



Performance Testing of Low-Cost Sensor Technology for Laboratories

Cooperative Research and Development Final Report

CRADA Number: CRD-20-17428

NREL Technical Contact: Amanda Kirkeby

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-88388
December 2023



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NOTICE

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Cooperative Research and Development Final Report

Report Date: September 29, 2023

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Xmark Labs, LLC

CRADA Number: CRD-20-17428

CRADA Title: Performance Testing of Low-Cost Sensor Technology for Laboratories

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s): U.S. Department of Energy Federal Energy Management Program (FEMP)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	\$24,768.00
Modification #1, #2	\$0.00
TOTALS	\$24,768.00

Executive Summary of CRADA Work:

This work will gather real-world data on the performance and potential industry impact on laboratory ventilation control of a new low-cost, open-source sensor that reports important metrics of the laboratory environment. A small network of sensors will be installed at an NREL laboratory facility.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope, and/or
- Uses the laboratory’s core competencies

Summary of Research Results:

Purpose:

Implementing sensors in research laboratories can inform dynamic controls to optimize safety of researchers, enhance quality of research, energy efficiency, reduce waste, and improve facility resilience. Existing in-lab sensors focus on safety and offer precision and critical reliability, but at a high cost.

The objective of this work is to test the performance of a new low-cost laboratory environmental sensor technology and related software under real-world conditions and the potential industry impact of such technologies on laboratory ventilation control. The sensors report important metrics of the laboratory environment, and the results, data, and methods of this work will accelerate research and development to improve collection of environmental data and enhance dynamic ventilation control strategies for high-performance laboratories.

Statement of Work: Task Descriptions, Deliverables, and Estimated Completion Dates

Task 1 – Provide Equipment for Sensor Deployment

Description

Xmark Labs, LLC shall provide all equipment necessary for a successful installation of a small network of sensors to NREL via mail, including hardware and software. Xmark Labs, LLC shall be responsible for providing NREL with virtual/remote guidance for the installation and testing of the sensors and collection of data. Xmark Labs, LLC shall be responsible for following the guidelines established by NREL regarding cybersecurity to safeguard NREL operations. No external or remote access to the NREL server or network shall be established.

All equipment shall be thoroughly tested by Xmark Labs, LLC prior to shipment to ensure they are functioning as expected and adhere to cybersecurity and safety standards set forth by NREL. Additional testing may be performed by NREL to ensure cybersecurity and safety standards are met. Should additional safety, cybersecurity, or other measures not be met, Xmark Labs, LLC shall revise the sensor equipment following recommendations by NREL.

Result

All equipment necessary for a successful installation of a small test network of sensors was provided to NREL via mail by Xmark Labs, LLC. Figure 1 exhibits an image of all equipment received to install a sensor network, which included:

- 10 sensor nodes
- 1 gateway node
- 1 gateway touchscreen module and power supply
- 1 Chromebook and power supply, used to visualize data.
- All necessary cords and cables.



**Figure 1. Sensor network test equipment as received by NREL from Xmark Labs, LLC.
(Photo Credit: Amanda Kirkeby, NREL)**

Equipment was accompanied by a detailed guide describing the installation and setup of the sensor network in accordance with NREL cybersecurity standards, requiring no external or remote access to the NREL server or network.

Task 2 – Installation of Sensor Network in a NREL research space.

Description

NREL shall install a small (10-20 sensor nodes) network of sensors in a NREL research space with equipment provided by Xmark Labs in Task 1. The research space shall have sufficient activity to gather real-world, useful data on environmental quality metrics including temperature, barometric pressure, humidity, an estimated TVOC level, relative light level, and simple PIR occupancy data. The installation shall not disrupt or inhibit current research operations or endanger the safety and security of NREL employees or operations.

The small network (10-20 sensors) will be self-contained in a single lab space (for example, the System Performance Lab in ESIF) and be isolated from the NREL network, with each sensor reporting to a gateway. Each sensor is approximately 4"x4", battery powered, with wall mounts. There shall be no direct connection between any sensor node and the NREL network, nor shall there be any direct connection between the gateway and the NREL network.

Result

Following the installation and setup guide provided by Xmark Labs, LLC, NREL installed the network of sensors in the Systems Performance Laboratory in the Energy Systems Integration Facility (ESIF) on the NREL South Table Mountain Campus. This research space selected was agreed upon for this pilot by both Xmark Labs, LLC and NREL; the space adequately exhibited sufficient activity such that real-world data within the lab environment could be collected without inhibiting on other research activities within the space. All necessary permissions by ESIF research management and environmental health and safety staff were acquired, and all NREL safety procedures were followed during the installation process.

Prior to installation, the sensor nodes were fully charged, and the gateway node was connected to the touchscreen module, as directed in the installation instructions provided by Xmark Labs, LLC. The sensor nodes were then mounted to the wall using double-sided tape at 15' intervals, as shown in Figure 2.



Figure 2. Installation of the sensor nodes in the ESIF's Systems Performance Laboratory on the NREL STM Campus. (Photo Credit: Otto Van Geet, NREL)

Task 3 – Data Collection of Laboratory Metrics

Description

NREL shall supervise data collection over a one-month period, in a plan as agreed upon with the Xmark Labs, LLC and NREL facilities and research staff. Data will be collected and stored on a gateway and NREL shall manually transfer sensor data from the isolated sensor network to the Partner for analysis via a USB key, email, or an online database as needed.

