



PREPARING TK-12 SCHOOLS FOR CALIFORNIA'S CHANGING CLIMATE: HEALTH AND ENERGY CONSIDERATIONS FOR PREPARING FOR WILDFIRE SMOKE

A Report by the **Smoke: Wildfire Science and Policy Practicum**¹ | October 2023

Stanford | Climate & Energy Policy Program
Woods Institute for the Environment

Acknowledgements

This report was produced by scholars with the Smoke: Wildfire Science and Policy Practicum. The practicum is a collaboration between the Stanford Law School's Environmental and Natural Resources Law & Policy Program and the Stanford Woods Institute for the Environment's Climate and Energy Policy Program. The Woods Institute is part of the Stanford Doerr School of Sustainability, which provided additional funding for the practicum through its Sustainability Accelerator.

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The authors are grateful to **Dr. Lisa Patel** (Stanford University), **Wenhao Chen** (California Department of Public Health), **Erin Ross** (California Department of Education), and **Patrick Murphy** (PSE Healthy Energy) for their invaluable review of this work.

We also extend our sincere appreciation to the facilities managers and other school officials in the Palo Alto Unified and Mariposa County Unified School Districts and Woody Delp of the Lawrence Berkeley National Laboratory for their input in the process of writing this report.

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1 Stanford’s Smoke: Wildfire Science and Policy Practicum engages students in learning about and helping to craft policy solutions to some of the significant challenges wildfires pose. The Practicum is directed by Michael Wara and Deborah Sivas. Report authored by Arjan Walia under the direction of the teaching team.



EXECUTIVE SUMMARY

Wildfire smoke is a growing threat to public health in California and across the American West, and children are one of the groups most vulnerable to its health effects. Given the amount of time children spend in school, TK-12 schools represent promising sites for interventions to decrease exposure to the unhealthy air pollutants released by wildfires such as particulate matter (PM_{2.5} and PM₁₀) and volatile organic compounds (VOCs). Recent federal and state funding and policy initiatives have emphasized the importance of increasing energy efficiency in schools in addition to improving indoor air quality as requirements for funding. Though both components are necessary as schools look to use these funds to upgrade their air filtration and ventilation systems, no guidance about wildfire smoke events that considers both of these goals together currently exists for policymakers and school administrators.

To aid California's schools and districts in making these upgrades, this report provides recommendations for improving indoor air quality in schools during wildfire smoke events while meeting energy efficiency targets. In addition to summarizing the purpose and function of heating, ventilation, and air conditioning (HVAC) systems and portable high efficiency particulate air (HEPA) filters, the report offers recommendations for how schools can use these tools to maximize gains in indoor air quality while simultaneously prioritizing the energy efficiency of these systems. Low-cost air quality sensors placed both indoors and outdoors can provide schools with helpful information before and during smoky days to facilitate decisions about how to best prepare for and respond to wildfire smoke. The report offers possible starting points for policy-level changes that would facilitate the adoption of these recommendations at individual schools and districts across California.



ABBREVIATIONS

ACH	Air changes per hour
AQI	Air quality index
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CalEPA	California Environmental Protection Agency
CARB	California Air Resources Board
CADR	Clean air delivery rate
CFM	Cubic feet per minute
eACH	Effective air changes per hour
HEPA	High efficiency particulate air
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
MERV	Minimum efficiency rating value
PM2.5	Particulate matter less than 2.5 µm in diameter
US EPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
WHO	World Health Organization
WUI	Wildland-urban interface

I. INTRODUCTION

The wildfire crisis in California has worsened dramatically in the past decade, with the number of acres burned by wildfires growing each year and fire behavior becoming more erratic and destructive.² Intensified by climate change, over a century of fire suppression, and increasing human activity in the wildland-urban interface (WUI), these fires pose an urgent and growing threat to public health. Wildland fire events release millions of tons of particulate matter, noxious pollutants from structures, and other harmful products of combustion into the atmosphere each year, producing hazardous air quality that affects communities even hundreds of miles away.³ These air pollutants have clear effects on human health such as causing or exacerbating asthma and producing other inflammatory responses in the body, and wildfire smoke is associated with greater numbers of visits to the emergency room and even premature death in high-risk groups.⁴

Children are among the most vulnerable to the negative health effects of wildfire smoke. Because they are in a period of rapid lung development, children breathe more rapidly and therefore inhale relatively more of the pernicious pollutants in wildfire smoke per pound of body weight than do adults. In particular, the smallest particulate matter less than 2.5 microns (μm) in diameter (PM_{2.5}) can become trapped in the smaller branches of their developing lungs called bronchioles and alveoli, which can cause inflammation and is correlated with higher rates of asthma.⁵ While these pollutants most often result in subclinical symptoms that do not require medical attention, many children—especially those with preexisting vulnerabilities such as asthma—can experience severe or life-threatening reactions.⁶ The poor air quality caused by wildfire smoke is correlated with greater rates of hospitalization in children, as with other vulnerable populations such as older adults.⁷ Particularly pressing for schools, a growing body of evidence suggests that poor indoor air quality, including that caused by wildfires, can diminish cognitive function and academic performance in children.⁸

2 “Stats and Events,” CalFire, February 21, 2023. www.fire.ca.gov/stats-events/

3 “Why Wildfire Smoke is a Health Concern,” *United States Environmental Protection Agency*, October 20, 2022. www.epa.gov/wildfire-smoke-course/why-wildfire-smoke-health-concern

4 Carolyn Black et al., “Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue,” *Environmental Toxicology and Pharmacology* 55 (2017): 186-195; Stephanie M. Holm et al., “Health effects of wildfire smoke in children and public health tools: a narrative review,” *Journal of Exposure Science and Environmental Epidemiology* 21 (2021): 1-20.

5 Maria C. Mirabelli et al., “Respiratory Symptoms Following Wildfire Smoke Exposure: Airway Size as a Susceptibility Factor” *Epidemiology* 20, no. 3 (2009): 451-459.

6 Ettie M. Lipner et al., “The Associations Between Clinical Respiratory Outcomes and Ambient Wildfire Smoke Exposure Among Pediatric Asthma Patients at National Jewish Health, 2012-2015,” *GeoHealth* 3, no. 6 (June 2019): 146-159; Benjamin J. Marsh, “Wildfire Smoke Exposure Is Associated with Adverse Respiratory Events under General Anesthesia in At-risk Pediatric Patients,” *Anesthesiology* 137, no. 5 (November 2022): 543-554.

7 Rosana Aguilera et al., “Fine Particles in Wildfire Smoke and Pediatric Respiratory Health in California,” *Pediatrics* 147, no. 4 (2021): e2020027128; Nino Künzli et al., “Health Effects of the 2003 Southern California Wildfires on Children,” *American Journal of Respiratory and Critical Care Medicine* 174, no. 11 (2006): 1221-1228; Linn E. Moore et al., “Impacts of Wildfire Smoke and Air Pollution on a Pediatric Population with Asthma: A Population-Based Study,” *International Journal of Environmental Research and Public Health* 20, no. 3 (January 2023): 1937.

8 Jeff Wen and Marshall Burke, “Lower test scores from wildfire smoke exposure,” *Nature Sustainability* 5 (November 2022): 947-955; Dave E. Marcotte, “Something in the air? Air quality and children’s educational outcomes,” *Economics of Education Review* 56 (February 2017): 141-151; Juliana Carneiro et al., “The Effects of Air Pollution on Students’ Cognitive Performance: Evidence from Brazilian University Entrance Tests,” *Journal of the Association of Environmental and Resource Economists* 8, no. 6 (November 2021): 1051-1077; “Evidence from Scientific Literature about Improved Academic Performance,” United States Environmental Protection Agency, September 14, 2022.

Because children spend more time in school than any other place except their homes, schools are ideal locations for interventions to protect the health of children. The COVID-19 pandemic highlighted the importance of indoor air quality (IAQ) in classrooms to prevent the transmission of the SARS-CoV-2 virus and spurred efforts across the country to upgrade school infrastructure to increase the number of air changes per hour (ACH) and decrease CO₂ levels in classrooms—indicators of how well ventilation systems are functioning. Many schools in California are similarly looking to upgrade their ventilation and air filtration systems to protect students from the health consequences of wildfire smoke as well as other more consistent forms of air pollution in environmental justice communities.

In addition, California has set ambitious goals to reduce the amount of energy consumed in buildings across the state as part of the broader transition to carbon neutrality by 2045.⁹ In 2017, the Public Utilities Commission aimed to have all new commercial construction be “zero net energy” and 50 percent of existing commercial buildings retrofitted by 2030.¹⁰ The most recent Building Energy Efficiency Standards, which took effect on January 1, 2023, encourage new buildings to include low-energy technologies such as heat pumps, rooftop solar panels, and electric water heating to facilitate the construction of net-zero buildings in the state.

As part of the recent Bipartisan Infrastructure Law and economic relief bills enacted during the height of the COVID-19 pandemic, the federal government has allocated tens of billions of dollars for schools across the country to modernize their infrastructure.¹¹ Eligibility for many of these grants emphasizes maximizing indoor air quality and reducing energy consumption through the selection of high-performing, energy efficient systems. The Efficient and Healthy Schools Campaign run by the federal Department of Energy is one result of this increased interest in improving indoor air quality and energy performance, with schools across the nation joining the campaign and utilizing its materials to make such upgrades.¹²

Initiatives in California such as the Bright Schools Program and the School Bus Replacement Program have additionally focused funds towards improving air quality and energy efficiency in and around schools in particular.¹³ Future bond bills and school infrastructure improvement funds in the state such as the recently proposed Master Plan for Healthy, Sustainable, and Climate-Resilient Schools (SB 394) will likely continue this work even as the limited federal funding is exhausted.¹⁴

9 “Carbon Neutrality by 2045,” Governor’s Office of Planning and Research, 2022. <https://opr.ca.gov/climate/carbon-neutrality.html>

10 “Zero Net Energy,” California Public Utilities Commission, 2017. <https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/zero-net-energy>.

