United States Government Accountability Office

Report to Congressional Addressees

March 2024

TECHNOLOGY ASSESSMENT

Air Quality Sensors

Policy Options to Help Address Implementation Challenges

Accessible Version

GAO-24-106393

The cover image displays graphical examples of how lower-cost air quality sensors may be incorporated into a community, including near a school and city intersection, to measure air quality concerns, such as vehicle exhaust or smoke from distant wildfires.

Cover source: GAO. | GAO-24-106393

GAO

Highlights of GAO-24-106393, a report to congressional addressees

March 2024

TECHNOLOGY ASSESSMENT

Air Quality Sensors

Policy Options to Help Address Implementation Challenges

Why GAO did this study

U.S. ambient air quality is monitored by federal, state, and local agencies through the national ambient air quality monitoring system. However, that system is unable to provide some of the information that users may need to better manage health risks from air pollution. Lower-cost air quality sensors have the potential to help meet some of the monitoring information needs that require pollution measurements in additional locations or more real-time data.

This report describes (1) sensor technologies for monitoring air quality, (2) their benefits and uses, (3) how well they perform and factors that affect their performance, (4) challenges to their use, and (5) options policymakers could consider to help address these challenges.

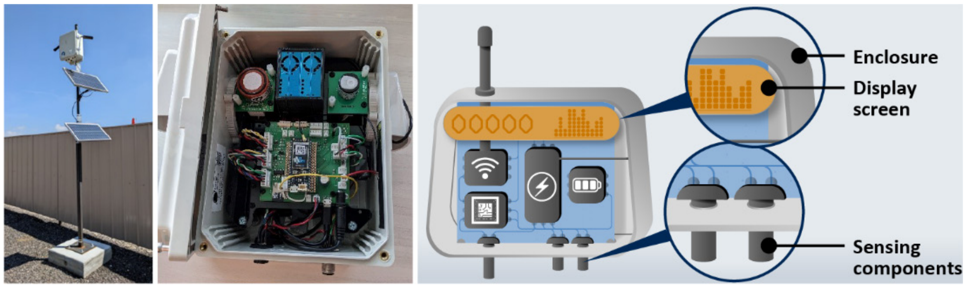
GAO reviewed key reports and scientific literature; interviewed federal and state agency officials and other stakeholders from academia, industry, and nongovernmental organizations; attended a workshop on issues related to lower-cost air quality sensors; and convened a 2-day meeting of 12 experts. These experts included those who conduct research on sensor technologies and their uses, develop or manufacture sensor technologies, or use or consider using sensor technologies and data. GAO is identifying policy options in this report.

View GAO-24-106393. For more information, contact Karen L. Howard at (202) 512-6888, HowardK@gao.gov or J. Alfredo Gómez at (202) 512-3841, GomezJ@gao.gov.

What GAO found

Lower-cost air quality sensors (sensors) are portable devices that can measure local air quality in real time. Although these sensors are generally less accurate than more expensive instruments, they can be deployed in large number to supplement information provided by the national air quality monitoring system. Among their many uses are identifying pollution hot spots, monitoring industrial sites and nearby neighborhoods, and conducting scientific research. Sensors can be more accurate for some pollutants, such as fine particulate matter, than others. They are as of yet unavailable for certain air toxics such as benzene and metals.

Air Quality Sensors



Source: GAO (photo, left); GAO (photo, middle); Adaption of Figure 1-1 in Environmental Protection Agency, *The Enhanced Air Sensor Guidebook* (2022) (illustration, right). | GAO-24-106393

GAO identified several challenges users face in implementing sensor technologies. For example, some users have struggled to:

Access expertise and resources. Some users may lack the knowledge or funding to select the right sensors or deploy them in a way that best fits their goals. Potential sources of expertise—such as universities or state and local agencies responsible for air quality management—may lack incentives or resources to partner with those users.

Understand sensor capabilities. Some vendors are not transparent about sensor performance. For example, some stakeholders told GAO that some vendors claim capabilities that are questionable. In the absence of reliable information on performance, users may struggle to choose appropriate sensors.

Compile and compare sensor data. Sensors produce data in many formats, and there are currently no widely accepted standards for reporting data from these different formats. In addition, some users do not report metadata that describe information such as environmental conditions or correction factors. Both issues can make it difficult for users to compile or compare data.

Spur action. Some users collect sensor data to spur action. But users and decision-makers may have different expectations about the level of quality assurance required. For example, some users seek evidence of pollutants that could trigger regulators to investigate a pollution source. However, these users may not realize that their data are not of sufficient quality for that purpose due to unclear guidance on the level of quality assurance needed.

GAO identified seven policy options that could help address challenges to developing and using air sensors. The options identify possible actions by policymakers, including legislative bodies, government entities, academia, industry, and other groups. See tables 5–11 in the report for a full list of the policy options, potential implementation approaches, and opportunities and considerations.

Policy Options to Address Challenges to Developing and Using Air Sensors

Policy Option	Opportunities	Considerations
Maintain status quo (report p. 31)	• Current efforts may address some challenges without additional resources. • Resources that would be allocated to additional interventions could be used for other opportunities.	• Current efforts are not likely to address all challenges described in this report.
Enhance sensor performance transparency (report p. 32) *For example, government entities or standards-setting organizations could establish additional standardized performance testing protocols and targets.*	• Standardized testing could increase transparency and build trust among users. • Performance targets could help ensure sensors work adequately for specific uses.	• Reaching consensus on standards can take considerable time. • Standardized testing could increase costs. • Industry could choose not to adopt voluntary performance testing protocols and targets.
Support innovation in sensor technologies (report p. 33) *For example, the sensor industry could choose to invest in additional research and development to improve existing sensors or develop new sensor technologies.*	• Could enable detection of additional pollutants or existing pollutants at lower levels.	• Time frames for research and development are unclear. • Could require substantial funding and other resources.
Facilitate access to expertise (report p. 34) *For example, universities could collaborate with others to establish technical assistance mechanisms that connect users with experts.*	• Could help users identify and collaborate with experts to ensure optimal use of sensors. • Could alleviate the burden on government entities or provide additional resources to carry out this work.	• Some government entities and other experts may require additional resources to fully collaborate with communities. • Participating experts may be overwhelmed by inquiries or requests for help.
Improve access to guidance (report p. 35) *For example, nonprofit organizations and other policymakers could collaborate with others to maintain a website with links to or copies of existing guidance.*	• Could help users locate guidance more easily, helping them improve sensor use. • Could enable users to compare guidance more easily, allowing them to select guidance that best aligns with their needs.	• Could be time and resource intensive and may need frequent updates. • Users may not know such a resource exists or trust it without endorsement and advertisement by a trusted entity. • Storing guidance in a repository may require consent from authors and owners.
Improve data management and sharing (report p. 36) *For example, standards-setting organizations could collaborate with others to develop data and metadata standards.*	• Data standards could help facilitate data aggregation, comparison, and sharing. • Metadata standards could help users ascertain whether data are comparable.	• Standards require consensus, which takes time and resources to build. • Organizations may not adopt voluntary data standards, especially if they were created without their input. • May be time and resource intensive.
Clarify level of quality assurance needed to spur action (report p. 37) *For example, government entities could collaborate with others to develop guidance on the level of quality assurance required for various applications.*	• Clarity on the level of quality assurance required could help users collect data that are appropriate for their specific purposes.	• Given the number of current and potential sensor applications, it may be difficult to clarify the level of quality assurance for each one.

Source: GAO. | GAO-24-106393

Table of Contents

Tables

Figures

Abbreviations

AQ-SPEC	Air Quality Sensor Performance Evaluation Center
CO	carbon monoxide
EPA	Environmental Protection Agency
IRA	Inflation Reduction Act of 2022
PM	particulate matter
TEMPO	Tropospheric Emissions: Monitoring of Pollution
VOC	volatile organic compound

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
Washington, DC 20548

March 19, 2024

The Honorable Tom Carper
Chairman
The Honorable Shelley Moore Capito
Ranking Member
Committee on Environment and Public Works
United States Senate

The Honorable James Comer
Chairman
Committee on Oversight and Accountability
House of Representatives

The Honorable Jennifer McClellan
House of Representatives

The U.S. has reduced air pollution significantly over the last 30 years, but poor air quality continues to harm public health in some places. The country has a national ambient air monitoring system that provides essential air quality information, but it can miss pollution at local scales and in rural areas.[1] Furthermore, the national system has limited monitoring of air toxics, a large category of air pollutants that may cause cancer or other serious illnesses. In November and December 2020, we reported that emerging lower-cost air quality sensors (called a "sensor" hereafter) could be used to supplement the national system, but users desired more information about the reliability and appropriate uses of this technology.[2]

The use of sensors is increasing, driven in part by policy and public interest about air quality stemming from wildfire smoke, neighborhoods near pollution sources, and other concerns. At the federal level, the Environmental Protection Agency (EPA) announced 132 community air monitoring projects to be conducted by groups including nonprofits, state and local agencies, and Tribes that would receive $53.4 million from the American Rescue Plan Act of 2021 and the Inflation Reduction Act of 2022 (IRA).[3] More than half of these monitoring projects plan to use

[1]EPA regulations implementing the Clean Air Act define ambient air as "that portion of the atmosphere, external to buildings, to which the general public has access." 40 C.F.R. § 50.1(e).

[2]GAO, *Air Pollution: Opportunities to Better Sustain and Modernize the National Air Quality Monitoring System*, GAO-21-38 (Washington, D.C.: Nov. 2020). GAO, *Science & Tech Spotlight: Air Quality Sensors*, GAO-21-189SP (Washington, D.C.: Dec. 2020).

[3]The American Rescue Plan Act of 2021 includes a provision for EPA to fund "activities that identify and address disproportionate environmental or public health harms and risks in minority populations or low-income populations under section 103(b) of the Clean Air Act (42 U.S.C.7403(b)." Pub. L. No. 117-2, tit. VI, § 6002 (a)(1), 134 Stat. 4, 93. The Inflation Reduction Act of 2022 includes a provision providing EPA with $3 million to support deployment, integration, and operation of air quality sensors in low-income, disadvantaged communities through grants and other activities. Pub. L. No. 117-169, tit. VI, subt. A, § 60105 (c), 136 Stat. 1818, 2068.

sensors, according to EPA officials. The IRA includes additional provisions to address air pollution, in which sensors may play a role.[4] For example, it provides $117.5 million for fenceline and other air monitoring, $37.5 million to monitor and reduce greenhouse gas emissions and other air pollutants at schools in low-income and disadvantaged communities, and $2.8 billion for environmental and climate justice block grants.[5]

At the state level, a regulatory requirement in Colorado has driven an increase in the use of sensors. As of 2021, Colorado requires certain owners or operators of oil and gas drilling operations to monitor air quality starting before pre-production and continuing through early production.[6] Some operators are using sensors to meet this requirement.

Individuals and community groups are also increasingly interested in using sensors to better understand their local environment and make decisions to manage their own risks. We reported in 2020 that the increasing availability of various types of local-scale, real-time information—such as for traffic and weather—is creating a public demand for a similar type of information on air quality, which sensors can potentially provide. In addition, the wildfire smoke episodes across the U.S. in 2023 prompted multiple news reports that increased public awareness about air quality.

In light of congressional interest in the role of sensors in identifying air pollution hot spots, fenceline monitoring, and community monitoring, among other uses, we conducted this technology assessment under the authority of the Comptroller General.[7] This report describes (1) sensor technologies for monitoring air quality, (2) their benefits and uses, (3) how well they perform and factors that affect their performance, (4) challenges to their use, and (5) options policymakers could consider to help address these challenges. We limited our scope to lower-cost, ground-based sensors for measuring regulated or unregulated air pollutants in ambient air that have a direct effect on human health.[8] We assessed the status of the field of sensor technology as a whole, but we did not assess any particular brand of sensors.[9]

---

[4]See for example Pub. L. No.117-169, tit. VII, subt. A, §§ 60105 (a), 60106 (a),(b), 60201(a),(b), 136 Stat. at 2067-69, 2078-79.

[5]Fenceline monitoring is the use of monitoring technologies to measure pollutants in ambient air along the property boundary, or the fenceline, of an industrial site, according to EPA and industry sources.

[6]5 CODE COLO. REGS. 1001-9, pt. B, VI.C.1a, VI.C.1.b.(ix).

[7]31 U.S.C. § 717(b)(1).