Xmark Labs, LLC shall provide NREL with a summary of results and an analysis of laboratory metric data collected by sensor network. The results shall be discussed in a phone call with NREL. If further data collection is required to obtain useful results, the data collection period may be extended.

A component of the data collection could include performing a tracer gas test with isopropyl alcohol to measure/verify sensor effectiveness in reporting real-time TVOC concentration. This shall be dependent on the preliminary results and further action shall be agreed upon by both Xmark Labs, LLC and NREL. Xmark Labs, LLC will provide specific guidance for performing this test.

Result

NREL supervised the data collection of the sensor network over a one-month period, as agreed upon with Xmark Labs, LLC. During the one-month period, the environmental metric data, including temperature, barometric pressure, humidity, an estimated TVOC level, relative light level, and simple PIR occupancy, were collected by the sensor nodes and transmitted to the gateway provided by Xmark Labs, LLC for storage. Figure 3 displays the data collected from the sensor network. The sensor network operated in complete isolation from the NREL network in adherence to NREL cybersecurity guidance.

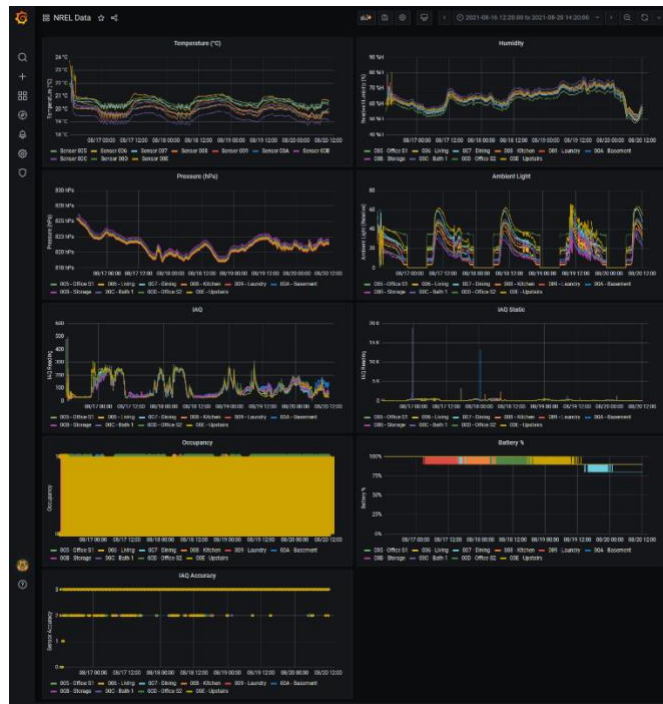


Figure 3. An example of data collected by the sensor network during the test pilot. (Image Credit: Graphana Labs)

On two-week intervals, the sensor nodes were removed from their installed location on the walls and recharged using the charging cables provided, as directed by Xmark Labs, LLC. The data stored on the gateway was downloaded to a USB drive and shared via email with Xmark Labs, LLC for analysis. Figure 5 displays an example of the analysis performed by Xmark Labs, LLC.

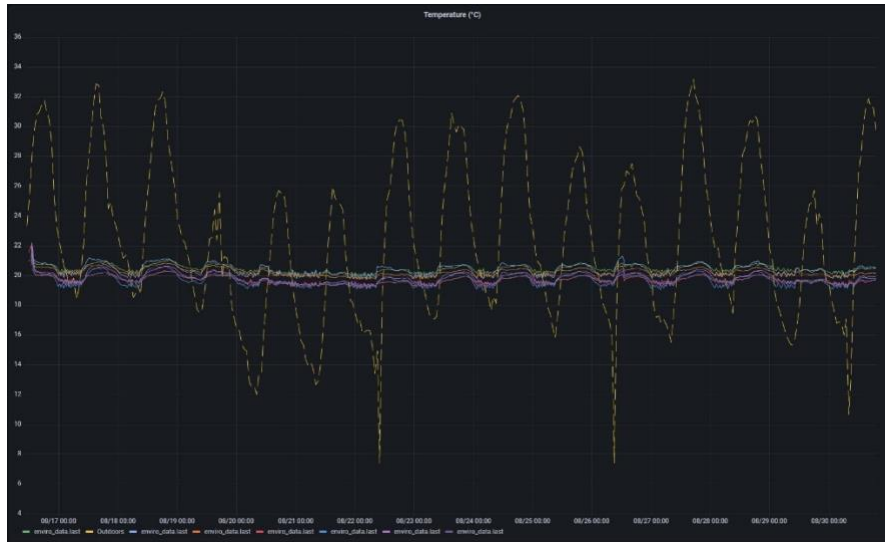


Figure 4. Example of an analysis performed by Xmark Labs, LLC. This specific analysis compares temperature data collected within the lab and the outdoor environmental temperature weather data over a two-week period. (Image Credit: Nicholas Napp, Xmark Labs, LLC.)

At the end of the initial test period, Xmark Labs, LLC and NREL reviewed the preliminary results and determined the tracer gas test component of data collection described in the Task 3 description would not be performed. This decision was made in agreement by both parties.

Task 4 – Document Results in a Technical Report

Description

Best practices and findings of the sensor deployment performance under real-world conditions shall be summarized in a technical report. NREL and Xmark Labs, LLC shall be coauthors of the report and the final report shall be made publicly available in the NREL publication database.

