Science & Technology Innovation Program

Authors

Alison Parker,
The Wilson Center

Shannon Dosemagen,
Open Environmental Data Project

Katie Hoeberling,
Open Environmental Data Project

Alexandra Novak,
The Wilson Center and Columbia University

Open Science Hardware:

A Shared Solution to Environmental Monitoring Challenges

May 2023

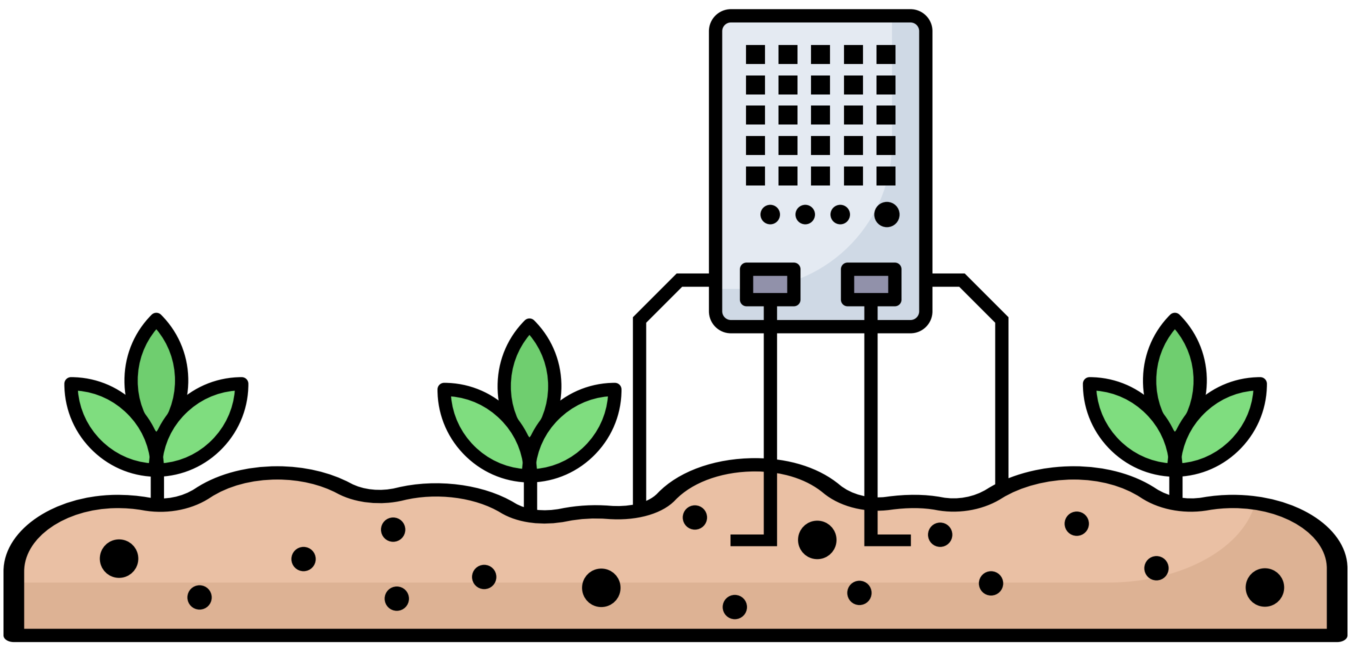


Image source: shmai / Shutterstock, all rights reserved.

Foreword

Environmental protection, regulation, and compliance requires monitoring, whether towards meeting government requirements, or in the case of communities and partners, to demonstrate where there are potential environmental threats. The physical tools of environmental monitoring are largely proprietary technology, high-cost, and complicated to use because of inaccessible documentation or support. Open science hardware (OScH) can be an impactful tool for understanding and addressing environmental issues—across the reasons for monitoring—with the prioritization of partnership and collaboration between government, technologists, and communities impacted by environmental issues. Although the research and development of OScH has proliferated, this has largely happened outside of formalized monitoring practices. To productively move these spaces closer together, in spring of 2022, the authors convened a virtual roundtable centered on open tools for environmental monitoring and decision-making; specifically, discussing current trends, identifying the issues, and proposing possible solutions for United States public policy. The shared goal was to identify next steps to increase the value and interest of open scientific tools for local, state, tribal, and US federal government.

Conveners

- The Woodrow Wilson International Center for Scholars' Science and Technology Innovation Program
- Open Environmental Data Project

Workshop Contributors

- Julieta Arancio, Center for Science, Technology & Society, Drexel University
- Greg Austic, Our Sci
- Michelle Cheripka, Open Environmental Data Project
- Kasie Coccaro, National Geographic Society
- Janet Coffey, Gordon and Betty Moore Foundation
- John Dawes, The Commons
- Priyanka deSouza, University of Colorado, Denver
- Tim Dye, TD Environmental Services
- Scott Ensign, Stroud Water Research Center
- Caitlyn Hall, The University of Arizona
- Mary Clare Hano, US Environmental Protection Agency
- Ana Hoffman, Community Robotics Education and Technology Empowerment (CREATE) Lab at Carnegie Mellon University
- David Lang, Experiment Foundation
- Juan P. Maestre, The University of Texas at Austin
- Corey Mocka, US Environmental Protection Agency
- Luis Felipe Murillo, University of Notre Dame
- Jef Pearlman, USC Gould Intellectual Property & Technology Law Clinic
- Kelly Poole, The Environmental Council of the States

- Keith Porcaro, The Digital Governance Design Studio (DGDS) at Duke Law School
- Andrew Putnam, Colorado Department of Public Health and Environment
- Ashley Schuett, The Wilson Center
- Shah Selbe, FieldKit
- Meghan Smart, Arizona Department of Environmental Quality
- Julie Vastine, Dickinson College's Alliance for Aquatic Resource Monitoring
- Emelia Williams, Open Environmental Data Project
- Dana Williamson, Environmental Health Fellow hosted at the United States Environmental Protection Agency

Following the discussion, participants and others were invited to author short contributions to a curated collection of posts describing the opportunities and challenges in this new era of environmental information (Dosemagen et al., 2022). These posts, listed below, help us better align and understand the co-existing opportunities and challenges faced by the policy-making community and developers and users of open hardware from across a broad array of disciplines.

- Open science hardware for environmental monitoring, Shannon Dosemagen, Alison Parker, Katie Hoeberling, Ashley Schuett
- Open data and open hardware: Tools for collaborative solutions to water challenges, Scott H. Ensign
- Opening your science with community engagement, Caitlyn A. Hall
- Valuing work "on the ground": Making the hidden work visible in open hardware, Julieta Arancio
- Sustaining community cohesion and enthusiasm with a cadence of "sparks" and social activities, Brianna Johns and Pen-Yuan Hsing
- Circumventing silos in open hardware to create opportunities for interconnection, shared agendas, and collective resources, Ashley Schuett, Juan Pedro Maestre, and Katie Hoeberling
- A holistic approach: Intentional planning to set community data collection programs up for success, Julie Vastine
- The need for open technology standards for environmental monitoring, Shannon Dosemagen and Luis Felipe Murillo
- *Beyond Access: Broadening the role of open science hardware in environmental monitoring innovations,* Shannon Dosemagen and Alison Parker

This publication is a reflection and compilation of the ideas of workshop participants and Medium articles. Many of the ideas presented in the articles are further explored here.

Acknowledgements

The Wilson Center Science and Technology Innovation Program's work on low-cost and open hardware is supported by the Alfred P. Sloan Foundation.

We greatly appreciated suggestions, ideas, and draft review from Jenny Molloy and Waldo Jaquith.