[8]We limited the scope of the assessment to lower-cost air quality sensors because their costs relative to other instruments offer unique opportunities for air quality monitoring. We adopted EPA's definition of lower cost to mean a device that costs up to $2,500 per pollutant it measures, up to a maximum cost of $10,000. For the purposes of this definition, we are referring only to the cost to purchase the device. Typical purchase cost of a sensor is $100–$5,000. In contrast, typical purchase cost of an instrument used in methods approved for use in the national ambient air quality monitoring system is $15,000–$40,000. Monitoring air quality using sensors incurs costs beyond the price of the device itself, such as the costs of maintenance and data storage. See EPA, *The Enhanced Air Sensor Guidebook,* EPA/600/R-22/213 (Washington D.C.: Sept. 2022). Although sensor applications include measuring indoor air quality, this report focuses on measuring outdoor air quality.

[9]For evaluation of sensor performance, see Environmental Protection Agency, "Evaluation of Emerging Air Sensor Performance," *Air Sensor Toolbox* (June 6, 2023), accessed December 5, https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-sensor-

GAO's prior work on air pollution and the national ambient air quality monitoring system informed our assessment.[10] We also interviewed federal, state, and local agency officials and other stakeholders, including sensor users; visited selected sites where air quality sensors were used or tested; convened an expert meeting; attended EPA's 2023 Air Sensors Quality Assurance Workshop; and reviewed agency documents and other literature.[11] See appendix I for a full discussion of the objectives, scope, and methodology and appendix II for a list of experts who participated in our meeting.

We conducted our work from November 2022 to March 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

performance and South Coast Air Quality Management District, "Evaluations," *Air Quality Sensor Performance Evaluation Center*, accessed December 5, 2023,https://www.aqmd.gov/aq-spec/evaluations.

[10]GAO, *Wildfire Smoke: Opportunities to Strengthen Federal Efforts to Manage Growing Risks*, GAO-23-104723 (Washington, D.C.: Mar. 2023); GAO, *Air Pollution: EPA Needs to Develop a Business Case for Replacing Legacy Air Quality Data Systems*, GAO-23-105618 (Washington, D.C.: Sep. 2023); GAO, *Air Quality Information: Need Remains for Plan to Modernize Air Monitoring*, GAO-22-106136 (Washington, D.C: Jul. 13, 2022); GAO-21-189SP; GAO-21-38.

[11]Stakeholders included individuals, organizations, and agencies that conduct research on sensor technologies and their uses; develop or manufacture these technologies; and use or consider using these technologies and the data they produce.

1 Background

1.1 Why monitor air quality?

Air quality data are important for tracking air pollution levels across time and location to inform air quality management and personal decisions to reduce exposure. Decades of research have shown that exposure to air pollution increases the number and seriousness of health problems. For example, exposure to particulate-matter air pollution has been linked to cardiovascular and respiratory health effects, certain cancers, and premature deaths.[12] Research has shown that some groups, including children, pregnant women, older adults, and people with preexisting heart and lung disease, are more susceptible to air pollutants. Air pollution may disproportionately affect Asian, Black, and Hispanic people in part because they are more likely to be living near air pollution sources such as major highways and industrial facilities.

1.2 Current state of air quality monitoring

In the 1970s, amendments to the Clean Air Act led to the establishment of the national ambient air quality monitoring system.[13] The system, which is cooperatively managed by EPA and state and local agencies, consists of sites equipped with monitors that measure air pollution levels around fixed locations across the country.[14] The system provides information essential for assessing compliance with the Clean Air Act and public information on air quality. In addition, it provides "gold standard" information for research or for testing new air quality measurement technologies, according to literature and some stakeholders.

The majority of the system's monitoring sites measure one or more of six "criteria" pollutants—carbon monoxide, lead, ozone, particulate matter, nitrogen dioxide, and sulfur dioxide—for which EPA has established standards for the allowable levels of each pollutant in the ambient air.[15] The monitoring system also includes a network of 25 National Air Toxics Trends Stations, which provide

[12]Particulate matter refers to a mixture of solid particles and liquid droplets found in the air.

[13]Specifically, section 319 of the Clean Air Act requires EPA to establish an air quality monitoring system throughout the U.S. which, among other things, utilizes uniform air quality monitoring criteria and methodology and measures such air quality according to a uniform air quality index. Clean Air Act Amendments of 1977, Pub. L. No. 95-95, tit. III, §309, 91 Stat. 685, 781-82 (codified as amended at 42 U.S.C. § 7619). The Clean Air Act also requires that EPA review the National Ambient Air Quality Standards every 5 years and revise them if the review deems that a change is warranted. The monitoring system has evolved over time in response to regulatory changes and new technologies, according to EPA officials.

[14]EPA and state and local agencies play different roles in the system's design, operation, oversight, and funding. For example, EPA establishes minimum requirements for the system, and state and local agencies operate the monitors and report data to EPA.

[15]EPA calls these pollutants "criteria" air pollutants because EPA sets the standards for these pollutants based on health-based criteria, which are characterizations of the latest scientific information regarding their effects on health or welfare. These standards, known as National Ambient Air Quality Standards are established by EPA for criteria pollutants to protect public health as required by the Clean Air Act. 42 U.S.C. §7409. Data from the national ambient air quality monitoring system are used to support compliance with the National Ambient Air Quality Standards.

information of consistent quality on trends of certain air toxics across the country.[16] In addition, state and local air agencies (called agencies hereafter) operate hundreds more air toxics monitoring sites each year.[17] In this report, we refer to the methods approved for comparison with the national ambient air quality monitoring system as "reference methods" and the instrumentation used by those methods as "reference monitors."[18]

In November 2020, we found that decision-makers, researchers, and the public needed additional information to better understand and address health risks from air pollution, according to officials from EPA and selected state and local agencies.[19] For example, we found that the monitoring system was unable to meet needs for information on:

- air pollution hot spots, or local areas of high pollution, that may occur between existing monitoring sites;
- real-time information on short-term changes in air quality;
- air quality in rural areas, which may have limited or no monitoring.

The national network that monitors air toxics may not provide information in key locations near identified cancer clusters, industrial facilities, and other potential hot spots. In addition, all samples of air toxics at those stations are collected over a 24-hour period once every 6 days to align with the program goal of detecting trends in annual average concentrations. More frequent and timely information on air toxics could help understand pollution sources and reduce human health risks. We reported that sensors have the potential to help meet some of the monitoring information needs that require pollution measurements in additional locations or more real-time data.[20]

1.3 What are sensors for monitoring air quality?

A sensor is an integrated device that a user can deploy "out of the box" to measure one or more pollutants in air (see fig. 1). It includes a sensing component that physically or chemically interacts with the target pollutant to generate a signal. It also typically includes several components, such as an enclosure, a microprocessor, and a power source.

---

[16]The National Air Toxics Trends Stations network provides data to assess trends and the effects of emissions reduction programs, and to help validate and inform air quality models. See https://www3.epa.gov/ttnamti1/natts.html. According to EPA officials, there is no requirement for a broader national monitoring program for air toxics. EPA defines air toxics as pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. EPA has not established National Ambient Air Quality Standards for listed air toxics, but regulates them by establishing standards that limit the amount of emissions allowed from certain individual pollution sources. EPA uses the term "hazardous air pollutants" for air toxics that are specifically listed as relevant to programs in the Clean Air Act. Some air toxics are not included on the list of hazardous air pollutants.

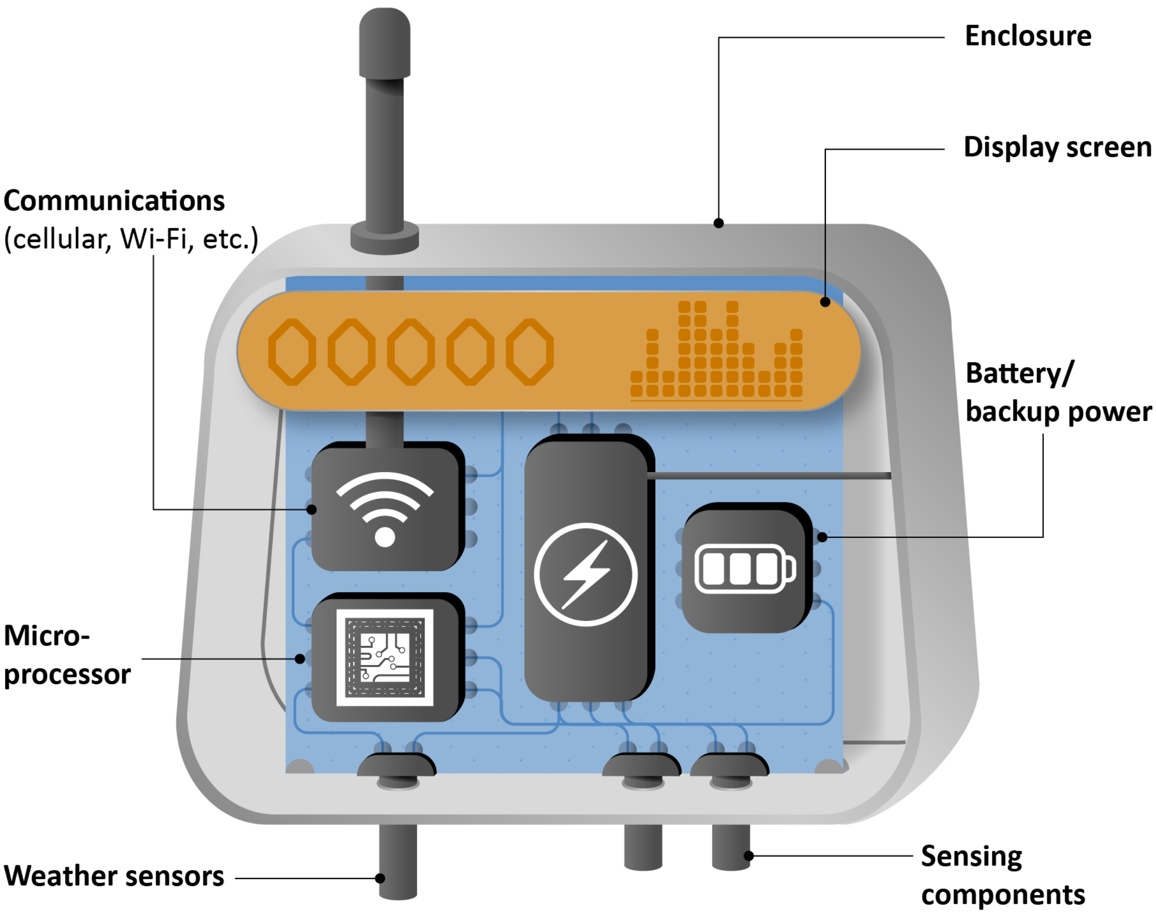
[17]Certain state and local air toxics monitoring programs use common methods for producing data. However, since these are not required networks, the use of common methods across all state and local air toxics monitoring is not assured. See GAO-21-38 for additional information on the networks that constitute the national ambient air quality monitoring system.

[18] See https://www.epa.gov/amtic/air-monitoring-methods-criteria-pollutants.

[19]GAO-21-38.

[20]GAO-21-38.

Figure 1: Typical air sensor components



Source: Adaption of Figure 1-1 in Environmental Protection Agency, *The Enhanced Air Sensor Guidebook* (2022) (illustration). | GAO-24-106393

Although there are many sensors on the market today, they generally fall into four different types, depending on how they measure pollution: light scattering, electrochemical, metal oxide semiconductor, and photoionization (see table 1).

Table 1: Types of air quality sensors and their target pollutants

Sensor type	Target pollutants in ambient air
Light-scattering sensors	Particulate matter of different size fractions—PM_1, $PM_{2.5}$, PM_{10} (and sometimes other size fractions)[a]
Electrochemical sensors	Gas-phase pollutants including ozone (O_3), nitrogen oxides (NO_X), carbon monoxide (CO), sulfur dioxide (SO_2), total volatile organic compounds (VOC)[b]
Metal oxide semiconductor sensors	Gas-phase pollutants including O_3, CO, NO_X, total VOCs
Photoionization detectors	Total VOCs

Source: GAO analysis of literature. | GAO-24-106393

[a]Particulate matter (PM) consists of particles of different sizes. PM_X refers to the size fraction of particulate matter, with “x” referring to the maximum particle diameters in micrometers.

[b]According to the Environmental Protection Agency, nitrogen oxides (NO_X) are a family of seven compounds (N_2O, NO, N_2O_2, N_2O_3, NO_2, N_2O_4, and N_2O_5).

