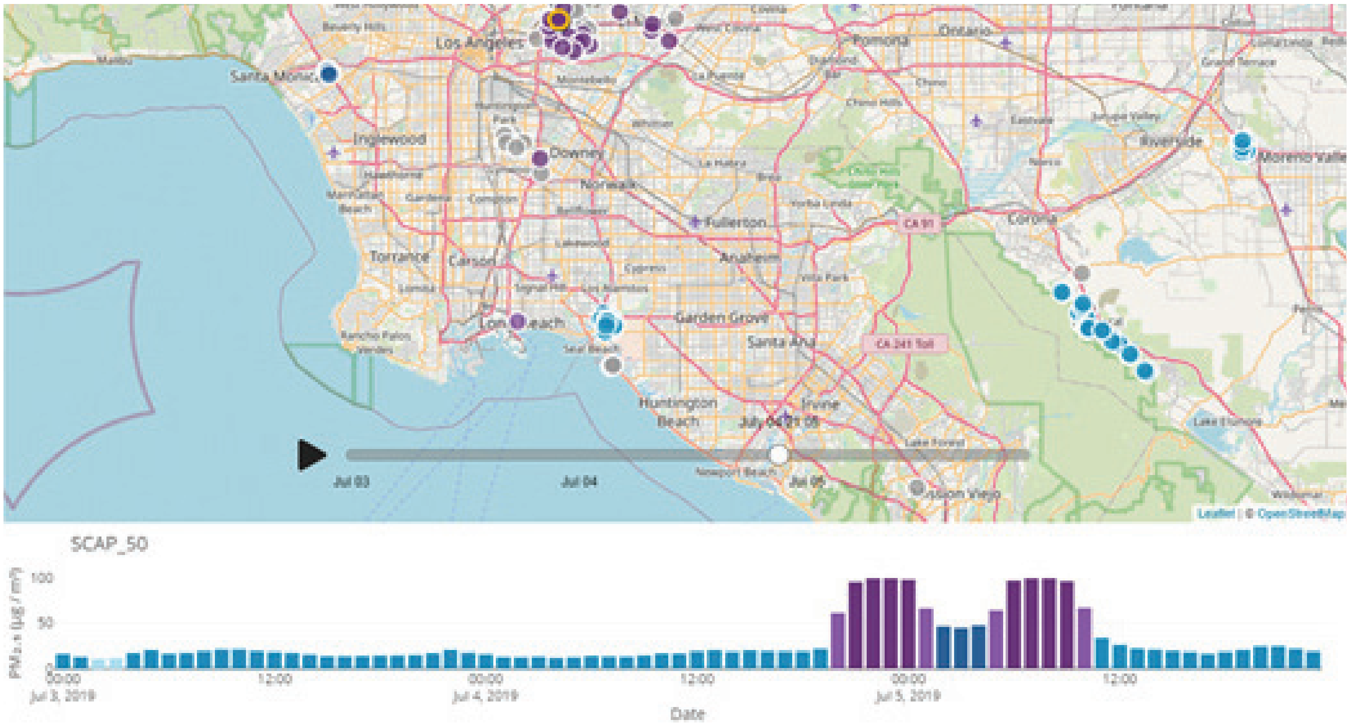
The following examples show how you can use different data visualizations to learn from and explore your sensor data. These data visualizations were developed using the AirSensor DataViewer tool[16] described here and in Appendix L.

Calendar Plots

Calendar plots are useful for showing daily data over time when there may be weekly, monthly, and yearly patterns. These plots provide an overview of the data from an entire year by showing the daily 24-hour averages, as indicated by a color, on a calendar. Use this type of plot to do the following:

- Identify interesting trends or events.
- Observe how $PM_{2.5}$ levels vary from season to season.
- Find days where higher concentrations of $PM_{2.5}$ occur and consider whether the high concentrations correspond to days when you might expect elevated $PM_{2.5}$ levels.

Calendar plots provide a useful first look at the data. For example, the user can observe long-term trends, begin to connect higher pollutant levels to events they experienced, such as wildfire, and even see when problems with the sensor resulted in data loss.



Color Hex # (RGB)	$PM_{2.5}$ Concentration (µg/m³) 24-hour averages	$PM_{2.5}$ Concentration (µg/m³) 1-hour averages
#ABE3F4 (171,227,244)	$PM_{2.5} \leq 8$	$PM_{2.5} \leq 12$
#118CBA (17,140,186)	$8 < PM_{2.5} \leq 20$	$12 < PM_{2.5} \leq 35$
#286096 (40,96,150)	$20 < PM_{2.5} \leq 35$	$35 < PM_{2.5} \leq 55$
#8659A5 (134,89,165)	$35 < PM_{2.5} \leq 55$	$55 < PM_{2.5} \leq 75$
#6A367A (106,65,122)	$PM_{2.5} > 55$	$PM_{2.5} > 75$

Figure 4-9. *Map and time series from the AirSensor DataViewer tool[16] showing high $PM_{2.5}$ concentrations on July 4th. The time series at the bottom is for the site highlighted in yellow on the map, and the concentration bins and colors are provided in the table at left.*

In **Figure 4-8**, elevated pollutant levels possibly associated with the 4th of July holiday are circled.

Maps and Time Series

Maps provide a spatial view of pollutant concentrations while time series provide a temporal view.

- Maps illustrate where sensors are located, and combining this information with pollutant concentration data can tell us about the spatial variability of pollutants, or how the levels of pollutants vary across a geographic area.

- Time series reveal how pollutant levels have varied over time. Time series are particularly useful for examining specific events.

A closer look at $PM_{2.5}$ levels around the 4th of July holiday is shown in **Figure 4-9**. The time series (shown as a bar graph of hourly averages) depicts the increased concentration at the site highlighted in yellow on the map. The map also depicts the averages at all sensor sites during this period. Using these types of visuals, you can see precisely when in time the increased concentrations occurred and whether higher concentrations were observed throughout the sensor network. In this case, the timing does suggest that the increased concentrations may have been the result of 4th of July fireworks because concentrations increased in the late evening hours and high concentrations were observed by nearby sensors.

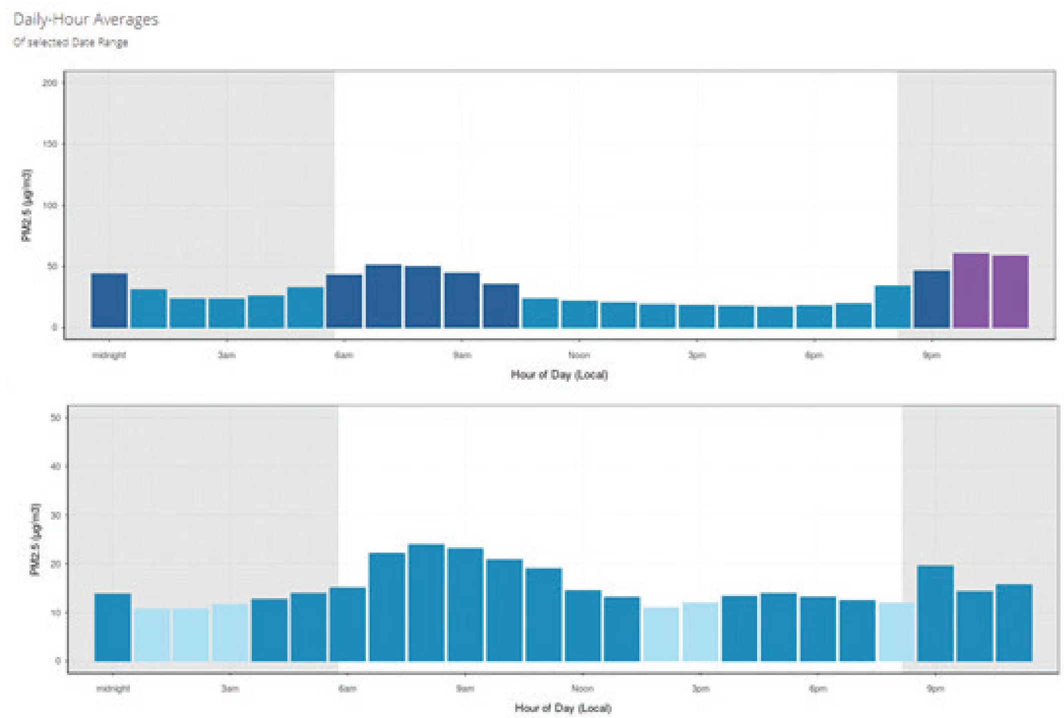


Figure 4-10. Daily trend plots of $PM_{2.5}$ concentrations exploring the week of July 4th at two sites.