Results

The results from the sensor test pilot were documented and summarized in a technical report coauthored by NREL and Xmark Labs, LLC. The report was submitted as a conference paper to the Association of Energy Engineers (AEE) World 2021 Conference. The conference paper was selected for publishing in the *AEE Journal for Energy Management*, and in agreement with the journal publication policies, Xmark Labs, LLC, and NREL, the final article was made publicly available on the NREL Publications database. For more information, the full article is included as Appendix herewith and is located here: <https://www.nrel.gov/docs/fy22osti/81894.pdf>.¹

Task 5 – CRADA Final Report: Preparation and submission in accordance with Article X.

Result

This report serves to satisfy the requirement for the CRADA Final Report in accordance with Article X.

Modifications 1 and 2 to the original agreement were No Cost Time Extensions (NCTE) which added neither funding nor scope.

Subject Inventions Listing: None

ROI #: None

References:

(1) Kirkeby, A.; Romero, R.; Van Geet, O.; Napp, N. Optimizing Ventilation Using Low-Cost Sensors to Improve Health, Safety, and Energy Efficiency. *International Journal of Energy Management*. 2021, Vol. 3 - No. 6, 34–50. (See Appendix A below.)

Appendix A

International Journal of Energy Management

Steven Parker, PE, CEM, Editor-in-Chief

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Contents

- 5 *Editor's Desk*—Can the People of This World Manage Carbon? Can We Mitigate Climate Change?
- 10 Sir David Attenborough's Address to World Leaders at the United Nations Climate Change Conference (COP26), Glasgow, Scotland, United Kingdom, November 2, 2021
- 15 COP26: Zero Emissions Require a "New Green Revolution"—*Javier Cervera*
- 21 Recognizing the duty of the Federal Government to create a Green New Deal (House Resolution 332, 117th Congress)—*Ms. Alexandria Ocasio-Cortez*
- 34 Optimizing Ventilation Using Low-Cost Sensors To Improve Health, Safety, And Energy Efficiency—*Amanda R. Kirkeby, Rachel L. Romero, Otto Van Geet and Nicholas Napp*
- 51 Using Analytics to Improve Operational Results and Energy Efficiency—A Day in The Life of a Facility Manager—*John Petz*
- 65 Advancing Building Electrification Projects at an EPIC Scale—*Tracy Phillips*
- 73 Software Application to Accelerate Building Audits and Efficiency Targets—*Herbert Dwyer*
- 79 Call for Papers

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Optimizing Ventilation Using Low-Cost Sensors to Improve Health, Safety, and Energy Efficiency

Amanda R. Kirkeby, Rachel L. Romero, PE, Otto Van Geet, PE, LEED AP, and Nicholas Napp

ABSTRACT

Air is the primary carrier of hazards within a space, whether it be hazardous byproducts of laboratory research activities or airborne pathogens. As a result, building ventilation is a primary defense against unseen airborne hazards. Critical laboratory facilities require effective mitigation of exposure to research-related, airborne hazards, providing a proving ground for effective ventilation strategies that optimize safety of occupants and reduce energy use. The heart of smart laboratory building operation is dynamic, analytics-based ventilation, which requires an in-depth intimate knowledge of building environmental conditions achieved through contaminant-detection systems. Unfortunately, currently many contaminant-detection solutions are expensive, elaborate systems that raise barriers for building managers. Through the successful deployment of a novel low-cost, modular sensor technology, we have developed a demand-control ventilation protocol effective in improving safety and reducing energy in critical laboratory environments. In this article, we will highlight best practices and lessons learned through this deployment that can be applied beyond laboratories. This article describes a low-cost sensor to support providing a safe, healthy building environment and reduce energy use through effective and efficient ventilation.

BACKGROUND

The average adult breathes more than 3,000 gallons of air every day [1]. Necessary to human existence, air is the primary carrier for essential oxygen. Unfortunately, air is also the primary carrier of airborne hazards, from allergens to pathogens to life-threatening toxins. For the indoor environment, building ventilation is essential to not only providing healthy indoor air quality, it is also the first line of defense against airborne hazards.

Considering the COVID-19 pandemic, building ventilation has fallen under heavy scrutiny in regard to its ability to mitigate occupant exposure to airborne pathogens. Increased ventilation rates, open windows to allow natural ventilation, and enhanced filtration: many of these strategies adopted during the pandemic have increased energy consumption of heating, ventilating, and air conditioning (HVAC) systems across the globe. In a case study of China, energy consumption increased by 128% [2].

With ventilation systems, “more is better,” is often touted across the building industry (i.e., increased ventilation rates yield increased safety, worker comfort, and research productivity). The discussion here centers on how optimizing, rather than maximizing, ventilation using dynamic, demand-based controls can both improve indoor air quality and reduce energy use.

LABORATORIES AS A PROVING GROUND

While HVAC systems in the general building stock may be under enhanced scrutiny with “unprecedented” tacked-on as a label for the ventilation challenges faced during the COVID-19 pandemic, these challenges are not new. For decades, critical laboratory facilities have demanded effective mitigation of exposure to research-related airborne hazards. Laboratories provide a proving ground for effective ventilation strategies that both optimize occupant safety and reduce energy.