Introduction

Environmental protection is at an inflection point as environmental challenges grow more intractable and complex. Climate change is no longer a distant threat but for many, a present reality; environmental injustice permeates environmental monitoring and decision-making; and, there are major gaps in baseline data for environmental quality and health throughout the US and the world. At the same time, expertise and innovation are growing too. Meeting our environmental challenges requires a shift in perspective; we can no longer rely solely on top-down policies and programs to address environmental challenges. Instead, governments must harness ingenuity and expertise in all sectors of civil society, and channel it toward efforts that can have collective impact. The best way to do this is by creating the infrastructure and capacity for open science. Within this approach, there is a clear role for open science hardware (OScH), which encompasses tools and equipment for science that can be designed, obtained, assembled, used, studied, modified, shared, and sold by anyone (Open Source Hardware Association, n.d.).

Promising recent actions are getting us part of the way there. Recent legislation has opened up substantial resources for science and for environmental monitoring. Importantly, this legislation supports community involvement in environmental monitoring and directs some capacity and funding toward communities partnering with non-profit and government institutions at the national, state, local, and tribal level. For example, the American Rescue Plan (ARP) attributes $100 million to the US Environmental Protection Agency (US EPA) to address health outcome disparities from pollution and COVID-19, and the Inflation Reduction Act (IRA) allocates $30 million to a grant competition for community air monitoring projects (Inflation Reduction Act, 2022). The Justice40 Executive Order requires that 40% of government investment flows to "disadvantaged communities that have been marginalized, underserved, and overburdened by pollution," including enhancing environmental monitoring.

However, although this influx of resources is both necessary and beneficial, the legislation primarily serves to build capacity for independent efforts. Examples include the deployment of 40 low-cost air quality sensors in East Las Vegas, the use of data collected from low-cost particulate matter 2.5 (PM2.5) sensors by the Confederated Tribes of the Colville Reservation in north-central eastern Washington, and tracking pollutants in real-time from petrochemical industries in the Ohio River Valley (US EPA, n.d. -a). These efforts will have a local impact in the communities. However, the use of proprietary tools limits the possibility of reusing and amplifying the efforts of communities in other locations.

The Biden Administration's Office of Science and Technology Policy (OSTP) and US federal funding agencies have declared 2023 the Year of Open Science (OSTP, 2023). Following their lead, now is the time to direct agency resources to build an infrastructure of science to allow all kinds of institutions, organizations, communities, and individuals to contribute to environmental monitoring and protection in a way that builds upon each of their efforts. The infrastructure of open science should be a priority for all new federal legislation and initiatives that support environmental monitoring. More specifically, prioritizing OScH will generate tools and resources that build collective capacity for environmental monitoring and improvement, within government institutions and more importantly, in all sectors.

Open Science Hardware

The vast majority of physical tools used for science, or science hardware, are proprietary, meaning that they cannot be fully inspected or customized, and are expensive to procure and maintain. This includes standard lab equipment like microscopes, as well as auxiliary materials like sensors and both analog and digital electronic components. In contrast to proprietary hardware, OScH is an alternative approach to the creation and use of scientific instrumentation and tools (Gathering for Open Science Hardware, n.d.). OScH is encompassed by open hardware (or open source hardware), tangible artifacts—machines, devices, or other physical things—whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things (Open Source Hardware Association, n.d.).

Background

Environmental monitoring has been a key module in OScH since even before the concept of open hardware came into its own. For instance, the bucket air monitoring tool was created in 1995 as a low-cost alternative to the summa canister used by the EPA (Ottinger & Dosemagen, 2020; US EPA, 1995). Communities were able to follow instructions provided by environmental "intermediary" organizations, such as the now-defunct Global Community Monitor, to source parts and compile bucket monitoring tools. However, the bucket was not formally documented as an open source tool until 2020.

2008-2012 was generally an important time for the development of collaborative and open practices that focused on the engagement of citizens and residents as critical members of civic spaces. Communities and organizations such as Public Lab, SafeCast, and OpenROV captured this spirit by applying the tools of open science—including OScH—toward working with communities on monitoring their environments.

These early projects captured, and yet were also bounded by; ideas in critical making (Wylie et al., 2014), participation as an ultimate right (United Nations Human Rights: Office of the High Commissioner, 2020), and play as a necessitating factor in understanding the relationship of people to place (Breen et al., 2019).

OScH in environmental monitoring continued to grow over the years with more open communities coming together and also new independent environmental monitoring projects (e.g. FieldKit).

As OScH opportunities continue to grow in civil society, the US government has not promoted the unique benefits of OScH. Instead OScH is included with low-cost tools as applicable to community monitoring for the purposes of education, organizing and interacting with media (National Advisory Council for Environmental Policy and Technology, 2016).

In 2023, with the launch of the "Year of Open Science", we argue that OScH has distinct benefits beyond low-cost tools, and that the value and promise of open hardware goes far beyond community monitoring (OSTP, 2023). OScH has also created impactful strides in research, including CERN's work on data acquisition systems, open source microscopy, open agriculture, and conservation, and can be a model for environmental monitoring and climate and energy solutions (Heikkinen et al., 2020).

Image source: GoodStudio / Shutterstock, all rights reserved

The Unique Benefits of Open Science Hardware

Environmental monitoring relies on scientific instrumentation to monitor air, water, and soil quality; including sensors and samplers that measure pollutants, microscopes for identifying contaminants, probes and data loggers, automatic pipettors and analyzers, among others.

Alongside the development of OScH in a variety of scientific fields and for different purposes, other initiatives (low cost and DIY/Maker as described below), are working toward making environmental monitoring more accessible. However, as described in Beyond Access: Broadening the role of OScH in environmental monitoring innovations, the unique features of OScH include, but also go beyond, broadening access and participation (Dosemagen & Parker, 2022).

Low-Cost Tools

For example, increasingly more low-cost environmental sensors are now available and are changing the way that regulatory agencies and the public interact with environmental data. More and different data can be collected, including by individuals with no formal training in environmental monitoring. In air quality research particularly, low-cost sensors can provide data of sufficient value on local patterns and changes in air quality for different uses (Gabrys et al., 2016). Simultaneously, large datasets can produce high-resolution air quality maps, ground truth other datasets, and may close gaps in coverage. Low-cost air quality sensors are generating significant interest in the public and within regulatory agencies, and inspiring questions about how low-cost sensors may contribute to regulatory decisions. For example, questions from state and local agencies prompted the US EPA to contribute to research on sensor performance and recognize the need to respond to non-regulatory data such as that provided by low-cost air quality sensors (US EPA, 2020).

However, the vast majority of these low-cost sensors are proprietary, and most do not generate open data. Even when data are available to the public, most air sensor manufacturers apply some kind of data adjustment method to the raw data produced by the sensors. This improves data quality, but the manufacturers rarely, if ever, share the methods used to clean and process data (Hagler et al., 2018). For example, Jaffe et al. (2023) report that "The Plantower sensor reports PM mass concentrations…presumably based on the pulse height of the scattered radiation, although the exact procedure is not documented by Purple Air."

> **"Transparency is essential to build trust in air sensor data, which is a challenging issue for many sensor developers where algorithms applied are valuable intellectual property. This limitation may be overcome through the provision of unprocessed, original sensor data output, allowing scientists to develop and openly document independent algorithms. Secondarily, trust in the processed data would be increased if developers share which parameters are incorporated in post processing, communicate when algorithms are updated, and show the comparison of unadjusted and adjusted data." (Hagler et al., 2018)**

This is a missed opportunity. By obscuring openness in the tools used for data collection, the use of proprietary tools creates transparency issues for more than the tools themselves; it creates a lack of transparency along the entire toolchain, including the software, data, and research products that result.

