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Perspective

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Harness low-cost sensors for the targeted assessment of policy

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In this Perspective, we present the case for low-cost sensors (LCS) to be taken up in a new and specific application: the targeted assessment of individual policies. We present examples in which LCS have been used to this end, discuss their strengths and weaknesses, and provide a rubric for conducting such targeted policy assessments. We encourage the strategic deployment of LCS for the measurement of air quality in this context.

The growing role of LCS in air quality management

The last several decades have seen steady and expansive growth both in the development and the application of low-cost sensors (LCS) in the field of air pollution research. These are demarcated from typical reference instruments not only by their eponymous lower cost, but also their smaller size and greater versatility. As a result, LCS can now be found all around the world, measuring air quality in remote, rural, and urban areas, by citizens, air quality managers, scientists, and more. The more settings they are deployed in and characterizations they undergo, the more we learn about the applications for which they are most appropriate, and what factors need to be considered for the generation of robust data. Much has been learned about LCS and their technical capabilities[1] and it has become clear that LCS will be part of the future of air quality management worldwide, especially in low-income countries where reference-grade monitoring is sparse.

As air pollution remains a "wicked" problem globally – not one that is evil in the moral sense but rather one that is so complex, that traditional scientific methods are ineffective for managing them[2] – creative solutions will be required at a variety of scales to tackle it. In many cases, higher-level air pollution reduction policies are broad in scope and devolve the impetus of change to lower levels of decision-making. Often, this means that these measures are designed, implemented, and enforced at the local scale in local administrations. For example, the European Ambient Air Quality Directive[3] is translated into national and even federal state law, but air quality management measures that require improvements to e.g., mobility infrastructure often occur at local neighborhood scales. Additionally, a milieu of other policies that are not necessarily designed to affect air quality may do so regardless of their actual intent. For example, a climate policy that encourages the use of biofuels to reduce CO_2 emissions can have the unwanted side effect of particulate matter emissions, depending on the efficiency of the combustion process and technology used. Alternatively, traffic-calming measures implemented to address noise pollution may change local air pollution distributions, thereby impacting residents' exposure to harmful pollutants. However, a key component of this policymaking that is all too often missing is the real-world assessment of policies' impact on air quality.

These developments highlight the potential for a specific application for LCS to address an implementation gap by providing air quality information at scales and time resolutions that were not previously feasible. In this Perspective, we argue that LCS can and should be used for the targeted assessment of policies that affect air quality. While there are increasing numbers of (urban) networks of LCS deployed across cities, the aim behind these deployments seems to be focused on generating large datasets at high spatial resolution. This is valid, but if such deployments were to consider possible policy changes, the data could be used much more effectively. Speaking with a decade of experience in the use of LCS for the measurement of air quality, including the targeted assessment of mobility policies for their impact on local air pollution, we present an argument for increasing the uptake of LCS in such applications.

Demonstrating targeted policy assessment using low-cost sensors

A number of recent studies have demonstrated the value of LCS as an effective tool for evaluating the impacts of policy measures on urban air pollution. These sensors enable real-time assessments, support evidence-based decision-making across diverse contexts, and use different types and numbers of LCS—from a handful of sensors to larger networks—for stationary and mobile measurement of indoor and outdoor air quality. Many of these studies follow a version of the five steps we have outlined in Fig. 1, which provides a general rubric that we developed for using sensors for a targeted policy assessment.

While larger sensor networks can also be used, it is more often the case that for targeted policy assessments, deployments of a dozen or fewer LCS are sufficient. In Berlin, using Alphasense electrochemical cell sensors installed in EarthSense Zephyrs, Schmitz et al.[4] observed decreased NO_2 exposure among cyclists due to new bike lanes. Similarly, Caseiro et al.[5] assessed a pedestrianization intervention on a central shopping street in Berlin and found that restricting traffic reduced local NO_2 pollution to the