Occupant safety is the main driver of laboratory ventilation system design and operation. The system’s primary function is to effectively control airborne hazards to mitigate risk to people, property, and the environment. Challenged by complex HVAC controls, laboratory facility managers often take the stance that increased ventilation yields increased safety, comfort, and research productivity. As shown in Figure 1, ventilation is the largest consumer of energy in a laboratory building, accounting for 40% to as much as 85% of total energy use [3].

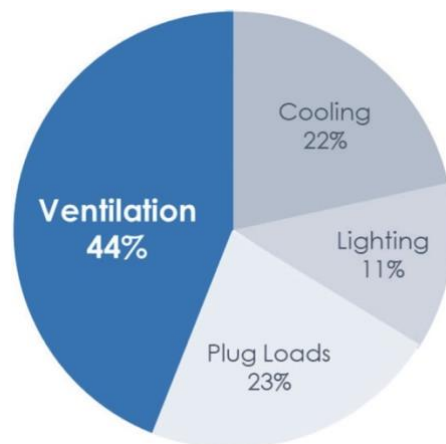


Figure 1. Annual electricity use in Louis Stokes Laboratory, National Institute of Health, Bethesda, MD. (Source: Labs for the 21st Century Best Practice Guide [4])

As a result, a typical laboratory consumes 3 to 4 times more energy than a typical commercial office building [5]. Laboratory scientific discovery is crucial to the advancement of the society, categorizing laboratories as mission-critical facilities that are often overlooked for opportunities for energy efficiency. However, beyond energy-intensive operation, increased ventilation rates can have the opposite effect on occupant safety than intended. High ventilation rates can create turbulence, remixing contaminants back into the space and risking exposure to occupants. Higher ventilation rates can also lead to a positive pressure lab, releasing contaminants into surrounding areas. Rather than more air, a smarter approach to ventilation control is required to provide a safe work environment without compromising energy efficiency.

The Smart Labs Approach

The Smart Labs approach establishes a smart labs program to enable ongoing safe and efficient world-class science to occur in laboratories. As the largest driver of energy use and occupant safety in a laboratory, ventilation is also the largest opportunity for improving both. A Smart Lab program designs and operates labs based on containing ventilation risk as determined by a ventilation risk assessment. This is completed through various methods, but especially includes:

- Containing hazards within exposure control devices such as fume hoods and providing ventilation to the lab from a HVAC system with high ventilation effectiveness like that in Figure 2.

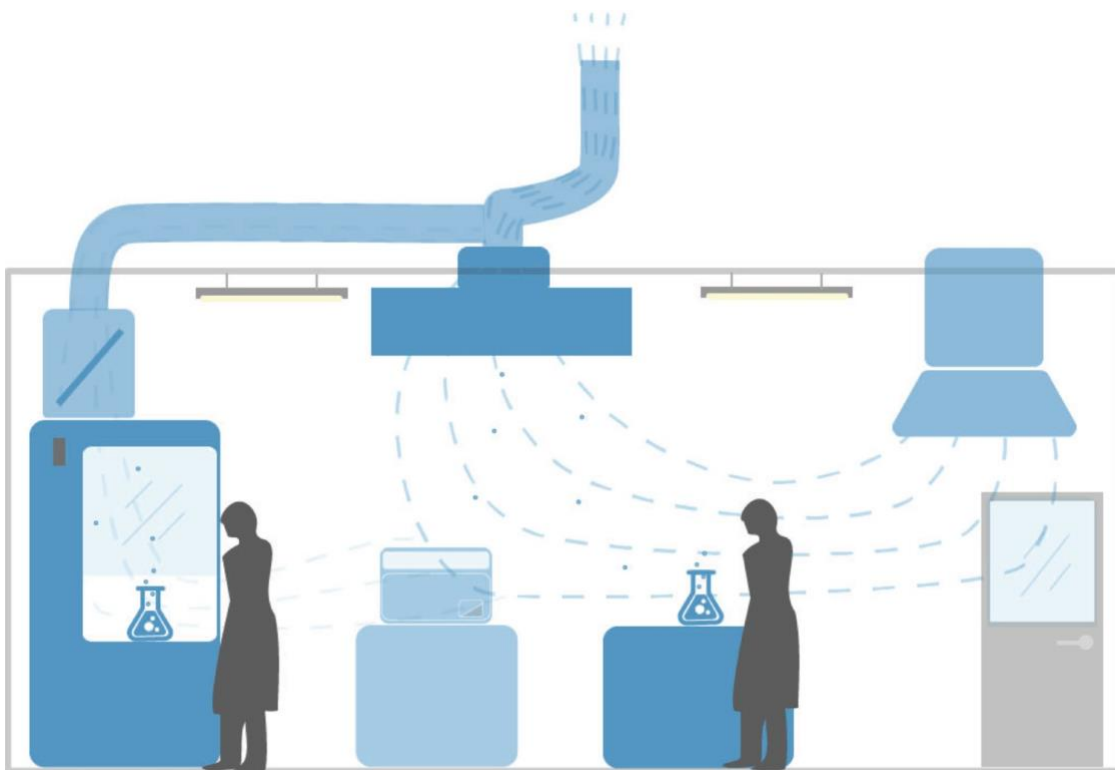


Figure 2. Smart Labs strategies for optimizing safety and energy efficiency through optimizing air flow in the lab space. Air flow sweeps across the lab space, carrying contaminants away from occupants. (Image Credit: Amanda Kirkeby, NREL)

- Using controls, software, and sensors to make building systems dynamic and smart with precision demand-based HVAC control zone-by-zone with data stream with commissioning [3].