Purple Air

As one example of a particularly impactful low-cost air sensor, Purple Air sensors are used to measure particulate matter, an air pollutant harmful to human and environmental health. The tool was developed in 2015, when the tool developer wanted to locally monitor particulate matter near his house, an area that was not covered by EPA sensors (Bowles, 2018). Starting as a "backyard" project, by April 2022 there were more than 30,000 Purple Air sensors deployed whose data is uploaded in real time to their publicly available air quality map. Purple Air is low cost and has generated attention for its relatively high accuracy and precision (US EPA, n.d. -b). Citizen and community scientists use Purple Air sensors, such as the AirKeeper Program and Concerned Ohio River Residents (Raheja et al., 2022), to understand the air quality in their regions and advocate for better conditions. At the federal level, National Aeronautic and Space Administration (NASA)'s Air Quality Citizen Science project uses Purple Air sensors to validate satellite measurements for aerosols (Doraiswamy, n.d.). The US EPA, in partnership with the US Forest Service as well as state, tribal, and local air monitoring groups has come up with a correction method for Purple Air sensor data and included this data on their AirNow Fire and Smoke Map.

Purple Air is an example of a proprietary sensor. Proprietary low-cost sensors are affordable for many people, including many outside traditional science institutions. At the same time, there are limitations with proprietary air quality sensors that can be avoided. Only the companies that hold intellectual property rights may create and manufacture the sensors, they cannot be easily modified and customized for specific purposes and environments, and the data they generate is not easily reproducible. Any public investment in proprietary sensors, such as by environmental agencies and other government institutions, benefits the company and the specific users of the sensors and their data, but may not contribute to a "commons" of scientific tools and approaches as we might expect from public funding.

For truly impactful and collaborative environmental monitoring on air quality, we need sensors that are low-cost, accurate, precise, and open source.

Do-it-Yourself (DIY) and Maker Tools

Another distinct category of tools are DIY tools for environmental monitoring. Gaining in popularity alongside the maker movement, these tools can be constructed using easily accessible materials and community fabrication facilities, such as makerspaces, hackerspaces, and Fablabs that often house digital fabrication tools such as 3D printers and laser cutters. For example, the US EPA published instructions for building the AirMapper, an air sensor for measuring carbon dioxide and particulate matter. Publications like Make Magazine share tools like a water sensor you can hear (Platt, 2019). These tools provide the opportunity to better understand the engineering, science, and technology involved in air and water quality monitoring.

Designers and users of DIY and maker tools prioritize accessibility, designing and making tools as easy to build and inexpensive as possible, using the most accessible materials. These tools are generally perceived as great opportunities for education or public engagement, but are often not considered useful for environmental monitoring or decision-making. They sometimes use proprietary components and do not necessarily license designs with open licenses, limiting the benefits of tools and approaches to those creating and using them directly.

The Compounding Benefits of Open Science Hardware

With benefits beyond low-cost, DIY, and maker tools, OScH should be considered an essential part of the infrastructure of open science (Murillo, 2021). OScH is often much less expensive than traditional monitoring equipment, making it more affordable and accessible for work within and outside traditional scientific institutions. In addition to being cost-effective and accessible, OScH goes further by building a scientific infrastructure that is replicable, modular, and customizable. OScH supports greater reproducibility in that available blueprints and plans for tools allow scientists and others to replicate studies. Moreover, the collaborative nature of OScH allows users to adapt tools to their local circumstances and add new features easily, sharing this knowledge back for others to reuse. As a result, the return on investment for open tools is many times that of proprietary instrumentation; small investments in just one tool or approach builds capacity across the entire scientific enterprise and supports the development of infrastructure to support all science and all scientists (Pearce, 2020). It supports an ecosystem of approaches that allows all kinds of experts to contribute to solving environmental problems, rather than reinventing the wheel each time.

With advances and growth in the open science community, OScH can be put to use in a plethora of circumstances in the environmental sector. Current tools can be used for a range of monitoring and measurement purposes, such as EnviroDIY's Mayfly, a data logger used for water measurements, FloodNet, which measures street flooding, and FieldKit, which currently features both a water and weather sensing kit. These tools and others offer additional promise with adequate investment, including in the energy sector. For example OSE for Consumer and Academic Scale Renewable Energy Adoption will create an open source ecosystem that increases the adoption of renewable energy technologies in the academic and consumer sectors, including hardware.

SenseCAP K1100 - Sensor Prototype Kit with LoRa and AI Supports SenseCraft is a plug and play kit that allows users to create DIY sensors for data collection. Because it has low-power, long-distance, and long-term data collection capabilities, it is ideal for remote sensing. It has been deployed to measure weather data in parks, for smart agriculture applications, algae bloom monitoring, mosquito growth monitoring, among other applications.

Image source: Seeed Studio, all rights reserved.

[FloodNet](#) is a network of low-cost, open source sensors used to detect street water levels during flooding events. The network, which was developed in 2020 through collaborations between academic researchers, the New York City government, and grassroots communities, will provide local data on the frequency, severity, and impacts of flooding. Currently, 31 out of the 500 sensors have been deployed in neighborhoods prone to flooding (Misdary, 2023). The real-time, publicly-accessible data can be used for a variety of applications including improving flood predictions, resilience planning, and disaster response.

Image source: FloodNet, all rights reserved.

FieldKit is an open source or DIY hardware for environmental sensing that includes data visualization and analysis software as well as a community forum. FieldKit currently features a water sensing kit that measures pH, conductivity, dissolved oxygen, and water temperature as well as a weather sensing kit that measures wind speed, direction, rainfall, air temperature, humidity, and barometric pressure. They plan to bring an air quality sensing kit to market soon.

Image source: Image by FieldKit is licensed under CC BY-NC 4.0.

Prioritizing OScH will result in an open library of tools for environmental monitoring that are replicable, customizable, and, in some cases, inexpensive. Beyond that, prioritizing OScH would create, alongside the tools themselves, an ecosystem of open toolchains to enable interoperability and accessibility in environmental monitoring. Recently, agencies like the National Science Foundation (NSF) and the US EPA have supported the development of open source software, open data systems, and open access to scientific information in general. However, they largely omit OScH. OScH cannot be separated from open source software and open data, each of which brings a return on investment well beyond each individual project, tool, and system. At the same time, the impact of current investments in open source software and open data will expand with an ecosystem approach to open tools that includes hardware (Dosemagen & Murillo, 2022). Prioritizing OScH as an integral part of open science, and encouraging the use of OScH in federally-funded projects would support more meaningful collaboration, reduce project duplication, and foster innovation for scaled impact.

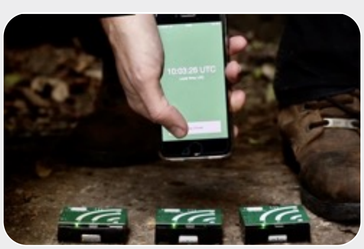
Open Hardware is an Opportunity to Build Better Science

The 2021 policy brief Open Hardware: An Opportunity to Build Better Science offers a value proposition for prioritizing open hardware in a national science strategy (Parker et al., 2021). The brief outlines the key benefits of open hardware, including that open hardware yields a high return on investment and reduces the cost of research, links science and society, supports better and more accessible STEM education, and builds capacity for innovative manufacturing.

Prioritizing OScH and an ecosystem of open tools and practices directly supports the missions of agencies that engage in environmental monitoring, research, and regulations, and will have massive return on investment. As the implementation of recent legislation and investment in science infrastructure continues over the next several years, agencies should incentivize or require the creation, use, documentation, and dissemination of open tools, alongside open source software and open data. The result will be a library of tools for affordable, replicable, and customizable use; the foundation of a scientific infrastructure that can support more and better environmental monitoring; and most importantly, an engaged network of experts, communities and institutions across all sectors of civil society building and innovating on existing work (Dosemagen & Parker, 2022).

To do this, we offer an overarching recommendation: that environmental agencies, other government institutions, and funders prioritize OScH for environmental monitoring, including 1) directly supporting the development of OScH, 2) using OScH, and 3) incentivizing others' use of OScH.

