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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].

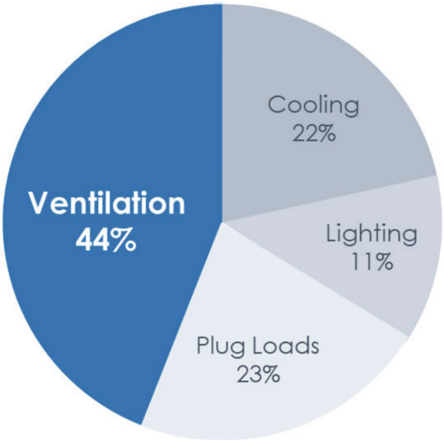

Figure 1. Annual electricity use in Louis Stokes Laboratory, National Institute of Health, Bethesda, MD. (Source: Labs for the 21st Century Best Practice Guide [4])

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.

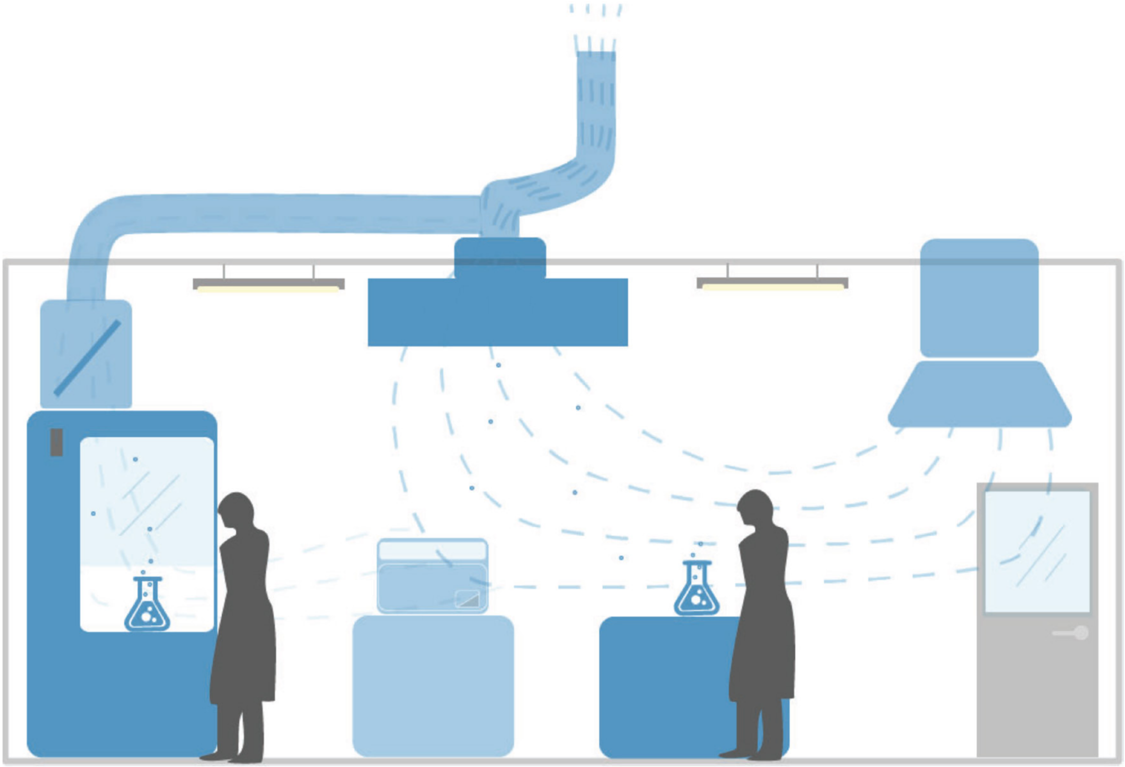

Figure 2. Smart Labs strategies for optimizing safety and energy efficiency through optimizing air flow in the lab space. Air flow sweeps across the lab space, carrying contaminants away from occupants. (Image Credit: Amanda Kirkeby, NREL)

- 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.

