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POLICY BRIEF: Low-Cost Real-Time Sensors for Air Quality Monitoring

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Building Healthy Cities
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INTRODUCTION

Human health depends on clean air. When air is polluted with fine particulate matter ($PM_{2.5}$), black carbon, or other aerosolized pollutants, our health suffers. Air pollution is linked to over 3 million deaths each year, and nearly all inhabitants of the world's largest cities are exposed to air pollution levels that are above the healthy limits (Lim et al. 2012). In addition, while air pollution affects everyone equally, it does not affect everyone equitably. Children are most vulnerable to air pollutants, and respiratory tract infections led to over half-a-million deaths of children under five in 2016 alone (UNICEF 2019). Air pollution is also closely tied to income level: families living in poverty have a higher risk of being exposed to deadly air pollutants than families that live above the poverty line (Mikati et al. 2018).

The places where people live, work, and play have major effects on health. Recognizing that improving these "social determinants of health" can have a greater effect on people's health than clinical preventive care, the U.S. Agency for International Development (USAID)-funded Building Healthy Cities (BHC) project is working with cities to test innovative approaches to urban health planning across sectors for existing Smart Cities in India, Indonesia, and Vietnam. A core activity of the BHC project relates to air pollution and monitoring air quality in different neighborhoods across the three cities, as understanding the depth of the problem is the first step to improving air quality in Asia.

This policy brief is intended for Smart City officials, health planners, and environmental health offices. It contains information on low-cost air quality sensors (AQSs), including:

- How low-cost, commercially available AQSs differ from traditional air quality monitors.
- Benefits of using low-cost AQSs for municipal monitoring.
- Limitations of low-cost AQSs.
- Comparison of various low-cost AQSs.
- Recommendations for purchasing low-cost AQSs that will work best in the three BHC partner cities.

I. Benefits of Low-Cost AQSs

Typically, air quality monitoring is conducted by researchers or government officials for research purposes and creating environmental air pollution policies (Castell et al. 2017). Monitoring stations are currently maintained by government authorities, scientists, or other health experts, and the stations are equipped to measure regulated pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x, NO, NO_2), ozone (O3), and particulate matter (PM_{10}, $PM_{2.5}$). The sensors for these pollutants are large, bulky, and expensive (Castell et al. 2017).

The cost of installing and maintaining traditional monitoring stations are also relatively high. Moreover, while these stations typically provide accurate data, they are too few and too sparsely spread across cities to provide neighborhood-level measures of air pollution levels. Readings tend to satisfy regulatory requirements for air pollution measurement, but do not present a practical, usable description of air quality at the community level that can be compared to, for instance, local health issues or traffic patterns (Castell et al. 2017).

Table 1. Key Definitions

Term	Definition
AQS	Air quality sensor
FRM	To support U.S. monitoring efforts, EPA scientists develop and evaluate methods for accurately and reliably measuring pollutants in outdoor air. These methods — called Federal Reference Methods — are considered the "gold standard" in air quality testing.
Particulate matter	Particulate matter comprises liquid droplets and solid particles, which can include dust, dirt, soot, smoke, and other inhalable substances that can be harmful to human health.
PM_{10}	Particulate matter with diameter of 10 micrometers or smaller. Particulate matter in this category are dust, pollen, and mold, among other inhalable pollutants.
$PM_{2.5}$	Particulate matter with diameter of 2.5 micrometers or smaller. Particulate matter in this category are combustion particles, organic compounds, metals, among other inhalable pollutants. Particulate matter of this size has been linked to decreased lung function, aggravated asthma, irregular heartbeat, and premature death in people who have respiratory problems.
CO_2	Carbon dioxide is a naturally occurring gas that is released through organic respiration or decomposition, the weathering of carbonate rocks, deforestation, and volcanic eruption. Human activities such as burning coal, oil, and natural gas also contribute to global CO_2 concentrations. In large quantities, excessive atmospheric CO_2 raises global temperatures, which have major impacts on human health.
NO_2	Nitrous oxide is also a byproduct of burning fossil fuels, and most of the NO_2 in cities comes from vehicle exhaust. Natural sources of NO_2 include forest fires and lightning strikes, but the majority of atmospheric NO_2 come from anthropogenic sources. Excessive exposure to NO_2 can inflame the linings of lungs and reduce immunity to lung infections.
O_3	Ozone is found at both the upper and lower parts of the atmosphere. Occurring naturally at upper levels, stratospheric ozone is beneficial to human health because it forms a shell that shields humans from harmful ultraviolet rays. Less beneficial is tropospheric ozone, which is created when nitrous oxide and volatile organic compounds react with sunlight. As these gases are emitted by vehicles, industrial facilities, and electric utilities, they react with sunlight to create harmful ozone that hinders people's ability to breathe. Tropospheric ozone is the main component in smog, which many major cities around the globe suffer from.
SO_2	Sulfur dioxide is a pollutant emitted during fossil fuel combustion at power plants and industrial facilities. Breathing in SO_2 is harmful to the respiratory system, and people with respiratory issues are particularly susceptible to large concentrations of SO_2 in the air.