2 Benefits and Uses of Air Quality Sensors

In addition to their lower costs, sensors are small and portable, require minimal infrastructure, and provide real-time or near-real-time measurements. These attributes enhance the feasibility of deploying multiple sensors as a network to capture variations in air quality at a higher spatial resolution than reference monitors and other expensive instruments. Sensors are accessible to many different stakeholders because of their lower costs. Academic researchers, individuals, businesses, government entities, and nonprofits are using them to monitor air quality in areas without reference monitors, at the fencelines of industrial facilities, in urban and rural communities, and near wildfires. Their purposes range from raising awareness to gathering information to shape policy decisions. As technology develops and improves, sensors may become available for additional pollutants or new uses.

2.1 Sensors can provide high resolution data

Sensors complement other methods for air quality monitoring, including reference monitors and satellite-based instruments (see table 2), by providing higher spatial resolution data. The differences in the characteristics of these methods, including their costs, complexity to operate, and infrastructure needs, offer or limit opportunities to collect data for various applications.

Table 2: Differences between sensors and other technologies for monitoring air quality

	Ground-based sensor	Ground-based reference monitor	Satellite-based instrument
Typical purchase cost of equipment	$100–$5,000	$15,000–$40,000	N/A[a]
Measurement frequency	Sub-hourly	Sub-hourly, hourly, daily	Hourly, daily
Application examples	Many (e.g., personal use, local traffic planning, disaster response, research, education)	Determining whether certain pollutants are below allowable levels under the Clean Air Act[b] Standardized monitoring of regional or national air quality trends	Measuring air pollution across large areas for air quality forecasts and to address scientific inquiries
Example pollutants	Criteria pollutants (except lead), black carbon, and some other gases (including total volatile organic compounds)[c]	The six criteria pollutants and some air toxics	Some criteria pollutants and formaldehyde
Operators	Anyone	Regulatory and research entities[d]	Government and research entities
Relative data quality	Variable (see ch. 3)	High	Variable

	Ground-based sensor	Ground-based reference monitor	Satellite-based instrument
Infrastructure needs	Low: self-contained, low power (even solar), remote data logging	Medium: shelter building, power, technician visits to collect samples	High: rocket launch capability to send measurement instrument such as spectrometer to space
Measurement	Measures pollution at the ground level	Measures pollution at the ground level	Estimates pollution at the ground level based on energy reflected from or through the entire air column above the Earth

Source: GAO analysis of table 2-3 and figure 2-8 in Environmental Protection Agency, *The Enhanced Air Sensor Guidebook* (2022); literature; interviews; and websites. | GAO-24-106393

[a]There are not many satellite-based instruments for measuring air quality to make a statement about typical purchase cost of equipment. For comparison, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument to measure air quality in North America from space cost about $90 million.

[b]Under the Clean Air Act, the Environmental Protection Agency (EPA) has established standards for levels of certain pollutants in the ambient air intended to protect public health. See 42 U.S.C. § 7401 et. seq.; 40 C.F.R. pt. 50.

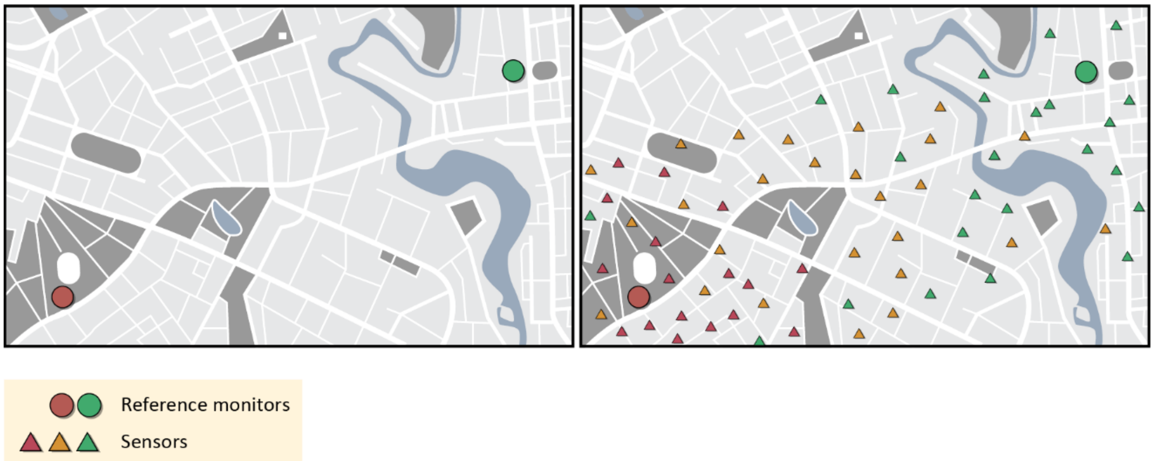
[c]The six criteria pollutants are carbon monoxide, lead, ozone, particulate matter, nitrogen dioxide, and sulfur dioxide. EPA calls these “criteria” air pollutants because EPA sets the standards based on health-based criteria, which are characterizations of the latest scientific information regarding their effects on health or welfare.

[d]By “regulatory entities,” we mean the state and local agencies that operate reference monitors in the national ambient air quality monitoring system. According to EPA, the national system database may not include data collected by reference monitors operated by research entities.

Sensors can provide frequent measurements (high time resolution) and detect spikes in pollutant levels. They can measure pollution in real time. By contrast, while some reference monitors can collect information in real time, some cannot. Satellite-based instruments can collect hourly or daily data only during daylight hours and cannot measure pollution below clouds.

In addition to enhancing time resolution, the lower purchase cost of sensors combined with their portability and lower infrastructure requirements also makes it easier to improve spatial resolution (see fig. 2). Specifically, users can deploy multiple sensors as a network to track movement of pollutants and measure them at a finer geographical scale.

Figure 2: Spatial resolutions for measuring ambient air quality with sensors and reference monitors



Source: South Coast Air Quality Management District, *Community in Action: A Comprehensive Guidebook on Air Quality Sensors* (2021) as modified using Marina/stock.adobe.com (map). | GAO-24-106393

A dense network of reference monitors can be cost-prohibitive. For example, one piece of reference monitoring equipment typically cost $15,000–$40,000. In addition, reference monitors are typically housed in climate-controlled shelters at additional infrastructure cost (see fig. 3).[21]

[21]Some reference monitors require controlled conditions to be approved for use in the national ambient air quality monitoring system as reference methods. According to EPA officials, the monitoring shelters and security fences around the perimeter are important to securing reference monitors and data collection or transmission equipment to ensure no tampering has occurred at any point in the process of measuring, recording, transferring, and reporting results.

Figure 3: Infrastructure needs of different air quality monitoring methods

Solar-powered sensor mounted on a pole (left) and a sensor (right).

Climate-controlled shelter for reference monitoring (left) and equipment inside a reference monitoring shelter (right).

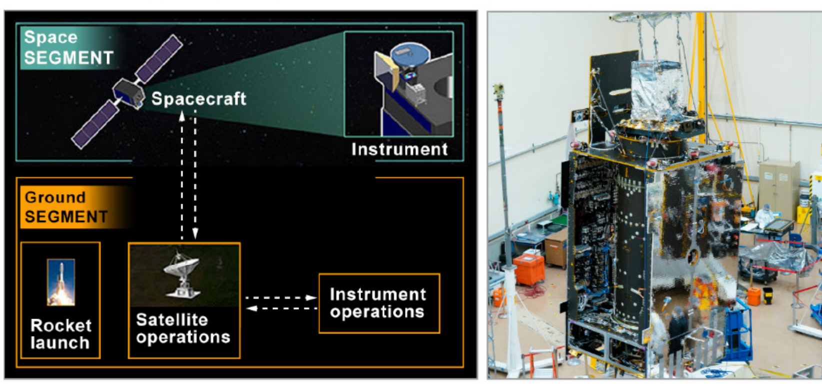


Illustration of the infrastructure needed to collect data from the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument from space (left) and integration of the TEMPO instrument with a satellite (right).

Source: GAO (photo, top left); GAO (photo, top right); GAO (photo, middle left); GAO (photo, middle right); National Aeronautics and Space Administration (illustration, bottom left); Maxar (bottom right). | GAO-24-106393

Satellite-based monitoring also requires high-cost instrumentation and infrastructure. For example, the National Aeronautics and Space Administration supported the development of the Tropospheric Emissions: Monitoring of Pollution instrument, which cost about $90 million. It began measuring air pollutants across North America in 2023 after about 10 years of planning and development.

2.2 Stakeholders use sensors to inform decisions and raise awareness about air quality

Sensors can benefit users from various stakeholder groups by helping them gather information to inform decisions about air quality management, conduct research, educate themselves and others, and for other uses (see table 3). If users deploy sensors as a network, they can track differences in air quality across locations or movement of pollutants over time to inform decisions to protect public health. However, these sensors cannot be used to meet federal monitoring requirements because they do not currently meet the standards set for reference methods.

Table 3: Illustrative examples of why, where, and who may use air quality sensors

Why sensors might be used (i.e., application)	**Where** sensors might be used	**Who** might be involved	Example
Decision-making			
Measure hyperlocal air quality to help reduce personal exposure	Residential properties or any specific location of interest	Individuals	Some individuals have used sensor data to decide when to go outside or which route to take to avoid pollution sources.
Improve occupational health and safety	Work sites	Industry, workers	Some companies have used sensors to monitor ambient pollution levels to ensure occupational health and safety.
Respond to emergencies or supplement information during natural disasters	Areas affected by wildfires, volcanic eruptions, or hurricanes	Community groups, government entities, individuals	Government agencies have used sensors during wildfires to track smoke plumes and provide information to communities.
Identify hot spots to manage local air quality	Roadways, parking areas	Local environmental entities, local governments	A local government has used sensors to detect pollution hot spots and make modifications to address road traffic and raise awareness to discourage vehicle idling.
Monitor industrial sites	Industrial facilities, oil and gas production sites	Industry	Some companies have used sensors to continuously monitor for leaks and respond quickly should there be one.
Regulatory network support			
Inform new regulatory monitoring site selection	Sites under consideration for regulatory monitoring	Regulatory entities[a]	Some regulatory entities have used data from sensor networks to help decide where to locate reference monitors.

Why sensors might be used (i.e., application)	Where sensors might be used	Who might be involved	Example
Inform regulatory entities of problems with reference monitors	Various	Community groups, regulatory entities, researchers	A regulatory entity identified issues with a reference monitor when a community group noted that data from the reference monitor and local sensor network data did not match.
Other			
Perform research	Various	Research organizations, universities	Some researchers have used data for air quality modeling, atmospheric science, epidemiology, and other research.
Conduct outreach	Various	Community groups, government entities	Some government entities and community groups have used sensors to raise awareness about air quality in neighborhoods.
Enhance education	Various	Universities, K-12 schools	Some academic institutions have used sensors as a tool to teach concepts in science, technology, engineering, and math.
Monitor neighborhoods near pollution sources and support environmental justice	Neighborhoods near pollution sources such as industrial facilities and highways	Communities, government entities, researchers	A community group has used sensors to demonstrate and raise awareness about disproportionate air pollution in an overburdened county.[b]

Source: GAO analysis of information from literature, expert meeting, interviews, and other sources. | GAO-24-106393

[a]By “regulatory entities,” we mean the state and local agencies that operate reference monitors in the national ambient air quality monitoring system.

[b]The Environmental Protection Agency (EPA) defines overburdened communities as “minority, low-income, tribal, and Indigenous populations or communities in the United States that potentially experience disproportionate environmental harms and risks due to exposures or cumulative impacts or greater vulnerability to environmental hazards.” See EPA, “What is the definition of ‘overburdened community’ that is relevant for EPA Actions and Promising Practices?” *Permitting Under the Clean Air Act* (July 18, 2023), https://www.epa.gov/caa-permitting/what-definition-overburdened-community-relevant-epa-actions-and-promising-practices.

Costs of deployment vary according to which of these purposes sensors serve. For example, purchasing one sensor to measure hyperlocal air quality at someone’s home will cost less than deploying a network of sensors to monitor neighborhoods near pollution sources. In addition to sensor purchase, other cost factors include human resources to maintain sensors, along with infrastructure and human resources to store, manage, and analyze data produced and to disseminate information.