With these advances in technology, OScH can support the US government in meeting goals of programs such as Justice40, by expanding access to the tools needed to localize environmental and climate solutions. As US federal agencies herald 2023 as a focused "Year of Open Science," OScH and its role in enhancing environmental and climate monitoring and solutions should be front and center as a place of promise (OSTP, 2023).



AudioMoth is a low-cost, open source acoustic logger used to monitor wildlife. Due to the modularity of the device, it has been used for many applications ranging from detecting the presence of insect species, tracking illegal hunting activities, and even underwater monitoring.

Image source: Andy Hill, all rights reserved.

Rodeostat: A low-cost, open source potentiostat which uses electrochemical reactions to detect levels of contaminants in water. For example, this tool was used in Mexico to detect arsenic contamination in groundwater.

Image source: Image by Rodeostat is licensed under CC BY 4.0

Born out of the founder's desire to learn more about caves and aquifers, the Cave Pearl Project is an arduino-based data logger that can be used for a wide variety of environmental monitoring applications. Currently, there are over 100 of these data loggers installed across the world. They monitor surface weather, underground drip, micro-climate recorders, water level, borehole pressure, and more.

Image source: Figure 11 by Patricia A. Beddows and Edward K. Mallon is licensed under CC BY 4.0.

NSF's POSE program Phase I funded a project titled "OSE for Consumer and Academic Scale Renewable Energy Adoption." The project plans to create an open source ecosystem that increases the adoption of renewable energy technologies in the academic and consumer sectors. The project will include open source software, hardware, and data that can be used to "control, connect, and modify renewable systems." By enabling increased adoption, this project hopes to help the US gain energy independence and reduce greenhouse gasses.

Image source: Walmart de Mexico renewable wind energy by Walmart is licensed under CC BY 2.0.

The ARP Enhanced Air Quality Monitoring Competitive Grants

The ARP attributed $100 million to the EPA to address health outcome disparities from pollution and COVID-19. Fifty percent of these funds went to air quality monitoring. This funded a $20 million grant competition for community air monitoring projects, directly provided $22.5 million to agencies at the state, tribal, and local level for PM2.5 monitoring, and provided $5 million to agency mobile labs or air sensor loan programs for equipment. Similarly, Congress passed the IRA to help fight inflation, reduce deficit, increase investment in domestic energy production, and reduce carbon emissions. Within the IRA, $30 million was allocated to a grant competition for community air monitoring projects.

Funded by both ARP and IRA, the ARP Enhanced Air Quality Monitoring Competitive Grants are funding 132 air monitoring projects in 37 states, nearly half of the projects led by community based organizations or non-profits. For example:

Buen Aire Para Todos is a project aimed to improve the air quality monitoring capabilities in East Las Vegas, a primarily Hispanic, low-income area that is disproportionately impacted by air pollution. Funding from the EPA will support the deployment of 40 sensors, which includes 10 Purple Air sensors, that will monitor outdoor, indoor, and mobile air quality. The project will also include data sharing, outreach, and education components to help the community better understand the air quality issues in their community.

PM2.5 Monitoring for Upper Columbia River Communities is a project carried out by the Confederated Tribes of the Colville Reservation in north-central eastern Washington. This project plans to install 52 Purple Air PM2.5 sensors to help residents understand their exposure to air quality pollution during smoke season. Through community engagement and data dissemination, residents can use the data collected from their sensors to inform their activities during times of high pollution.

FracTracker Alliance is a community organization in the Ohio River Valley that uses low-cost monitors to track pollutants in real-time from unconventional oil and gas developments and petrochemical industries in the region. EPA funding for their project "Community-Based Ambient Air Monitoring to Evaluate Criteria Pollutants and Air Toxics Related to Unconventional Oil and Gas Development in the Ohio River Valley" will help this group expand on their community science efforts to additional regions in the valley, providing further opportunities for increased community participation in improving air quality.

The EnviroDIY Mayfly takes real time measurements of water temperature, depth, conductivity, and turbidity. It can be built open source or also purchased and assembled as a DIY kit.

Image source: Image by EnviroDIY_Mayfly_Logger is licensed under CC-BY-SA

Potential for Impact: Strategies for integrating OScH as a core component of environmental monitoring

OScH tools could have transformational impacts on environmental monitoring. Progress, however, has been limited mostly to efforts outside government, as academia, NGOs, and entrepreneurs push the boundaries of innovative and accessible tools. For OScH's potential to be fully realized, policymakers and regulators at all levels must reconsider how they assess tools for science and the data they provide.

Ultimately OScH communities need to prioritize building trust between sectors to tackle challenges and act on opportunities in environmental monitoring. Work by government, community-based organizations and nonprofits, researchers, and industry tends to happen in relative isolation. As Ashley Schuett, Juan Pedro Maestre, and Katie Hoeberling discuss in Circumventing silos in open hardware to create opportunities for interconnection, shared agendas, and collective resources, siloes between these sectors have led to duplicated efforts, stalled progress, and distrust (Schuett, Maestre, & Hoeberling, 2022). On the one hand, there is skepticism from communities that have historically been harmed or underserved by the government, scientific institutions, or industry. On the other hand, R&D spaces in industry and government lack confidence in the quality of OScH (as well as low-cost and DIY/Maker tools) and the data it provides. Opportunities for collaboration in environmental monitoring that prioritize openness through OScH can help work through these tensions to meet the needs of all sectors. Furthermore, the process of collaborating and learning together creates opportunities for expanding understanding and collective knowledge.

The roundtable identified two key areas for supporting collaboration and building trust in the OScH and environmental monitoring ecosystems: The tools and data, and the culture of environmental monitoring .

The Tools and Data

OScH is a key but overlooked component of the broader open science landscape. Clearly identifying the role of OScH in open science policy and practice has the potential to broadly support more inclusive, equitable, and agile science and technology innovation in the US Beyond serving as important physical tools for conducting environmental research, there is a place for OScH as part of environmental R&D's critical infrastructure (Murillo, 2021). To ensure the place of OScH in broader open science ecosystems, multi-sector attention is needed to make strong, clear, and well-resourced connections to OScH.

Holistic Approaches: Software in Tandem with Hardware, the Life and Afterlife of Data, and Intentional Planning

Recent attention to open data and open source software has centered on making these digital objects more accessible and usable; however, initiatives tend to focus on one aspect of the open data lifecycle without considering other essential elements like open infrastructure and hardware. This creates additional challenges for open environmental data, such as not providing enough context to enable understanding, ensuring privacy, sharing data in broadly usable formats, and supporting data integration and reuse to answer new questions. With intentional planning and consideration of sustainability, interoperability, and usability, we can broaden efforts to focus on the entire lifecycle of data; from collection, to storage, to reusability. Efforts to modernize data and software systems can leverage and strengthen innovation by including OScH, as well as supporting connections, learning, and collaboration between open software, data, and hardware communities.

Standardizing Resources: Hardware, Software, Data, and Interpretation

Standards serve not only to facilitate connections between technical objects, but also to facilitate community building. As Dosemagen & Murillo (2022) discuss in The need for open technology standards for environmental monitoring, the process of standardizing hardware, software, analytical tools, and data can bring experts together to address and avoid "1) overlapping and redundant research projects (due to the lack of data sharing); 2) waste of resources on tools that cannot be improved (due to the closed nature of research instruments); and 3) lack of expertise in Free and Open Source Software (FOSS) tools (given the prevalence of proprietary scientific libraries in certain domains of scientific practice)." Leveraging standardization processes in environmental monitoring, federal, and open hardware communities can strengthen connections between these communities, communicate data needs, capacities, and contexts, and translate technical terms. For example, the co-creation of OScH certification systems could provide standard documentation useful for developers, researchers, and decision-makers alike.