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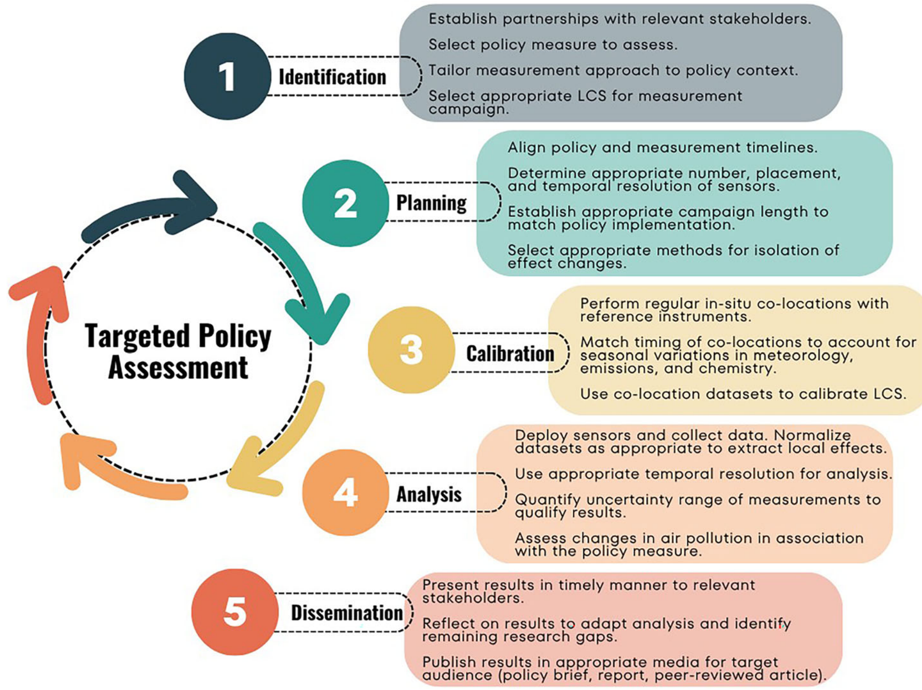

Fig. 1 | A rubric for conducting targeted policy assessments using LCS. These five broad steps should be seen as cyclical, as policymaking typically does not have a logical start and end, but is instead fluid and dynamic. As such, targeted policy assessments should seek to match these policymaking processes as much as is realistically possible.

levels of the urban background, without increases to pollution levels on neighboring streets. In contrast, the evaluation of changes to particulate matter concentrations using Plantower PMS5003 sensors, integrated in the EarthSense Zephyrs, showed that for the same policies no significant changes in $PM_{2.5}$ levels were detected[6]. These before and after measurements of a policy intervention studies followed the 5-steps outlined in Fig. 1. Hofman, et al.[7] validated the performance of Kunak Air A10 and Airly PM + Gas sensors for evaluating traffic-reduction policies near schools and public areas in Belgian cities, demonstrating significant local reductions in NO_2 and NO and negligible change in PM, associated with the local (traffic) sources. These studies underscore the complexity of air pollution dynamics and highlight differences between gaseous pollutants and particulate matter responses to urban mobility policies.

Additional examples associated to non-traffic air pollution sources demonstrate similar utility of LCS. For example, Costa-Gómez et al.[8] employed Dylos DC1700 sensors to identify negative impacts of leaf blower use in street cleaning, reporting significant localized increases in fine and coarse particulate matter (PM). Similarly, Jaafar et al.[9] used LCS to capture the impacts of construction activities on neighborhood air quality, identifying localized hotspots of $PM_{2.5}$ near the construction sites. Connerton et al.[10] highlighted how deploying LCS in São Paulo's urban parks allowed researchers to precisely measure localized air quality differences between vegetated park areas and heavily built-up roadsides. To determine the main sources of pollution from various locations in Birmingham, Bousiotis et al.[11] performed source apportionment techniques using LCS data. These types of studies highlight the utility of LCS for understanding the implications of urban planning by collecting data to inform the potential need for policy interventions, including capturing transient pollution spikes linked to specific, often time-limited, urban activities.

Beyond providing real-world quantification of the effect of policies and urban planning decisions on (localized) air quality, LCS can also provide an evidence base for policy planning and modeling, which currently rely largely on emission factors. LCS sensors and sensor networks can be used to provide information on higher resolution spatiotemporal air pollution distribution. For example, Manchanda et al.[12] integrated mobile and fixed-site LCS measurements of black carbon to bridge spatiotemporal data gaps, to support a spatiotemporal model, which was able to reveal features not captured by either approach in isolation, such as sharp concentration gradients identified near emission sources. Similarly, Schmitz et al.[13] used LCS to capture vertical and horizontal pollutant gradients in several street canyons in Berlin. While Liang et al.[14] deployed LCS for PM measurement on vehicles, to derive high-resolution spatiotemporal data to pinpoint pollution sources in Rizhao, China. By applying advanced analytical methods, they were able to identify specific contributions from industrial activities and traffic emissions. Finally, Skoulidou et al.[15] integrated a dense LCS network with high-resolution chemical transport model simulations (LOTOS-EUROS) in Eindhoven, Netherlands, which significantly improved the accuracy of the PM_{10} and $PM_{2.5}$ predictions, demonstrating how sensor networks could correct biases in existing air quality models, and illustrates the utility for such hybrid approaches for evaluating policy options assessing the range of outcomes for a proposed policy change. Taken together, these studies underscore how LCS can be used to improve our understanding and parameterization of urban air pollution at scales relevant to human exposure, to improve urban model performance, refine emission inventories, and provide policymakers with valuable insights (Step 5, Fig. 1) for air quality management.