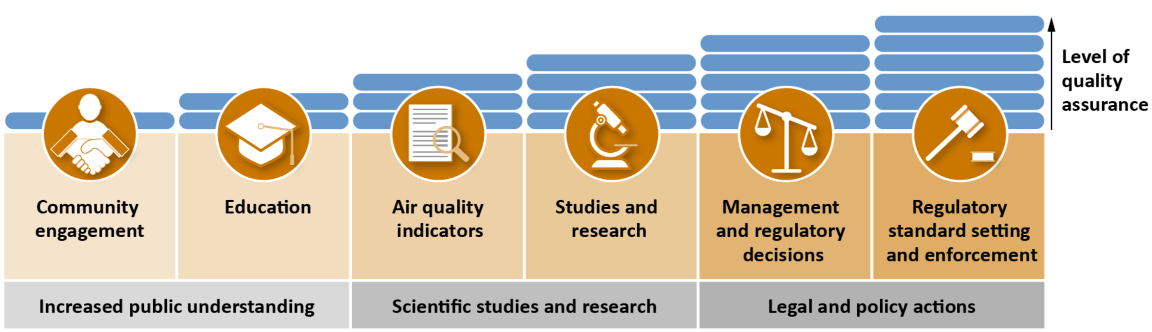
The purpose of sensor use also affects the level of quality assurance needed (see fig. 4). In the context of air quality monitoring with sensors, quality assurance can include user training, sensor maintenance, and documentation of procedures. Some sensor applications require more rigorous steps to achieve higher quality results than other purposes. For example, data collection for scientific studies and research requires a higher level of quality assurance than for educational and illustrative purposes because researchers need to ensure conclusions are sound. The vignettes at the end of this chapter highlight how sensors are currently used in common contexts and how the level of quality assurance needed may differ among uses.

2.3 Applications of sensors may expand in the future

As technology develops and improves, sensors may become available for new uses or to measure additional pollutants. According to our interviews with stakeholders, some users would like to have sensors that can reliably measure particle composition or specific air toxics, given that EPA's 2019 AirToxScreen identified many communities facing elevated health risks.[22] For example, users are interested in the development or improvement of sensors to measure:

- **Black carbon**. These particles are produced from incomplete combustion of carbon-based fuels, such as diesel or wood. They are reliable indicators of harmful pollution—such as toxic organic chemicals—produced from fires and burning fossil fuels.
- **Benzene**. This air toxic is a known carcinogen, and workers exposed to benzene have higher incidences of leukemia. At least three stakeholders we interviewed told us they want to monitor benzene in neighborhoods near industrial facilities or oil and gas sites.

Figure 4: The level of quality assurance needed depends on the purpose of air quality monitoring



Source: GAO adaption of Environmental Protection Agency information; GAO (icons). | GAO-24-106393

[22]For more information, see Environmental Protection Agency, "2019 AirToxScreen: Assessment Results," *Air Toxics Screening Assessment* (June 15, 2023), https://www.epa.gov/AirToxScreen/2019-airtoxscreen-assessment-results. By "many communities," we mean more than nine.

- **Ethylene oxide**. This air toxic is carcinogenic, when inhaled and exposure increases people's risk of lymphoid and breast cancer. Ethylene oxide is used to produce antifreeze and in medical sterilization facilities.
- **Metals**. Some air toxics are metals that are highly toxic even at low concentrations (e.g., hexavalent chromium).[23] Officials from one state agency told us that they would like to use sensors to monitor for metals in direct emissions from industrial facilities to detect accidental releases.

Some users are already extending the capabilities of sensors by combining them with other methods. For example, some users are pairing sensors that lack specificity with another method that can differentiate between specific air toxics—such as benzene, hexane, and toluene—to reduce cost. Specifically, they use a sensor that measures the combined concentration of a class of air toxics known as volatile organic compounds (VOC). When this sensor detects a signal above a set threshold, it triggers collection of an air sample in a canister (see fig. 5). The users send the canister sample to a laboratory for detailed chemical analysis, which provides information about levels of specific air toxics that were present when the sensor signal exceeded the threshold. This approach has been used, for example, in detection and identification of specific air toxics at industrial facilities to help determine the source of the emissions and local short-term air pollutant concentrations, according to EPA officials.

Figure 5: A sensor that triggers collection of an air sample in a canister when it detects a signal above a set threshold

Source: Environmental Protection Agency, Eben Thoma, Office of Research and Development, Center for Environmental Measurement and Modeling, Air Methods & Characterization Division (photo). | GAO-24-106393

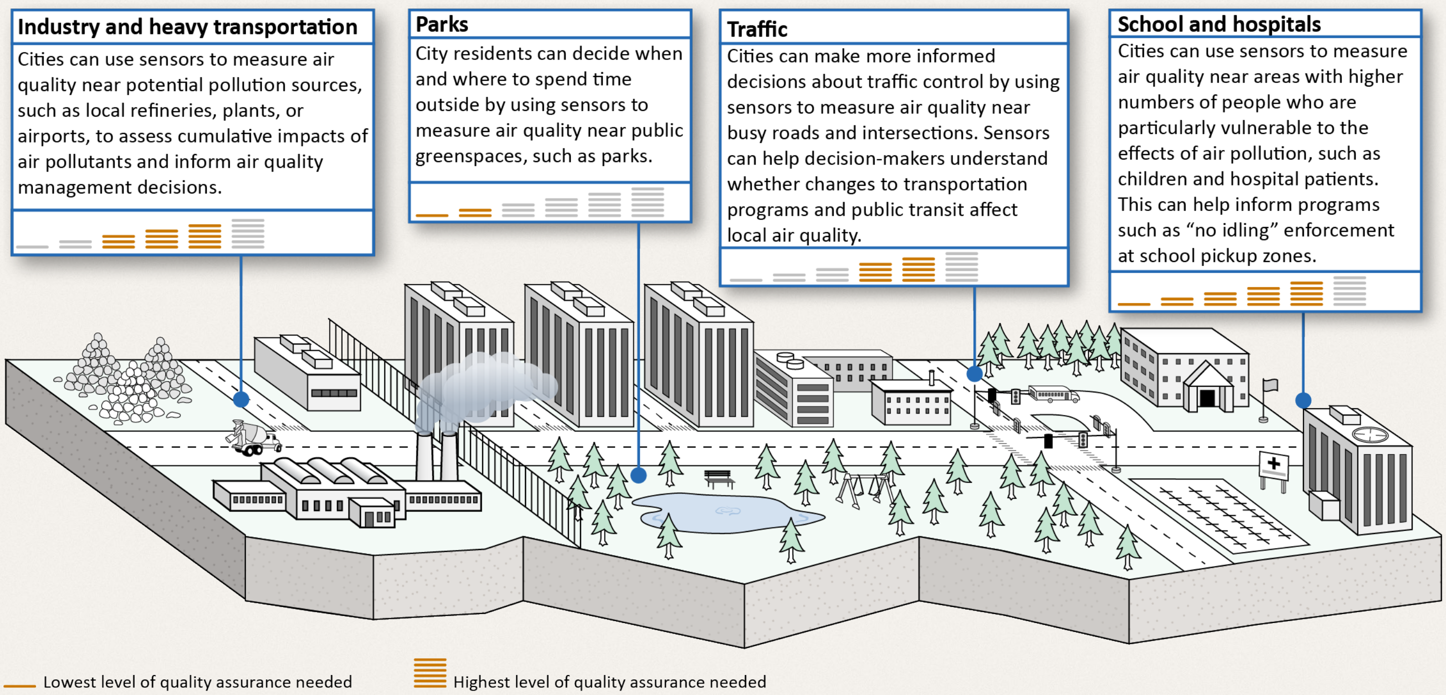
[23]Some air toxics are challenging to monitor even with reference monitors or other instruments more expensive than sensors. Hexavalent chromium is a highly toxic metal compound used for chrome plating, dye and pigment manufacturing, and other uses. Continuous or repeated inhalation of hexavalent chromium increases the risk of lung, nasal, and sinus cancer.

Air Quality Sensors for

CITIES

Air quality is often worse in urban areas due to a higher number of pollution sources, and reference monitors are often too far apart to observe how air pollution varies spatially within a city. Decision-makers have used sensors to understand how traffic, local industry, and land use affect local air quality. For example, some city planners have experimented with real-time traffic signal changes to reduce air pollution from idling vehicles. Local policymakers have used sensor data when considering choices about infrastructure and urban expansion, which could affect future air quality.

Highlighted examples



Source: GAO (analysis and illustration). | GAO-24-106393

Challenges

Recent studies suggest sensors that are popular for use by the public are often concentrated in census tracts with above-average income and higher shares of White residents. Cities may therefore not always capture air quality data in overburdened communities despite their higher likelihood of exposure to air pollution.[24]

Source: GAO analysis of literature, interviews, and expert meeting discussions; GAO (illustration, background); pakatip/stock.adobe.com (illustration, top right); Man As Thep/stock.adobe.com (illustration, bottom left). | GAO-24-106393

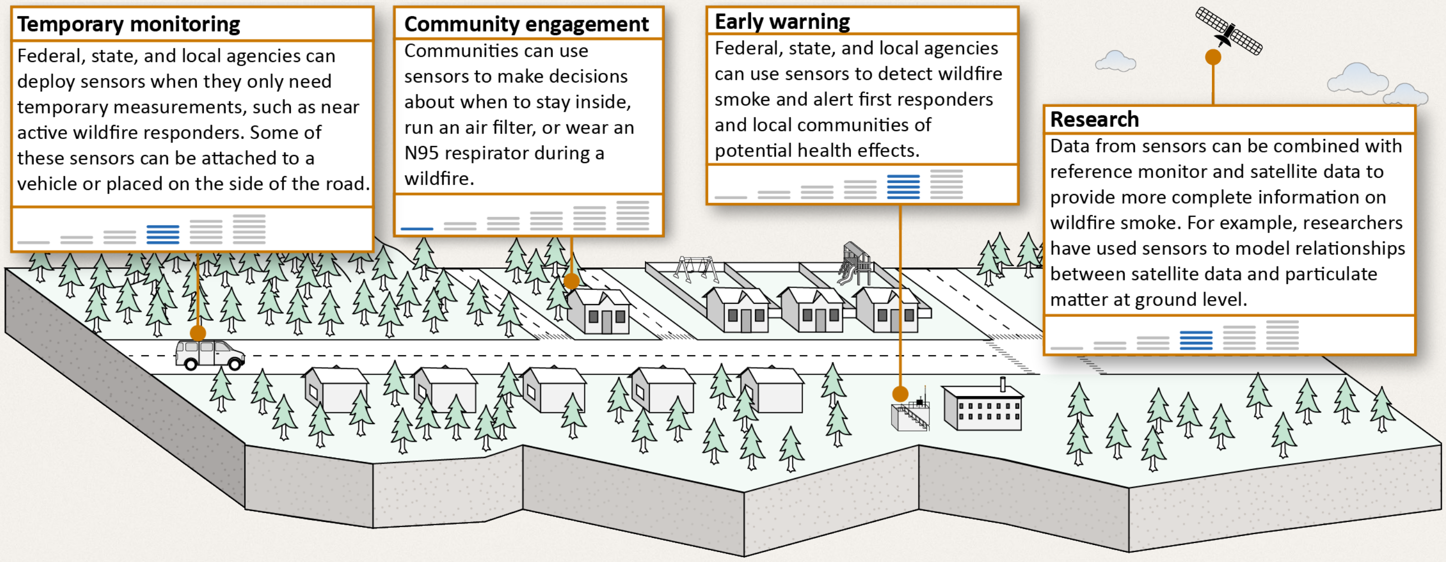
[24]EPA defines overburdened communities as "minority, low-income, tribal, and Indigenous populations or communities in the United States that potentially experience disproportionate environmental harms and risks due to exposures or cumulative impacts or greater vulnerability to environmental hazards."

Air Quality Sensors for

WILDFIRE SMOKE

In recent years, smoke from large wildfires has created unhealthy air quality conditions for tens of millions of Americans. Community groups, researchers, and government entities use sensors to monitor smoke from wildfires. For example, the U.S. Forest Service has used sensors to measure air quality and provide information to communities affected by wildfire smoke. Sensors are particularly useful for monitoring wildfire smoke in areas without nearby permanent reference monitors. Because sensors are small and portable, they can be deployed quickly during an emergency.

Highlighted examples

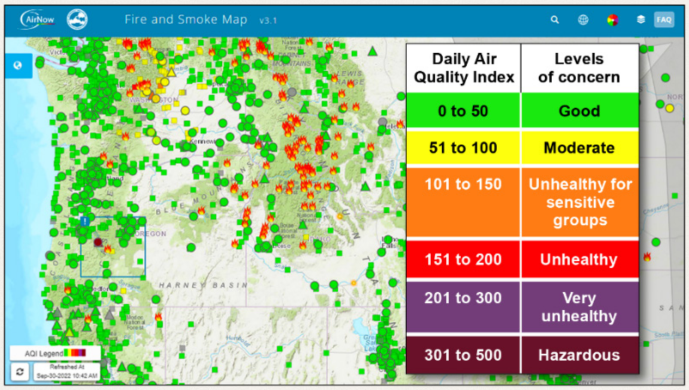


Lowest level of quality assurance needed — Highest level of quality assurance needed

Source: GAO (analysis and illustration). | GAO-24-106393

Challenges

Sensors are more accurate when they have been calibrated against a reference monitor, but this might not be possible if users need to deploy sensors quickly during an emergency. Additionally, particulate matter (PM) sensors may not measure wildfire PM accurately because of its composition and size distribution.