Coming Together on Tool Evaluation and Quality Assurance/Quality Control (QA/QC)

OScH is usually developed to meet the needs of specific projects, but as the projects grow and gain interest, so do opportunities to build and modify tools to serve additional needs, growing their impact for environmental monitoring. However, despite the potential for use in research and decision-making, they do not easily fit into institutional approaches for tool evaluation and QA/QC. As Vastine (2022) notes in A holistic approach: Intentional planning to set community data collection programs up for success, it is essential that planning, study design, and QA/QC get significant attention at the outset of any data collection effort. Regulations are designed to use proprietary technologies for compliance and enforcement decisions, and, at the same time, tool developers and users struggle to understand how agencies and other institutions approach tool evaluation. There is a need for knowledge sharing and collaborative problem-solving to overcome these barriers in communication; cross-sector programs and communities of practice can meet this need and support the integration of OScH in environmental monitoring. Increased investment in OScH can also support more thorough and transparent OScH documentation practices. Such transparency can make it easier to assess the quality of openly-designed and fabricated tools and the data they produce to meet government standards.

Accessible and Usable Data

Resources are increasingly being funneled into collecting environmental data and opening environmental datasets. For example, the White House released guidelines and EPA released several funding opportunities that support community environmental monitoring, and Creative Commons recently launched a four-year Open Climate campaign. However, less support is focusing directly on the broader understandability, usability, and interoperability of this data, both in its original intent and its reuse and interpretation by other researchers, communities, and data users. Much like open source and well-documented OScH, open data shared with reusability in mind can enable more diverse applications and reduce duplicated collection efforts. By considering the diverse applications of data and developing social and digital infrastructure to enable these, institutions can make environmental data much more broadly usable beyond its original purpose. For example, agencies and organizations could employ stewards to curate open data and manage metadata, integrating documentation and information from QA/QC processes. They could also support data seekers in finding data or the proper OScH tools to collect it. For example, Ensign (2022) mentions in Open Data and Open Hardware:Tools for Collaborative Solutions to Water Challenges that federal support is needed to support technical service providers who can maintain water data's quality and accessibility in order to enable impact.

The Year of Open Science presents opportunities to strengthen connections between OScH, the broader open science ecosystem, and environmental monitoring projects, people, and resources (OSTP, 2023). A socially- and digitally-networked environmental monitoring landscape can leverage collective expertise and goals to collectively address technical challenges and build common resources. Although recognizing the value of cooperation and collaboration in competitive landscapes and capitalist economies can be a challenge, shared agendas and clearly articulated needs and opportunities can set a foundation for mutual and broadly accessible benefits.

The Culture of Environmental Monitoring

Beyond increased monitoring and available technology, as promised by recent investments in environmental monitoring like those in the ARP, culture change—through new labor and institutional practices—can foster broader impacts of this work. Right now, conditions are conducive to cultural and institutional change; in addition to significant investment, the US labor force is primed to think differently about work processes in light of experiences during the COVID-19 pandemic.

Rethink Funding for Scale

Philanthropic contributions to OScH in the environmental space have largely been piecemeal and project-oriented, resulting in tools that do not scale or lack resources for long-term maintenance and adaptation. These projects are increasingly entering stages of maturity where more sustained support could significantly bolster impacts in environmental monitoring. Philanthropic organizations could ensure longevity of OScH tools and communities through strategizing together about how to best support the maintenance of impactful work, community-building, and coalitions of innovators to support more meaningful collaboration, reduce project duplication, and foster innovation for broad scale impact. Additionally, the Year of Open Science creates an opportunity for federal agencies to further explore ways to adopt open practices and tools into their operations.

Technology and Innovation Outpace the Speed of Government Processes

It has never been easier or cheaper to build or modify scientific tools, but challenges related to the use of open tools and their data limit their adaptability; this can slow the pace of innovation or limit it to private companies who lack accountability to communities. Often the use of tools and their data falls within the control of environmental agencies and other government actors, but new tools and new approaches to environmental monitoring do not easily fit into current government processes. Prioritizing OScH and open source software in procurement and granting processes can make these tools more widely accessible, enabling more people outside of government and technology companies to understand and improve on them. It also allows for improved documentation of OScH so that they are able to meet the quality standards set by the government.

The Complexity of Contracting

Current contracting and procurement practices in agencies like the US EPA are complex, time-intensive, and difficult for anyone to navigate, let alone developers or users of OScH, who tend to be individuals or small organizations. These processes tend to default to private and proprietary technology; this is because contracting processes can be opaque, based on hidden regulatory information such as cost codes and minimum procurement standards held by highly specialized staff, and are informed by agency "Requests for Information," which tend to be submitted by corporations with the resources to best respond. If agencies are to meaningfully engage with open science and encourage the development, use, and improvement of OScH, both contracting processes and the culture that surrounds them must shift toward openness. Defaulting open can make it easier for agencies or contractors to collaborate, and for members of the public to assess and build on their tools, making room for improvements (e.g., De-risking Government Technology) (General Services Administration, 2020). There is precedence for this in how agencies have shifted (and continue to shift) in procuring and encouraging the use of open source software products. For example, the developers of FarmOS have been commissioned to write recommendations for the United States Department of Agriculture (USDA) about prioritizing FOSS in systems that will collect and store data for research and grant reporting.

Considering Labor Towards Sustainability: Valuing Work "On the Ground," Re-Considering the Meaning of Expertise

While participatory approaches to science have historically been considered by government agencies to be mechanisms for outreach, environmental monitoring, especially of one's own community, is a form of labor that requires adequate resources, as described by Arancio (2022) in Valuing work on the ground: Making the hidden work visible in open hardware. If community monitoring efforts are to have meaningful impact, agencies like the EPA must value this labor as more than just outreach and engagement. There should be a continued focus on rethinking forms of expertise that are utilized in creating open communities of practice that feed into and contribute tools and solutions for environmental monitoring and decision-making. Although it is attractive to fund new projects and collaborations, an equal (if not greater) emphasis should be placed on the sustainability and maintenance of projects and teams. The physicality of OScH presents unique opportunities to observe the types of labor—from technical development to community building to marketing and operations—and the places where this labor is prioritized or overlooked. Coupled with a clear connection to the broader open science ecosystem, OScH is an exciting case to implement and test new models for valuing and assessing labor involvement in ways that can lead to stronger collaboration and coordination.

Building Trust Between Communities and Governments

With the investments in recent legislation related to climate action and environmental justice, more resources than ever are supporting communities in monitoring their environments. These investments have the potential to rebuild trust between federal agencies and communities experiencing environmental injustice. This trust is at risk, however, if environmental agencies and other government actors cannot or do not use the data from these monitoring efforts to hold polluters accountable. Agencies can demonstrate their commitment to communities by prioritizing transparency, including: 1) explaining data, 2) communicating how data are used or not used, 3) providing justification when data are not used, for example if minimum standards are not met, and 4) by investing in OScH and other forms of openness. As described by Hall (2022) in Opening your science with community engagement, federal agencies "must engage with the community like any other collaborator: working 'with' the community, not 'in' or 'on'."

Interconnected Resources and Pathways to Shared Solutions: Connecting Needs with Opportunities

Open communities emphasize collaboration and connections; for example, project-based "search and find" efforts in the Gathering for Open Science Hardware forum regularly connect community members in need of skills or resources with those who have them, and the Research Data Alliance connects people around topics through "marketplaces" that span domain and information disciplines. These efforts are a good starting place, but a more mature marketplace could facilitate higher-impact connections between more people and organizations, which is what the field needs. This area for growth is a high-impact opportunity for investment. Such a space would require strong searchability, as well as ways to clearly label project needs or potential opportunities.