Daily Patterns (or Diurnal Trend Plots)

A diurnal trend plot depicts the average for each hour of the day across a 24-hour period. Use these plots to:

- Understand how pollutant levels typically vary over the course of a day.
- Identify times of day when $PM_{2.5}$ concentrations are highest or lowest.
- Attempt to understand what types of sources or meteorological conditions might be causing these patterns.

Continuing the example, data from July 1st through July 7th has been averaged to create both plots shown in **Figure 4-10**. The top plot is from the same site viewed in the previous time series, and the 4th of July firework emissions seem to cause higher hourly averages during the evening hours. When this site is compared to another site that appears to be less impacted by the 4th of July emissions, relatively lower levels are observed in the evening with the highest concentrations occurring in the morning hours.

Pollution Rose

A pollution rose summarizes where the wind was coming from during the specified period. The colors indicate the pollutant concentrations seen from each direction, while the size of the wedge indicates the proportion of wind data from each direction. These plots can help you understand the direction from which the highest concentrations are observed. In the pollution rose shown in **Figure 4-11**, the wind was primarily blowing from the southwest

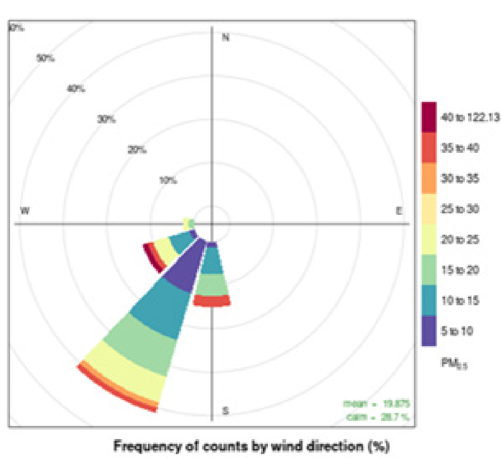
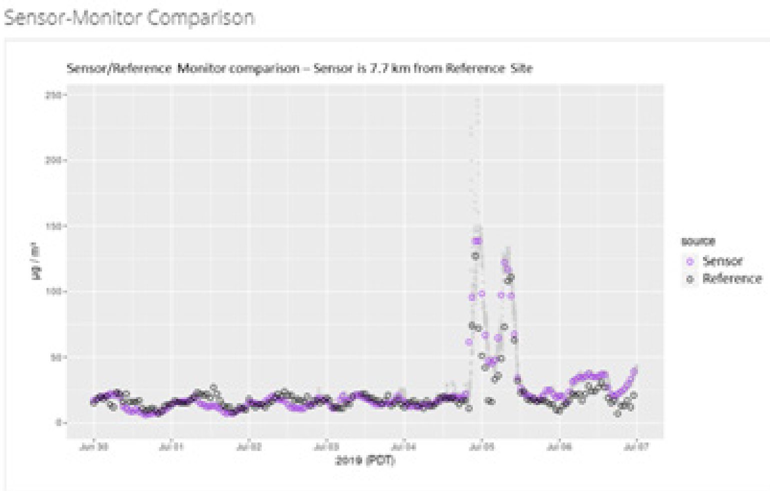


Figure 4-11. Pollution rose showing the frequency of $PM_{2.5}$ concentrations by wind direction for the week of July 4th.



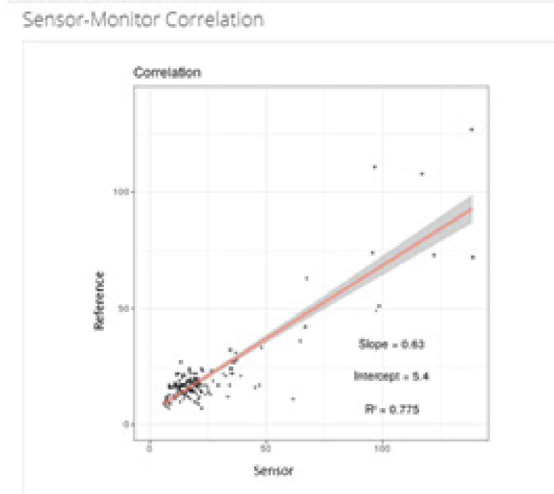


Figure 4-12. *Comparison plot of sensor and regulatory monitor data. The sensor data compare reasonably well with the reference and captured a higher concentration event.*

for the entire time period being examined. This period includes the elevated $PM_{2.5}$ levels on the 4th of July, and this plot suggests that the elevated $PM_{2.5}$ may have been transported from the southwest.

Comparison Plots

These plots are used to compare data from a low-cost sensor to data from either a nearby reference site or a monitoring site operated and maintained by a government agency. These plots allow you to assess how well your sensor data agree with the reference data.

- Are concentrations similar?
- Are trends in the data (such as daily patterns) similar?
- If not, what factors, such as distance between the locations, or predominant wind direction, might explain the differences?

Figure 4-12 shows sensor data compared to data from a reference monitoring site 7.7 km away. The agreement between the two datasets tells us that the sensor was likely not malfunctioning and that the high concentrations potentially resulting from the 4th of July fireworks were observed over a broader area. In terms of the statistics, a slope close to 1.0 indicates that the low-cost sensor and the reference site are measuring similar concentration patterns. A slope greater than 1.0 indicates that higher values are seen at the regulatory monitoring site and a slope of less than 1.0 indicates lower values are seen at the regulatory monitoring site. The intercept can be an indicator of bias (e.g., whether the sensor may be consistently under- or over-predicting pollutant concentrations). The coefficient of determination, R^2, tells us how well the trends agree between the two sites; an R^2 closer to 1.0 indicates more agreement and an R^2 closer to 0.0 indicates less agreement. A slope of 0.63, indicates that higher concentrations are observed by the sensor. An R^2 of 0.775, indicates relatively good agreement between the sensor and the regulatory monitor.

This is one example of how you can approach the analysis of sensor data. There are many other ways, plots, and tools you can use.

Here are a few more actions/questions to consider:

- Look for patterns across multiple sensor sites (e.g., are concentrations at some sites consistently higher or lower than other sites?) or in time (e.g., try comparing night/day or weekday/weekend data, are there specific days of the week that always have higher or lower concentrations?).

- If you have data from a network of sensors, do you see any gradients in pollutant levels across multiple sites (i.e., patterns with pollutant levels moving from high to moderate to low)? These may occur at certain times (e.g., at night), during emission events, or when winds are above a certain speed and originating from a particular direction.