The rapid increase of smartphone ownership has led to a growing number of start-up companies that offer low-cost, wireless AQSs (Bowles 2018). Examples of these new low-cost AQSs are Atmotube, PlumeLab, Awair, Aeroqual, and PurpleAir (Bowles 2018). Some are sold for a few dollars each, while others range from $150 to $1,500; in general, the lower-cost AQSs have reduced sensitivity and/or specificity of data (Lewis and Edwards 2016). These types of AQSs connect to an individual's smartphone over Wi-Fi and can be placed on a porch or even strapped to a backpack to measure neighborhood-level air quality (Bowles 2018).

Many of these start-up companies were founded by residents who felt the effects of poor air quality in their neighborhoods. For example, Adrian Dybwad, the founder of PurpleAir, lives in Draper, Utah near a large mine. When heavy winds blew, they carried dust and particulate matter toward his house, and his family started to feel the effects. With a background in computer engineering and surface-mount electronics, Mr. Dybwad built his own monitoring device to track air pollution levels in his immediate area. As interest grew around the neighborhood, Mr. Dybwad began building more sensors, and soon had installed 80 in his community. The sensors picked up high amounts of floating particulate matter, particularly on very windy days, which the nearest government run monitoring station—located over 10 miles away—wasn't picking up. PurpleAir now has 3,000 AQSs worldwide, and lists a detailed map of air quality readings on its website, free for anyone to browse (Bowles 2018).

Stories like this are increasingly common: fed up with a lack of data about air quality in their communities, individual citizens have taken it upon themselves to learn more about the air they are breathing. As more companies enter the field of wireless, low-cost AQSs, there is an increasingly large pool of air quality data that is available to the public. In large polluted cities, such as Beijing, citizens use this data to decide if the air quality on a given day is safe enough to go outside without wearing a mask or let their families participate in outdoor activities (Lewis and Edwards 2016).

II. Limitations of Low-Cost AQSs

While there are many benefits to the increasing availability and equity of air quality data, expansion via low-cost AQSs comes with some cautions. First, the quality and calibration of data collected via low cost AQSs varies widely. Traditional monitoring station technology was tested rigorously in laboratory settings and the findings peer reviewed prior to sale (Lewis and Edwards 2016). Low-cost AQSs, on the other hand, are often not subjected to the same level of testing before they become commercially available, and quality variation makes it difficult for governments and researchers to assess and calibrate their data.

Second, low-cost AQSs vary by which pollutants and gases they measure, making it difficult to compare them to each other (Lewis and Edwards 2016). For example, Air Quality Eggs can detect at least one contaminant, NO_2, CO_2, CO, O_3, SO_2, particulate matter, and volatile organic compounds (Air Quality Egg 2018). Other sensors measure particulate matter only.