11 “Fact Sheet: The Biden-Harris Action Plan for Building Better School Infrastructure,” *White House*, April 4, 2022.

12 “Efficient and Healthy Schools,” *Lawrence Berkeley National Laboratory*, <https://efficienthealthyschools.lbl.gov/>.

13 “Bright Schools Program,” *California Energy Commission*, <https://www.energy.ca.gov/programs-and-topics/programs/bright-schools-program>; “School Bus Replacement Program,” *California Energy Commission*, <https://www.energy.ca.gov/programs-and-topics/programs/school-bus-replacement-program>.

14 Importantly, SB 394 (2023) draws upon the tax credits in the federal Inflation Reduction Act to finance these upgrades, meaning that the pool of money available could potentially be limitless. “California Senate Bill 394,” *LegiScan*, May 23, 2023, <https://legiscan.com/CA/text/SB394/id/2794090>. See also AB 927 (2023) (“AB-927 School buildings: construction plans,” *California Legislative Information*, February 14, 2023) and SB 22 (2021); (“SB 22 – Education Finance: Education Facilities Bond Act of 2022,” January 20, 2021, cappa.memberclicks.net/assets/StateLegislation/2021/SB%2022%20-%20Ed%20Bond%20Bill%20Fact%20Sheet.pdf

The majority of guidance from state and federal agencies to schools on the question of wildfire smoke has focused primarily on restricting physical activity for students and implementing strategies to improve indoor air quality without considering the energy tradeoffs of these interventions.¹⁵ To date, no recommendations exist to assist schools in determining the best way to safeguard student health while utilizing available state and federal funds to improve the facility's energy efficiency. This report provides recommendations for schools considering upgrades to protect against wildfire smoke exposure in schools through the lens of both indoor air quality and energy efficiency.

This report examines strategies that schools can use to protect students from air pollution during wildfire smoke events in order of their effectiveness in protecting indoor air quality, namely installing or upgrading heating, ventilation, and air conditioning (HVAC) systems and high efficiency particulate air (HEPA) filters. For each, the report gives background information about the intervention method and recommendations for schools based on the current scientific evidence and the policy landscape. Then, it provides recommendations for using low-cost sensors to develop IAQ protection plans for wildfire smoke events and build a use case for greater investments in IAQ infrastructure in schools. To conclude, the report provides preliminary recommendations for statewide policy changes encouraging upgrades across California that would both provide protections from wildfire smoke and help the state reach its energy efficiency and decarbonization goals.

I.1 Considerations for Indoor Air Quality during Wildfire Smoke Events

Engineers typically compare air filtration systems by measuring the air changes per hour (ACH), or the volumetric flow rate of air in cubic feet per hour divided by the total cubic feet of the room, which indicates how often the air in the room is recirculated and ventilated with outdoor air. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has different standards for the amount of *outdoor* air that should enter buildings each hour per volume of the room and the number of occupants, depending on the room's primary uses. For example, ASHRAE 62.1 and 62.2 provide minimum outdoor ventilation recommendations for acceptable AQI.¹⁶ For most TK-12 schools, this typically means 2.2 to 3 ACH to ensure adequate removal of indoor air pollutants—though during the COVID-19 pandemic, many other sources recommended between five and six to prevent the transmission of the SARS-CoV-2 virus.¹⁵ These ASHRAE guidelines assume that, because occupants are exhaling CO₂ and many objects in rooms produce harmful volatile aerosol compounds, the indoor air is more contaminated than fresh, outside air. The solution to improving indoor air quality in these ideal conditions is therefore to recommend ventilation, the movement of presumably cleaner outdoor, or ambient, air into buildings to dilute those contaminants.

15 "Guidance for Schools During Wildfire Smoke Events," *California Environmental Protection Agency*, December 12, 2019; David Hochschild et al., "California Schools Healthy Air, Plumbing, and Efficiency Ventilation Program Guidelines," *California Energy Commission*, June 10, 2022; Gregory Joseph et al., "Evidence on the Use of Indoor Air Filtration as an Intervention for Wildfire Smoke Pollutant Exposure," *Centers for Disease Control and Prevention*, July 2020.

16 Jennifer A. Isenbeck et al., "ANSI/ASHRAE Standard 62.1-2022: Ventilation and Acceptable Indoor Air Quality," *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*, 2022; Mike Moore et al., "ANSI/ASHRAE Standard 62.2-2022: Ventilation and Acceptable Indoor Air Quality in Residential Buildings," *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*, 2022. Andrew Persily, "Development and application of an indoor carbon monoxide metric," *Indoor Air* 32, no. 7 (July 2022): e13059. Paddy Robinson, "ASHRAE Recommended Air Changes Per Hour," *Smart Air*, October 22, 2022.

Such assumptions of the benefits of bringing outdoor air into buildings clearly do not hold up during wildfire smoke events. Several strategies used to increase the amount of outdoor air entering buildings such as opening windows and doors would expose occupants to unhealthy levels of particulate matter and allow air pollutants and ash to deposit in carpets, vents, and other hard-to-clean surfaces. To protect the health of a building's occupants in such unhealthy air quality events, adequate air movement instead must rely on filtration through systems such as HVAC and HEPA filters that do not bring in the same quantity of ambient air. Although ACH is a useful measurement to enforce minimum ventilation rates in most situations, this report instead uses the terminology of effective air changes per hour (eACH) to account for the fact that, while some technologies such as portable HEPA filters do not ventilate buildings with ambient air, they can nonetheless remove harmful pollutants from the air and improve IAQ during exceptional outdoor air quality events such as wildfires. The target number of eACH should be equal to guidelines for ACH in order to provide similar levels of protection. In the case of TK-12 classrooms, for example, schools should plan to achieve five to six eACHs to match IAQ recommendations from the COVID-19 pandemic.

II. HEATING, VENTILATION, AND AIR CONDITIONING (HVAC) SYSTEMS

As a key component of ensuring thermal comfort in schools across California, heating, ventilation, and air conditioning (HVAC) systems represent an ideal target for improving wildfire smoke resilience while achieving energy savings. California’s General Education Code mandates that schools with HVAC systems should maintain their “mechanical systems, including heating, ventilation, and air-conditioning systems,” in “good repair”—meaning, in part, that the systems can “supply [an] adequate amount of air to all classrooms, work spaces, and facilities,” as defined by ASHRAE ventilation standards. In maintaining their HVAC systems in “good repair,” schools are not required, and often do not have enough funding, to upgrade buildings and equipment “beyond the standards to which the facility was designed and constructed” originally.¹⁷ Consequently, the majority of classrooms in the state, including some recently retrofitted with new HVAC equipment, are not meeting ASHRAE recommendations for adequate ACHs and are inadequately ventilating classrooms.¹⁸ Furthermore, according to a report from the Sean N. Parker Center for Allergy and Asthma Research at Stanford University, between 15 and 20 percent of California’s TK-12 schools have no mechanical ventilation systems at all, with an additional 10 percent requiring significant repairs or replacement to function properly.¹⁹ Such lack of adequate HVAC systems will only become more urgent as climate change increases the cooling needs of many schools, including those in places that historically have not required air conditioning at all.

Inadequate ventilation conditions pose a threat to student and staff health even beyond the COVID-19 pandemic, which attracted increased attention to indoor air quality in schools—particularly as wildfire smoke events grow more intense.²⁰ Proper filtration and ventilation are key to student health and academic performance during the annual fire season. Because of their significant energy demands, HVAC systems are also key areas for interventions to improve the energy efficiency of schools. With the increased funding available for HVAC retrofitting projects because of the COVID-19 pandemic and the Inflation Reduction Act (IRA) and more state funds proposed for such upgrades, schools across California will have more opportunities to prepare for wildfire smoke events while addressing other needs such as thermal comfort and energy efficiency.

17 Cal. Educ. Code § 17002(d)(1)(B)(ii).

18 Wanyu R. Chan et al., “Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation,” *Building and Environment* 167 (January 2020): 106426; William J. Fisk, “The Ventilation Problem in Schools: Literature Review,” *Indoor Air* 27, no. 6 (July 2017): 1039-1051. To calculate the number of ACHs an HVAC system is producing, use the following formula: $(CFM \cdot 60) / (V_{room})$, where CFM is the volume of air (in cubic feet per minute) delivered to the room by the air handler and V_{room} is the volume of the room in cubic feet. See “How to Calculate Air Changes Per Hour,” *Camfil*, October 22, 2021.

19 Lisa Patel et al., *Climate Resilient California Schools: Safeguarding Children’s Health and Opportunity to Learn in TK-12* (Stanford, CA: Sean N. Parker Center for Allergy and Asthma Research, 2023), 21.

20 Betty Márquez Rosales and Carolyn Jones, “California schools struggle to pay for ventilation upgrades, key to safely reopen campuses,” *EdSource*, January 8, 2021.