- If you have data from sensors measuring different pollutants, how do the trends from each pollutant compare? If two different sensors repeatedly show increases in concentrations at the same time – this might mean that they are detecting a single source that emits both pollutants. Examining data from multiple pollutant types along with wind speed and direction can help to narrow down potential sources of emissions.

- Do the trends in the data agree with your perceptions of air quality? For example, compare your observations or Log Notes with the sensor data and see if your observations of poor air quality coincide with elevated levels of pollutants. Agreement between the two would support the idea that the sensors are measuring the same pollutant(s) potentially responsible for the poor air quality you are noticing. Disagreement between the two may indicate any number of issues.

- Do concentrations at some sites correlate while others do not? What might that tell us about sources?

When comparing concentrations among sites, consider if the site of interest has concentrations that are:

- Statistically significantly higher or lower than other sites (mean, median, or another metric).

- Higher or lower when the wind is from a certain direction.

- Higher or lower than concentrations at other sites in the community, region, state, and/or nation.

- Higher than expected given local population and emissions sources.

When looking at emissions sources, analyses can demonstrate that:

- Concentrations of certain pollutants are higher when winds are from the direction of a source.

- Changes in concentrations with time of day, day of week, or season are consistent with emissions activity from the source.

- Concentrations at nearby locations are higher than at other sites farther from the source.

Air Quality Index	Who Needs to be Concerned?	What Should I Do?
Good 0-50		It's a great day to be active outside.
Moderate 51-100	Some people who may be unusually sensitive to particle pollution.	**Unusually sensitive people:** *Consider reducing* prolonged or heavy exertion. Watch for symptoms such as coughing or shortness of breath. These are signs to take it easier. **Everyone else:** It's a good day to be active outside.
Unhealthy for Sensitive Groups 101-150	Sensitive groups include **people with heart or lung disease, older adults, children, and teenagers.**	**Sensitive groups:** *Reduce* prolonged or heavy exertion. It's okay to be active outside, but take more breaks and do less intense activities. Watch for symptoms such as coughing or shortness of breath. **People with asthma:** should follow their asthma action plans and keep quick-relief medicine handy. **If you have heart disease:** Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider.
Unhealthy 151-200	**Everyone**	**Sensitive groups:** *Avoid* prolonged or heavy exertion. Consider moving activities indoors or rescheduling. **Everyone else:** *Reduce* prolonged or heavy exertion. Take more breaks during outdoor activities.
Very Unhealthy 201-300	**Everyone**	**Sensitive groups:** *Avoid all* physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. **Everyone else:** *Avoid* prolonged or heavy exertion. Consider moving activities indoors or rescheduling to a time when air quality is better.
Hazardous 301-500	**Everyone**	**Everyone:** *Avoid all* physical activity outdoors. **Sensitive groups:** *Remain* indoors and keep activity levels low. Follow tips for keeping particle levels low indoors.

Figure 4-13. *EPA's AQI and actions for people to take when the AQI is at different levels.*

Interpreting Your Results: What do the Sensor Readings Mean?

Sensors provide a snapshot of air quality – in many cases, a 1-second, or 1-minute snapshot. However, scientific studies have not yet been conducted that tell us what a single second or minute of exposure means for health. The AQI, built upon regulatory data, provides some guidance in thinking about sensor readings. The AQI takes into account long-term exposure (e.g., multiple hours) rather than short-term exposure (e.g., seconds to minutes). **Figure 4-13** shows actions for people to take when the AQI is at different levels.

If the AQI at one site in a network is higher than at other sites, causes could include:

- The site with higher AQI is situated near a very localized source which is impacting the measurements.
- The measurements at that site may be biased high relative to other sites.
- The sensor may be malfunctioning.

If there are several sites where the AQI is consistently higher than the rest of the network, there may be a source or sources which impact a larger area. For both situations, you can learn more about the causes by exploring the meteorology, understanding sources near the sites, and ensuring the validity of the data.

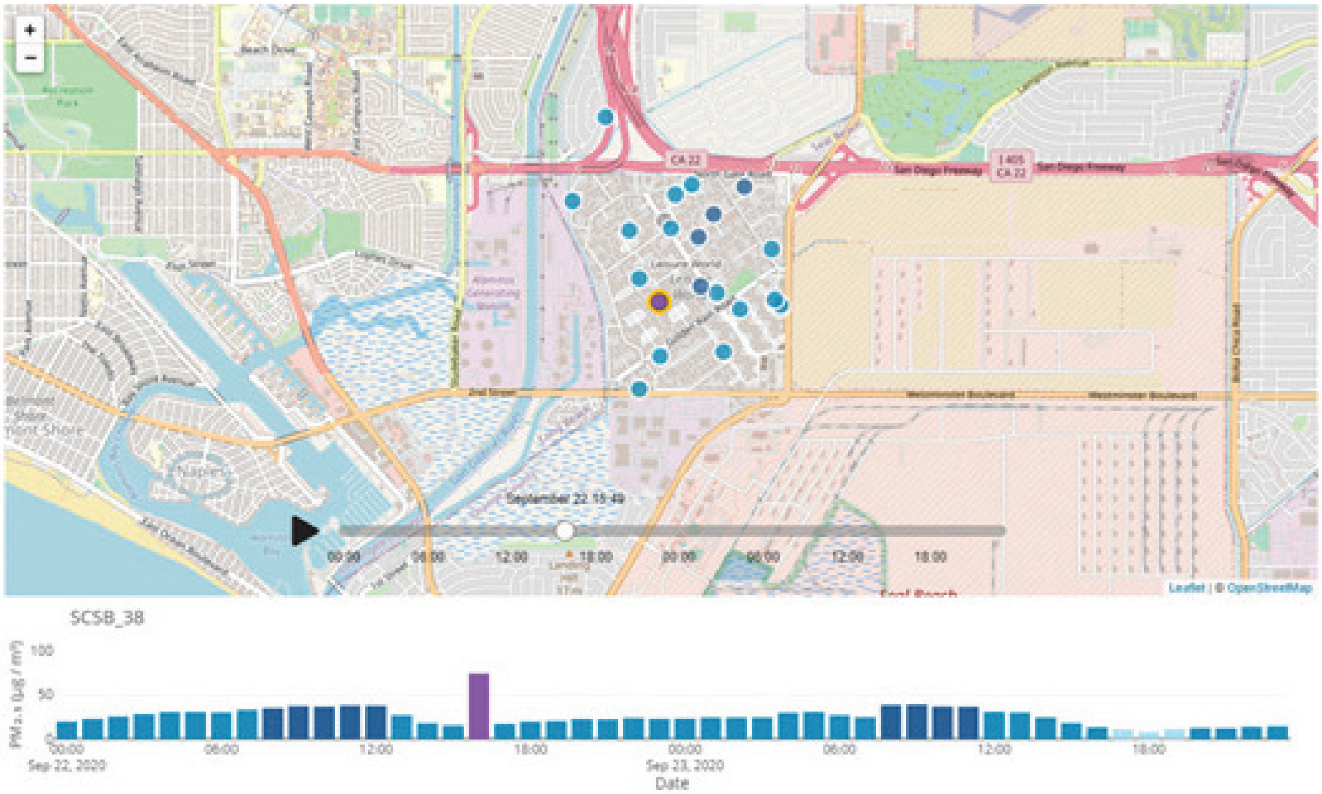


Figure 4-14. *Example screenshots from DataViewer exploring neighborhood differences in sensor readings.*

To further explore differences, a visualization tool, such as the AirSensor DataViewer tool,[16] can be very useful. **Figure 4-14** shows a neighborhood where one sensor in the network seems to experience high concentrations for an hour relative to the surrounding hours at that site and to other sensors in the area. It is possible that this may be a passing plume, very localized emission source, or a temporary malfunction. Continuing to review time series, the map, and wind speed and direction over a few weeks may reveal a pattern or provide further evidence that this period of high concentration was an unexplained "blip."