Towards More Relevant and Useful Systems: Building Partnerships Upfront

Efforts in environmental monitoring face the continued challenge of siloes: between sectors, disciplines, grass-roots communities and institutional spaces. As previously described, efforts towards standards, philanthropy for scale, and interconnected resources will partially ameliorate this challenge. Additionally, a targeted effort to build cross-sector partnerships in the early stages of project planning will lessen project duplication, clarify constraints, and elucidate potential challenges of incorporating tools into environmental monitoring systems. This is true for institutional and community partnerships, as well as for partnerships between government and tech developers, including those focused on OScH.

Making Progress Through Enthusiasm, Sharp Focus, and Collaboration

As noted by Johns & Hsing (2022) in Sustaining community cohesion and enthusiasm with a cadence of 'sparks' and social activities, many community-led advocacy campaigns for environmental justice are catalyzed by an urgent or high-profile issue, such as an oil spill, nuclear accident, or highly visible pollution. For example, the Fukushima nuclear disaster and the Deepwater Horizon oil spill "galvanized concerned citizens to develop and build open source hardware instrumentation for environmental monitoring (Johns & Hsing, 2022)." These responses can and often do evolve into broader and more impactful movements if they have access to sustained resources and can find ways to maintain and channel momentum toward sharply focused challenges. Building the relationships and cultivating the resources and knowledge necessary for sustaining progress takes time that is rarely offered by project-based funding. By tangibly valuing openness and creating opportunities for meaningful collaboration through OScH, agencies and funders can support communities in building the social infrastructure to help projects grow and sustain themselves. This can be especially important in the face of often inevitable major disruptions like pandemics or major political shifts, or when efforts fail.

Focusing on institutional change brings with it great promise when considered in tandem with the current investment in environmental monitoring and addressing climate change. By prioritizing open tools and approaches, we can help ensure that current investments in environmental monitoring provide long-term benefits to both the communities impacted and the broader environmental monitoring ecosystem. The importance of culture change goes well beyond the specific case of OScH; however, OScH is a tangible and high impact opportunity to demonstrate the promise of openness in addressing environmental issues truly collaboratively.

Creating space and investing in community, and building opportunities to learn and share together, are slow but important steps toward culture change. With these initial steps, the infrastructure of environmental monitoring will better match the promise of OScH projects, people, and communities.

Conclusion: Where We Go from Here, a Brief Roadmap

OScH, and transparency more broadly, can strengthen collaborations and trust between the public, government, researchers, and technologists by opening up designs and data to scrutiny, making it easier and less expensive to build on and modify tools for new purposes, demonstrating accountability and responsibility to the public, and encouraging collaboration in environmental monitoring and advocacy. One can imagine a world where public health agencies regularly mobilize open communities to develop tools for monitoring and treating diseases, climate planning offices utilize data from OScH to ensure adaptation technologies meet environmental justice needs, and technologies are developed in collaboration or consultation with governments and communities.

However, this trust and progress must also learn from and meet the evolving challenges in open science. Open questions perpetuate around building an effective and inclusive open science ecosystem, such as: How can we facilitate the broad adoption of open practices around thorough and understandable documentation and metadata? What infrastructure and processes are needed to ensure privacy and prevent harms from the misuses or breaches of environmental data collected by OScH in communities? What licensing or trademark norms should be established to maintain the openness of OScH designs?

In the concluding section, we identify points of recommendation around three goals: 1) directly supporting the development of OScH, 2) using OScH, and 3) incentivizing others' use of OScH. Within each we look at the incremental steps necessary to achieve these goals by providing steps we can do now, what needs to happen in the next few years, and "then" (starting in five years). Within each of these steps there is more work to be done in ensuring strategic progress, but we hope these leave the reader with an initial roadmap of future progress.

Supporting the Development of Open Science Hardware

Agencies and other institutions can support—through funding, efforts directed at collaboration, and techni-

cal incubation—the development of OScH tools, methods, and practices that produce high quality, reproducible data.

Strong communities already exist around OScH tools, and these tools are being used for specific and narrow purposes including environmental monitoring. However, this has happened in relative isolation. Moving forward, we can build a landscape of OScH tools, connected to other open products and processes, that will enhance and expand OScH for a range of environmental monitoring purposes.

Starting NOW:
We can create spaces and resources to solidify cross-sector partnerships during the early stages of project planning. This will serve to lessen project duplication, clarify constraints, and elucidate potential challenges and opportunities of incorporating tools into environmental monitoring systems.
We can include OScH in efforts to modernize data and software systems, and include open software, data, and hardware communities in that process.
... and then NEXT:
Models such as communities of practice can facilitate ongoing knowledge-sharing and collaborative problem-solving around tool development, evaluation, and standardization. Modeled after groups such as the Research Data Alliance, and others, these spaces can promote and ensure cross-sectoral integration of OScH in broader environmental monitoring discussions.
By investing in documentation of OScH to meet government quality standards as well as prioritizing open hardware and software in procurement and granting processes, these tools will become more widely accessible, enabling more people outside of government and technology companies to understand and improve on them.
Finally, THEN:
Environmental tool development, evaluation, and standardization will be more intimately connected, including models of shared learning and best practices. An appropriate emphasis on sustainability and maintenance of projects and teams allows for continued, sustained progress.

Using Open Science Hardware

With the enhancement of OScH tools for a spectrum of environmental monitoring purposes, we can build open source into policies for tool procurement.

A piecemeal approach to OScH and other open science tools fosters innovation, but lacks efficiency and limits replication. With a portfolio of tools ready for use, procurement policies can begin to match technological development.

Starting NOW:
We can assess models of open source software procurement to build a similar model for OScH while also recognizing the unique requirements. A suite of templates and best practices will support the uptake for open science policies, and procurement of OScH.
We can build capacity in government for the procurement of OScH. Open communities can engage with regulators and decision-makers to share information and best practices, agencies can develop internal expertise in OScH, and developers and intermediaries can assess and evaluate OScH for a range of purposes.
... and then NEXT:
We can institute institutional shifts that consider diverse applications of how environmental data is broadly usable beyond its original purpose. By procuring digital infrastructure, we can support agencies and organizations in employing stewards of social infrastructure—to curate OScH data, manage metadata, and integrate documentation and information from QA/QC processes.
Finally, THEN:
With this infrastructure in place, agencies can work alongside partners and communities to clearly establish mechanisms and methods to communicate how data are used or not used, adequately provide justification for when data are not used, and demonstrating where and how investment in OScH and other forms of openness is enhancing the ability of environmental monitoring to further environmental justice, climate solutions, and agency missions.

Incentivizing Others' Use of Open Science Hardware

With clear development, evaluation, standardization, and procurement practices in place, incentivize the use of OScH, alongside open software, data, and methods, when distributing resources, including when awarding grants.

To increase the landscape of use and the sustainability of the field of OScH, understanding the value and contributions that open practices and tools can make is of primary importance. With increased access to OScH for environmental monitoring, direct and clear communication alongside the incentivization of use for open practices, beyond initial requirements, can demonstrate value and compound benefits.

Starting NOW:
Through clear articulation of the opportunities and boundaries of "open," a shared vocabulary for what "open" means in the context of data privacy, intellectual property, and other concerns needs to be developed, as indicated by people connected to the data being collected.
Philanthropic organizations, including government funding agencies, can strategically support the maintenance of impactful OScH development, community and coalition building of innovators in environmental monitoring. This can work to further support more meaningful collaboration, reduce project duplication, and foster innovation for broad scale impact.
... and then NEXT:
As part of the work to create policies around OScH procurement, instituting openness as a default can ensure ease of access for agencies, contractors, and others to collaborate, and for members of the public to assess and build on their tools. This will make room for continued iteration and improvement.
By creating a mature marketplace of OScH and associated open tools, we can facilitate high impact connections between people and organizations.
Finally, THEN:
By valuing openness and creating opportunities for meaningful collaboration through OScH, government agencies and funders support communities in building the infrastructure to help projects grow and sustain themselves.
Strengthened connections between OScH contributors and users, a result of shared standardization practices, allow for communication of data needs, capacities, and contexts.