Strengths of LCS for targeted policy assessment

What is it exactly about LCS that makes them suitable for targeted policy assessment? While the term "low-cost" has become ubiquitous in academia for referring to this category of sensors, their true costs increase substantially[16–18] when scaled up to large networks due to intensive calibration and maintenance requirements. In targeted assessments, however, the lower cost of such sensors can still be leveraged, as fewer sensors would be required when selectively measuring air quality in urban environments alongside the implementation of policy measures, as outlined in Step 2 of Fig. 1. The same cohort of sensors can be repeatedly calibrated and deployed in different areas of a city, thereby maximizing their utility over their shorter life-times and minimizing the exponential increases in maintenance and calibration costs associated with larger scale deployments. Moreover, in cities with budgets constraining large-scale network deployments of LCS, targeted assessments could serve as a more cost-effective way to learn about local air quality, especially local sources and hotspots.

A targeted deployment could also take advantage of another strength of LCS—their potential for high spatial resolution measurements. It is well known that the complexity of urban air pollution is owing to the various factors that influence concentrations, including meteorology, photochemistry, local emission sources, and urban topology[19]. Individual monitoring sites with reference instruments provide valuable information on urban air pollution, but often are too sparsely located to account for complex dynamics affecting pollution dispersal. LCS, however, has been shown to reliably measure air pollution at high spatial resolution in accordance with expectations from urban-level modeling studies[13,15]. Of particular interest is the vertical and horizontal distribution of air pollution in cities, and LCS could be deployed in various areas of the city to understand local dispersal dynamics. Such measurements, especially when normalized to the urban background, would provide local policymakers with a better understanding of how local and regional pollution intermingle to create unique, highly localized conditions of poor air quality affecting their citizens' health.

The qualities that make LCS so flexible in deployment (smaller size, lower cost, weather resistance for outdoor deployment, LTE/Wi-Fi compatibility, etc.) enable deployments not only by scientists and air quality managers, but also by citizens. They can be mounted on lampposts or just as easily on windowsills, balconies, or roofs as long as they have access to a stable power supply[4]. As such, targeted deployments need not focus solely on utilizing lampposts or municipal infrastructure, which can incur further administrative and/or personnel costs, but can also leverage local citizens' interests in air quality and health to install them in their private homes[20]. When combined with appropriate information campaigns, such an approach would not only simplify the logistics of deployment, but could also increase local engagement and interest in air pollution[21]. Moreover, the inclusion of communication hardware, such as LTE or Wi-Fi, often combined with data infrastructure and real-time dashboards, allows for consistent interaction with live air pollution data. Such engagement could foster better understanding and support for policy measures enacted to improve air quality (e.g., traffic-calming neighborhoods, reducing speed limits, congestion charging), which can incur substantial resistance.

Limitations and challenges of LCS

While LCS shows great potential for targeted policy assessment, there are also key characteristics that constrain such applications. First and foremost, LCSs have higher uncertainties, largely because they suffer from sensor drift over short time scales (months), have high inter-sensor variability and sensitivity (even for the same models, sometimes even batch-specific), suffer from significant cross-sensitivities to different chemical species, and have shorter lifetimes than reference instruments[1,22,23]. Though these technologies have improved in recent years and standardized calibration approaches to ensure higher data quality have emerged[24,25], the focus on reducing costs in their development inevitably leads to design compromises that affect performance. As such, rigorous calibration approaches are a fundamental requirement for effective targeted deployments and the generation of robust data[7,26,27].

While ensuring measurements achieve a level of data quality suitable for use in assessing changes in air quality associated with specific policies, or for discerning differences in pollution at high spatial resolution, the calibration requirement simultaneously serves as a barrier for entry for many users. Reference instrumentation is expensive, requires annual maintenance, must run in controlled environmental conditions, and requires trained users for proper deployment. As such, this calibration requirement (Step 3 in Fig. 1) substantially reduces the number of potential users for deploying LCS in targeted policy assessment. While we present an idealized scenario, citizens, countries and users in resource-poor regions, and anyone without access to reference instrumentation cannot reliably calibrate their LCS, as we have outlined here, for use in such targeted deployments. This is a major trade-off that comes with ensuring data quality objectives are met. Nonetheless, LCS can still be used in resource-poor environments to similar ends, but with different data quality objectives, such as those for indicative measurements as outlined in the European Ambient Air Quality Directive[3]. Although the quantification of an effect would be associated with greater uncertainty, indicative measurements can also provide critical information for policy decisions.