In another example, **Figure 4-15** shows a comparison of sensor 'a' to nearby sensors 'b', 'c', and 'd'. Sensor 'a' seems to exhibit higher concentrations than surrounding sensors. Consider the data uncertainty, that is, are the concentration differences significantly higher than sensor precision? Is the sensor with lower readings appropriately sited – for example, is there foliage or obstructions potentially blocking airflow? Are the concentrations consistent with the distance of sites from potential sources such as roadways?

It is also important to be aware that low-cost sensors are typically set up and deployed by the general public. For sensors such as PurpleAir, the user self-reports whether the sensor has been deployed inside or outside their residence, for example. Therefore, it is important to view large differences between sensors set up relatively close together with skepticism. **Figure 4-16** shows a neighborhood with some PurpleAir sensors during a wildfire smoke event in Northern California. The data from the sensor showing low concentrations is suspect given the widespread smoky conditions at the time. Could the sensor be inside a home with good filtration?

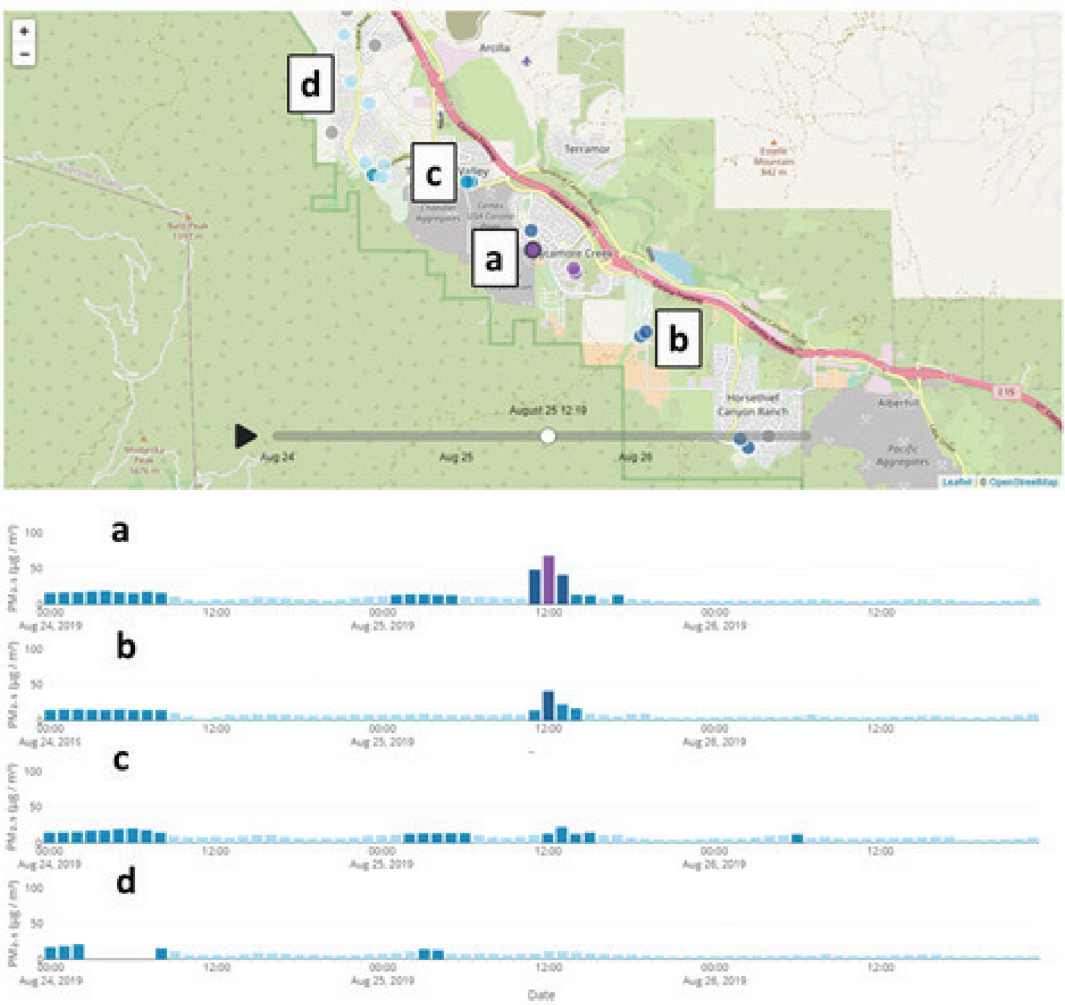


Figure 4-15. *Example screenshots from DataViewer showing a comparison of four neighborhood sensor readings.*

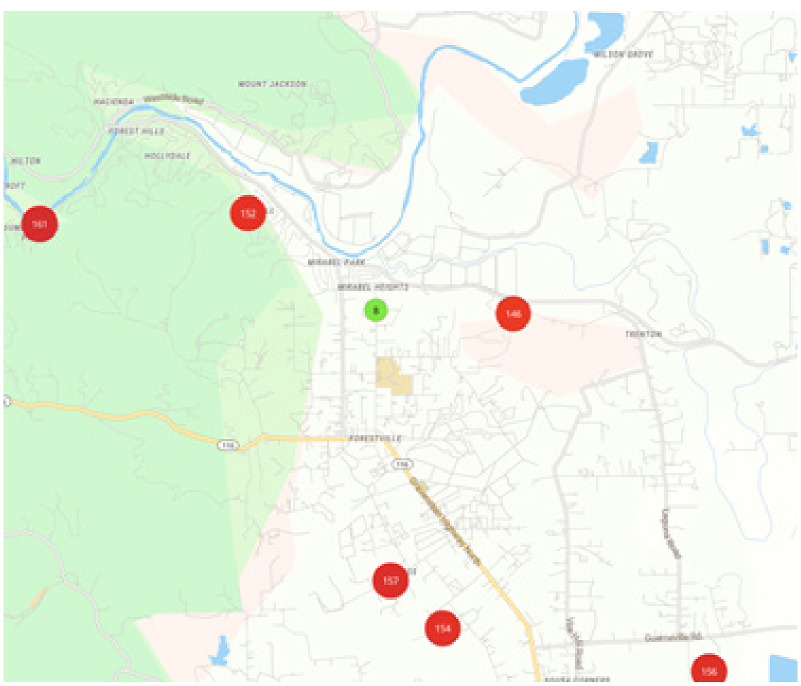


Figure 4-16. *PurpleAir map of concentrations observed during a wildfire smoke event in Northern California. The sensor with low concentrations (green dot) is suspect given the widespread smoke conditions.*

Maintain project momentum by sharing reports and holding occasional meetings.

Maintaining Momentum on a Project

There is typically excitement in the community at the beginning of a project, but that excitement can wane as time goes on. However, here is where you can get creative and leverage the skills and expertise in your community. Here are some examples of ways communities have found to keep participants interested and engaged:

- **Providing updates to the community.** Project leads can use data visualization tools to develop regular air quality reports or summaries, which can be shared with participants via email or by holding occasional meetings to share results and answer questions (see **Figure 4-17**).
- **Sending reminders to project participants.** Project leads can also send regular reminders via email or text, asking participants to take a look at their data or share anything they may have learned from their sensor or the sensor network.
- **Getting youth involved.** Students can develop science projects based on the community measurements. Students can even leverage the data from these sensors for science fair projects (see **Figure 4-18**). Also, consider reaching out to local teachers to let them know about the sensor network - they may be interested in using the data to teach in their classrooms.