The heart of smart laboratory building operation is dynamic, analytics-based ventilation, which requires an intimate knowledge of building environmental conditions achieved through contaminant-detection systems. Demand-control ventilation systems provide the dynamic controls needed to maintain safe environmental conditions within dynamic laboratory environments. Typically, these systems can identify malfunctioning fume hoods or poor lab practices that could otherwise go undetected and can provide a record of laboratory air cleanliness for reporting purposes. Beyond ensuring safety for occupants, demand controls improve energy efficiency by preventing

unnecessary excess ventilation when no contaminants are present. Stakeholders must weigh the benefits and costs of such a system to determine if the superior performance and energy efficiency of the lab is worth the increased complexity and cost.

Barriers to Adoption

A central component of Smart Labs, the control of ventilation to the demands of a space at any given time not only reduces energy use but enhances safety of the researchers working in the space. To allow for demand-controlled ventilation, sensor networks are implemented to detect contaminants in the space and whether an occupant is present, to inform the ventilation controls of current environmental status of the space. Ventilation rates can then be adjusted as necessary to adequately mitigate exposure to hazards present in the space. Sharp documented that, on average, laboratory rooms have clean air 98% of the time [6].

The use of building-wide environmental sensors can help reduce energy use by up to 50%, while also making buildings healthier by providing insight into building air flow patterns. Unfortunately, the only well-known contaminant-detection solutions used in laboratories are expensive, elaborate systems. These detection systems consist of multiple high-accuracy contaminant-sensing instruments in a central location connected to each lab space with air sampling tubing that draws air from the lab space. The system has relatively high first cost for equipment and installation, and high operational cost for the periodic switching of calibrated sensing instruments. System implementation costs can be as high as \$7.00 per square foot, and installation can be highly disruptive. As a result, cost introduces a barrier to implementation for building owners wishing to deploy such a system. Furthermore, the system detects contaminants but does not detect occupancy. Even if occupancy data is gathered from other sources, this data is not integrated with the detection system.

The high cost and complexity raise a barrier to entry for laboratory owners interested in employing Smart Labs practices for demand-controlled ventilation, but who are operating with a limited budget to deploy such systems. The cost barrier is especially significant for small labs because the detection system cost for hardware and operations are fixed independent of lab size, but the potential savings are limited for a small lab. The need for a low-cost sensor technology that is easy to install and integrate into existing laboratory ventilation control systems could provide laboratories with the opportunity to employ demand-controlled ventilation protocols (contaminant-sensing and/or occupancy-based), especially for those with limited budgets.

A LOW-COST SOLUTION

To achieve both improved energy performance and healthier indoor environments, building facility managers require data to inform ventilation controls. Providing a means to collect this data in a way that is affordable, easy to understand, and easy to maintain without specialized staff or skills is the challenge.

One approach is to deploy many low-cost sensor units throughout the building, rather than hosting elaborate, complex air-sampling equipment in a central location. Few sensors exist and often do not

capture all environmental metrics necessary to provide detailed information on air flow within a space. A prototype system developed by XMark Labs, LLC. relies on individual environmental sensors that relay data via a mesh network. The total cost of ownership may be up to 90% lower than other available devices. Lower upfront cost can enable monitoring of entire buildings by deploying more sensors, not just in critical areas. The building-wide sensor data allows for a whole-building approach to optimizing indoor air quality and energy use in commercial buildings.

The entire system is self-configuring, with each sensor node communicating via a mesh network to relay data to a central gateway. A photograph of the sensor prototype is included in Figure 3.



Figure 3. A photograph of the prototype sensor units and touchscreen gateway prior to installation. Each sensor has dimensions of 4"x4"x2". (Image Credit: Amanda Kirkeby, NREL)

Each sensor is a stand-alone, battery-powered unit that collects mappable environmental metrics, including:

- Simple occupancy
- tVOC concentrations
- Temperature
- Light
- Pressure
- Humidity.

PILOT DEPLOYMENT

A pilot deployment of the low-cost sensor prototype was launched in a real-world laboratory space to investigate applications in demand- control ventilation protocol. The installation included a total of 10 prototype sensors in 2,067 ft² lab space with a room volume of 70,278 ft³. The lab space hosts electronics and appliance-based research, posing minimal airborne hazards for this initial pilot deployment.

For the purpose of this pilot, the sensor network was completely isolated from the network and building control system within the lab. After initial charging of each sensor, the sensors were installed using double- sided tape approximately 20 feet apart at a height of 6 feet on vertical wall faces. The layout of sensors is illustrated in Figure 4. As each sensor was installed, the sensor was powered on, initiating an automatic configuration process—no manual configuration of the network was required.

The length of the period of study was a total of 1 month. Periodic system checks were performed every 2 weeks to download data collected by the sensor network and charge the sensors as needed. With the prototype units used in this pilot, each unit required charging every 2 weeks.

Data Collection

Each sensor unit collected environmental metrics at an interval of 5 minutes. Combined with a greater density of sensor units within the space, increased frequency of sampling provided highly granular data that revealed trends in environmental conditions. Temperature and ambient light trends, as shown in Figure 5, exhibit expected behavior, rising during daylight hours and falling at night during unoccupied periods. Especially regarding ambient light levels, trends reinforce expected behavior that light levels are higher in the morning because of east-facing windows.