The rapid expansion of low-cost AQSs has prompted the U.S. Environmental Protection Agency (EPA) to evaluate these sensors and compare them against Federal Reference

Methods (FRM)-tested traditional monitoring stations (Conner et al. 2018). The following table compares FRM-tested monitors against low-cost AQS in a variety of categories.

Table 2. Comparing FRM-tested Monitors to Low-Cost AQSs

	FRM-tested Monitors	Low-Cost AQSs
Cost	\$15,000 to \$50,000	\$100 to \$2500
Operating expense	Expensive	Inexpensive
Portability	Stationary (building/trailer needed)	Mobile (portable with basic weather shielding)
Staff training	Highly-trained technical staff	Little or no training
Data quality	Known and consistent in a variety of conditions	Less precise and may vary from sensor to sensor and in different weather condition
Sensitivity	High	Low and less chemically specific to the compound or variable of interest
Operating lifetime	10+ years (calibrated and operated to maintain accuracy)	1 year
Used for regulatory monitoring	Yes	No

Source: Conner et al. 2018

The primary benefit of low-cost AQSs is that they are portable, can be operated with little to no training on monitoring for air quality, and much less expensive than FRM monitoring stations. Many low-cost AQSs can take air quality readings at frequencies of minutes or even seconds, making them particularly effective at mapping pollution hotspots at a neighborhood-level throughout the day (Conner et al. 2018). The primary concerns with low-cost AQSs are data quality and accuracy.

III. Evaluating Low-Cost AQS

In a 2014 EPA field evaluation, researchers tested eight low-cost (under \$2,500) AQSs for data accuracy, ease of use, calibration, and other factors. No single AQS stood out as a clear best choice. Among the problems were data accuracy (Met One Model 831); interoperability (Sensaris Eco PM, Dylos DC1100, Carnegie Mellon Speck); and storage (AirBase CanarIT). Other AQSs lacked adequate weatherproofing (Shinyei PMS SYS-1) and operability under certain temperature conditions (CairPol CairClip $PM_{2.5}$) (Williams et al. 2014). The study did not specify cost of each AQS.

Another evaluation conducted in 2018 by the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) tested 39 different AQSs, including some of the newest models. This testing included categories such as pollutants measured, data accuracy (both in the real world and laboratory settings), and cost (AQ-SPEC 2018). The top 10 models that measure $PM_{2.5}$ from that evaluation are shown in the table below.

Table 3. Comparing Top AQS Models that Measure PM2.5

Make	Est. Cost (USD)	Pollutant	Field R^2	Lab R^2
PurpleAir (PA-II)	$200	$PM_{2.5}$	0.93–0.97	0.99
PurpleAir (PA-I)	$150	$PM_{2.5}$	0.90–0.92	0.99
Air Quality Egg (2018 Model)	$249	$PM_{2.5}$	0.84–0.85	0.99
Moji China (Airnut)	$150	$PM_{2.5}$	0.81–0.88	
Shinyei (PM Evaluation Kit)	$1,000	$PM_{2.5}$	0.80–0.89	0.93
Clarity (Node)	$1,300	$PM_{2.5}$	0.73–0.76	0.99
Magnasci SRL (uRADMonitor A3 HW105)	$500 ~	$PM_{2.5}$	0.72–0.81	
Magnasci SRL (uRADMonitor INDUSTRIAL HW103)	$1300 ~	$PM_{2.5}$	0.70–0.78	
IQAir (AirVisual Pro)	$270	$PM_{2.5}$	0.69–0.73	0.99
RTI (MicroPEM)	$2,000	$PM_{2.5}$	0.65–0.90	0.99

Source: AQ-SPEC 2018

The low-cost AQSs that performed best against FRM monitors when testing for PM2.5 were PurpleAir (PA-II), PurpleAir PA-I (all models), and Air Quality Egg (2018 model). Each of these AQSs costs under $300 and had an R^2 value of .84 or higher, meaning their measurements were closely calibrated against FRM monitors (AQ-SPEC 2018).