The AirNow Fire and Smoke Map, developed by the Environmental Protection Agency and Forest Service, shows fine particulate matter ($PM_{2.5}$) measurements from permanent reference monitors, temporary monitors deployed by agencies for smoke events, and sensors.[25]

Source: GAO analysis of literature, interviews, and expert meeting discussions; GAO (illustration, background); Oqvector/stock.adobe.com (illustration, top right); fire.airnow.gov (photo, bottom right). | GAO-24-106393

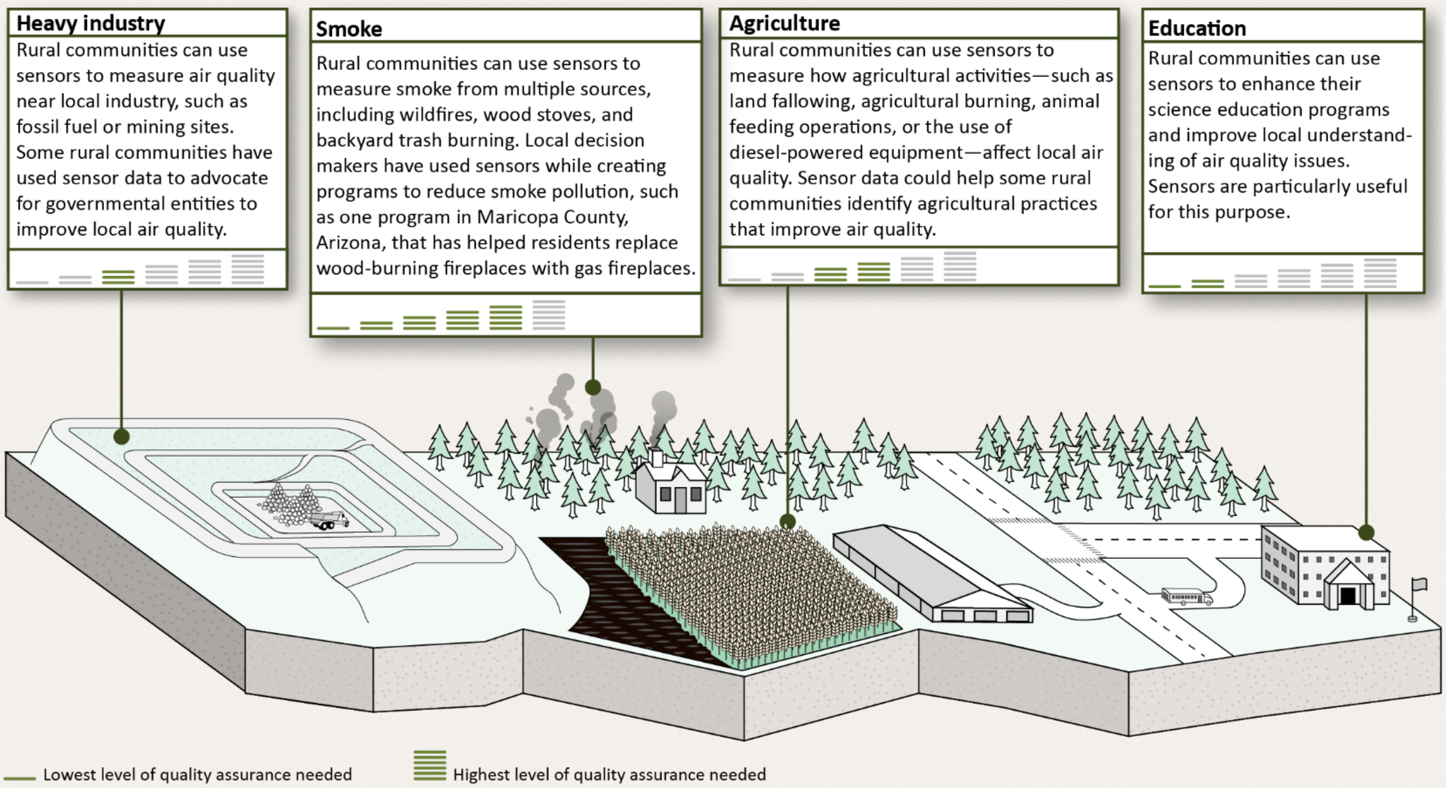
[25] https://fire.airnow.gov/

Air Quality Sensors for

RURAL COMMUNITIES

Rural communities have used sensors to help fill data gaps between reference monitors, and to advocate for improvements in local air quality. Rural air quality can be affected by several pollution sources, such as oil and gas sites, wood stoves, or agricultural activities. Further, some rural communities may be more prone to poor air quality from wildfire smoke due to their geographic locations, prevailing winds, and topography.

Highlighted examples



Source: GAO (analysis and illustration). | GAO-24-106393

Challenges

Sensors in rural networks may be further apart than in urban networks and thus require more travel time for users to maintain, service, or troubleshoot. Users in remote communities may struggle to reliably power their sensors or connect to Wi-Fi or cellular service to transmit the data. As a result, these users may have fewer options when selecting sensors that meet their needs. Additionally, certain uses require placing at least one sensor next to a reference monitor for data calibration, but these monitors are less common in rural areas.

Sources: GAO analysis of literature, interviews, and expert meeting discussions; GAO (illustration, background); Sylverarts/stock.adobe.com (illustration, top right); klio111/stock.adobe.com (illustration, bottom left). | GAO-24-106393

3 Performance

Sensor performance can vary significantly based on target pollutant, environmental factors, sensor attributes, and deployment approach. Market demand has driven research and development of new and improved sensors, which could help address some of the limitations of current sensors and provide new opportunities to measure pollutants that current sensors cannot measure. However, innovation and improvements may not occur if the current market demand and other mechanisms are absent.

3.1 Performance varies by target pollutant and other factors

Sensor performance depends on several factors, including some pertaining to the sensor hardware and its interaction with the environment and pollutants and others related to how a user deploys the sensor. Specifically, the following sensor-specific factors affect performance:

- **Target pollutant.** Sensors are more accurate for some pollutants than others and are unavailable for many pollutants. Light-scattering sensors for particulate matter are a widely deployed type of sensor. They generally produce more reliable results for $PM_{2.5}$ measurements than PM_{10}.[26] Performance of electrochemical sensors and metal oxide semiconductor sensors varies by brand and by target pollutants. Photoionization detectors for total VOCs have significant limitations that hinder their usefulness.[27] Table 4 shows common performance characteristics of these sensors. In addition, sensors are not available for all pollutants. For example, no lower-cost sensors exist to measure ambient levels of specific air toxics, such as ethylene oxide and metals.[28] Furthermore, today's sensors cannot measure the size distribution of ultrafine particles emitted from industrial processes and burning fossil fuels, which pose health risks.

Table 4: Characteristics of different types of air quality sensors

Sensor type	Target pollutants	Some common characteristics
Light-scattering sensors[a]	Particulate matter (PM)	• Reasonable accuracy for $PM_{2.5}$[b] • Not a direct mass measurement and requires calibration to report values as a pollutant level (e.g., in mass per volume of air)[c]

[26]There are two types of light-scattering sensors: nephelometers and optical particle counters. This report does not differentiate them, and vendors often do not specify the type of light-scattering sensor used in their product.

[27]VOCs are a large group of gases emitted from a variety of sources. Some VOCs are air toxics, such as benzene, 1,3-butadiene, and vinyl chloride.

[28]Sensors exist that measure specific air toxics, such as ethylene oxide, but they typically lack the sensitivity needed for ambient use.

Sensor type	Target pollutants	Some common characteristics
		• Requires assumptions about particle density and size distribution to derive quantities for each particle size class (e.g., $PM_{2.5}$ or PM_{10}) • Some cannot detect particles smaller than 0.3 micrometers (e.g., ultrafine particles from vehicle exhaust) • Most cannot reliably measure PM_{10} (e.g., dust) • Cannot measure chemical composition of particles
Electrochemical sensors and Metal oxide semiconductor sensors	Gas-phase pollutants	• Responds to non-target pollutants and produces a reading even in the absence of target pollutant (also known as cross sensitivity), but electrochemical sensors may perform better for some targets (e.g., carbon monoxide or ozone) when non-target pollutants can be accounted for • Subject to drift and decrease in sensitivity with age[d]
Photoionization detectors	Total volatile organic compounds (VOC)	• Cannot be correlated to pollutant concentration when more than one VOC is present • Cannot identify which VOCs are present • Responds to non-target pollutants and produces a reading even in the absence of target pollutant • Cannot detect some VOCs at all

Source: GAO analysis of information from literature and interviews. | GAO-24-106393

[a]There are two types of light-scattering sensors: nephelometers and optical particle counters. This report does not differentiate them, and vendors often do not specify the type of light-scattering sensor used in their product.

[b]Particulate matter (PM) consists of particles of different sizes. PM_X refers to the size fraction of particulate matter, with "X" referring to the maximum particle diameter in micrometers. Thus, $PM_{2.5}$ refers to particles with diameters of 2.5 micrometers and smaller (e.g., smoke).

[c]The National Ambient Air Quality Standards for PM to protect public health are set in units of mass per volume of air.

[d]Drift refers to a gradual increase or decrease in a sensor's response to pollutant concentration over time.

- **Environmental conditions.** Sensor hardware is sensitive to temperature, humidity, and other conditions. Unlike reference monitors, which are typically kept in climate-controlled shelters, sensors are not as well protected, so extreme or variable conditions can damage them or affect their readings. For example, high humidity and low temperatures can cause condensation inside of sensors, damaging their electronics, according to EPA.
- **Pollutant concentration.** The concentration of the target pollutant also

affects performance. For example, gas sensors may not be sensitive enough to detect sulfur dioxide at ambient concentrations that are typically low.

- **Design.** Sensor design affects performance in a variety of ways, including how well the sensing component is protected from environmental conditions and how efficiently the pollutant reaches the component. For example, the air flow of PM sensors varies by their design, and sensors with low air flow may detect fewer of the larger particles.
- **Age.** Sensor performance can deteriorate over time even before the sensor fails. All sensors have a finite lifespan that depends on sensor type, environmental conditions, and how well the sensor is maintained. In general, sensors can be expected to last 1 to 5 years before the sensing component (or entire sensor) must be replaced.

Beyond factors pertaining to the hardware, performance also depends heavily on the following factors related to how users deploy sensors, including:

- **Siting.** Inappropriate siting of sensors may result in data that do not reflect ambient air quality. Sensors perform best when installed in a position that allows unobstructed air flow and at locations far enough from concentrated pollution sources to ensure the measurements reflect the surrounding air quality as opposed to the pollution source.
- **Maintenance.** Routine maintenance is required if sensors are to remain accurate. For example, dust and dirt need to be removed regularly, and filters and other parts may need replacement. Spiders or wasps have made homes in sensors, causing abnormal measurements. In addition, users need to monitor sensors for changes in baseline readings, known as drift, and recalibrate them. Users also need to replace sensors if they lose sensitivity.
- **Data processing.** Techniques, including calibration and averaging, can be applied to data and may be needed to improve sensor performance (see text box). Conversely, using the wrong calibration could skew the data collected by the sensor.

Examples of sensor data processing

Calibration is a common strategy to help improve the accuracy of sensor data. In the context of sensors, calibration means correcting the data based on comparison to a reference monitor or a known, standard concentration of the target pollutant. Calibration can factor in variables such as temperature and humidity to help compensate for local conditions. Calibrations are often developed by placing a sensor next to a reference monitor under the same conditions expected during deployment.

Averaging can reduce background "noise" and help users identify trends. Pollution often needs to be measured as an average over a certain period. However, some applications of sensors, such as leak detection, require higher-resolution data, so averaging over longer periods is not appropriate.

Source: GAO summary information from literature and interviews. | GAO-24-106393

3.2 Market demand drives research and improved performance

The performance of future sensors is likely to improve, driven by factors such as market demand, according to sensor developers and a research funder we interviewed. For example, researchers are now developing sensors to measure specific VOCs, such as benzene, because fenceline communities have attributed chemical odors to industrial facilities. Some communities have increased their interest in measuring benzene and other pollutants.