Figure 4-17. *Promoting a project and organizing a workshop using social media (Facebook).*

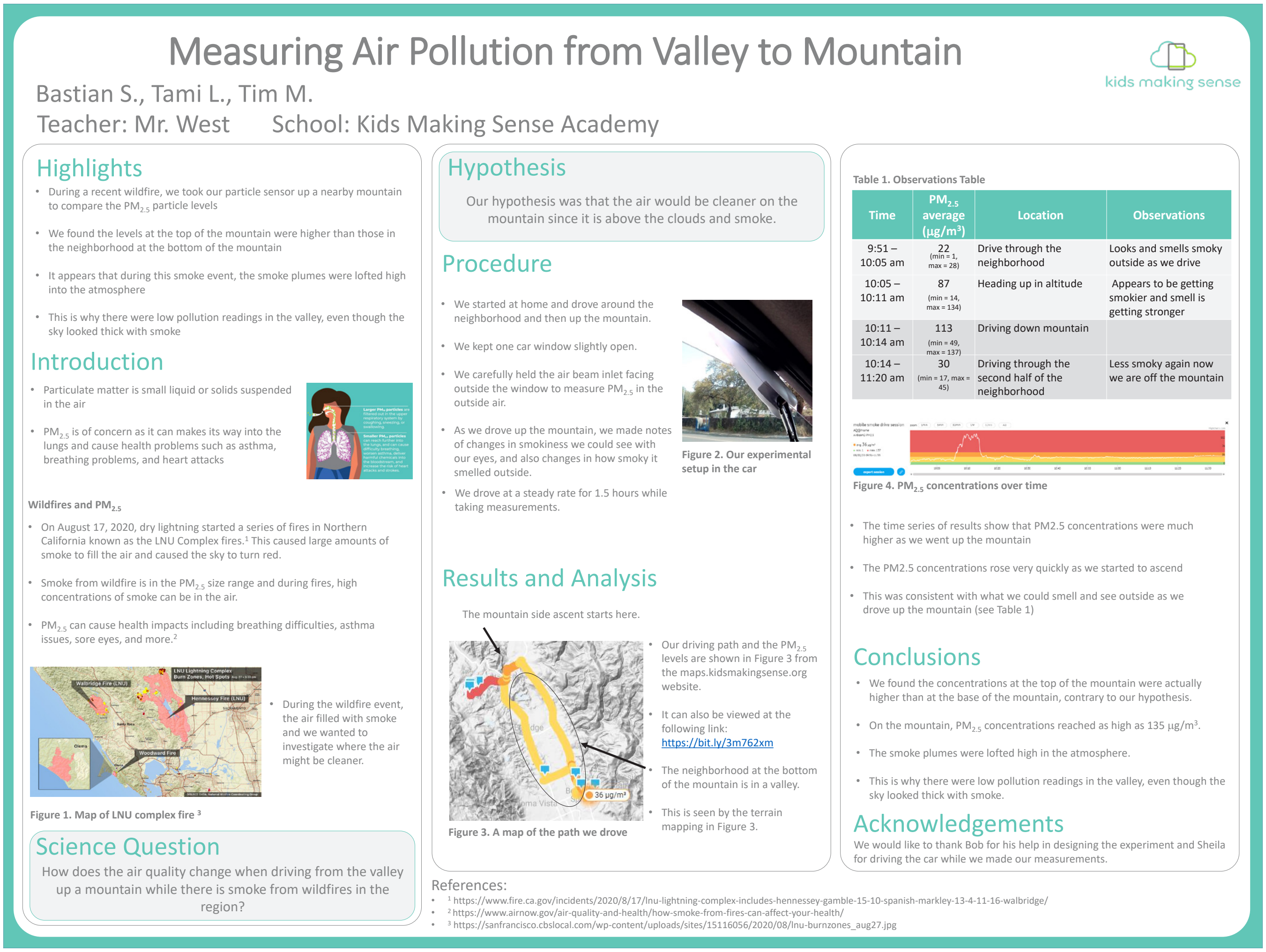


Figure 4-18. *Science fair project using low-cost sensor data.*

Using social media to keep conversations going about observations found by the participants about their data. Community members can share observations related to air quality, and these platforms allow others to comment – providing a variety of input about the observations (see **Figure 4-19**). Additionally, using social media for these conversations can provide a time-stamped record that may serve as a useful reference during the data analysis phase of the project. This outreach approach requires active participation to keep the social media account active and engaging.

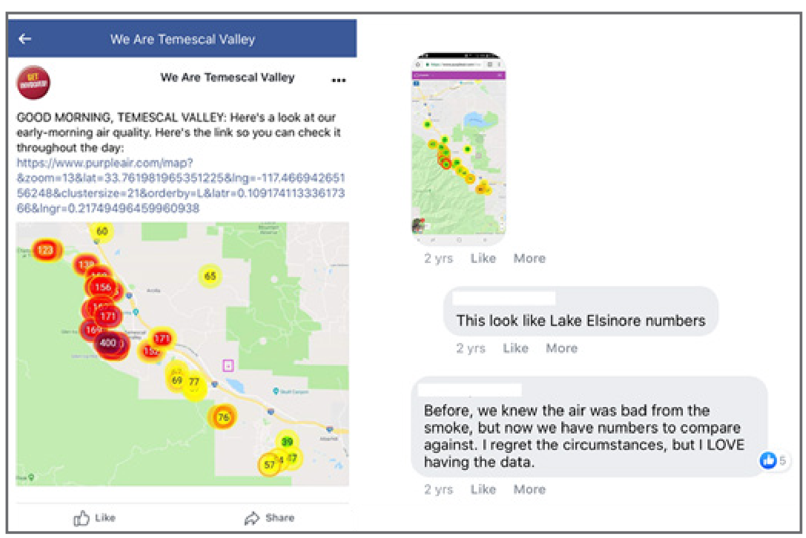


Figure 4-19. *Community sharing and discussion of data from low-cost sensors during a wildfire event through social media (Facebook).*

Supporting data analysis work by community members. Community members may have their own questions about air quality or the sensors themselves and their interest can be encouraged and supported where possible (see **Figure 4-20**). For example, a community member may wish to learn more about sensor performance by collocating at a specific reference monitoring station. Having a few extra sensors and helping to facilitate relationships, such as with the local regulatory agency, can help make this work possible.

Having community members create custom and engaging data visualizations. There may be individuals in your community who have the programming skills to create unique and engaging data visualizations (see **Figure 4-21**). Project leads may be able to support this work by providing access to data.

Connecting the sensor deployment to other projects happening in the community. Challenge the community to think about how different issues interrelate, such as the built environment, local industry, traffic patterns, and local air quality (see **Figure 4-22**).