Another limitation to targeted policy assessment with LCS is the isolation of the signal and determination of the size of the effect. This is especially challenging because of the higher uncertainty associated with LCS measurements (even when rigorously calibrated). To quantify any changes in air quality related to a policy implementation, this signal will need to be isolated from a variety of other factors, such as meteorology-induced regional changes or urban background concentrations. That air pollution levels are also strongly dependent on meteorology and chemistry means that short-term deployments may not always account for typical or "normal" pollution conditions. To account for this, normalization to urban background levels can ensure that regional-scale meteorological changes do not overshadow a local signal of change in air quality. However, this normalization requires information on background concentrations or control sites. To achieve this, either reference instrumentation from an existing network or a greater number of sensibly deployed sensors is needed.

As the goal of targeted policy assessments is to directly measure changes to the status quo based on the implementation of a new policy measure, there will always be a risk that macro-scale impacts on air pollution make this assessment challenging or not possible. Depending on the complexity of the measure, implementation may require challenging logistics that can dramatically affect deployment timelines. Especially in situations where targeted deployments are not coordinated by the same individuals implementing the policies, matching measurement timelines with policy timelines can be difficult. In this sense, developing science-policy partnerships with a co-creative, transdisciplinary approach can increase feasibility and uptake of results, as outlined in Fig. 1[2].

Furthermore, certain policies may find heterogeneous effectiveness in improving air quality, thereby muddying the waters of "success". A new bike lane, for example, can substantially reduce cyclists' exposure to NO_2 but not change local air quality overall[4]. Implicitly, such a measure will have improved air pollution exposure for some individuals, but not all. This can complicate the narrative surrounding the policy measure, and it is therefore critical that targeted assessments of air quality consider other potential metrics of change (e.g., traffic counts, noise pollution, etc.) when designing the deployments. In such a scenario, which is most often the case from a decision-making perspective, air quality is but one aspect taken into consideration when designing and implementing policy measures. Recognizing this context is key, as it will provide the necessary framing for how to appropriately design measurement campaigns to assess these policies. It is precisely because of the complexity of the policy environment that, despite clear evidence of improvements in local air quality, a policy measure may be discontinued to serve other political goals[5].

Strategically deploy LCS to support targeted policy assessment

While the body of evidence for using LCS for targeted policy assessment is currently limited, available studies clearly demonstrate the feasibility and utility of LCS for air quality management. As such, this promising application for LCS should be further developed, with more studies published in differing contexts to expand the current body of literature. As more targeted deployments occur alongside varying policy measures, the transferability of policy measures and thereby the evidence base will provide an improved foundation for air quality management. We need to move away from the deployment of LCS for characterization of sensor performance and the production of 'more data' and consider the potential that LCS have when deployed strategically to support evidence-based decision making. That is not to say, however, that sensor characterization studies or the large-scale deployment of sensor networks are senseless. Instead, we argue that the added value of targeted deployment of a handful of LCS to a measurement network could be leveraged to provide a much larger impact on air quality management if these various aims (expanding sensor networks; supporting evidence-based decision making) are considered together.

Ambitious policy goals, such as Europe's Zero Pollution Action Plan[28], with the aim to reduce air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems by 2050, will only be achieved if the policies implemented are targeted and effective. As such, a detailed understanding of the spatial and temporal distribution of air pollution is needed to ensure that hot spots are identified, the correct sources targeted, and the most effective policy measures implemented. Limited numbers of sensors can provide critical insights into the effectiveness of policy measures when deployed in targeted campaigns. Larger networks of LCS can do the same, but only when strategically placed in coordination with air quality management policy. As discussed, LCS can also support modeling tools by improving model predictions and correcting biases, which means improved effect estimates. The growing application of digital twins in policy similarly provides an opportunity for integrating LCS that can support hyperlocal and temporally rich datasets for anticipating and managing pollution dynamically[29]. Targeted deployments can therefore also work in tandem with both urban-scale modeling efforts and scenario analyses for policy assessment.

To support the growth of this nascent application in the field of LCS, we have developed a simple rubric for targeted policy assessment (Fig. 1). It is broad in scope so as to find relevance in a variety of different contexts, but specific enough to ensure that the adherence to these five steps can lead to the successful production of a policy-relevant evidence base of LCS measurements. The field of air quality research is an applied science; targeted policy assessment is therefore a logical developmental step in the field of LCS research. We encourage its further uptake and remain optimistic that this approach can transform the evidence base for local policy decision-making, to create a step change in the tools and data used for mitigating air pollution and providing clean, healthy air for all.

Data availability

No datasets were generated or analyzed during the current study.

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S.S. and E.v.S. conceived of the ideas, wrote the perspective, and prepared the manuscript together. S.S. designed and created Figure 1.

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