Schools in California utilize several broad categories of HVAC systems, and which system is selected depends on the type of building, floor area, and heating and cooling requirements, among many other factors. Each category contains still more types of HVAC systems, all with their own distinct heating and cooling technologies. Decentralized air conditioning units, a broad category of self-contained units typically used to ventilate individual rooms or small buildings, are perhaps the most common type used in schools given their suitability for small- to medium-sized spaces.²¹ Packaged terminal units, which are small, ductless systems installed underneath windows, typically supply only the smallest classrooms and office spaces and are more often seen in hotel rooms. These systems typically consume between 1.7 and 5.3 kW for cooling and/or heating while having low initial installation costs.²²

Perhaps the most ubiquitous HVAC unit in California schools is the wall-mounted package unit, most often seen on portable or bungalow classrooms. Because large commercial equipment companies such as Bard manufacture them already ready for installation, these systems, which can provide both heating and cooling, have low initial costs and do not require ductwork. While more accessible than larger central HVAC equipment, these systems typically have shorter lifespans (between ten and fifteen years), consume more energy, and can be noisier.²³ Given the prevalence of portable classrooms in TK-12 schools in California, these units are particularly important targets for upgrades to protect student health and reduce energy consumption.

While these decentralized units work best for smaller structures with only one or two classrooms, central HVAC systems are typically more practical for larger buildings. Package rooftop units are among the most versatile and common central HVAC systems that can be used in schools. As the name implies, these units are typically mounted on the roofs of buildings and can provide both air conditioning and heating. The conditioned air travels from the HVAC unit through ducts to rooms throughout the building. Though smaller units (<50kW) are usually only single-zone—meaning that the unit is either in cooling or heating mode and therefore that every room in the building can only either cool or heat—larger units (50-175 kW) can be multizone, which allows each room to choose whether they want heating or cooling. There are many possible configurations of these systems that utilize natural gas, electric resistance, or heat pumps for heating, and their energy efficiency can vary dramatically.²⁴ The largest type of HVAC systems, centralized air handlers, are exceedingly rare in schools, being suitable only for buildings with more than five stories or greater than 14,000 m² (about 159,000 ft²) in floor area.²⁵

21 “Decentralized Cooling and Heating,” in *2020 ASHRAE Handbook - HVAC Systems and Equipment* (SI Edition) (Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2020) [hereafter “*2020 ASHRAE*”], 2.1.

22 “Room Air Conditioners and Packaged Terminal Air Conditioners,” in *2020 ASHRAE*, 49.5-6.

23 “Decentralized Cooling and Heating,” 2.3-4.

24 “Furnaces,” in *2020 ASHRAE*, 33.5 and 33.7-8.

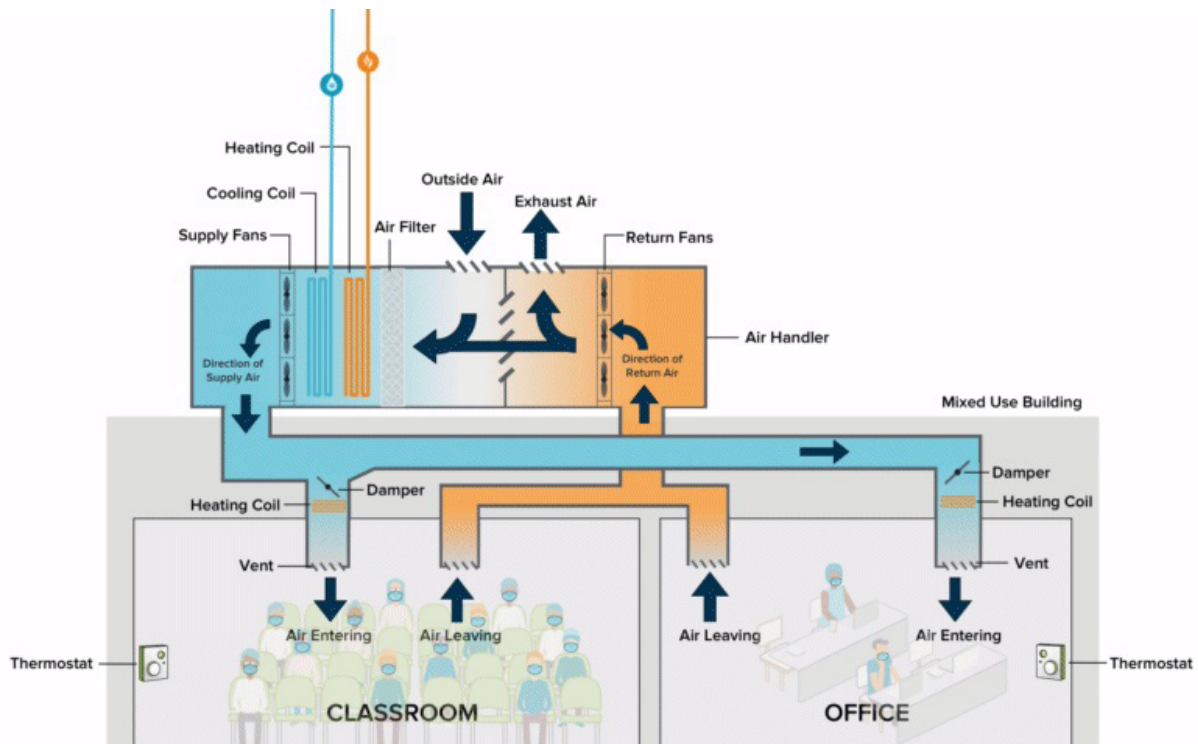
25 “Central Cooling and Heating Plants,” in *2020 ASHRAE*, 3.1

Though they can provide the greatest levels of filtration when using filters with high minimum efficiency reporting value (MERV) ratings, the high cost of installing and maintaining HVAC systems and their relatively high energy consumption are two of their key drawbacks. According to an analysis by the Center for Climate Integrity, California will need to spend approximately \$2.4 billion to install HVAC systems at 678 schools that currently do not have them and about \$39 million to upgrade or retrofit those in 1,191 schools that urgently need repairs. An additional \$220 million is necessary to maintain and operate all of the HVAC systems in the state annually, including the energy required to run them.²⁶ Numerous energy-saving technologies noted later in this section can help ensure adequate air filtration during wildfire smoke events while reducing the energy usage of air conditioning or heating and therefore operating costs in the long run. Despite these costs and considering that California's schools serve nearly five million students, these systems are the most robust and effective intervention in schools because of their superior thermal comfort benefits during heatwaves and protection from smoke during wildfire events—environmental conditions that will certainly worsen as the climate continues to warm.



Examples of (from top left, clockwise) a packaged terminal unit, wall-mounted package unit, package rooftop unit, and centralized air handler. (From Sylvane, Bard Air Conditioning, Wikimedia Commons, and Green Leaf Air, respectively.)

26 "California," Center for Climate Integrity, 2021, <https://coolingcrisis.org/uploads/media/CCI-StateReport-California.pdf>.



A schematic of air flow through a roof-top package unit. Air enters the system from outside the building, then passes through the filter before being either heated or cooled and then passing into the building via vents. Air exits the room through another set of vents, where it can either exit the building or pass through the filter once again before reentering the room. (From UC Davis Facilities Management, “Building Ventilation and Filtration.”)

Conclusions

- Because they can move indoor air with the greatest efficiency and therefore remove pollutants when maintained properly, HVAC systems are key resources in protecting indoor air quality during wildfire smoke events.
- Myriad HVAC systems are available depending on the size, heating and cooling demands, energy efficiency goals, and layout of schools, and schools typically choose which type to install to fit the specific needs of their facility.
- Though funding from the federal and state governments spurred by the COVID-19 pandemic and recent interest in improving school infrastructure have made more funds available to finance indoor air quality and/or energy efficiency upgrades in schools, many schools across California are not meeting indoor air quality standards and require urgent upgrades.

Recommendations

- Given their high filtration abilities and sizable energy requirements, HVAC systems should be the primary target of efforts to improve indoor air quality and energy efficiency in TK-12 schools across California.
- Schools should assess the specific heating and cooling needs of each of their buildings to determine which types of HVAC systems are most suitable and to maximize their effectiveness.
- Schools should utilize federal and state funding to finance the installation of or upgrades to HVAC systems.
- Schools that have delayed critical maintenance to their HVAC systems and poorly performing or failing systems should be prioritized for upgrades to maximize the benefits of these oftentimes expensive projects.
- The California Department of Education should assemble resources and deploy experts in HVAC systems for under-resourced schools to secure the lowest possible costs and work with HVAC companies to ensure that schools are not being oversold—perhaps through technical assistance ‘strike teams’ of sorts.

II.1 Mechanical Filtration

Every type of HVAC system utilizes filters in order to remove aerosols from both the outdoor air that the system intakes and the air recirculated within the building itself. These filters come in a wide range of sizes, shapes, and materials but are “generally one to four inches thick, made of polyester and/or fiberglass, and styled in a flat or pleated pattern.”²⁷ While electrostatic filters are cheaper and widely available, mechanical filters—which utilize a fine, pleated material to trap particles as air flows through the HVAC system—achieve greater filtration of the small particles in wildfire smoke that pose the greatest risks to human health. These fine (0.1-2.5 μm) and ultrafine (<0.1 μm) particulates are “less likely to be removed by gravitational settling” than coarse (>2.5 μm) particles and can even deposit on vertical surfaces, posing long-term hazards to classroom occupants.²⁸ The MERV classifies filters available for residential and commercial HVAC systems on a scale of 1 to 16 based on its ability to remove airborne particulate matter. As table 1 shows, only filters with MERV ratings of 13 or higher can remove the majority of the smallest and most unhealthy aerosols.

27 “High-MERV Filter,” *Office of Energy Efficiency & Renewable Energy*, October 7, 2022.