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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.

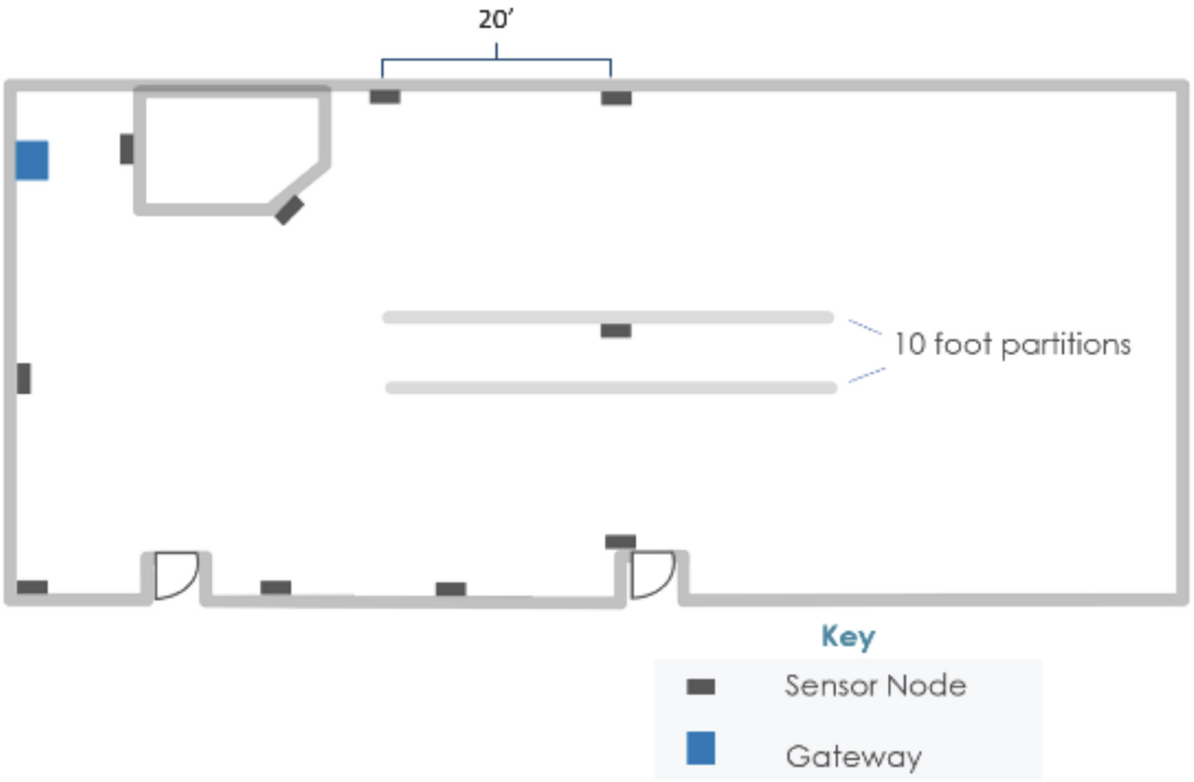

Figure 4. Schematic layout of sensor network. Two partitions in the lab space are illustrated, as well as major doorways and an enclosed office space. (Image Credit: Amanda Kirkeby, NREL)