Regulatory requirements can also increase market demand for sensors. According to EPA officials and a stakeholder we interviewed, most sensor technology development to date has targeted federally regulated criteria pollutants. Similarly, emerging air quality regulations at the state or local levels may influence future technology development. For example, Colorado recently required certain facilities to begin real-time monitoring of benzene and other specified air toxics.[29] Vendors and researchers are developing sensors to measure these pollutants, according to literature and stakeholders we interviewed.

Two expert meeting participants and a stakeholder we interviewed told us that there is a need for fundamental research on sensing components.[30] One way to encourage such research is through federal funding opportunities and incentives. One such incentive we identified is a prize competition called the Wildland Fire Sensors Challenge, led by EPA. Other potential sources of funding are the Small Business Innovation Research and Small Business Technology Transfer funding opportunities across federal agencies, but they are not limited to outdoor air quality sensor research.

[29]See COLO. REV. STAT § 25-7-141(5) (2023).

[30]Twelve experts attended our meeting including representatives from academic, governmental, industry, and nonprofit sectors. See appendix II.

4 Challenges

Air quality monitoring with sensors is increasing, but using sensors and managing the resulting data can pose challenges. Some users lack access to expertise and other resources that are helpful in setting up a network, such as agency staff or reference monitoring sites for calibration. In addition, some sensor vendors are not transparent about sensor performance or how their sensors process data internally or on proprietary data management systems, making it difficult for new and expert users alike to compare sensors or data. There are no widely accepted standards for how to report sensor data, creating challenges for users combining information from different sensors or networks. Further, some users are unclear on the steps they need to take to spur action with data they collect.

4.1 Some sensor users lack access to expertise and resources

Some users lack access to the expert advice and additional resources needed to achieve their goals. EPA told us sensors are easier to use than other instruments such as reference monitors, but throughout our review we found that users often need additional expertise and resources to appropriately deploy sensors and interpret the resulting data.

In some cases, users partner with government agencies or research institutions to access expertise and guidance. For example, the Tribal Air Monitoring Support Center is a partnership between Tribes, EPA, and Northern Arizona University that provides technical support, training, and assistance.[31] Established in 1999, the center was designed to meet the needs of Tribes involved in air quality management. The center offers individual support and training on a variety of air quality and sensor-related topics. As another example, the Denver Department of Public Health and Environment's Love My Air program has provided education materials, curricula, and information on replicating their program to other users, including other local governments, at no cost.[32]

However, some users have struggled to access similar support. For example, a nonprofit representative we interviewed told us that local agencies would not collaborate with communities in their area. Representatives from another nonprofit that helps community science projects find relevant experts told us that access to expertise from researchers at academic institutions can be limited because such researchers lack incentives to participate in community initiatives. Government entities and vendors provide some guidance to support planning and deployment of

[31]For more information, see Northern Arizona University, “About TAMS,” accessed December 4, 2023, https://www7.nau.edu/itep/main/tams/About/.

[32]The Love My Air program is a citywide monitoring network that provides near real-time air quality data using sensors. For more information, see City and County of Denver, “Love My Air,” accessed December 4, 2023, https://www.denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Public-Health-Environment/Environmental-Quality/Air-Quality/Love-My-Air

sensors by users who may not have direct access to experts themselves. However, expert meeting participants told us these resources are not in one place for users to easily find.[33]

Users who need but cannot access expertise and guidance may not select and deploy sensors in a way that fits with their goals. For example, officials from one state agency told us that some users have placed sensors in unsuitable locations that prevent the sensor from working as intended (see fig. 6). One expert meeting participant told us that some users have selected sensors before understanding which pollutants affect local air quality or which measurements would be most meaningful for their intended goals. Further, some community users have faced project delays because they named specific sensors in EPA grant proposals; when they later realized those sensors would not measure the pollutants of interest in their communities, they had to revise their plan.

Figure 6: Examples of unsuitable and suitable locations to place sensors

This sensor is too close to the ground. **The airflow to this sensor is blocked.** **This sensor has appropriate siting.**

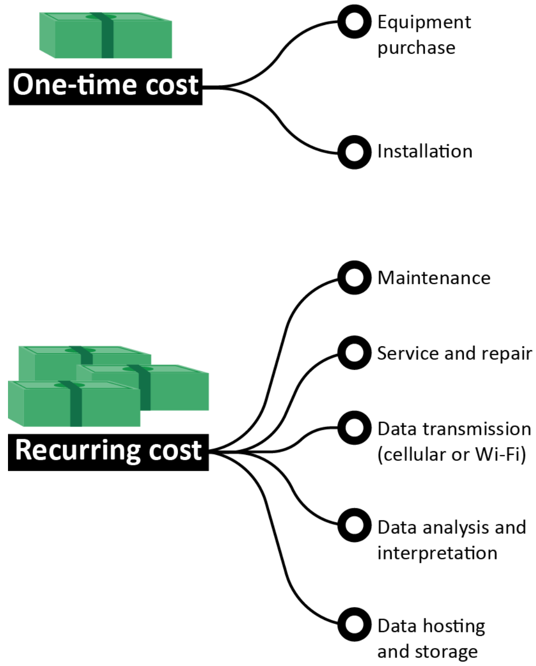
Source: GAO adaption of South Coast Air Quality Management District and Environmental Protection Agency information; GAO (illustrations). | GAO-24-106393

[33]For examples of guidance, see Environmental Protection Agency, "Air Sensor Toolbox" (Jan. 16, 2024), accessed February 20, 2024, https://www.epa.gov/air-sensor-toolbox or South Coast Air Quality Management District "Science To Achieve Results," *Air Quality Sensor Performance Evaluation Center*, accessed February 20, 2024, http://www.aqmd.gov/aq-spec/special-projects/star-grant.

Some users may also struggle to analyze and interpret sensor data, which can require knowledge of tools, such as programming languages. Some tools exist to work with sensor data, but users may not know how to use these tools according to two expert meeting participants. Although some users rely on experts for data analysis and interpretation, others may perform these actions themselves. However, two expert meeting participants told us these users may struggle when they rely on tools that are less fit-for-purpose, such as spreadsheets.

Predicting necessary resources is another key challenge. Sensors may be attractive for their lower cost, but during this review we learned they also have recurring operational costs, including staff time, service contracts, and maintenance costs, that can make it difficult for some users to predict the resources they will need (see fig. 7). One expert meeting participant told us sensors do not always have predictable maintenance schedules, which makes it difficult to plan for these needs. Another said some vendors' repair processes lack transparency, which can make it difficult for users to predict repair costs.

Figure 7: Examples of factors contributing to the cost of deploying and sustaining a sensor network



Source: GAO analysis of literature, interviews, and expert meeting discussions; GAO (icons). | GAO-24-106393

Users may also lack access to the physical resources they need. For example, certain uses require placing at least one sensor next to a reference monitor for data calibration. But not all communities have a reference monitor nearby. And even when they do, agencies do not always provide access to the monitoring site, for various reasons. For example, officials from six selected state agencies told us they either do not always own the properties where their reference monitors are located and cannot grant access or they are concerned about liability, security, or staff availability.

Even when reference monitoring sites are accessible, some users may struggle to correctly place their sensors without additional assistance, which agencies may not always be able to provide (see text box).

In one case, described to us by a state agency official, a researcher working on a community project installed sensors at a state monitoring site but did not build adequate weather protection for their power supplies (see fig. 8). This tripped the site's circuit breaker and cut power to the monitoring station. As a result, the state agency lost air quality data from its reference monitor. Unintended consequences such as those in this example are another reason why agencies may be less inclined to provide access to their reference monitor sites.

Figure 8: Sensors installed at a state monitoring site without adequate weather protection

Source: New York State Department of Environmental Conservation, Division of Air Resources (photo). | GAO-24-106393

Some agencies lack sufficient resources to assist sensor users

Some state and local agencies struggle to accommodate increasing demands to train and assist users, which have increased in part due to federal grants that incentivize and fund community sensor networks. Expert meeting participants told us that some agencies do not have dedicated funding to support community efforts. Additionally, state and local agencies may not have enough staff to assist users, according to officials from one state agency.

Source: GAO summary information from expert meeting, interviews, and other sources. | GAO-24-106393

Some users have also struggled to predict data-related costs and may struggle to acquire or sustain funding for data infrastructure or access. For example, one nonprofit representative we interviewed told us their organization and other EPA grant recipients were pooling resources to build data infrastructure that could manage and share their data.[34] Some sensor vendors offer data-related tools, but they charge subscription fees, and a nonprofit representative told us that users who cannot continue to pay may lose access to the data they collected.

4.2 Lack of transparency and standards can pose challenges

Sensor vendors are not transparent about how they have tested sensors for performance, what the results were, and what that means for how they can be used. Stakeholders from the sensor industry and nonprofit representatives told us that some vendors claim sensor capabilities that are questionable. For example, vendors

[34]These organizations were recipients of EPA Enhanced Air Quality Monitoring for Communities Competitive Grants funded through the American Rescue Plan Act and the Inflation Reduction Act.

advertise that PM sensors can classify particles by size, but some studies we reviewed suggest these sensors do not provide meaningful representations of particle size distributions. In addition, EPA officials told us some vendors who use sensing components from another manufacturer may not have the capability to independently test the sensors' performance. The officials said that those vendors may simply restate the performance specifications of the sensing component from the other manufacturer. As discussed in the previous chapter, sensor hardware could also affect performance.

Users may struggle to compare or choose sensors when their actual capabilities or differences are not clear. Given these challenges, some sensor evaluators, such as the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) and EPA, are helping make performance information more transparent.[35] For example, AQ-SPEC evaluates sensor performance in the field and laboratory and provides information to the public at no cost. Additionally, EPA is engaged in efforts to establish performance targets and testing protocols for sensors.[36]

Transparency can also be a challenge after a sensor is purchased. For example, stakeholders told us some vendors do not describe how they calibrated the sensors and under what conditions. This can create challenges for users, such as academic researchers and government officials, who may prefer to apply their own calibrations.

In addition, users may not always own the sensor data they collect; for example, vendors may own the data. This can make it challenging to understand who owns previously collected data. If users do not understand who owns the data from other sensor networks, they may struggle to get permission to reuse the data later.

Another data-related challenge is that there are currently no widely accepted standards for reporting sensor data or metadata.[37] Sensors currently produce data in a variety of formats, and sometimes reported data are missing basic information, such as the time when a measurement was taken. This can make it difficult for users to combine or compare data. For example, one sensor network can include multiple brands of sensors, and users may spend considerable resources reformatting data to combine them into a complete picture of air quality across the network. In addition, expert meeting participants and a stakeholder told us some vendors and users do not report raw data alongside processed data, which can make it difficult for other users to assess whether data quality has been negatively affected, such as by sensor

[35]AQ-SPEC was established by the South Coast Air Quality Management District to evaluate and inform the public about the performance of commercially available sensors. For more information, see South Coast Air Quality Management District, *Air Quality Sensor Performance Evaluation Center*, accessed December 5, 2023, http://www.aqmd.gov/aq-spec.

[36]For more information, see Environmental Protection Agency, "Air Sensor Performance Targets and Testing Protocols," *Air Sensor Toolbox* (Apr. 13, 2023), accessed December 13, 2023, https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols.

[37]Metadata are structural or descriptive information about data. Sensor metadata could include information such as sensor versions, data processing algorithms, and where sensors are mounted.

malfunctions or overprocessing. Finally, sensors do not provide metadata that describe information such as detection limits or the sensor's age. Without such information, users may face challenges combining and analyzing multiple sets of data.

To help address these challenges, Colorado is developing data and metadata standards for sensor information reported to the state, according to a state official. The official told us that Colorado intends to release these standards and require users collecting data with public funds to adopt the standards in 2024. Further, these standards will help state authorities evaluate sensor data quality and determine whether data are appropriate for different uses.

4.3 Users are unclear about what is needed to spur action

Sensor users and decision-makers may have different expectations about the level of quality assurance needed for data to influence decisions. Three expert meeting participants told us that users face challenges understanding what steps they need to follow to produce actionable data without better guidance from authoritative entities. One state agency official we interviewed told us groups often collect sensor data to spur change. For example, the official said some seek evidence of pollutants that could trigger regulators to investigate a pollution source. However, these groups may not realize that their data are not of sufficient quality for that purpose. When expectations around procedures, documentation, and quality assurance are not communicated clearly and approachably to users from the beginning, they may spend resources to produce data that regulatory entities and decision-makers are not able or willing to use.