28 “Air Cleaners for Particulate Contaminants,” in *2020 ASHRAE*, 29.1-2.

Table 1: Minimum Efficiency Reporting Value (MERV) Average Efficiencies

MERV Rating	Efficiency for PM3.0-10	Efficiency for PM1.0-3.0	Efficiency for PM0.3-1.0
1-4	<20%		
5	≥20%		
6	≥35%		
7	≥50%		
8	≥70%	≥20%	
9	≥75%	≥35%	
10	≥80%	≥50%	
11	≥85%	≥65%	≥20%
12	≥90%	≥80%	≥35%
13	≥90%	≥85%	≥50%
14	≥95%	≥90%	≥75%
15	≥95%	≥90%	≥85%
16	≥95%	≥95%	≥95%

Source: “What is a MERV rating?” *United States Environmental Protection Agency*, February 27, 2023.

Particularly in the context of the adjustments that schools needed to safely reopen during the COVID-19 pandemic, public health agencies and indoor air quality experts have begun to recommend that school HVAC systems have filters with a MERV rating of at least 13 due to their high standards for filtration efficiency.²⁹ The US Environmental Protection Agency (EPA) and California Environmental Protection Agency (CalEPA) have since recommended the use of MERV 13 or greater filters to prevent smoke from infiltrating indoors. “Upgrading to a filter rated MERV 13 or higher,” the US EPA recommends, “can be especially important during smoky periods to effectively remove fine particle pollution from smoke in the indoor air.”³⁰ Policymakers have adopted these recommendations, with the School Energy Efficiency Stimulus Program of 2020 in California requiring that schools receiving grant funding for indoor air quality improvements install filters with a MERV of 13 or higher whenever possible.³¹

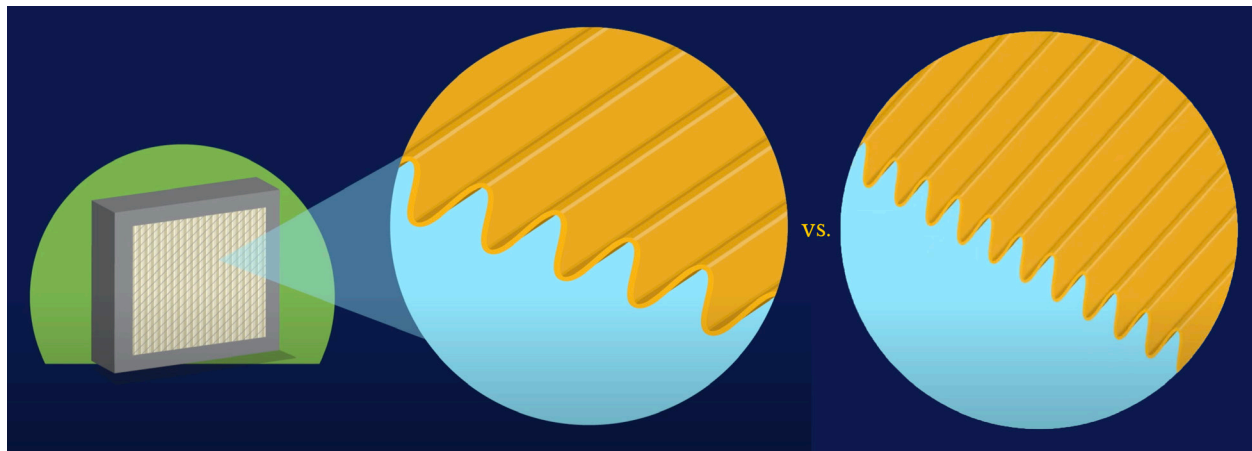
Not all HVAC systems produce sufficient air flow to accommodate some high efficiency filters, however. Because of the greater resistance that filters with higher MERV ratings typically produce, installing higher efficiency filters may strain the fan motors of some HVAC systems, particularly the longer the filter has been in use and the older the HVAC system. Importantly, many manufacturers produce high efficiency filters with lower pressure drop (Δp) and greater numbers of pleats per inch that put less stress on HVAC systems’ fans, as the Western Cooling Efficiency Center

29 Guidance for the Re-Opening of Schools,” *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*, August 20, 2020.

30 “Preparing for Fire Season,” *US Environmental Protection Agency*, January 19, 2023; “Guidance for Schools During Wildfire Smoke Events,” *California Environmental Protection Agency*, December 12, 2019.

31 Hochschild et al., “California Schools Guidelines,” 15.

at the UC Davis Energy and Efficiency Institute has noted. An analysis from the California Energy Commission even found that many models of MERV 13 filters have the same or lower pressure drops than some MERV 6 and 7 filters.³² Many HVAC systems likely can handle these MERV 13 or greater filters with lower Δp values, which may be the best option for schools looking to increase air filtration—though the system’s fan may need to expend more energy to produce equivalent airflow depending on the type of fan and layout of the system’s ducts. Schools with old or poorly functioning HVAC systems that cannot handle even these filters, however, should consider retrofitting or completely replacing their systems.



Comparison of filter with less pleats and therefore greater pressure drop versus a filter with denser pleats and lower pressure drop. Increasing the density of pleats may allow HVAC systems that cannot handle high resistance filters to use MERV 13 filters. (Edited image derived from UC Davis Energy, “The Importance of Filtration in Schools,” YouTube video, 8:12, May 13, 2021.)

To reduce strain on the HVAC system’s fan and ensure proper filtration of entering air, regular filter replacement is critical. Standard guidance for HVAC system maintenance includes checking and replacing filters approximately every three months, but during periods of especially thick smoke, building managers may need to replace them every several weeks and check them for soot or smoke accumulation even more frequently.³³ As wildfire smoke clogs the small openings in the filters, the resistance of the filter may increase, which can cause inadequate air flow and ultimately stress the system. Because of their ability to capture finer particulates than filters with lower MERV ratings, MERV 13 or greater filters begin to clog sooner and may need to be replaced more frequently than lower efficiency filters. The Washington State Department of Health recommends that schools check filters at least once per month for debris and dust accumulation and more often in heavy smoke conditions.³⁴ When possible, facilities managers may also want to measure the pressure drop across the filters to ensure adequate flow through the system.

32 Jeff Miller, “Staff Analysis of Air Filter Pressure Drop and Air Filter Sizing,” *California Energy Commission*, January 23, 2018; UC Davis Energy, “The Importance of Filtration in Schools,” YouTube video, 8:12, May 13, 2021. https://youtu.be/ycgLBUfIM_c

33 Thomas L. Paxson et al., “ANSI/ASHRAE/ACCA Standard 180-2018: Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems,” *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*, June 11, 2018, 8.

34 “Improving Ventilation and Indoor Air Quality During Wildfire Smoke Events: Recommendations for Schools and Buildings with Mechanical Ventilation,” *Washington State Department of Health*, June 2022, 2.

The consistent movement of air through the HVAC system is critical to ensuring adequate removal of particulate aerosols through the high MERV filters. Even when HVAC systems are set to recirculate indoor air and not intake outdoor air, small crevices and openings in the building envelope will nonetheless allow particulate matter to infiltrate into classrooms. Guidance from the Centers for Disease Control and Prevention (CDC) recommends setting fans to continuous operation “to pull indoor air through the filter, even when the HVAC system is not actively heating or cooling or when the heat/cool is intermittent.”³⁵ Continuous filtration—even when the room is already at the desired temperature—would increase the number of eACH in classrooms during the school day but with clear increases in energy usage. Because of its energetic cost, this strategy may be best suited for only the smokiest days of the year and therefore when particulates from wildfire smoke would infiltrate into buildings at the highest concentrations.

Conclusions

- Mechanical HVAC filters with a minimum efficiency reporting value (MERV) of 13 or greater offer the best protection against wildfire smoke contaminants, particularly PM_{2.5}.
- Manufacturers produce MERV 13 or greater filters in a variety of designs that can accommodate many HVAC systems' air flow capacities.
- The continuous movement of air through the HVAC filters, including when the system is recirculating the indoor air, removes the aerosols from wildfire smoke that can infiltrate into the building.

Recommendations

- Schools should utilize filters with MERV 13 or greater that are compatible with their preexisting HVAC systems and choose filters with higher pleat density and shallower depth when their HVAC systems do not generate sufficient air flow to accommodate standard ones.
- Schools should change their HVAC filters before the start of the peak wildfire smoke period in their area and monitor the filters as often as daily during periods of especially heavy air pollution to ensure proper filtration.
- Schools should consider running their HVAC systems on recirculation mode even when not heating or cooling during periods of the heaviest wildfire smoke in order to remove air pollutants that infiltrate into buildings.
- Where the cost of higher efficiency filters is an issue, schools should reserve filters with higher MERV ratings for the peak of the wildfire season in the late summer and early fall and can utilize lower efficiency filters (ex. MERV 8-11) during periods of better air quality.
- When wildfire smoke events occur during breaks in the school year such as the summer, schools should consider running the HVAC system in the days before students return to the classroom to ensure that particulates are sufficiently filtered from the indoor air.