Strategically assessing, implementing, and resourcing OScH in the context of a broader open science agenda can lead to further research, innovation and development in environmental monitoring. Recommendations require us to tackle not only the technical challenges of OScH development uptake, but also the social and cultural—institutional and otherwise—contexts in which OScH must work. Pointed focus, a dedication to de-siloing spaces towards building cross-sectoral trust and collaboration, and a commitment to ensuring OScH is a part of open science in R&D practices, are clear starting points to committing to open practices and methods in addressing present and future environmental challenges.

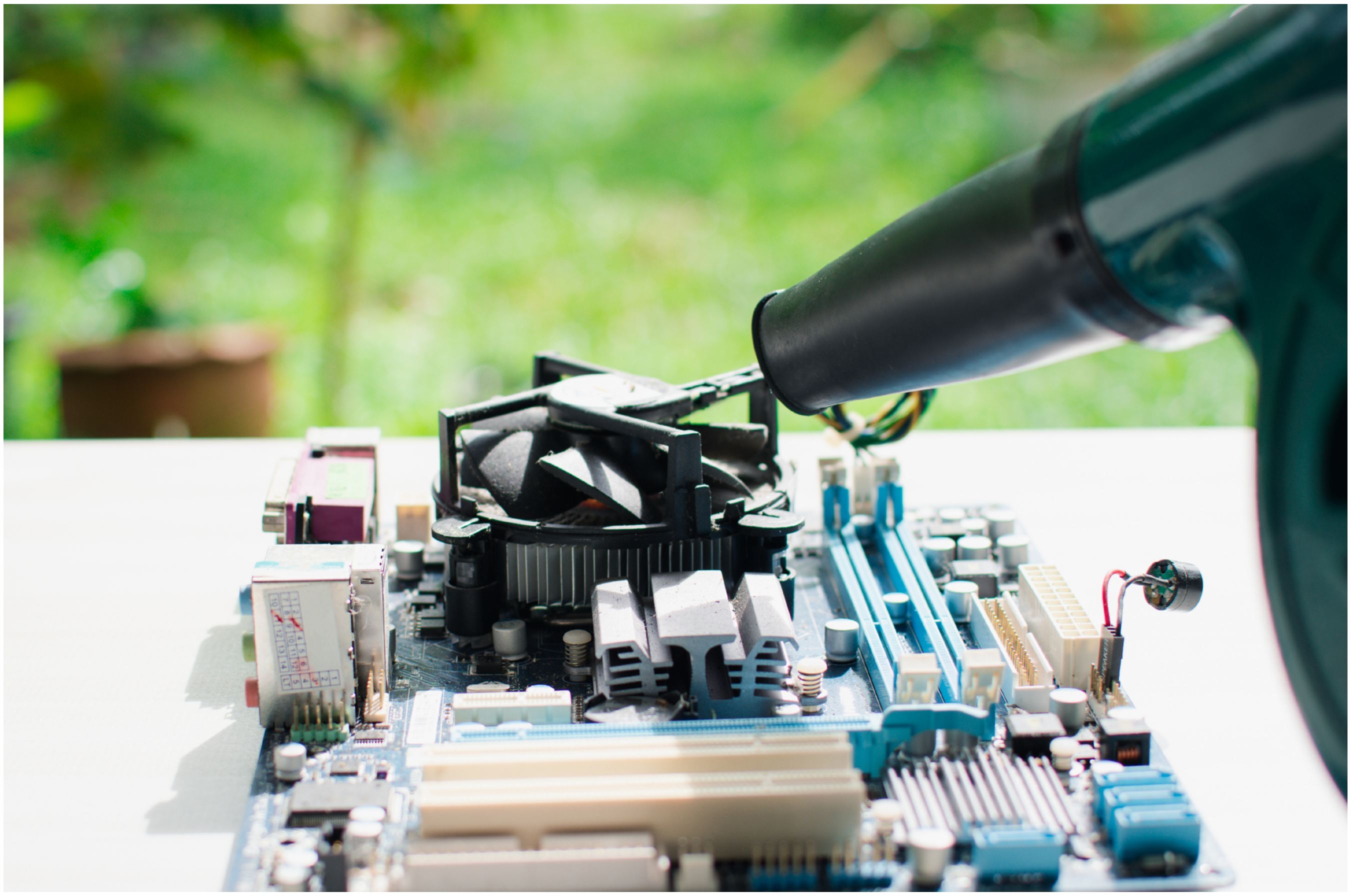


Image source: Mdisk / Shutterstock, all rights reserved.

References

Arancio, J. (2022). Valuing work "on the ground": making the hidden work visible in open hardware. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/valuing-work-on-the-ground-making-the-hidden-work-visible-in-open-hardware-b92f9ac16e45

Bowles, N. (2018, November 30). Do You Know What You're Breathing? *The New York Times*. https://www.nytimes.com/2018/11/30/style/air-quality-pollution-monitors.html

Breen, J., Dosemagen, S., Blair, D., & Barry, L. (2019). 8. Public laboratory: Play and civic engagement. *The Playful Citizen*, 162. https://www.jstor.org/stable/j.ctvcmxpds.12?refreqid=excelsior%3A29293beb45c674fa2349803a5fc78290&seq=1#metadata_info_tab_contents

Doraiswamy, P. (n.d.). *Can Citizen Science and Low-Cost Sensors Help Improve Earth System Data?* NASA Earth Data. https://www.earthdata.nasa.gov/esds/competitive-programs/csesp/improve-earth-system-data

Dosemagen, S. & Murillo, L.F. (2022). The need for open technology standards for environmental monitoring. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/the-need-for-open-technology-standards-for-environmental-monitoring-4427ff10922a

Dosemagen, S. & Parker, A. (2022). Beyond Access: Broadening the role of open science hardware in environmental monitoring innovations. *Journal of Open HW*. Retrieved April 11, 2023, from https://journalopenhw.medium.com/beyond-access-broadening-the-role-of-open-science-hardware-in-environmental-monitoring-innovations-ec1190d57a1e

Dosemagen, S., Parker, A., Hoeberling, K., & Schuett, A. (2022). Open Science Hardware for Environmental Monitoring. *Journal of Open HW*. Retrieved April 11, 2023, from https://journalopenhw.medium.com/open-science-hardware-for-environmental-monitoring-371702772a0

Ensign, S.H. (2022). Open Data and Open Hardware: Tools for Collaborative Solutions to Water Challenges. *Journal of Open HW*. Retrieved April 11, 2022 from https://journalopenhw.medium.com/open-data-and-open-hardware-tools-for-collaborative-solutions-to-water-challenges-18a09ec905d3

FracTracker Alliance. (2022, November 4). *FrackTracker Receives Two Federal Grants to Support Community Air Monitoring Initiatives in the Ohio River Valley*. https://www.fractracker.org/2022/11/fractracker-receives-two-federal-grants-to-support-community-air-monitoring-initiatives-in-the-ohio-river-valley/

Gathering for Open Science Hardware. (n.d.). *The GOSH Roadmap: Concrete actions to make Open Science Hardware ubiquitous* by 2025. GOSH: Gathering for Open Science Hardware. https://openhardware.science/global-open-science-hardware-roadmap/

General Services Adiministration (GSA). (2020). De-risking Government Technology: Federal Agency Field Guide. https://derisking-guide.18f.gov/assets/federal-field-guide-4dccc06e01cd56773eb140ff6e6b2805cc517a460d6bff6689e7edd0ef349598.pdf