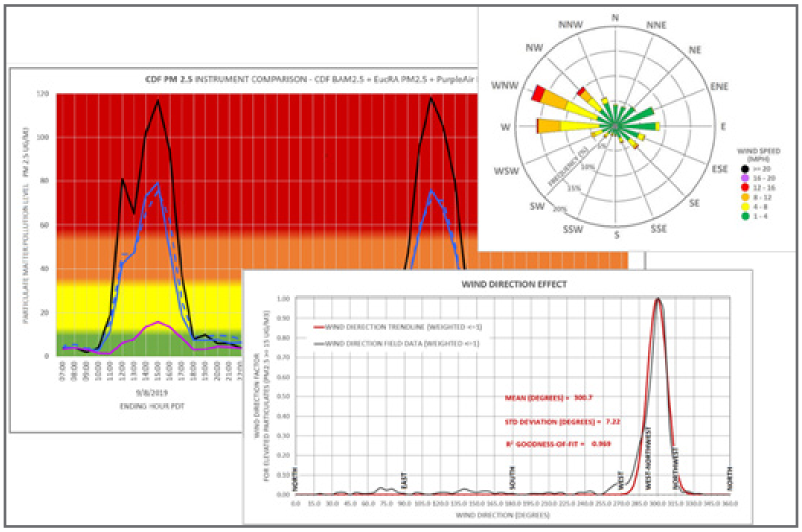


Figure 4-20. *Analysis of sensor performance and the relationship between air quality levels and wind direction, completed by a community member.*

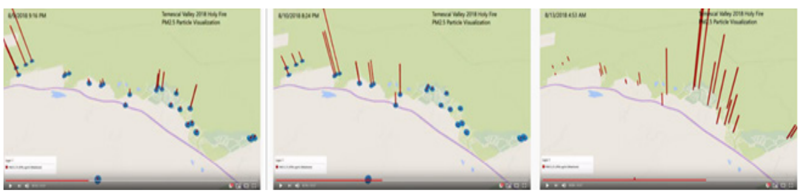
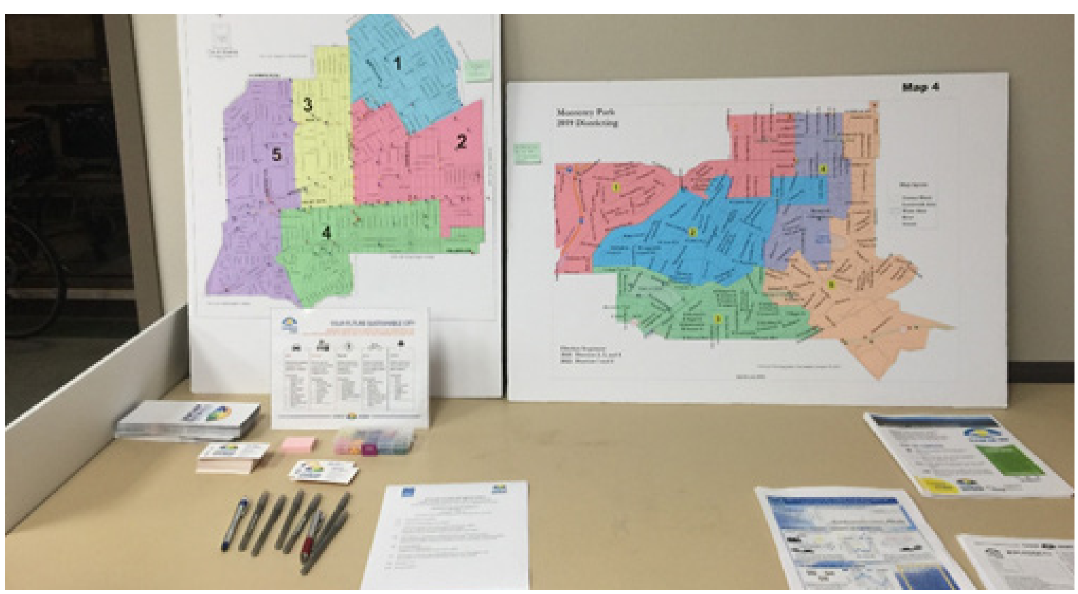


Figure 4-21. *Still images from an animated data visualization created by a community member to illustrate the dynamic $PM_{2.5}$ concentrations during a wildfire event (posted to YouTube and shared/discussed on the group's Facebook page). The height of the red bar indicates the $PM_{2.5}$ concentration (taller = higher concentrations), while the blue circle indicates the current wind speed (larger = higher wind speeds).*

Figure 4-22. *An activity during a community workshop, participants used different colored pins to identify various features (e.g., parks, high traffic areas, etc.) – these types of activities can be used to facilitate discussions about local air quality.*



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05 Taking Action

Now that you have data, what do you do with the results? Options include taking action locally to reduce emissions or your exposure, collecting more data to better clarify the problems, and/or sharing your results with policy makers.

Work with local sources of air pollution and your local air quality agency to reduce emissions.

Local Action

At the beginning of the project, the project team will have thought about actions that they hope to take locally to reduce exposure to pollution, to reduce emissions, or both. Questions to consider include:

- What can be done to reduce emissions and exposure? What have other communities done?
- Who do you need help from to take action? What do they need to know?
- What resources (e.g., funds, volunteers) are available? What other resources do you need? Where can you find additional resources?

Reducing Your Emissions

To reduce emissions, there are strategies and examples from which to build. For emissions reductions:

- If a **local emission source** is identified as a key contributor to pollutant levels, work with the source and the local air quality agency to reduce emissions.
  - It is useful to have had the local source involved throughout the project.
  - Good data quality from a well thought out plan and well executed project will help when appealing for involvement from the air quality agency.

If **vehicle emissions near a school** are identified as a problem, develop an anti-idling program.

- See for example, [U.S. EPA's Idle-Free Schools Toolkit for a Healthy School Environment](#).[1]
- Grant money could be sought to retrofit a school bus fleet to reduce emissions. There are resources available at national, state, and local levels. One source is the [Diesel Emissions Reduction Act (DERA) of 2010](#),[2] which allows EPA to offer rebates in addition to grants to reduce harmful emissions from older, dirtier diesel vehicles. In California, an [extensive list of resources is available](#).[3]

If **residential wood burning** is identified as a problem, work with the local air quality agency to develop a no-burning policy for days on which air quality could be greatly impacted by wood smoke.

- Grant money could be sought to replace older wood-burning appliances with cleaner home heating, such as EPA certified wood and pellet stoves, EPA qualified hydronic heaters and fireplace retrofits, or gas or electric appliances. EPA provides a [clearinghouse of information](#).[4]
- Community awareness could be increased through outreach and education (e.g., the Bay Area Air Quality Management District's [Spare the Air website](#)[5] or the South Coast AQMD's [Check Before You Burn program](#)[6]).

(Above) Create an anti-idling program to protect students from harmful vehicle emissions near schools.

(Left) Work with your local air quality agency to develop a no-burning policy for days with poor air quality.

Create a community awareness program that will help reduce emissions.

Students Move to Action

Kids Making Sense®[7] is a hands-on program that educators can use to teach students how to measure and monitor air quality and weather, to interpret the data they collect, and to take action to reduce their exposure to air pollution.

The program consists of STEM-based curriculum, hand-held air sensor technology, and support from professional air quality scientists. In recent Kids Making Sense® deployments in California classrooms, students used portable low-cost sensors to effect change.

In one example, portable classrooms located near a bus yard were moved because $PM_{2.5}$ concentrations inside the classrooms were high compared to other classrooms. Students concluded the higher concentrations may have been from idling buses just outside of the portable classrooms.

Using Kids Making Sense, high school students were concerned about pollution from idling vehicles. While there was little idling traffic at their high school, they noticed that there were many cars idling outside the adjacent middle school. The high school students worked with the middle school to implement a no-idle campaign.