Indoor air quality data collected over the course of the pilot is of more interest. Indoor air quality values are measured using the output resistance in ohms in the sensor unit. These values are then indexed on a scale from 0 to 500. Similar to the U.S. Environmental Protection Agency (EPA) Air Quality Index used for outside air, a unique index classification is employed by the sensors based on indoor air quality. The index scale is included in Figure 6 for reference.

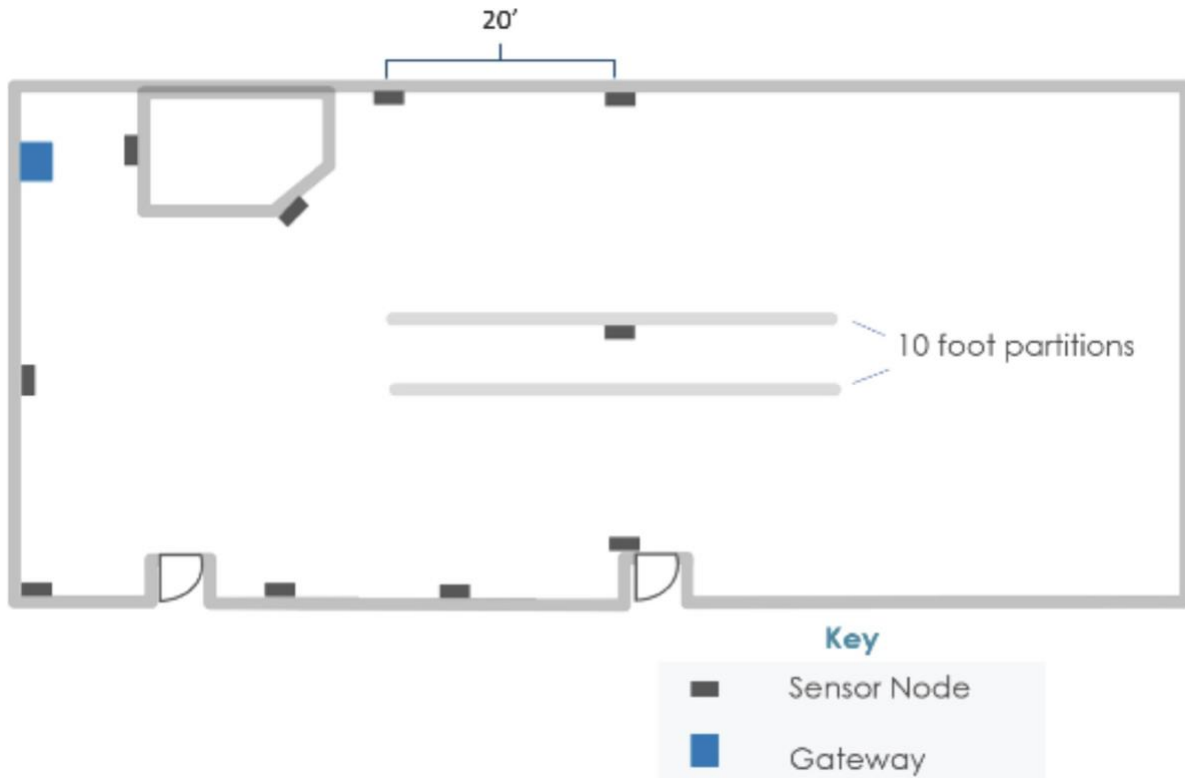


Figure 4. Schematic layout of sensor network. Two partitions in the lab space are illustrated, as well as major doorways and an enclosed office space. (Image Credit: Amanda Kirkeby, NREL)