Hagler, G. S., Williams, R., Papapostolou, V., & Polidori, A. (2018). Air quality sensors and data adjustment algorithms: When is it no longer a measurement?. *Environmental Science & Technology, 52*(10), 5530-5531. https://pubs.acs.org/doi/10.1021/acs.est.8b01826#

Hall, C.A. (2022). Opening Your Science with Community Engagement. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/opening-your-science-with-community-engagement-893256d7e5c9

Heikkinen, I. T. S., Savin, H., Partanen, J., Seppälä, J., & Pearce, J. M. (2020). Towards national policy for open source hardware research: The case of Finland. *Technological Forecasting and Social Change, 155*, 119986. https://www.sciencedirect.com/science/article/abs/pii/S0040162518313878?via%3Dihub

Hill, Andrew. (2021). Open hardware provides a better chance for scientific reproducibility. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/open-hardware-provides-a-better-chance-for-scientific-reproducibility-829ed23bb71d

Inflation Reduction Act of 2022, H.R.5376, USC § 117 (2022). https://www.congress.gov/bill/117th-congress/house-bill/5376/text

Jaffe, D. A., Thompson, K., Finley, B., Nelson, M., Ouimette, J., & Andrews, E. (2023). An evaluation of the US EPA's correction equation for PurpleAir sensor data in smoke, dust, and wintertime urban pollution events. *Atmospheric Measurement Techniques, 16*(5), 1311-1322. https://amt.copernicus.org/articles/16/1311/2023/

Johns, B. & Hsing, P.Y. (2022). Sustaining community cohesion and enthusiasm with a cadence of "sparks" and social activities. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/sustaining-community-cohesion-and-enthusiasm-with-a-cadence-of-sparks-and-social-activities-a9909a1e6b35

Misdary, R. (2023, February 16). A real-time flood tracker is expanding to help New Yorkers during major storms. *Gothamist*. https://gothamist.com/news/floodnet-real-time-flood-tracker-expanding-help-nyc-new-yorkers-during-major-storms

Murillo, Luis Felipe R. (2021). Open Hardware as critical infrastructure? *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/open-hardware-as-critical-infrastructure-a0ce320dfebe

National Advisory Council for Environmental Policy and Technology (NACEPT). (2016). Environmental Protection Belongs to the Public: A Vision for Citizen Science *US EPA*. https://www.epa.gov/sites/default/files/2020-04/documents/nacept_cs_report_final_508.pdf

Office of Science Technology and Policy (OSTP). (2023, January 11). *FACT SHEET: Biden-Harris Administration Announces New Actions to Advance Open and Equitable Research*. WH.gov. https://www.whitehouse.gov/ostp/news-updates/2023/01/11/fact-sheet-biden-harris-administration-announces-new-actions-to-advance-open-and-equitable-research/

Open Source Hardware Association (OSHWA). (n.d.). Definition (English). *Open Source Hardware Association*. https://www.oshwa.org/definition/

Ottinger, G. & Dosemagen, S. (2020, November 17). Ensuring the Bucket;s Continued Place in the Frontline Community Toolbox. *Toxic News*. https://toxicnews.org/2020/11/17/ensuring-the-buckets-continued-place-in-the-frontline-community-toolbox/

Parker, A., Dosemagen, S., Molloy, J. Bowser, A., & Novak, A. (2021). Open Hardware: An Opportunity to Build Better Science. *The Wilson Center*. Retrieved April 11, 2023 from https://www.wilsoncenter.org/sites/default/files/media/uploads/documents/STIP%20Open%20Hardware%20An%20Opportunity%20to%20Build%20Better%20Science_0.pdf

Pearce, J.M. (2020). Open hardware is economically efficient and generates a massive return on public investment. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/open-hardware-is-economically-efficient-and-generates-a-massive-return-on-public-investment-34c1b8e73913

Platt, Charles. (2019, February 7). Build A Water Quality Tester You Can Hear. *Make*. https://makezine.com/projects/build-a-water-quality-tester-you-can-hear/

Raheja, G., Harper, L., Hoffman, A., Gorby, Y., Freese, L., O'Leary, B., ... & Westervelt, D. M. (2022). Community-based participatory research for low-cost air pollution monitoring in the wake of unconventional oil and gas development in the Ohio River Valley: Empowering impacted residents through community science. *Environmental Research Letters, 17*(6), 065006. https://iopscience.iop.org/article/10.1088/1748-9326/ac6ad6/meta

Schuett, A., Maestre, J.P., & Hoeberling, K. (2022). Circumventing silos in open hardware to create opportunities for interconnection, shared agendas, and collective resources. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/circumventing-silos-in-open-hardware-to-create-opportunities-for-interconnection-shared-agendas-74fda3b058a

United Nations Human Rights: Office of the High Comissioner. (2020). *Participation (P)*. https://www2.ohchr.org/english/OHCHRreport2020/documents/Participation-P.pdf

US EPA. (1995). *Appendix A Standard Operating Procedures*. https://www.epa.gov/sites/default/files/2015-05/documents/appendix_a_-_standard_operating_procedures_0.pdf

US EPA. (2020, June 22). Air Sensors. Anne L. Idsal. https://www.epa.gov/sites/default/files/2020-07/documents/air_sensors_memo_june_22.2020.pdf

US EPA. (n.d.-a). *2021 American Rescue Plan & EJ Collaborative Problem-Solving Award Project Summaries*. https://www.epa.gov/system/files/documents/2021-12/2021-selected-ejcps-project-descriptions.pdf

US EPA. (n.d.-b). *AQ-SPEC: Air Quality Sensor Performance Evaluation Center*. http://www.aqmd.gov/docs/default-source/aq-spec/summary/purpleair-pa-ii---summary-report.pdf?sfvrsn=16

Vastine, J. (2022). A holistic approach: Intentional planning to set community data collection programs up for success. *Journal of Open HW*. Retrieved April 11, 2023 from https://journalopenhw.medium.com/a-holistic-approach-intentional-planning-to-set-community-data-collection-programs-up-for-success-91bc64b22d83

Wylie, S. A., Jalbert, K., Dosemagen, S., & Ratto, M. (2014). Institutions for civic technoscience: How critical making is transforming environmental research. *The Information Society, 30*(2), 116-126. https://doi.org/10.1080/01972243.2014.875783

WOODROW WILSON INTERNATIONAL CENTER FOR SCHOLARS

The Woodrow Wilson International Center for Scholars, established by Congress in 1968 and headquartered in Washington, D.C., is a living national memorial to President Wilson. The Center's mission is to commemorate the ideals and concerns of Woodrow Wilson by providing a link between the worlds of ideas and policy, while fostering research, study, discussion, and collaboration among a broad spectrum of individuals concerned with policy and scholarship in national and international affairs. Supported by public and private funds, the Center is a nonpartisan institution engaged in the study of national and world affairs. It establishes and maintains a neutral forum for free, open, and informed dialogue. Conclusions or opinions expressed in Center publications and programs are those of the authors and speakers and do not necessarily reflect the views of the Center staff, fellows, trustees, advisory groups, or any individuals or organizations that provide financial support to the Center.

Wilson Center | Science and Technology Innovation Program | OPEN ENVIRONMENTAL DATA PROJECT

The Wilson Center

- www.wilsoncenter.org
- wwics@wilsoncenter.org
- facebook.com/woodrowwilsoncenter
- @thewilsoncenter
- 202.691.4000

STIP

- www.wilsoncenter.org/program/science-and-technology-innovation-program
- stip@wilsoncenter.org
- @WilsonSTIP
- 202.691.4321

Open Environmental Data Project

- www.openenvironmentaldata.org
- info@openenvironmentaldata.org
- @OpenEnviroData
- linkedin.com/company/open-environmental-data-project/
- @OpenEnviroData

Woodrow Wilson International Center for Scholars
One Woodrow Wilson Plaza
1300 Pennsylvania Avenue NW
Washington, DC 20004-3027