A science class in Rosemead, CA explored air quality using Kids Making Sense and found high $PM_{2.5}$ concentrations inside a local fast food restaurant. Students noted that the concentrations were higher than measurements taken at a nearby freeway overpass. The students presented their findings to a South Coast AQMD board member, School District Superintendent, and school board member. The South Coast AQMD board member brought up the issue of PM emissions from restaurant charbroilers at the next board meeting of the South Coast AQMD. The board agreed to prioritize reconsideration of existing charbroiler regulations.[8]

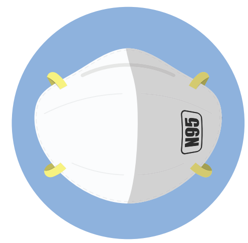
In addition to reducing emissions from sources, community members can also reduce their own emissions by:

- Reducing vehicle emissions;
  - Walking, biking, carpooling, or taking public transit.
  - Keeping vehicles tuned and tires inflated.
  - Avoiding excessive idling.
  - Combining errands and reducing trips.
- Making homes more energy efficient.
- Avoiding the use of gas-powered garden tools – review the South Coast AQMD's electric lawn and garden equipment program.[9]
- Reducing or eliminating fireplace and wood stove use.
- Avoiding burning leaves, trash, and other materials.

Reducing your Exposure

In order to reduce exposure to pollution, there are actions (in addition to those listed above) that individuals can take:

- If the AQI in your area (e.g., via AirNow.gov[10]) is Unhealthy for Sensitive Groups (sensitive groups include people with heart or lung disease, older adults, children, and teenagers) or higher, and you are a person with heart or lung disease, or an older adult, reduce strenuous exercise or exertion, and use your medication. Watch for symptoms such as coughing or shortness of breath as these are signs to reduce your activity.
  - For AQI levels at unhealthy or above, EPA recommends to shorten or reschedule outdoor activities or choose a less-strenuous activity.
- To reduce exposure to particle pollution, spend less time near busy roads or dusty environments.
- To reduce particle levels indoors when outdoor concentrations are high, close windows; avoid intake of air for heating, ventilating, and air conditioning (HVAC) systems when pollutants are highest (unless there is



Protect yourself when smoke is in the area by wearing an N95 mask, closing your windows, and running air purifiers to remove smoke that is already in your home.

How STAR Grant Participants Used Their Data

STAR Grant participants from different communities said they used sensor data to decide whether to exercise indoors or outdoors, or when to walk their dog. Residents also described checking the sensor data in the evening to decide whether or not to use their whole house fan (to pull outdoor air in).

One STAR Grant community described using the sensors to monitor and guide controlled burns, including notifying nearby schools of the potential for emissions from these controlled burns.

In another STAR Grant community, using paired indoor and outdoor sensors, residents used the data to adjust their behavior in relation to cooking (e.g., adjusting ventilation based on what type of food was being prepared). Residents of this community also described using sensor data to optimize the use of indoor filtration units (i.e., improving indoor air quality, while minimizing energy usage).

One community discussed how local industry was monitoring the data made available by their STAR Grant sensors, potentially using it to inform their operations.

a high-efficiency filtration system in place); eliminate tobacco smoke; reduce use of wood stoves and fireplaces; use HEPA filters and air cleaners designed to reduce particles; and don't burn candles. The California Air Resources Board developed a list of certified air cleaning devices[11] in California. Note that some devices advertised as air purifiers, air cleaners, or ozone generators purposely emit large amounts of ozone. Not only are such ozone generators ineffective at cleaning indoor air, but breathing ozone poses

serious health risks (see Chapter 2); these devices should not be used.

- If the AQI in your area is good, consider opening your windows. Particle and volatile organic compound levels outside may be lower than those indoors, especially if you are engaging in activities that increase indoor particle levels (such as cooking or vacuuming).

- Regularly check air monitoring data, for example through AirNow.gov[10], to inform plans for outdoor activities.

- Consider testing your home for radon,[12] especially if you live in a location with higher potential[13] for elevated indoor pollution levels.

Increasing Awareness

In addition to reducing your emissions and personal exposure, consider sharing your knowledge to increase awareness:

- **Develop informational material** for outreach to the community. An example is shown in Appendix E.

- Start a **school flag program**. An air quality flag program[14] alerts the community about the local air quality forecast. Communities can use this information to protect people's health, including the health of asthmatics. A school (or other organization) raises

An Air Quality flag program alerts the community to the local air quality forecast.

a flag that corresponds to the AQI: green, yellow, orange, red, and purple. EPA offers guidance on school flag programs.[15]

Consider a project that took **measurements indoors and outdoors** at a school.[16, 17, 18] Measurements were made at a Las Vegas high school both before and after the freeway adjacent to the school was widened. Measurements were made both in a classroom and outside the school. One outcome of the project was that teachers became educated about when pollutant concentrations were highest outside and changed when they had their doors or windows open to let in "fresh" air. Measurement projects can also increase awareness in other ways such as:

- Parents may learn about the impact of idling their vehicles at the school.
- Students may learn of lower-pollution routes to take to school for walking or biking.
- Coaches may learn about changing sports practices to a different time of day or to an indoor location based on pollution trends/ levels.

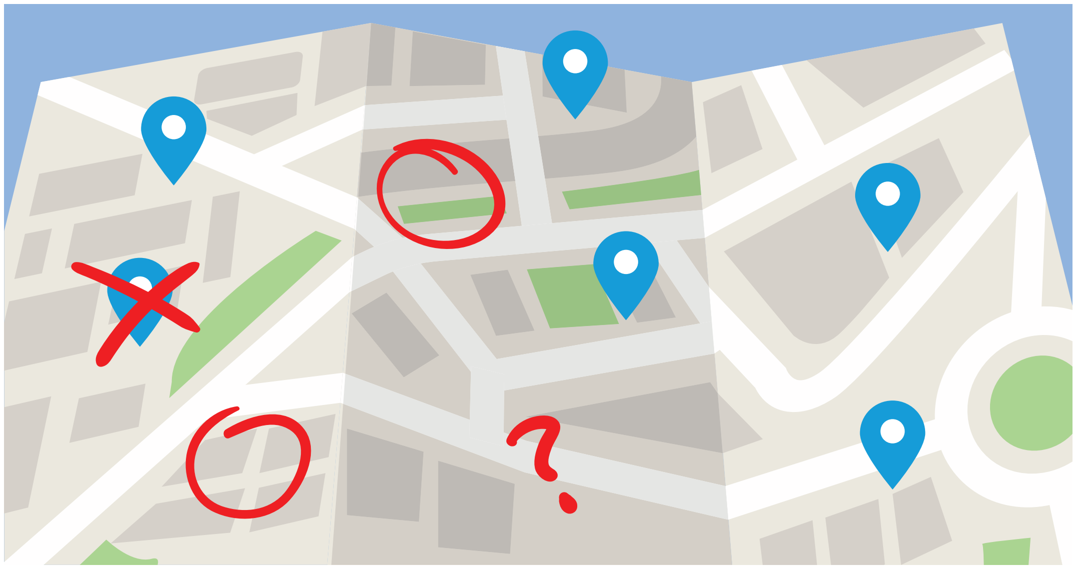
Other Mitigation Strategies

At a higher level of funding and city planning, there are other mitigation strategies to consider:

Make infrastructure changes. Look for funding to improve building filtration systems near a source, such as at a school near a heavily trafficked roadway.

Change a building design. For example, move the HVAC intake location away from sources such as a loading dock or heavy traffic.[19]

Add roadside vegetation to reduce pollution from roadways in nearby communities.[20]



Collecting More Data

Based on the project findings, there may be a need for additional monitoring. This could be led by the appropriate agency to further investigate hot spots or a particular source. Or this might be another round of data collection led by the community. For example, you may need to take measurements of other pollutants or take higher quality measurements (e.g., using improved instrumentation). Your community may need to redesign the study to focus on a new location or source type, add more calendar time, or add more locations. **Figure 5-1** provides a decision tree to assist in redesigning or expanding a study.