35 Gregory Joseph et al., “Evidence on the Use of Indoor Air Filtration as an Intervention for Wildfire Smoke Pollutant Exposure,” *Centers for Disease Control and Prevention National Center for Environmental Health*, 21

II.2 Energy-Saving Features

Because they consume nearly half of the energy consumed in school buildings in the US, HVAC systems are an important target for energy savings.³⁶ The most effective strategy to reduce energy consumption while simultaneously increasing filtration is to replace HVAC systems older than their recommended lifespans, which do not perform as well as newer, state-of-the-science technologies in either measure. Given the financial constraints that many school districts face, however, such projects are simply unfeasible for most schools.³⁷ Schools, particularly those with inefficient or outdated centralized systems, can often benefit from retro-commissions—that is, the process of testing and upgrading the preexisting HVAC systems to ensure that the systems are as functional and energy efficient as possible.³⁸ Depending on the needs of the school and constraints of the HVAC systems, the engineers overseeing retro-commission projects may recommend different upgrades to reduce energy consumption and improve filtration of wildfire smoke. Recent and proposed grant funding from the federal and state governments, including the Inflation Reduction Act and Bipartisan Infrastructure Law, can help finance such retro-commissions.³⁹

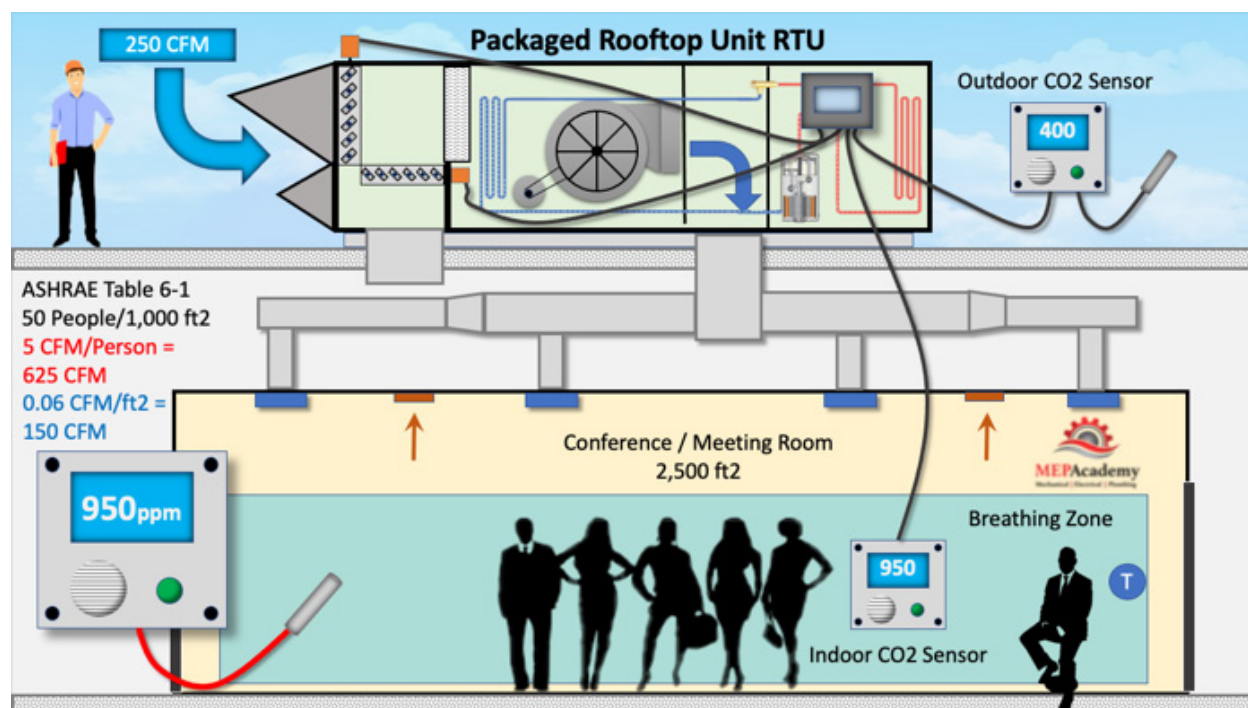


Diagram of a demand controlled ventilation system. The intake of outdoor air—and therefore the amount of energy used to cool or heat it—is modulated based on the readings of a CO² monitor inside the building. When the concentration of CO² passes the limit set on the system, in this case 950 ppm, the building intakes a greater volume of outdoor air. (From “Demand Controlled Ventilation DCV,” MEP Academy.)

36 “Guide to Operating and Maintaining EnergySmart Schools,” *US Department of Energy*, 23.

37 Patel et al., *Climate Resilient California Schools*, 14-15.

38 “Retrocommissioning,” *EnergyStar Building Manual*, October 2007.

39 “White House Toolkit: Federal Resources for Addressing School Infrastructure Needs,” *White House*, March 2022; Federal and State Resources, *US Department of Energy Office of Energy Efficiency & Renewable Energy*, <https://www.energy.gov/eere/buildings/federal-and-state-resources>.

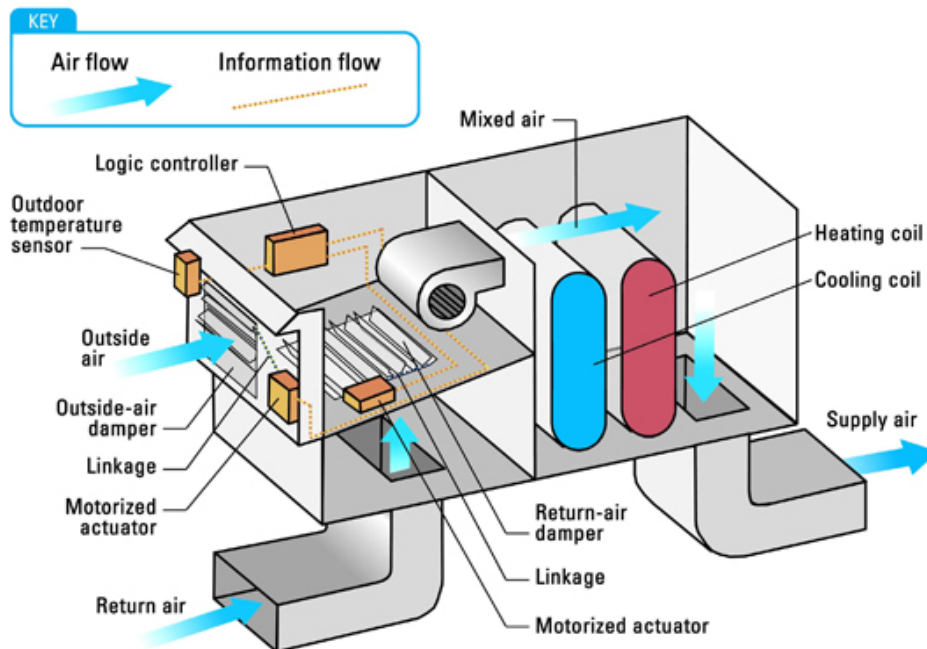


Diagram of an air-side economizer. The HVAC system brings outside air into the system by opening the damper when the outdoor temperature or humidity sensor detects favorable conditions. By utilizing the outdoor air to cool the interior of a building when it is closer to the desired temperature, economizers reduce the need for heating or cooling and therefore conserve energy. (From “Air-Side Economizer,” *Energy Star*.)

In recent years, many HVAC upgrades have increasingly utilized two technologies—economizers and demand control ventilation—to increase energy efficiency while ensuring proper ventilation of buildings. Economizers utilize outdoor air sensors to determine when the temperature and humidity are favorable, allowing the HVAC system to cool buildings with outdoor air instead of utilizing the air conditioning’s compressor at all times. These so-called air-side economizers can provide significant energy reductions in California’s mild climates, particularly along the coast and during periods of healthy ambient air quality. These systems require regular examination to ensure that the dampers that control the intake of outdoor air do not get stuck open and that the economizer’s sensors are properly calibrated to ensure that air only enters when conditions are suitable.⁴⁰ So long as buildings have properly functioning MERV 13 or greater filters that are regularly inspected, especially during wildfire smoke events, air-side economizers should not pose a threat to indoor air quality—particularly when used in conjunction with portable HEPA filters (see section III).⁴¹ During smoky days, this technology poses the obvious problem of requiring the HVAC system’s filters to remove larger volumes of particulates, in turn requiring them to be replaced more frequently. School facilities managers may therefore want to manually override economizers and set the HVAC system into recirculation mode when temperatures are favorable but smoke conditions are especially unhealthy, such as in the early mornings when smoke often settles in valleys. Facilities managers can use air quality sensors to monitor the concentration of air pollutants both indoors and outdoors and use this information to decide how to modulate ventilation settings (see section IV).

40 “What is an Economizer?” *Lawrence Berkeley National Laboratory*, <https://svach.lbl.gov/what-is-an-economizer/>; “Air Handling and Distribution,” in *2020 ASHRAE*, 4.8; “Guide to Operating and Maintaining EnergySmart Schools,” *US Department of Energy*, 23.

41 “Improving Ventilation and Indoor Air Quality During Wildfire Smoke Events,” *Washington State Department of Health*, 1.

Demand-control ventilation measures the indoor air quality so that the HVAC system is ventilating only when the concentration of certain indoor pollutants surpasses target levels. Particularly as a result of the COVID-19 pandemic, demand-control ventilation systems that monitor carbon dioxide concentrations have become popular, with CO₂ used as a proxy for human exhalation and therefore virus particles in the air.⁴² These systems bring outdoor air into the system when indoor conditions have surpassed the desired levels of the measured air pollutant, requiring filtration through the HVAC system's high efficiency MERV filters. By only running the HVAC system when the indoor air quality requires it and therefore preventing over-ventilation of buildings, these systems can dramatically lower energy expenditures. However, CO₂ and other air pollutant sensors need to be regularly calibrated since they are prone to drift—the slow decrease in the accuracy of readings over a sensor's lifespan—which adds an additional maintenance cost.