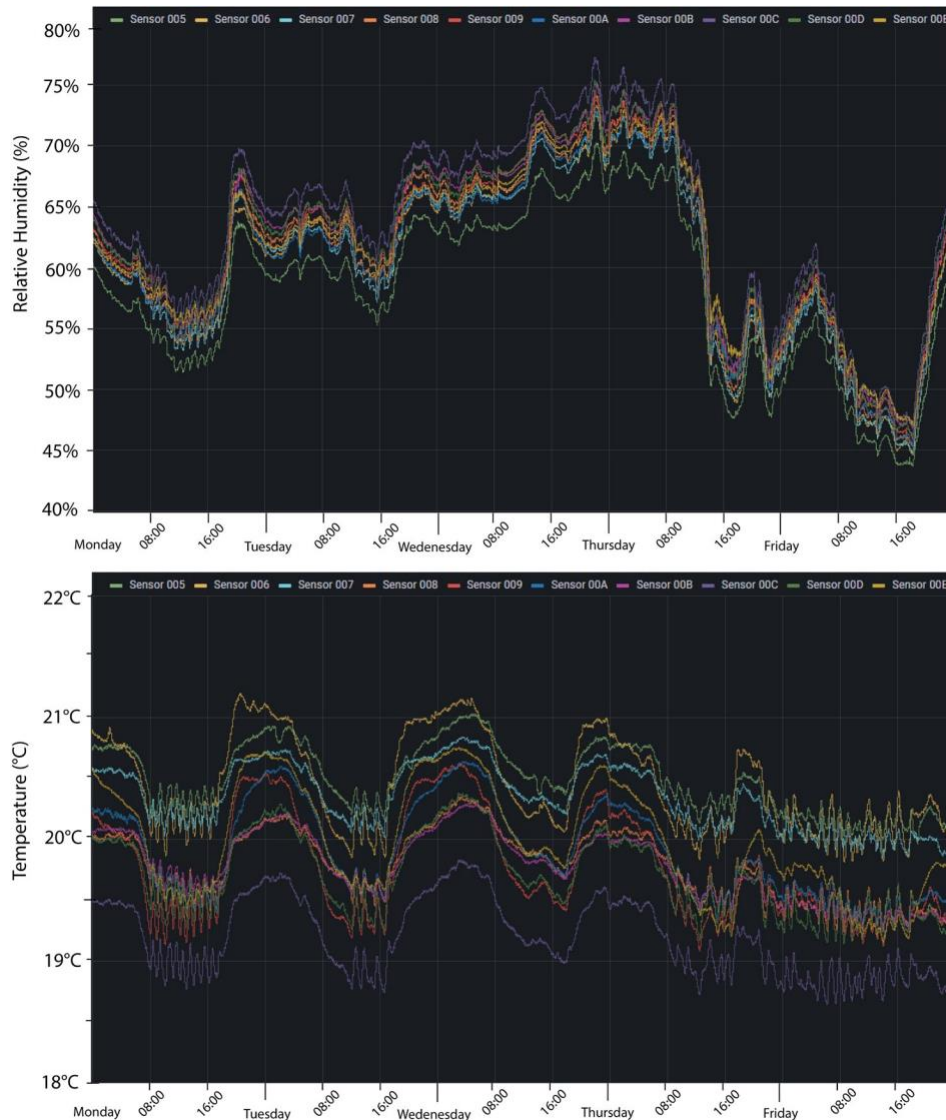


Figure 5. Environmental metric data collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments. (Image Credit: Grafana Labs)

In Figure 6, indoor air quality index of over 250—severely polluted—are documented periodically in the space. The short interval of these documented occurrences illustrates the importance of higher frequency sampling; these events may go unnoticed if sampling occurred every hour. While indoor air quality readings do not exceed a level of 250 for long periods of time, it is worth investigating which activity is causing these events and determine if further action to mitigate exposure is required. Furthermore, an indoor air quality index over 150—moderately polluted—is documented for longer time periods, up to 8 hours in some cases. The laboratory used for the pilot exhibited double-height ceilings, allowing for dilution; in smaller lab environments, similar activity could lead to more frequent events of severe pollution and present significant health impacts.

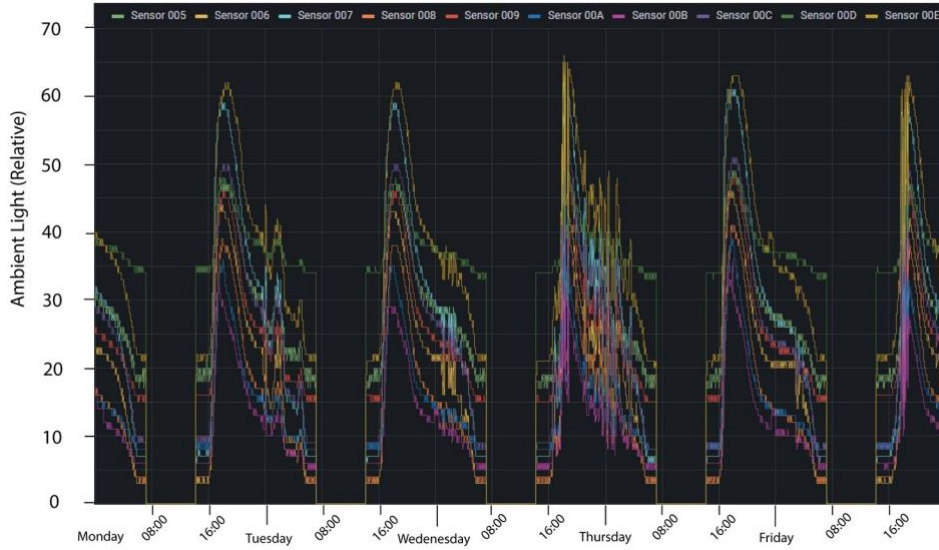


Figure 5 (Continued). Environmental metric data collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments. (Image Credit: Grafana Labs)