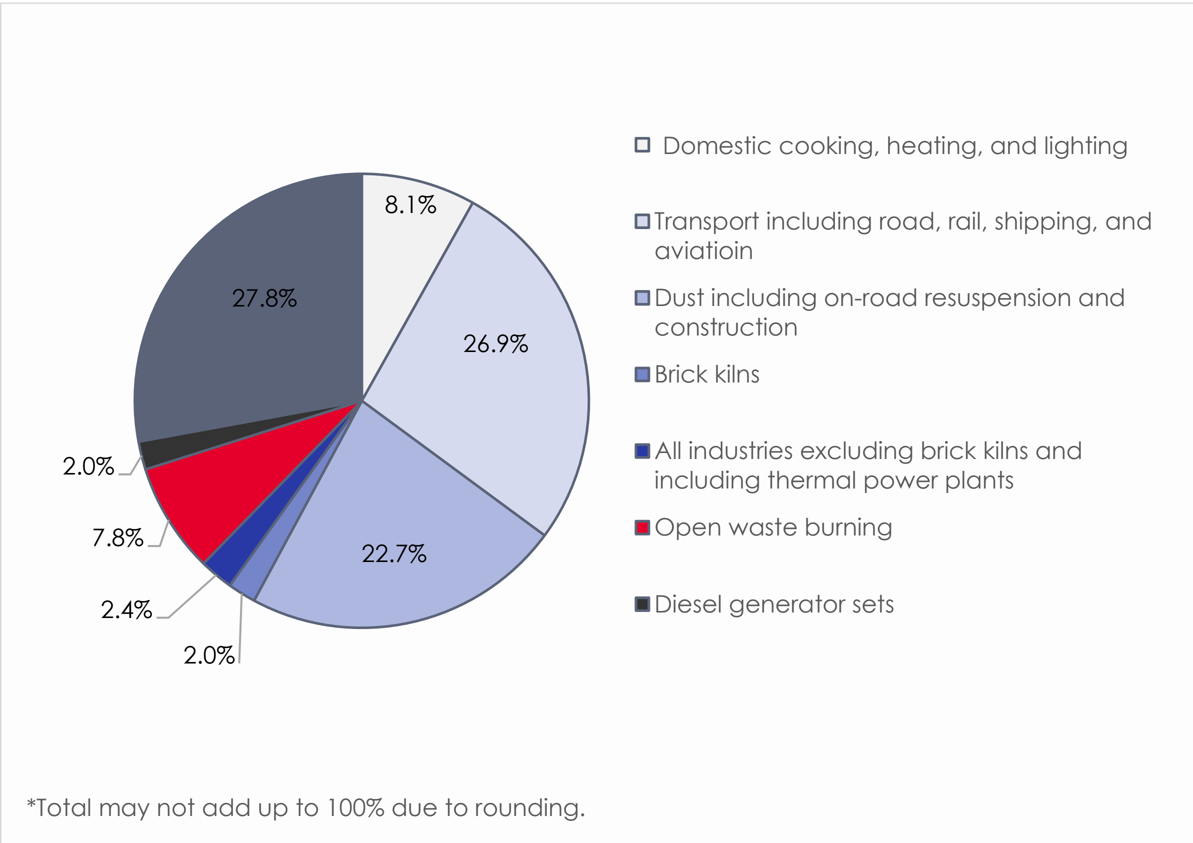
PurpleAir sensors were found to perform very reliably, but the researchers note that more rigorous field testing in extreme environmental conditions is required. In particular, the PurpleAir PA-II correlated very well with FRM monitors when testing for both $PM_{2.5}$ and $PM_{1.0}$ (R^2 0.93 and 0.96, respectively), but only marginally well when testing for PM_{10} (R^2 of 0.60). The PurpleAir PA-I also had a strong correlation with FRM monitors for $PM_{2.5}$ and $PM_{1.0}$ (R^2 value of 0.90 for both), but only a modest correlation for PM_{10} (R^2 of 0.45). The Air Quality Egg 2018 Model correlated slightly less strongly with FRM monitors for both $PM_{1.0}$ and $PM_{2.5}$, with an R^2 value of 0.86 for and 0.85, respectively. It did not correlate with FRM monitors for PM_{10}, with an R^2 value of only 0.18 (AQ-SPEC 2018).