During periods of especially smoky outdoor air, increasing the eACH is essential to remove particulate matter that infiltrates into buildings, so facilities managers may consider allowing the fan to run continuously in recirculation mode and increasing the permissible concentration of CO₂ in classrooms to prevent unnecessary intake of outdoor air.⁴³ Public health guidance, especially during the COVID-19 pandemic, has encouraged schools to maintain CO₂ levels below 1000 parts per million (ppm), but when outdoor air quality is poor, facilities managers may consider allowing levels higher than this to reduce the infiltration of particulates from smoke.⁴⁴ To remove these greater concentrations of CO₂ without unnecessarily straining the fan, these systems could ventilate buildings when air quality improves. As with economizers, installing filters with MERV ratings of 13 or higher will reduce the concentrations of particulate matter infiltrating into classrooms through the HVAC system, and indoor air quality sensors may be useful in making decisions about ventilation.

These energy-saving systems, while certainly imperfect under the unique stresses of the fire season, can nonetheless reduce energy consumption throughout the year while offering unmatched protections during wildfire smoke events. When used in combination with electrified heating and cooling technologies such as heat pumps, installing new HVAC systems at more schools across the state and retrofitting existing ones can be made compatible with California's net-zero emissions goals.⁴⁵ The California Energy Commission's Bright Schools Program, which can offer schools up to \$20,000 to pay for technical assistance or building energy audits, may be useful for schools with particularly antiquated systems looking to increase energy efficiency and indoor air quality via HVAC system upgrades specific to their needs.⁴⁶

42 "Demand-Controlled Ventilation," Lawrence Berkeley National Laboratory, <https://svach.lbl.gov/demand-controlled-ventilation/>. These systems can also use volatile organic compounds (VOCs) or PM2.5 sensors as proxies for the byproducts of off-gassing from products inside the building. See also Ji-Hye Kim, "Ventilation and Filtration Control Strategy Considering PM2.5, IAQ, and System Energy," *Atmosphere* 11, no. 11 (September 2020): 1140.

43 "Improving Ventilation and Indoor Air Quality During Wildfire Smoke Events," *Washington State Department of Health*, 1-2. Further research is needed to know at what ambient air quality index for PM2.5 schools should stop intaking outdoor air into their HVAC systems. At what ambient AQI value does the indoor air quality surpass an unhealthy level when the outdoor air is passing through HVAC filters of MERV 13 or greater?

44 Rich Prill, "Why Measure Carbon Dioxide Inside Buildings?" Washington State University Extension Energy Program, 2000. <https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html>

45 Patel et al., *Climate Resilient California Schools*, 20.

46 "Bright Schools Program," *California Energy Commission*, <https://www.energy.ca.gov/programs-and-topics/programs/bright-schools-program>.

Conclusions

- Energy-saving technologies such as economizers and demand-controlled ventilation systems can reduce yearly energy expenditures but may require greater maintenance and attention from building managers to function properly, particularly during wildfire smoke events.

Recommendations

- Schools should consider retro-commissioning preexisting HVAC systems with modern technologies such as economizers and demand-controlled ventilation to increase their energy efficiency using available state and federal funds.
- Schools that currently do not have HVAC systems but are seeking to install them should follow the state's General Education Code guidelines, which mandate the use of high MERV filters and energy efficient technologies for new construction.⁴⁷
- School facilities managers should modulate the ventilation of HVAC systems during periods of unhealthy wildfire smoke and allow their fans to run continuously on recirculation mode in order to increase the eACH and filtration of airborne particulates in classrooms.

⁴⁷ Cal. Educ. Code § 17002(d)(1).

https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=EDC&division=1.&title=1.&part=10.&chapter=12.&article=1.

III. PORTABLE HEPA FILTERS

Because of their high filtration capacity, relatively low energy demands compared to HVAC systems, and ease of installation, portable high-efficiency particulate air (HEPA) filters are an important supplemental intervention to improve indoor air quality and protect student health. Though ASHRAE standards classify HEPA systems as MERV 16 filters, they undergo more specific testing to ensure that they are highly efficient at removing fine and ultrafine particles. Consequently, they can be useful supplements to the filtration that HVAC systems can provide. While HVAC filters with a MERV rating of 13 remove at least half of the particulate matter between 0.3 and 1.0 μm in diameter, HEPA filters must remove at least 99.97% of 0.3 μm particles—the most penetrating particle size and most difficult for filters to remove. The removal of larger and smaller particles is therefore much more efficient than an HVAC system’s filtration.⁴⁸

Since all HEPA filters are bound to the same filtration efficiency standards, ratings of HEPA filters are often presented using the clean air delivery rate (CADR), which estimates a device’s effectiveness in reducing the concentrations of common aerosols in a given space. Utilizing the manufacturer’s assumptions of the maximum room size, these figures quantify the volume of clean air that the filter is able to deliver in units of cubic feet per minute (CFM). Often, manufacturers will test the CADR for different types of pollutants—including fine dust, pollen, and smoke (typically measured using tobacco smoke).⁴⁹ The Association of Home Appliance Manufacturers (AHAM), which certifies the reliability of room air cleaners, recommends that the CADR of an air cleaner be no less than two-thirds of a room’s area in square feet (e.g., if a room is 1000 ft^2 , the filter’s CADR rating should be at least 667 cfm).⁵⁰

While the standard testing of HEPA filters typically does not consider the context of wildfire smoke events, recent literature has validated their efficacy in these contexts as well. A review of the scientific literature by the CDC’s National Center for Environmental Health found that many studies concluded that the use of HEPA filters resulted in reduced levels of particulate matter, both $\text{PM}_{2.5}$ and PM_{10} , while some also noted decreases in other pollutants found in wildfire smoke such as volatile organic compounds (VOCs) and carbon monoxide (CO). These studies focused on the ability of HEPA filters to reduce concentrations of $\text{PM}_{2.5}$ indoors and minimize its effects on health outcomes such as blood pressure and asthma morbidity.⁵¹ Since the AHAM certifies commercially available HEPA filters to a high standard, all devices with certification will provide similarly high levels of filtration and, if used in a room of the correct size and maintained with proper filters, health protections. Because of the broad diversity of manufacturers producing HEPA filters, their sizes and energy consumption can vary widely (see Appendix 1).

48 “What is a MERV rating?” *United States Environmental Protection Agency*, February 27, 2023.

49 “Frequently Asked Questions about Testing of Portable Air Cleaners,” *Association of Home Appliance Manufacturers*, September 14, 2020.

50 “Air Filtration Standards,” *Association of Home Appliance Manufacturers Verifide*, <https://ahamverifide.org/ahams-air-filtration-standards/>.

51 Joseph et al., “Evidence on the Use of Indoor Air Filtration,” 14-20.

It is also important to note that, while true HEPA devices utilize mechanical filters to remove materials from the air, certain filters may contain a so-called ionizer or electrostatic filtration, which utilizes electric fields to kill viruses, bacteria, mold, or other biological contaminants. Popularized during the COVID-19 pandemic as a way to kill the SARS-CoV-2 virus, this filtration method produces ozone—a widely known respiratory irritant—and other toxic byproducts of airborne particles. Public health organizations and the California Air Resources Board (CARB) have consequently discouraged their use in any indoor spaces.⁵² Many filters that contain both true HEPA filtration and ionizers allow users to disable the ionizer, typically with no reductions in the output of filtered air and perhaps lowering overall energy usage.

While they are a useful tool to reduce indoor concentrations of wildfire smoke pollutants, HEPA air purifiers are nonetheless not likely adequate replacements for well-maintained HVAC systems. Given the building standards for HVAC systems that require adequate air movement per person, including when the system is in recirculation mode, HVAC systems are better suited to treat the entire volume of room air than even the largest HEPA filters. Furthermore, portable HEPA filters are not suited for larger spaces, particularly gymnasiums or multipurpose rooms, and classrooms with specific needs such as science labs. Though there is little, if any, data on the lifespan of these air purifier devices, they likely will not last longer than even the shortest-living type of HVAC units—wall-mounted package units, which typically have a maximum lifespan of fifteen years—given their less durable designs. HEPA filters can instead be used as temporary bandaids while schools plan for HVAC installation or upgrades to particularly old or inefficient systems or as a supplement to HVAC systems in classrooms to provide the greatest degree of protection from wildfire smoke and other air pollutants.



52 “Hazardous Ozone-Generating Air Purifiers,” *California Air Resources Board*, <https://ww2.arb.ca.gov/our-work/programs/air-cleaners-ozone-products/hazardous-ozone-generating-air-purifiers>; Joseph et al., “Evidence on the Use of Indoor Air Filtration,” 12; “Air Purifiers Fact Sheet,” *University of Massachusetts Amherst Environmental Health & Safety*, December 12, 2021, <https://ehs.umass.edu/air-purifiers-fact-sheet>.

Though they may not be adequate substitutes for HVAC systems in the long-term, portable HEPA filters can nonetheless be useful during wildfire smoke events by increasing filtration and eACH. Given their mobility, HEPA filters can be moved to classrooms with the greatest infiltration of particulate matter from wildfires, particularly when using air quality monitors indoors to assess needs across a school (see section IV). Schools can also use more than one HEPA filter device in each classroom to help meet the goal of 5-6 eACH and to cover the area of larger classrooms in which one filter would not suffice. Since they are less costly to purchase initially and to maintain throughout their lifespan, these devices may be particularly useful for schools that do not have the funding for immediate HVAC retro-commission or upgrade projects but want to provide partial protections in the interim. Finally, as table A1.1 shows, many of these filters can provide high levels of filtration with relatively low energy consumption given their reliance on mechanical filtration. These filters can therefore provide necessary reductions in exposure to wildfire smoke in schools without a high energy cost.