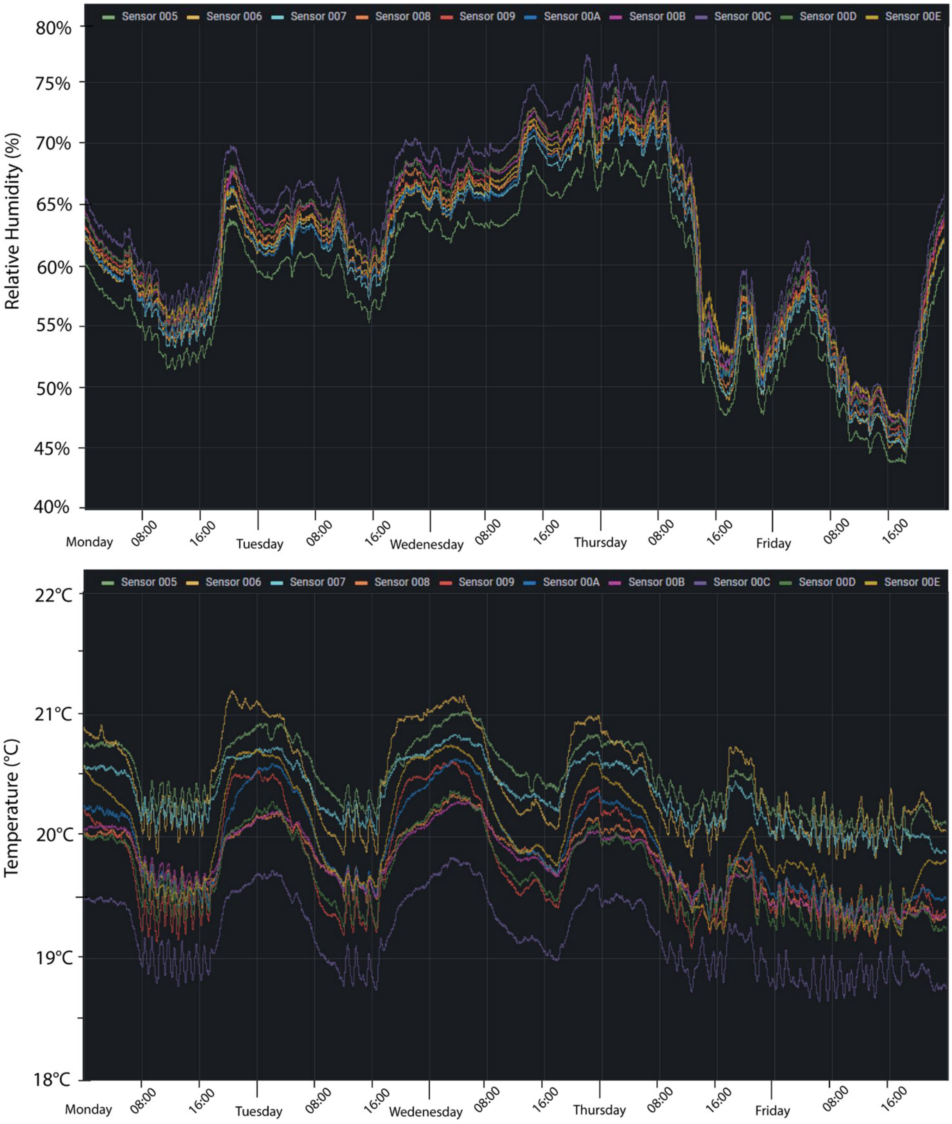

Figure 5. Environmental metric data collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments. (Image Credit: Grafana Labs)