Even users who collect data with more rigorous quality assurance procedures may struggle to convince decision-makers that their data can be used for certain applications. In 2018, EPA's Office of Inspector General reported that the agency did not use community air-monitoring data to guide decision-making because of data-quality and technical concerns and recommended that the agency identify data management requirements for using community monitoring data.[38] In response, EPA acknowledged the need for guidance on interpreting sensor data in a way that provides meaningful information to the public; however, the Office of Inspector General stated that the agency had not implemented any guidance to help make community monitoring data more usable, as of September 2023.[39] Instead, EPA provides resources on participatory science and sensors through webpages, such as the "Participatory Science for Environmental

[38]Environmental Protection Agency, Office of Inspector General, *EPA Needs a Comprehensive Vision and Strategy for Citizen Science that Aligns with Its Strategic Objectives on Public Participation*, Report No. 18-P-0240 (Washington D.C.: September 2018).

[39]Environmental Protection Agency, Principal Deputy Assistant Administrator, *Office of Air and Radiation*, Memorandum to EPA Regional Administrators Regions I – X (June 22, 2020); Environmental Protection Agency, Office of Inspector General, *The EPA Needs to Address Increasing Air Pollution at Ports*, Report No. 23-E-0033 (Washington D.C.: September 2023).

Protection" webpage and the "Air Sensor Toolbox" webpage.[40]

In addition, EPA officials told us that the agency is planning to open a competitive research funding opportunity under its Science to Achieve Results grant program to solicit community-based research in underserved communities. This grant opportunity aims to advance the use and communication of air pollution data and information to empower local decision-makers to take actions that address community-identified air pollution concerns.

4.4 Differing priorities and mistrust may hinder stakeholder collaboration

Users, agencies, and other stakeholders can have different priorities when collecting or using sensor data, and expert meeting participants told us their ideas of success may vary. Community groups may collect data for a variety of reasons, from increasing their understanding of local air quality to advocating for action and change. Researchers may work with communities to collect sensor data, but, according to a stakeholder we interviewed, some have priorities such as publishing in scientific journals. Meanwhile, agencies and other authoritative entities require rigorous data quality assurance, and their ideas of success may be different from those of community groups.

As a result of these differing priorities, some stakeholders struggle to build the trust needed to collaborate with one another. For example, a nonprofit representative told us that prior instances of government entities discarding community-collected sensor data have eroded the community's trust. The representative said their local community does not have confidence that decision-makers will use the data they have collected in any meaningful way.

Officials from several agencies have also faced challenges building trust in communities where they have deployed sensors. Some residents do not trust sensor technology, while others may be suspicious of government programs that monitor air quality near their homes, according to officials. One expert meeting participant told us that trust between community groups and agencies can break down when the agencies are unable to accommodate requests for assistance, due to lack of funding or staff. Further, state officials told us community groups may not trust how government entities or experts interpret data if it differs from their own interpretation, which can lead community groups to false conclusions about local air quality.

Sensor users may not trust others who do not share their data publicly. For example, one stakeholder we interviewed told us they mistrust industry because some of industry air quality data are not publicly accessible. A data repository to enable users to share and store data in a common

[40]See https://www.epa.gov/participatory-science and https://www.epa.gov/air-sensor-toolbox.

location could increase transparency between users.

Sharing data might increase transparency, but some users may not want to share data. For example, one sensor vendor told us that more than 95 percent of the data collected from their sensors are kept private by users, even though sharing the data publicly is an option. Additionally, some stakeholders we spoke to raised concerns over unintended consequences of data sharing. For example, studies aiming to increase awareness about inequitable air pollution in overburdened neighborhoods may have the unintended consequence of driving down home prices and school enrollment in those neighborhoods.

5 Policy Options

We identified seven policy options that policymakers—legislative bodies, government entities, academia, the sensor industry (which could include developers, manufacturers, or vendors), and other groups—could consider taking to help address challenges to the development or use of sensors for air quality monitoring. This list is not exhaustive but can provide policymakers with a broader base of information for decision-making. For each policy option, we present a table with one or more potential implementation approaches, opportunities the policy option may present, and factors to consider. The policy options we identified include:

- Maintaining status quo
- Enhancing sensor performance transparency
- Supporting innovation in sensor technologies
- Facilitating access to expertise
- Improving access to guidance
- Improving data management and sharing
- Clarifying level of quality assurance needed to spur action

Maintain status quo

Policymakers could choose to maintain the status quo and not take any new actions to support the development and use of sensors (see table 5).

Table 5: Policy option – Maintain status quo

Potential implementation approach	Opportunities	Consideration
Policymakers could sustain current efforts to address challenges to sensor use. This could include continuing EPA's ongoing efforts to develop performance testing protocols, metrics, and targets for five of the six criteria pollutants (particulate matter, ozone, nitrogen dioxide, carbon monoxide, and sulfur dioxide). Similarly, one state agency is developing data standards to improve its ability to exchange diverse air quality data sets. Incentives for sensor improvements could also continue. For example, a group of federal agencies held a prize competition to incentivize innovations in sensor technologies for measuring smoke during wildland fires.	Current efforts may address some challenges described in this report without additional resources. Resources that would be allocated to additional interventions could be used for other opportunities.	Current efforts are not likely to address all challenges described in this report.

Source: GAO. | GAO-24-106393

Enhance transparency and build trust in sensor performance

Users need information on how well sensors perform to be confident that sensors are appropriate for their anticipated use. Users who want to use their data to shape policy change or trigger regulatory entities' investigations need reliable information on sensor performance to understand how their sensor data compares to those from reference monitors. However, publicly available information on sensor performance is limited, which can complicate users' purchasing decisions and reduce their ability to effect change in their communities. Policymakers wishing to address this challenge could choose to promote actions that enhance transparency and build trust in sensor performance (see table 6).

Table 6: Policy option – Enhance sensor performance transparency

Potential implementation approaches	Opportunities	Considerations
Government entities or standards-setting organizations could establish additional standardized performance testing protocols and targets for sensors. For example, EPA could expand its current efforts and develop standardized testing protocols and performance targets for sensors that measure pollutants other than criteria pollutants.	Standardized testing could increase transparency and build trust among users. Performance targets could help ensure sensors work adequately for specific uses.	Reaching consensus on standards can take considerable time. Standardized testing could increase costs.
Government entities or standards-setting organizations could encourage the adoption of performance testing protocols and targets by the sensor industry. The sensor industry could adopt performance testing protocols and targets and publicly release information on the extent to which sensors meet those targets, including documentation of testing protocols and test results.	Encouraging the adoption of performance testing protocols and targets could help users select sensors appropriate for their anticipated uses.	Industry could choose not to adopt voluntary performance testing protocols and targets. Widespread adoption of performance testing protocols takes time. May not enhance sensor performance transparency if manufacturers update sensor models before performance testing on older models is completed.

Source: GAO. | GAO-24-106393

Help support innovation in sensor technologies

Some users would like to measure specific pollutants, such as hexavalent chromium, for which sensors are not available. Additionally, existing sensors for certain air toxics do not perform well enough for use in ambient air. Policymakers wishing to address these issues could support innovation in sensor technologies (see table 7).

Table 7: Policy option – Support innovation in sensor technologies

Potential implementation approaches	Opportunities	Considerations
Academia, government entities, or nonprofit organizations could provide funding or incentives for research to improve performance of existing sensors and to develop new sensor technologies for additional air pollutants, such as air toxics; and the sensor industry could choose to invest in additional research and development. For example, federal agencies could sponsor prize competitions to incentivize sensor innovations beyond technologies for measuring smoke during wildland fires.	Could enable detection of additional pollutants or existing pollutants at lower levels. Could reveal deficiencies in current sensor technologies and drive further innovation. Could spur entrepreneurship. Could encourage new entrants to sensor research and development.	Time frames for research and development are unclear. Could require substantial funding and other resources that could be used for other opportunities
Government entities or standards-setting organizations could establish additional and periodically update standardized performance testing protocols and targets to set expectations and drive innovation.	Performance targets could set expectations for manufacturers and help drive further technology development. Standardized testing protocols could provide stakeholders with a consistent method of determining whether sensors meet expectations, which could reveal deficiencies and drive further development or innovation.	Reaching consensus on standards could take a considerable amount of time. Industry could choose not to adopt voluntary standards.

Source: GAO. | GAO-24-106393

Help facilitate access to expertise

Some users may struggle to select sensors, site them in appropriate locations, or interpret the resulting data if they do not have access to the appropriate expertise. Policymakers could facilitate access to expertise to increase the likelihood of successful deployment of sensor projects (see table 8).

Table 8: Policy option – Facilitate access to expertise

Potential implementation approaches	Opportunities	Considerations
Academia, government entities, and the sensor industry could collaborate to establish technical assistance mechanisms that connect users with experts. For example, the Environmental Protection Agency partners with a university to provide technical assistance to Tribes with air monitoring programs.	Could help users identify and collaborate with experts, get questions answered, and get help designing and deploying networks. Could alleviate the burden on government entities or provide them with additional resources to carry out this work.	Some government entities and other experts may require additional resources to fully collaborate with communities.
Nonprofit organizations could expand or establish programs that match users with experts. Academia could participate in nonprofit matching programs. For example, one international nonprofit organization offers a program that matches community members with experts to get technical assistance on local science projects (including sensor projects).	Could help users identify and collaborate with experts to ensure optimal use of sensors.	Experts may not have incentives to participate in such programs. Participating experts may be overwhelmed by inquiries or requests for help. Matching users with experts may not result in successful collaborations.
The sensor industry could enhance the technical assistance it already provides to customers or offer subscriptions for technical assistance.	Could provide expert guidance and alleviate users' need to identify experts or develop in-house expertise.	Users will bear the costs of subscription-based technical assistance. If the technical assistance is cost prohibitive, some users may not be able to take advantage of it. Subscription-based technical assistance may be unaffordable for users needing support over longer periods of time.

Source: GAO. | GAO-24-106393

Help improve access to user-friendly guidance

Although guidance materials exist, some users may have difficulty finding, choosing, and understanding them. Policymakers could assist these users by improving the accessibility and usability of such materials (see table 9).

Table 9: Policy option – Improve access to guidance

Potential implementation approaches	Opportunities	Considerations
Government entities, nonprofit organizations, or the sensor industry could collaborate to maintain a website with links to or copies of existing guidance. One possible model is the World Health Organization's air quality management guidance repository, which compiles guidance documents and tools from different entities in a common location.	Could help users locate guidance more easily, saving them time and helping improve sensor use. Could enable users to compare guidance more easily, allowing them to select guidance that best aligns with their needs.	Could be time and resource intensive and may need frequent updates. Users may not know such a resource exists or trust it without endorsement and advertisement by a trusted entity. Storing guidance in a repository may require consent from authors and owners.
Community groups, government entities, or the sensor industry could develop additional user-friendly guidance on sensor use.	Could ensure information is accessible to users with different levels of expertise and experience.	Might not be helpful if intended users' input is not sought or considered. Could be time and resource intensive.

Source: GAO. | GAO-24-106393

Help improve data management and sharing

Expanded sensor use creates large amounts of data that need to be processed, stored, and potentially integrated with data in different formats. Users do not always have the infrastructure and support for these data management activities, which can limit their ability to share data. Policymakers who are interested in improving sensor data management and sharing could therefore choose to develop new or support existing data infrastructure and develop standards (see table 10).

Table 10: Policy option – Improve data management and sharing

Potential implementation approaches	Opportunities	Considerations
Government entities, the sensor industry, or standards-setting organizations could collaborate to develop data and metadata standards. For example, these standards could go beyond current state efforts.	Data standards could help facilitate data aggregation, comparison, and sharing. Metadata standards could help increase transparency around how data were generated, which can help users ascertain whether data are comparable.	Standards require consensus, which takes time and resources to build. Organizations may not adopt voluntary data standards, especially if they were created without their input.
Government entities could develop or support an existing publicly accessible air quality data repository to enable users to share and store data in a common location. One potential model for consideration is the Environmental Protection Agency's data repository for water quality data, which allows registered partners to submit and store their data. Anyone can access and download data stored in the repository.	Could help prevent data loss. Could alleviate the need for users to build their own databases. May encourage users to share their data, which can be used by others to better inform decision-making.	May be time and resource intensive. Users may hesitate to share data they own because there may be unintended consequences. Without data standards, users might upload their data in different formats, which would take time and resources to integrate. Without metadata standards, users might omit key information that describe the data and potentially reduce usefulness of data.

Source: GAO. | GAO-24-106393

Help clarify the level of quality assurance needed to spur action

Sensor users may not be aware of or understand the different levels of quality assurance needed to accomplish their goals. Policymakers who are interested in helping users collect data of sufficient quality to achieve their goals could therefore collaborate to clarify expectations about the level of quality assurance needed to trigger air quality investigations, decisions about air quality management, or other objectives (see table 11).