Conclusions

- HEPA filters provide levels of filtration greater than typical HVAC filters with MERV ratings of 13 or greater, removing more than 99.97% of particulates of even the most difficult-to-filter sizes.
- Emerging scientific evidence suggests that HEPA filters can remove particulate matter and other air pollutants from wildfire smoke and therefore can mitigate their health effects.
- Portable HEPA filter units best serve rooms with floor areas of up to 1500 ft² and will likely provide insignificant filtration for large rooms—especially those with high ceilings such as gymnasiums.
- Relying entirely on HEPA filters is likely an inadequate intervention for wildfire smoke, particularly on the smokiest days of the year.

Recommendations

- Schools should utilize HEPA filters to maintain adequate eACH during smoky days, whether in conjunction with well-maintained HVAC systems or as a temporary intervention to filter particulates in schools without adequate HVAC systems.
- Schools should never utilize HEPA filters with ionizers or other electrostatic technologies that produce ozone and instead seek out so-called “true HEPA” filters certified by the AHAM.
- For buildings with poor air filtration or in especially large rooms, schools should consider utilizing more than one HEPA filter in each classroom to ensure adequate eACH.
- Facilities managers and/or teachers should be trained to properly deploy and maintain portable HEPA filters across schools to ensure their maximum benefit.

IV. MONITORING WITH AIR QUALITY SENSORS

Indoor air quality sensors may be useful decision-making tools for schools during wildfire smoke events, particularly to determine the infiltration of smoky air and how to allocate resources between buildings or classrooms. Due to their growing affordability and availability to the public, low-cost air pollution monitors such as those manufactured by PurpleAir and IQAir can be used to monitor either indoor or outdoor air for specific air pollutants such as PM_{2.5} and CO₂. The South Coast Air Quality Management District (AQMD) has tested dozens of low-cost air quality sensors, both in laboratory and field settings, to determine the reliability of these sensors, and accurate and precise monitors are available at a wide range of costs.⁵³ Air quality monitors such as PurpleAir often need a “conversion factor” to make their readings more comparable to the air quality index (AQI) that the US EPA’s AirNow website displays.⁵⁴ According to the EPA, indoor air monitors should be installed in the “breathing zone”—that is, the height where a typical adult’s mouth and nose are when they are sitting or standing, usually between three and six feet above the ground—and away from windows, doors, or other potential pollutant sources.⁵⁵

The additional information that indoor and outdoor air quality monitors located on school sites provide may assist facilities managers of individual schools or school districts in better preparing for and responding to wildfire smoke events. By comparing the IAQ to the air quality outdoors, schools can determine the infiltration factor—that is, the ratio of outdoor to indoor concentrations of pollutants such as PM_{2.5}—of each classroom or building. Characterizing the infiltration of outdoor air pollutants into classrooms, including during periods of healthier air quality, would allow schools to develop plans to allocate resources to buildings with especially poor indoor air quality and to build a use case for more expensive but effective upgrades, such as HVAC systems.⁵⁶ For instance, classrooms with the highest infiltration of ambient pollutants on days where unhealthy air quality is not generated by wildfire could be prioritized for HEPA filters so that, when wildfires begin and smoke infiltrates into those spaces, their occupants are better protected.

During wildfire smoke events themselves, school facilities managers can use particulate matter readings from these sensors to inform their decision-making in real time. Facilities managers can use information about PM_{2.5} both outdoors and in classrooms to determine when to close the outdoor intake of air in HVAC systems and therefore only to recirculate air within the classroom. Similarly, readings of unhealthy concentrations of CO₂ in classrooms (for instance, at twice the recommended concentration, or 2000 parts per million) could encourage schools to allow more ventilation in certain buildings, which may require moving HEPA filters to neutralize the particulates that may be introduced through HVAC systems with lower MERV filters. Particulate matter monitors may also provide useful

53 “Air Quality Sensor Performance Evaluation Center,” *South Coast Air Quality Management District*, <http://www.aqmd.gov/aq-spec/evaluations/summary-pm>.

54 See AirNow, *United States Environmental Protection Agency*, [AirNow.gov](http://airnow.gov). Josh Hug, “Understanding PurpleAir vs. AirNow.gov Measurements of Smoke Pollution,” *The Bold Italic*, August 21, 2020, <https://thebolditalic.com/understanding-purpleair-vs-airnow-gov-measurements-of-wood-smoke-pollution-562923a55226>.

55 Low-Cost Air Pollution Monitors and Indoor Air Quality, *US Environmental Protection Agency*, <https://www.epa.gov/indoor-air-quality-iaq/low-cost-air-pollution-monitors-and-indoor-air-quality>.

56 Marissa Hauptman et al., “The hazards of wildfire smoke exposure for children,” *Current Problems in Pediatric and Adolescent Health Care* 50, no. 2 (February 2020): 100756.



readings to help determine when HVAC systems or portable HEPA filters are not filtering particles adequately and may need to be checked. In addition to considering occupancy, facilities managers can use hyperlocal readings of outdoor air quality to determine when wildfire smoke pollutants are lowest and therefore when to ventilate buildings to remove pollutants released from indoor sources. Schools without their own air quality sensors can determine the indoor air quality based on local air quality readings using a conservative estimate that about half of the PM_{2.5} from the exterior will infiltrate into buildings.⁵⁷

The accuracy and reliability of readings are key considerations for schools when considering installing air quality monitors. Perhaps the most important factor when calculating AQIs from low-cost portable air sensors is the choice of averaging period—that is, the length of time over which the sensor averages air quality readings to provide more accurate and less variable values. While the averaging period of the EPA's outdoor AQI readings can vary, particularly during events like wildfires with rapidly changing conditions, low-cost air filters such as PurpleAir and IQAir allow users to change the averaging periods when viewing readings. The EPA recommends utilizing a daily or hourly averaging period for outdoor air quality sensors to account for variability in readings and to make them more comparable to nearby regulatory stations.⁵⁸ However, Josh Hug, professor of computer science and data science at UC Berkeley, has shown that an averaging period of 10 minutes typically allows users to observe rapid fluctuations in air quality conditions more readily than the EPA's AirNow readings do.⁵⁹ Though no specific guidance exists for indoor air quality, these recommendations may reasonably apply to the use of low-cost sensors indoors as well. Additional research is needed to address the gaps in knowledge about indoor air quality monitoring and recommendations for the implementation of these filters in schools. Furthermore, like the CO₂ monitors on demand-controlled ventilation systems, the accuracy of these sensors typically diminishes over time, requiring additional maintenance in order to calibrate and cross-reference these readings with other sensors.

The most notable shortcoming of monitoring indoor air quality is certainly that little, if any, guidance currently exists about what levels of PM_{2.5} are acceptable indoors and therefore what the limit on particulate matter levels in schools should be. While ventilation experts and public health officials have recommended that CO₂ not surpass 1000 ppm in classrooms, neither the California and federal EPAs nor public health departments have issued recommendations for permissible levels of indoor PM_{2.5}. The World Health Organization's (WHO) 2021 update to its Global Air Quality Guidelines recommends a limit of 15 µg/m³ of PM_{2.5} for short-term (24-hour) exposures and of 5 µg/m³ for long-term (annual) averages given the emerging evidence of the harms of air pollution globally.⁶⁰ Previous iterations of that report have argued that these standards could be used for both indoor and outdoor air quality standards, therefore making this a potentially useful starting point for guidelines for indoor air quality.⁶¹ The US EPA's 24-hour standard for

57 This estimate assumes that a school has an older HVAC system that will prevent many particles from entering and that gravity will cause some of those that enter a building to settle out of the air. For instance, if the exterior AQI is 200 according to the closest AirNow reading, it is not unreasonable to assume that the indoor AQI could be around 100 at the highest. This estimate may allow schools to determine when to deploy portable HEPA filters or change the intake on HVAC systems just as indoor and outdoor air quality sensors would. Woody Delp, interview with author, February 27, 2023.

58 "A Guide to Siting and Installing Air Sensors," *US Environmental Protection Agency*, <https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors>.

59 Hug, "Understanding PurpleAir vs. *AirNow.gov* Measurements of Smoke Pollution."

60 World Health Organization, *WHO global air quality guidelines* (2021), <https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y>, 78 and 88.

61 World Health Organization, *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide* (2005), https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1, 10.

ambient particulate pollution of $35 \mu\text{g}/\text{m}^3$ or the “good” category of the Air Quality Index (representing an AQI of less than 50) may also be useful starting points for indoor air quality standards. However, these daily-averaged standards are unlikely to be useful for schools in making decisions in practice. Understanding how these recommendations translate to readings with 10-minute or one-hour averaging periods that may be more useful for schools is an important area for future research. Considerably more guidance from federal and state agencies is therefore needed on what constitutes healthy or acceptable indoor air quality.

Conclusions

- Low-cost sensors can provide schools with additional information about local outdoor air quality and indoor conditions within individual classrooms.
- There is currently little guidance specific to the operation and uses of indoor air quality monitors, particularly in regards to monitoring wildfire smoke.
- Indoor and outdoor air quality readings may allow schools to build a use case for grants for infrastructure upgrades, particularly HVAC systems.