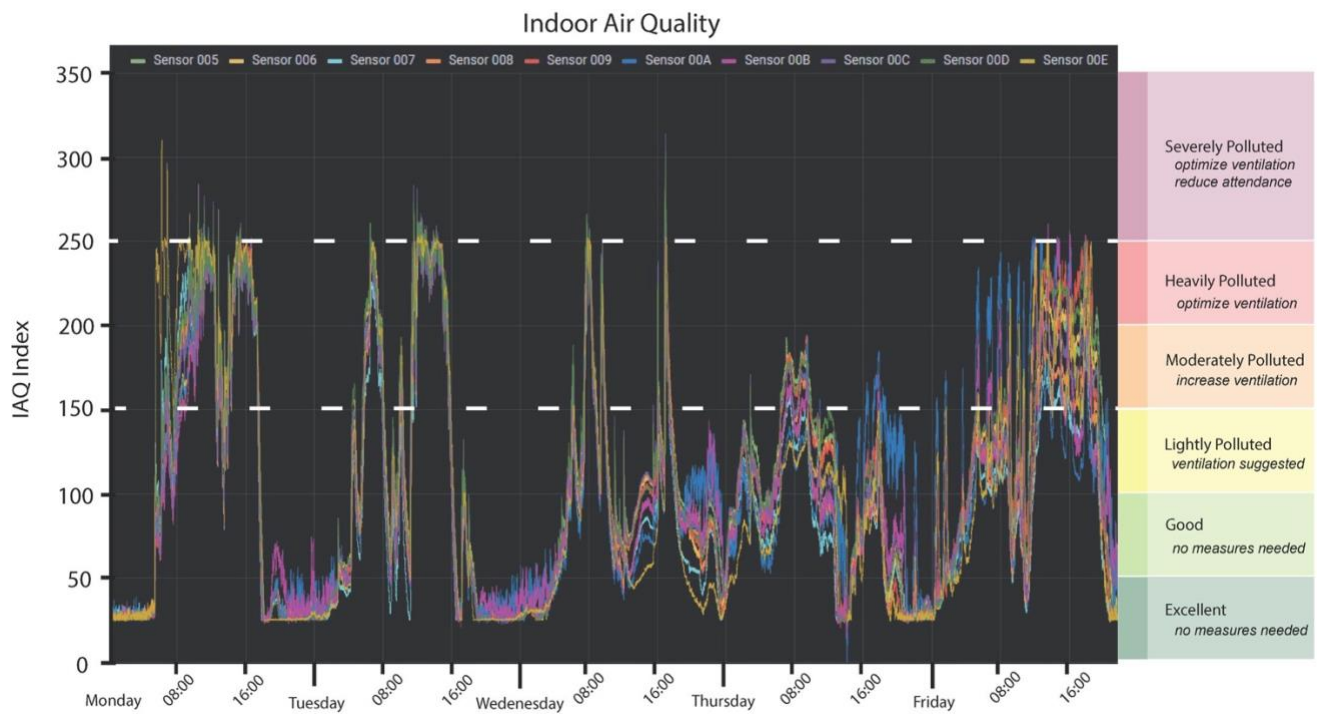


Figure 6. Indoor air quality readings collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments. IAQ index source: Bosch Sensortec. (Image Credit: Grafana Labs.)

DISCUSSION

The results of the pilot installation of low-cost sensors revealed the ability to collect high volumes of data, highlighting multiple avenues of applications. Enhancing laboratory analytics in such a way provides additional benefits, such as lowering barriers of entry to data collection of laboratory indoor environmental quality and mapping space use to better inform lab design. In broad terms, the primary application areas are understanding the true state of a building's environment and measuring actual performance against targeted performance. For many smaller labs, simply being able to cost-effectively assess the current state of their building will provide opportunities for improved safety and energy reduction.

Many facilities have few, if any, sensors located within each lab. As an example, the lab used for this pilot was previously monitored via a single temperature sensor. A higher density of sensors can provide more detailed insights into what is happening in any given space. The granularity of data throughout an indoor space can be related to pixels in an image—the more pixels, the clearer the image. In the case of sensors and analytics, the more sensors throughout the space, the clearer image the facility manager has of how the ventilation is operating. Comparing real-time measured operation to expected operation allows for fault detection and system improvements. For example, if a lower level of tVOC is present in a space, ventilation rates could be lowered accordingly to reduce energy use while maintaining a safe indoor air quality.

Potentially concerning issues could easily be masked by low-granularity data. However, it is also important to note that simply providing large volumes of raw data may not be of practical benefit. Raw data must be counterbalanced with data-driven actionable insights that are of practical use to a lab or building manager.

One potentially interesting area for future exploration is the addition of automated analysis that compares data between different sensors. For example, a significant temperature difference between sensors could be indicative of poorly mixed air flow within a space. Integrating this automated analysis into building controls could lead to further enhancement of dynamic, demand-based ventilation. Potential for 3D (three dimensional) visualization and modeling of air flow within a given space informed by real-time sensor data could also provide building facility managers with additional insight as to the interactions of environmental factors within the built environment. Combining these applications with external research on the effects of humidity and temperature on air quality and health can lead to the improvement of indoor air quality. In conjunction with occupancy data, data-informed, dynamic control of ventilation rates can optimize air flow to reduce energy consumption.

Through further testing of the accuracy of this technology and the breadth of application, a demand-controlled ventilation protocol can be developed that is centered around a low-cost solution for monitoring the lab environment. Enhancing laboratory analytics in such a way provides additional benefits, such as lowering barriers of entry to data collection of laboratory indoor environmental quality and mapping space use to better inform lab design.

CONCLUSION

As in the case of energy benchmarking, one cannot manage what one does not measure. To manage indoor air quality in dynamic environments, especially critical facilities that may pose life-threatening risks to researchers, a dynamic solution for measuring indoor air quality is needed. Existing solutions for contaminant detection, while accurate, often exceed the budget for laboratory facility management. The low-cost sensor prototype deployed in this pilot illustrates a potential solution for providing facility managers with data needed for dynamic management of indoor air quality. By employing demand-based controls informed by highly granular, real-time environmental data, ventilation can be optimized—rather than maximized—to achieve both healthy indoor air quality and energy efficient operation.

Acknowledgments

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