Often, funding is limited and your project may need to be thought of as a "pilot project" to inform next steps. A larger, well-funded project may be needed to provide potentially actionable data. Funding can be found through local, state, and federal programs.

Funding Opportunities

- EPA grant opportunities and information.[21]
- Training about EPA grants.[22]
- Example state-level grant opportunities.[23]
- Example state-level grant opportunities for environmental justice areas.[24]

Figure 5-1. *Use this decision tree to determine whether more measurements are needed to meet project objectives.*

Share your goals and results with the community early and often.

Sharing Your Results and Discussing Your Project

Working with your Local Regulatory Agency

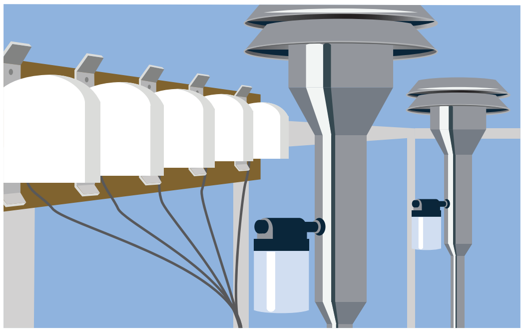
Every air district differs in terms of size and capacity, so we recommend reaching out to the public helpline or email address (e.g., web inquiry/complaint/outreach email). They will help direct your inquiry to the most appropriate person at your local district. Appendix J provides a list for California as an example.

In contacting your local regulatory agency, there are a range of objectives that you may have including project awareness and feedback, access to a regulatory site for collocation of your sensors, or to discuss project findings.

1. If you are interested in making your local regulatory agency aware of your project, or soliciting informal feedback on your planned project, consider including the following information:

- A brief summary of your project.
- What you hope to learn, your research question, or why you are conducting this project.

- The scope of your project (type of sensors, pollutants measured, how many sensors, where they will be deployed, and for how long).
- Who is involved (list the partners, communities, and/or other types of participants).



2. If you would like to request access to an official monitoring site in order to collocate your sensors, consider including everything listed above for Scenario 1 as well as the following:

- How many sensors you would like to collocate.
- The approximate size and weight of a single sensor.
- Where you would like to collocate (either name the monitoring site, or describe what type of site would be ideal, for example – a site with hourly-averaged $PM_{2.5}$ data available that is near a highly trafficked road).
- The ideal start and end dates for the collocation.
- What the sensors require in terms of power and in terms of connectivity (such as Wi-Fi).
- Whether or not you will need access to the sensor(s) during the collocation.

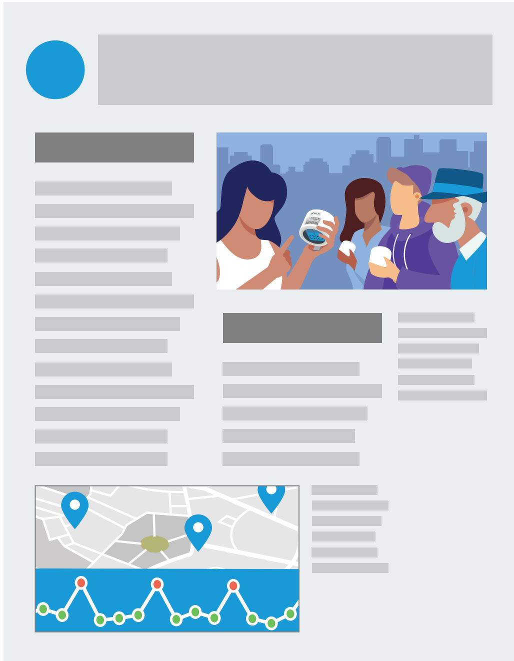
3. If you would like to discuss your data or results with your local regulatory monitoring agency, include everything listed for Scenario 1, as well as the following:

- A brief overview of your results and your interpretation of those results. It's best to limit the initial summary to a single page but be prepared to share more details or a longer report if requested.
- Describe how you processed and analyzed your data (including QA/QC steps applied and time-averaging).
- How you assessed sensor performance or developed and applied correction/calibration equations.
- Explain what you hope to learn or accomplish by discussing your study and the results with staff from the local regulatory monitoring agency.

Community Outreach

Throughout the project, it is important to engage community members early and often to ensure that community expectations are being met, that modifications are being made as needed based on community input, that the information is being disseminated to all affected citizens, and to maintain interest in the project.

Engage community members with different forms of communication, such as social media, email, and newsletters.



Data and simple interpretation guides, [like the EPA pilot messaging for ozone and $PM_{2.5}$](#),[25] should be readily available for all community members so that they can make informed actions to protect health.

Some ideas for outreach activities:

- Host monthly or bi-monthly community meetings to discuss sensor readings for the period, track project progress, and exchange ideas for actions to help protect community health.

- Publish monthly newsletters detailing sensor findings for the month, including averages, unexpected findings, patterns, and interpretations.

- Seek community feedback often through meetings and surveys to identify areas for improvement and address any concerns.

- Use multiple avenues for reaching out to community members, including in-person meetings, flyers and brochures in common areas, local newsletters, email listservs, a community Facebook page, a Twitter account, and any other appropriate methods.

- Leverage existing community social networks to engage citizens, for example, by presenting information at local churches, schools, and other institutions that bring people together.

It is also a good practice to make information easily accessible through multiple means to reach a broader audience.

Guidelines for Effective Communication

To communicate your results effectively, consider your audience – what is an appropriate technical level; what is of most concern to the audience; and what background information do they need to understand the story? A good story includes clear definitions, logical flow, and is appropriate to the audience.

- Organize information logically.

- Provide cues to help readers follow and find information.

- Make the proportion of space you give to any information reflect the relative importance of that information.

- Choose words precisely.

- Write clear, concise sentences.

- Tables and figures should "stand-alone" including all units, abbreviations, and descriptive footnotes; this is important so that tables and figures can be easily interpreted without the need to refer to text in the body of your report.

- Photos are useful in telling your story and making it more personal to your audience.
- Get ideas on graphic types, outline, structure, and formatting from other reports and presentations.

The above guidelines can be applied to different communication approaches such as infographics, reports, and websites. Well-made infographics can be used to summarize results and communicate them in an effective and engaging way. There is an example of an infographic developed for one of the STAR Grant communities in Appendix E.

Reports

Reports are more comprehensive and allow for an in-depth explanation of your results. Reports are most effective when tailored to the audience in terms of both the technical level and the interests of the audience. It is useful to consider what questions your audience has about the data collected. In Appendix M, there are three reports provided as examples. These reports were generated during the STAR Grant project, and both aim to answer questions that arose from the communities.

Websites

Websites are another effective way to support communication during your project and beyond. In one community during the STAR grant sensor deployment, a resident put together a website that aggregated all the information his fellow community members might be interested in. He also provided data visualizations and tools for working with the sensor data as shown in **Figure 5-2.** Note, you can learn more about the data analysis tools developed by this participant in Appendix M.

Figure 5-2. *Websites like PurpleAir offer free code for displaying real-time data from your sensors on your own website. You can also include links to background information and data analysis tools.*

For Further Reading

For more guidance and inspiration in terms of communicating your results, check out the following resources:

[The American Geophysical Union's Sharing Science Community][26]

[Informal Science: Dissemination and Sharing][27]

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For the Appendices section of the Guidebook or a digital copy of the entire Guidebook document, please visit:

https://www.aqmd.gov/aq-spec/special-projects/star-grant