Table 11: Policy option – Clarify the level of quality assurance needed to spur action

Potential implementation approach	Opportunity	Consideration
Government entities, academia, and nonprofit organizations could collaborate to develop guidance on the level of quality assurance required for various applications.	Clarity on the level of quality assurance required could help users select sensors and collect data that are appropriate for their specific purposes.	Given the number of current and potential sensor applications, it may be difficult to clarify the level of quality assurance needed for each one.

Source: GAO. | GAO-24-106393

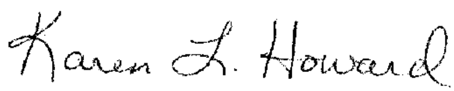
6 Agency and Expert Comments

We provided a draft of this report to the Environmental Protection Agency for review and comments. The Environmental Protection Agency provided technical comments, which we incorporated as appropriate.

We also offered our expert meeting participants the opportunity to review and comment on a draft of this report, consistent with previous technology assessment methodologies. Eight of those experts reviewed our draft report and provided technical comments, and we incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committees, relevant federal agencies, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or HowardK@gao.gov or J. Alfredo Gómez at (202) 512-3841 or GomezJ@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made contributions to this report are listed in appendix III.



Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

J. Alfredo Gómez, MS
Director
Natural Resources and Environment

Appendix I: Objectives, Scope, and Methodology

Objectives

We describe our scope and methodology for addressing the three objectives outlined below:

1. What are current and emerging lower-cost, outdoor air quality sensor technologies, and what are their performance characteristics?
2. What are current and potential applications of lower-cost, outdoor air quality sensors? What, if any, are benefits and challenges to developing and using air quality sensors?
3. What policy options may help address challenges to the development and application of air quality sensors?

To address all research objectives, we conducted four literature searches, reviewed key reports and peer-reviewed articles, and conducted an expert meeting. In addition, we interviewed a variety of stakeholders, including federal, state, and local agency officials; academic researchers; nonprofits; and private companies, including those that use sensors and sensor developers, manufacturers, and vendors. We also attended the Environmental Protection Agency's (EPA) 2023 Air Sensors Quality Assurance Workshop and conducted four site visits where sensors were used, colocated with a reference monitor, or tested.

Scope

We limited the scope of the assessment to lower-cost, ground-based sensors for measuring regulated or unregulated air pollutants in ambient air that have a direct effect on human health.[41] We adopted EPA's definition of lower cost to mean a device that costs up to $2,500 per pollutant it measures, up to a maximum cost of $10,000.[42] For the purposes of this definition, we are referring only to the cost to purchase the device. We assessed the status of the field of sensor technology as a whole, but we did not assess any particular brand of sensors.[43]

Methodology

Literature search

For all objectives, we reviewed relevant literature identified by agency officials, experts, stakeholders, and our literature search. We gathered additional information

[41]Ambient air means that portion of the atmosphere, external to buildings, to which the general public has access. 40 C.F.R. § 50.1(e).

[42]Environmental Protection Agency, *The Enhanced Air Sensors Guidebook,* EPA/600/R-22/213 (Washington D.C.: September 2022).

[43]For evaluation of sensor performance, see Environmental Protection Agency, "Evaluation of Emerging Air Sensor Performance," *Air Sensor Toolbox* (June 6, 2023), accessed December 5, 2023, https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-sensor-performance and South Coast Air Quality Management District, "Evaluations," *Air Quality Sensor Performance Evaluation Center*, accessed December 5, 2023, https://www.aqmd.gov/aq-spec/evaluations.

using a snowball technique.[44] A GAO research librarian conducted four literature searches—one exploratory search for both objectives 1 and 2, and additional searches for each of the three objectives after we refined the search terms—to find articles regarding performance and uses of sensor technologies, and policy options. The librarian searched a variety of databases, including Dialog Energy and Environment Content Collection, ProQuest (Science Database, SciTech Premium Collection, and Technology Collection), and SCOPUS. We narrowed our search to articles published since 2018 to capture recent development and uses of sensors. Results of these searches could include scholarly or peer-reviewed material; government reports; trade or industry papers; and association, nonprofit, and think tank publications. We selected the articles most relevant to our objectives for further review.

Expert meeting

We convened a virtual expert meeting to inform our assessment of sensor technologies. The meeting was held over two days with 12 experts. (See app. II for a list of experts and their affiliations.) We identified subject matter experts covering significant areas of our assessment from a range of stakeholder groups across sectors (federal, state, and local governments; academia; industry; and nonprofits) based on information from our interviews, literature we reviewed, web searches, and archived videos of relevant conferences. Stakeholder groups include those who conduct research on sensor technologies and their uses, develop or manufacture sensor technologies, or use or consider using sensor technologies and data.

We evaluated the experts for potential conflicts of interest, which were considered to be any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair competitive advantage for any person or organization. We determined the 12 experts to be free of reported conflicts of interest, except those that were outside the scope of the meeting or where the overall design of our meeting and methodology was sufficient to address them, and the group as a whole was determined to not have any inappropriate biases. The comments of these experts generally represented their individual views and not the organizations with which they were affiliated and are not generalizable to the views of others in the field.

We divided the 2-day meeting into five moderated discussion sessions: (1) sensor technologies: their performance characteristics, and research and development; (2) their benefits and applications; (3) calibration, maintenance, and sustainment of sensor networks; (4) data challenges with sensor networks; and (5) other challenges and opportunities with developing or using sensors. We assigned 4–5 experts to be panelists in each session based on their preferences and expertise. After the panelists responded to all questions and materials, the discussion was opened to all experts for the time remaining in each session. The meeting was

[44]The snowball technique involves identifying new articles or reports within those we had already reviewed on the topic.

professionally transcribed to ensure that we accurately captured the experts' statements. After the meeting, we reviewed the transcripts to synthesize the responses and to inform our understanding of all three researchable objectives. We offered the experts at our meeting the opportunity to review and provide technical comments on a draft of our report. We received comments from 8 of the 12 experts, which we incorporated, as appropriate.

Interviews

We interviewed a selection of key stakeholders with experience and perspectives on the above objectives. We identified these stakeholders from our review of literature, agency interviews, and prior GAO work. Stakeholders included

- EPA's Office of Air and Radiation, Office of Enforcement and Compliance Assurance, Office of Environmental Justice and External Civil Rights, Office of Research and Development, and Region 2;
- Four state, county, or city government agencies;
- Six academic researchers;
- Eight private companies including those that use sensors and sensor developers, manufacturers, and vendors; and
- Six nonprofits.

Because this is a purposeful selection of the stakeholders involved in developing and using sensors, the results of our interviews are illustrative and represent important perspectives but are not generalizable.

Analysis of quality assurance for sensor applications

For objective two, we assessed the minimum level of quality assurance needed for various sensor applications for illustrative purposes. Based on information from EPA, we determined a scale for quality assurance needed. We then analyzed literature, interviews, and expert meeting transcripts to assign values to each application in relation to this scale. The results are presented as qualitative information and are not meant as guidance for sensor users.

Policy options

We intend policy options to provide policymakers with a broader base of information for decision-making.[45] They are also not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular fashion. Additionally, we did not conduct work to assess how effective the options may be and express no view regarding the extent to which legal changes would be needed to implement them.

We developed seven policy options with possible implementation approaches that could help address the challenges to development and use of sensors. We then analyzed each approach by identifying potential opportunities and considerations.

[45] Policymakers is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

The policy options and analyses were supported by documentary and testimonial evidence.

We conducted our work from November 2022 to March 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Expert Participation

We convened a 2-day meeting of experts to inform our work on air quality sensor technologies; the meeting was held virtually on July 17 and 19, 2023. The experts who participated in this meeting are listed below. Many of these experts gave us additional assistance throughout our work, including seven who provided feedback on an early iteration of policy options and eight who reviewed our draft report for accuracy and provided technical comments.

Taylor Borgfeldt

Environmental Program Manager

Alaska Department of Environmental Conservation

Tim Dye

President

TD Environmental Services

Bradley Flowers

Principal Scientist and Program Manager

AECOM

Jason Peng Gu

Chief Technology Officer

SENSIT Technologies

Hilary R. Hafner

Chief Operating Officer and Chief Scientist

Sonoma Technology

David Hagan

Founder and Chief Executive Officer

QuantAQ

Geoff Millener

Chief Operating Officer

The Enterprise Center

Ali Mirzakhalili

Air Quality Division Administrator

Oregon Department of Environmental Quality

Michael Ogletree

Division Director of the Air Pollution Control Division

Colorado Department of Public Health and Environment

Andrea Polidori

Assistant Deputy Executive Officer

South Coast Air Quality Management District

Albert Presto

Research Professor

Carnegie Mellon University

Colleen Marciel F. Rosales

Strategic Partnerships Director

OpenAQ

Appendix III: GAO Contacts and Staff Acknowledgments

GAO contacts

Karen L. Howard, PhD, Science, Technology Assessment, and Analytics, (202) 512-6888 or HowardK@gao.gov

J. Alfredo Gómez, **MS**, Natural Resources and Environment, (202) 512-3841 or GomezJ@gao.gov

Staff acknowledgments

In addition to the contacts named above, the following staff made key contributions to this report:

Katrina Pekar-Carpenter, PhD, Assistant Director and Senior Physical Scientist

Anne Hobson, PhD, Assistant Director

Evonne Tang, PhD, Analyst-in-Charge and Senior Biological Scientist

Megan Harries, PhD, Physical Scientist

Ivan Hernandez, MS, Analyst

Shelby Johnston, PhD, Physical Scientist

Kate Shouse, MPP/MS, Senior Analyst

Craig Starger, PhD, Biological Scientist

These staff also contributed to this work:

Sharron Candon, MA, Senior Analyst
Philip Farah, PhD, Assistant Director
Dan Luo, PhD, Senior Economist
Anika McMillon, Visual Communications Analyst
Amy Pereira, JD, Senior Attorney
Rebecca Sero, PhD, Senior Research Methodologist
Ben Shouse, MS, Lead Communications Analyst
Amber Sinclair, PhD, Senior Research Methodologist
Bethann E. Ritter Snyder, MPIA, Senior Analyst
Britney Tsao, MIA, Senior Analyst
Chris Turner, MS, Coordinator, Sustainability and Climate Resilience Initiatives

GAO's Mission

The Government Accountability Office, the audit, evaluation, and investigative arm of Congress, exists to support Congress in meeting its constitutional responsibilities and to help improve the performance and accountability of the federal government for the American people. GAO examines the use of public funds; evaluates federal programs and policies; and provides analyses, recommendations, and other assistance to help Congress make informed oversight, policy, and funding decisions. GAO's commitment to good government is reflected in its core values of accountability, integrity, and reliability.

Obtaining Copies of GAO Reports and Testimony

The fastest and easiest way to obtain copies of GAO documents at no cost is through GAO's website (https://www.gao.gov). Each weekday afternoon, GAO posts on its website newly released reports, testimony, and correspondence. To have GAO e-mail you a list of newly posted products, go to https://www.gao.gov and select "E-mail Updates."

Order by Phone

The price of each GAO publication reflects GAO's actual cost of production and distribution and depends on the number of pages in the publication and whether the publication is printed in color or black and white. Pricing and ordering information is posted on GAO's website, https://www.gao.gov/ordering.htm.

Place orders by calling (202) 512-6000, toll free (866) 801-7077, or
TDD (202) 512-2537.

Orders may be paid for using American Express, Discover Card, MasterCard, Visa, check, or money order. Call for additional information.

Connect with GAO

Connect with GAO on Facebook, Flickr, Twitter, and YouTube.
Subscribe to our RSS Feeds or E-mail Updates.
Listen to our Podcasts and read The Watchblog.
Visit GAO on the web at https://www.gao.gov.

To Report Fraud, Waste, and Abuse in Federal Programs

Contact: Website: https://www.gao.gov/fraudnet/fraudnet.htm
Automated answering system: (800) 424-5454 or (202) 512-7470

Congressional Relations

A. Nicole Clowers, Managing Director, ClowersA@gao.gov, (202) 512-4400,
U.S. Government Accountability Office, 441 G Street NW, Room 7125, Washington, DC 20548

Public Affairs

Chuck Young, Managing Director, YoungC1@gao.gov, (202) 512-4800
U.S. Government Accountability Office, 441 G Street NW, Room 7149, Washington, DC 20548

Strategic Planning and External Liaison

Stephen Sanford, Managing Director, spel@gao.gov, (202) 512-9715
U.S. Government Accountability Office, 441 G Street NW, Room 7B37N, Washington, DC 20548