Data recovery for both PurpleAir sensors and the Air Quality Egg was between 95–99 percent for all units tested, meaning that there was very little chance of data being lost due to technical or other issues (AQ-SPEC 2018). The Air Quality Egg and PurpleAir AQSs connect with smartphone apps, which allows users to analyze data from devices placed all over the world in real time (Air Quality Egg 2018; PurpleAir 2019). PurpleAir integrates well with Google maps, so that users can see sensors distributed around their neighborhood in a familiar format (PurpleAir 2019). Results are displayed in dynamic graphs that chart air quality levels throughout the day, and users can zoom in to view air quality during specific times (PurpleAir 2019). All three are user-friendly, with the goal of making air quality information accessible for all citizens.

IV. Co-Benefits of Installing AQS In Indore

Although the AQSs mentioned above were tested rigorously in laboratory settings, the researchers maintain that additional field-testing to develop a more comprehensive analysis of each AQS' full capabilities is needed. Installing these sensors across Indore is an opportunity to do this, with benefits for AQS companies, city officials, and perhaps most importantly, citizens of Indore. Pollutant concentrations in Indore come from eight primary sources (figure 1).

Figure 1. Average Annual Source Contributions to PM2.5 Concentrations in Indore



Source: Guttikunda et al.

The three largest sources of $PM_{2.5}$ in Indore are outside sources, transport (including road, rail, shipping and aviation), and dust (including on-road suspension and construction) (Guttikunda, Nishadh, and Jawahar 2019). 'Outside sources' refers to regional conditions that affect concentrations of $PM_{2.5}$ in the urban air shed, and are often out of municipal regulatory control.

The next two largest sources of $PM_{2.5}$ are transport and dust, at 26.9 and 22.7 percent, respectively (Guttikunda, Nishadh, and Jawahar 2019). As such, monitoring the air quality at transport hubs (major bus and train stations, Indore Airport, and along busy thoroughfares) and construction sites is critical for city officials seeking to reduce air pollution. Understanding the distribution of $PM_{2.5}$ sources in Indore will allow regulators to place AQSs in areas of greater need.

Because of their affordability, local governments can purchase and deploy AQSs across their cities. City officials can deploy these sensors during an initial pilot period to ensure that they are collecting reliable data prior to installing them on a wide scale across Indore. With more sensors collecting data, city officials will know more about air pollution hotspots across Indore, and can implement policies based on reliable data. This is also a valuable opportunity for private AQS companies. Based on the AQ-SPEC's findings, further research is required to improve many of these low-cost AQSs, and Indore offers a real-world testing ground for these companies. Assessing how these sensors perform in extreme heat environments, which are common in India, can improve their overall operability.

CONCLUSION

Based on the results from the AQ-SPEC and EPA research, the PurpleAir models appear to be the top low-cost AQSs available. Their data are closely calibrated to the FRM monitors and they are relatively easy to use. The primary limitation of the evaluations thus far is that PurpleAir units have yet to be tested in extreme environmental conditions, including the type of conditions seen in Indore. Furthermore, the quality of their data is higher than similarly priced AQSs. At $150–200 each, PurpleAir are also highly affordable. It may be worth testing them against their closest two competitors in BHC smart cities first before deciding which ones to deploy for any interventions. Using these powerful devices, Smart Cities in Asia can begin to paint a more substantial picture of air quality across their cities, and begin to improve health outcomes for all citizens. Selecting the right AQS is the first step toward accomplishing that goal.

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