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

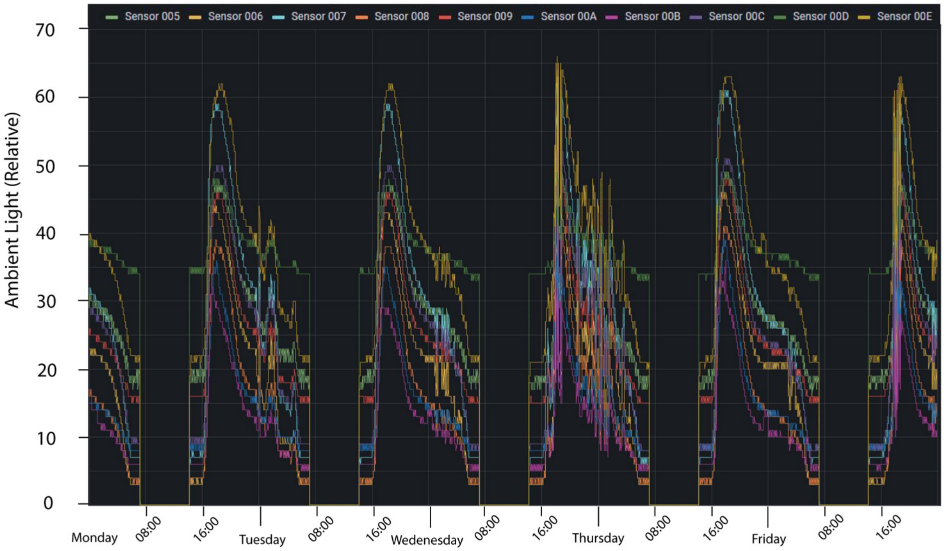

Figure 5 (*Continued*). **Environmental metric data collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments.** (**Image Credit: Grafana Labs**)

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.

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

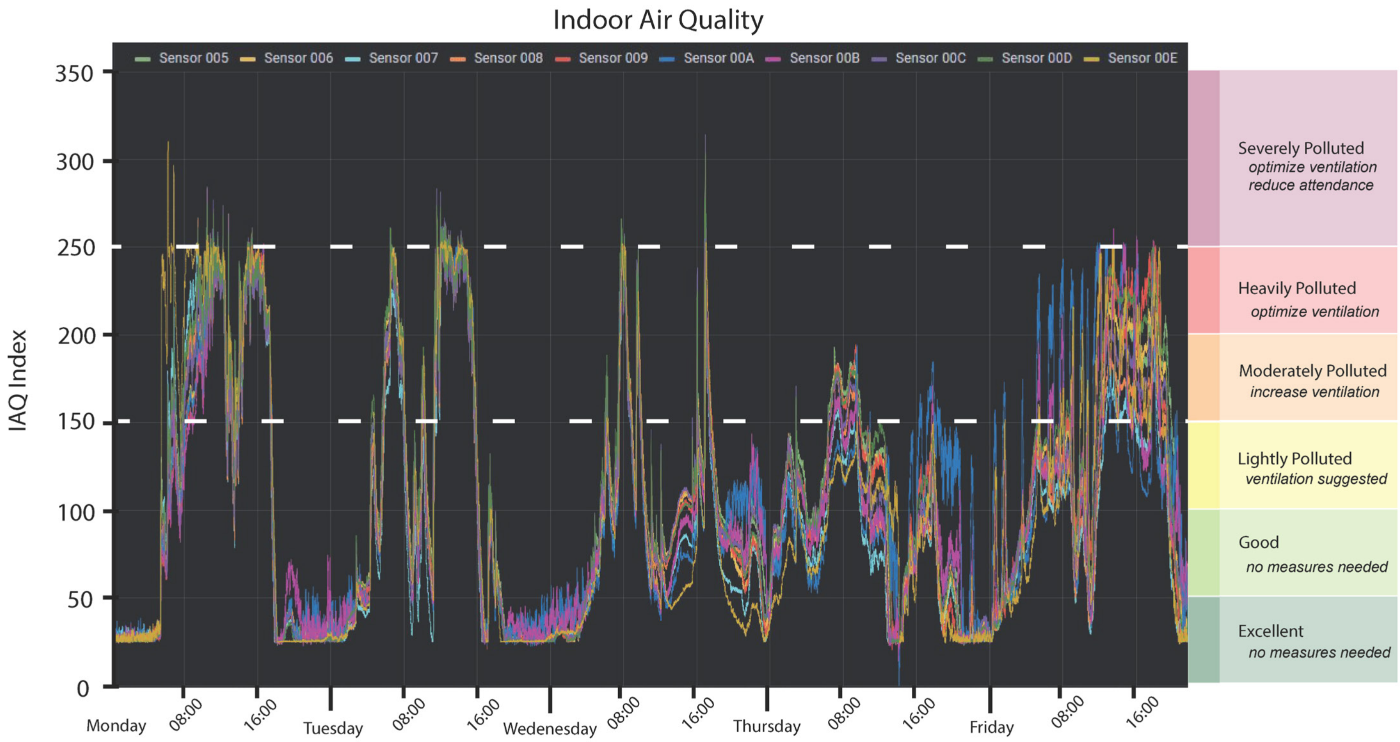

Figure 6. Indoor air quality readings collected by sensor network. The data displayed is for a 5-day interval, with reference listed in 8-hour increments. IAQ index source: Bosch Sensortec. (Image Credit: Grafana Labs.)

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.

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AUTHOR BIOGRAPHIES

Amanda Kirkeby is an energy engineer in the Energy Security and Resilience Center at the National Renewable Energy Laboratory (NREL) in Golden, CO, U.S.A. She supports the development of resources for high-performance laboratories and other building systems related initiatives across the lab. She also supports the U.S. Department of Energy Solar Decathlon Design Challenge. Amanda Kirkeby joined NREL in 2019 as a science undergraduate laboratory intern with the Commercial Building and Building Energy Science Groups and a research participant program intern with the Applied Engineering Group. Her interest in high-performance buildings began with the Race to Zero Competition, now the Solar Decathlon Design Challenge, in which she was part of the Middlebury undergraduate team that designed an award-winning zero energy elementary school. Amanda Kirkeby may be contacted via email at Amanda.Kirkeby@nrel.gov.

Rachel Romero, PE, is an energy engineer and project leader at the National Renewable Energy Laboratory. Rachel is the competition manager for the U.S Department of Energy Solar Decathlon Design Challenge, which has inspired over 4000 collegiate students in 7 years to be the next generation to design net zero buildings. Also, she provides technical assistance to the to the Department of Energy's Smart Labs program, which provides technical assistance to university and national laboratory partners across the US. She was a main author of the Smart Labs Toolkit, which describes a systematic process to achieve safe, efficient, and sustainable laboratories. Rachel obtained her Bachelor of Science in mechanical engineering from Hope College and then received her master's degree in building systems engineering at the University of Colorado Boulder. Rachel Romero may be contacted via email at Rachel.Romero@nrel.gov.

Otto Van Geet, PE, LEED AP, is a principal engineer at the National Renewable Energy Laboratory. Otto Van Geet has been involved in the design, construction, and operation of energy-efficient research facilities such as laboratories and data centers, office and general use facilities, and low-energy-use campus and community design. He was one of the founding members of the Labs21 (Smart Labs) program and provides technical guidance for the program. His experience also includes renewables screening and assessment, photovoltaic (PV) system design for on- and off-grid applications, energy audits, and minimizing energy use. He has authored many technical reports and conference papers and been recognized with many awards from professional associations, including the 2007 Presidential Award for Leadership in Federal Energy Management and the 2011 GreenGov Green Innovation Presidential Award for the NREL Research Support Facility data center. Otto Van Geet may be contacted via email at Otto.VanGeet@nrel.gov.

Nicholas Napp is a co-founder of Xmark Labs, LLC, and a senior member of IEEE. He has brought over 40 products to market across a wide range of consumer and enterprise markets. He is a systems thinker with broad skills in business development; product development; innovation and technology; and strategic marketing and partnerships. He is particularly focused on the integration of strategy, technology, and corporate narrative to accelerate business growth. His prior roles include leading multiple startups; lead external technology scout, North America for Sony Ericsson; and vice-president, animation, Rainbow Studios (sold to THQ, Inc.). He is also Chairman of the Board at FabNewport, a nonprofit makerspace for middle school and older students. Nicholas Napp may be contacted via email at nick@xmarklabs.com.