Recommendations

- Schools should use indoor air quality readings to determine whether particular classrooms or buildings with greater levels of particulate matter need additional filtration, particularly by moving portable HEPA filters into those rooms.
- Schools should use information from indoor and outdoor air quality monitors before wildfire smoke events occur to determine which rooms have greater outdoor air infiltration and therefore to develop an indoor air quality protection plan that can be implemented during wildfire days.
- Schools generally should use a one-hour running average of measurements for both indoor and outdoor air quality readings and should only utilize shorter averaging periods when wildfire smoke conditions are changing rapidly. When doing so, school officials should also note the overall trend in wildfire smoke pollutants.
- Facilities managers can use both indoor and outdoor air quality readings to alter the operation of HVAC systems during poor air quality days, including by setting systems to recirculation mode or closing dampers on economizer or demand-controlled ventilation systems.

V. SUMMARY

Given the historic federal and state investments in school infrastructure to protect indoor air quality while reducing energy consumption, schools in California have a unique opportunity to prepare for worsening wildfires. To accomplish these goals simultaneously, schools will need to prioritize HVAC systems and HEPA filters in these retrofitting or installation projects. Installing HVAC systems with sufficient fan capacity to accommodate a filter with a MERV of 13 or higher and modern, energy-saving technologies provide the greatest potential for improvements in both indoor air quality and energy consumption. Given their portability and high filtration efficiency, HEPA filters can be used to remove additional particulate matter from rooms experiencing particularly high levels of wildfire smoke infiltration and to increase the number of eACH where more air movement is necessary. Air quality monitors placed both indoors and outdoors can help school administrators and building managers make better-informed decisions about resource allocation and maintenance during wildfire smoke events, particularly when conditions are changing quickly. A decision map tool is available in Appendix 2 for schools hoping to upgrade their infrastructure based on the current status of their HVAC systems and their budget for such projects.

In order to maximize the health and energy-saving benefits of these upgrades, school districts should develop plans for the proper use and maintenance of these systems during both normal and smoky conditions. With such an indoor air quality protection plan, schools will ensure that they enter wildfire season prepared to withstand smoke and distribute the work of monitoring these symptoms among staff members so as not to unduly burden facilities managers during these emergencies. Further research on this topic should consider statewide policies or grant programs to incentivize or fund upgrades to school infrastructure in order to make both healthy indoor air quality and energy efficiency more attainable for California's schools.

Final Recommendations

- Schools and districts should prioritize energy efficiency and indoor air quality when applying for federal and state grant monies for infrastructural upgrades.
- Schools and districts should develop a plan for how to properly operate and maintain indoor air systems that includes how schools will: alter HVAC operation to prevent unnecessary intake of smoky, outdoor air while ensuring adequate air movement; monitor and replace filters on HVAC and portable HEPA systems; and shuffle resources to buildings or classrooms where indoor air quality monitoring indicates they are necessary.
- To better understand the quality of the air that students are breathing, the California State Legislature should fund the implementation of a statewide dashboard of indoor and outdoor low-cost air quality sensors at schools similar to the one in Boston, Massachusetts.⁶²

62 Indoor Air Quality (IAQ) Sensor Dashboard, Boston Public Schools, <https://www.bostonpublicschools.org/Page/8810>.

- In addition to allocating more money for infrastructure upgrades, the California Department of Education and State Legislature should provide public schools and districts with more funding to hire and train facilities managers to properly maintain and operate complex equipment such as HVAC systems, HEPA filters, and IAQ monitors.⁶³

Table 2: Resources to Find Federal and State Funding

Agency	Name	Description	URL
California Energy Commission	California Energy Commission Programs	List of resources in the state of California for energy efficient building construction and retrofitting.	https://www.energy.ca.gov/programs-and-topics/programs
US Department of Energy	Federal and State Resources	List of federal and state resources for energy efficient building upgrades.	https://www.energy.gov/eere/buildings/federal-and-state-resources
	Renew America's Schools	Resources for schools looking to increase energy efficiency, including grant opportunities.	https://www.energy.gov/scep/renew-americas-schools
US Environmental Protection Agency	Air Grants and Funding	Grants and funding for air quality improvement projects, including for schools.	https://www.epa.gov/grants/air-grants-and-funding
Grants.gov	Grant Programs	Federal clearinghouse for all grants and loans available. Use search terms such as "energy efficient," "indoor air quality," and "school upgrades" to locate possible programs.	https://www.grants.gov/

A list of possible funding sources to finance indoor air quality and wildfire resilience upgrades for schools. The landscape of these resources changes rapidly, and these websites provide detailed information about current and future funding opportunities.

⁶³ For an example of training for facilities managers that could be adapted specifically to the context of TK-12 schools, see "PG&E Energy Centers," PG&E, https://www.pge.com/en_US/small-medium-business/business-resource-center/training-and-education/energy-centers.page.



APPENDIX 1: COMPARISONS OF FILTRATION CAPACITY AND ENERGY CONSUMPTION IN HEPA FILTERS

Air purification devices with HEPA filters are certified by the Association of Home Appliance Manufacturers (AHAM) to filter the vast majority of particles of even the most difficult to remove sizes, but there is notable heterogeneity of filtration capacity and energy consumption between manufacturers and models. Furthermore, since these devices are often marketed to homeowners, many of the commercially available ones have recommended room areas that are far smaller than the typical classroom. Supplemental Table 1 shows examples of HEPA filters marketed for larger rooms that may be better suited for classrooms. As a measure of energy efficiency, the final column gives the estimated filtration per unit energy consumed, calculated by dividing the CADR rating (using the smoke rating, when available, given in cfm) by the energy consumption at maximum speed in watts (W). Additional data about the recommended room size, eACH, and upfront cost of purchasing that filter (as given by the manufacturers on their websites) are also given to allow schools to determine which models may be best suited for the needs of each classroom.

Table A1.1: Examples of HEPA Filters Currently Available

Name (full price)	Maximum Recommended Room Area (ft ²)	(Smoke) CADR (ft ³ /min)	Approx. eACH (at max room area)	Energy Consumption, at max speed (W)	Filtration per unit energy (cfm/W)
Levoit Core 600S Smart True HEPA Air Filter (\$299.99)	625	410	5	49	8.367
Blueair Classic 605 (\$829.99)*	775	500	4.8	100	5.000
RabbitAir SPA-780A (\$599.95)	815	180	2	61	2.951
Medify Air MA-40 Air Purifier (\$349.00)*	840	226	2	68	3.324
Medify MA-112 (\$800.00)*	865	546	4.8	95	5.747
Alen BreatheSmart HEPA Air Purifier (\$649.00)*	1100	300	2	105	2.857
IQAir HealthPro Plus (\$899.00)	1125	300	5	135	2.222
Alen BreatheSmart 75i True HEPA Air Purifier (\$749.00)*	1300	347	2	45	7.711
HATHASPACE Smart Air Purifier (\$549.99)	1500	450	1	100	4.500
Coway Airmega 400S (\$749.00)	1560	328	2	66	4.970

Air filtration and energy specifications of ten examples of HEPA filters that are recommended for larger spaces, including classrooms.

* = contains an ionizing feature that can be disabled

Note that the maximum recommended room area and effective air changes per hour (eACH) are inversely proportional, so increasing one would decrease the other. For instance, a filter for a room of 1000 ft² that provides 2 eACHs could instead be used in a 500 ft² space with 4 eACH or in a 2000 ft² space with only 1 eACH.

APPENDIX 2: DECISION MAKING TOOL FOR SCHOOLS

Because of the complexity of air filtration and ventilation systems, many school administrators and facilities managers may not know where to begin their upgrades. The decision tool below offers schools guidance on where to begin infrastructure upgrades to protect against wildfire smoke based on the recommendations in this report. The report has argued that HVAC systems are *the* key piece of infrastructure that can protect indoor air quality and reduce energy consumption, and the tool takes the age and functionality of a school's current HVAC infrastructure as its starting point. More recently installed systems will need fewer interventions to offer adequate protections, assuming that they were constructed to state education code standards, whereas schools with very old systems may not offer significantly better protections than school buildings without heating or cooling systems at all if they are not bringing an adequate volume of air into the building as recommended by the ASHRAE. The cutoff between newer and older HVAC systems is drawn from recommendations from HVAC consultants about the recommended lifespan of commercial HVAC systems before they should be retrofitted or altogether replaced with more efficient technologies.⁶⁴

For older systems and HEPA filters, the tool also distinguishes between more and less expensive options depending on the availability of grant funds to pay for more extensive upgrades and purchase replacement filters in bulk. The cutoff used in this decision map (\$2,750) is meant to be a rough average of the costs across the state that assumes the Medify Air MA-40 HEPA filter and the PurpleAir Touch Indoor Air Quality Monitor (both being state of the art and moderately priced in 2023) as examples and takes into account not only the price of equipment but also quarterly filter replacement and labor costs over a five-year period.⁶⁵ This report recognizes that many, if not most, schools do not have this amount of money available for each classroom and gives several options to reduce costs, including choosing cheaper filters and indoor air quality monitors. As the lower budget option in the decision map shows, schools could also reduce costs by reducing the number of portable HEPA filters that schools need to purchase and maintain or limiting the use of those HEPA filters to the wildfire season, therefore reducing how often filters need to be replaced. To get a better sense of the cost of portable HEPA filters and air quality monitors, a budget tool is available to determine approximate costs of purchasing these systems given a school's requirements.⁶⁶ Recommendations for HEPA filters are similar across schools regardless of the current condition of their HVAC systems, though schools in areas with greater wildfire impact, particularly wildland-urban interface (WUI) zones, and those without HVAC systems at all should consider using the higher budget recommendations until more extensive upgrades can be made to their HVAC systems.

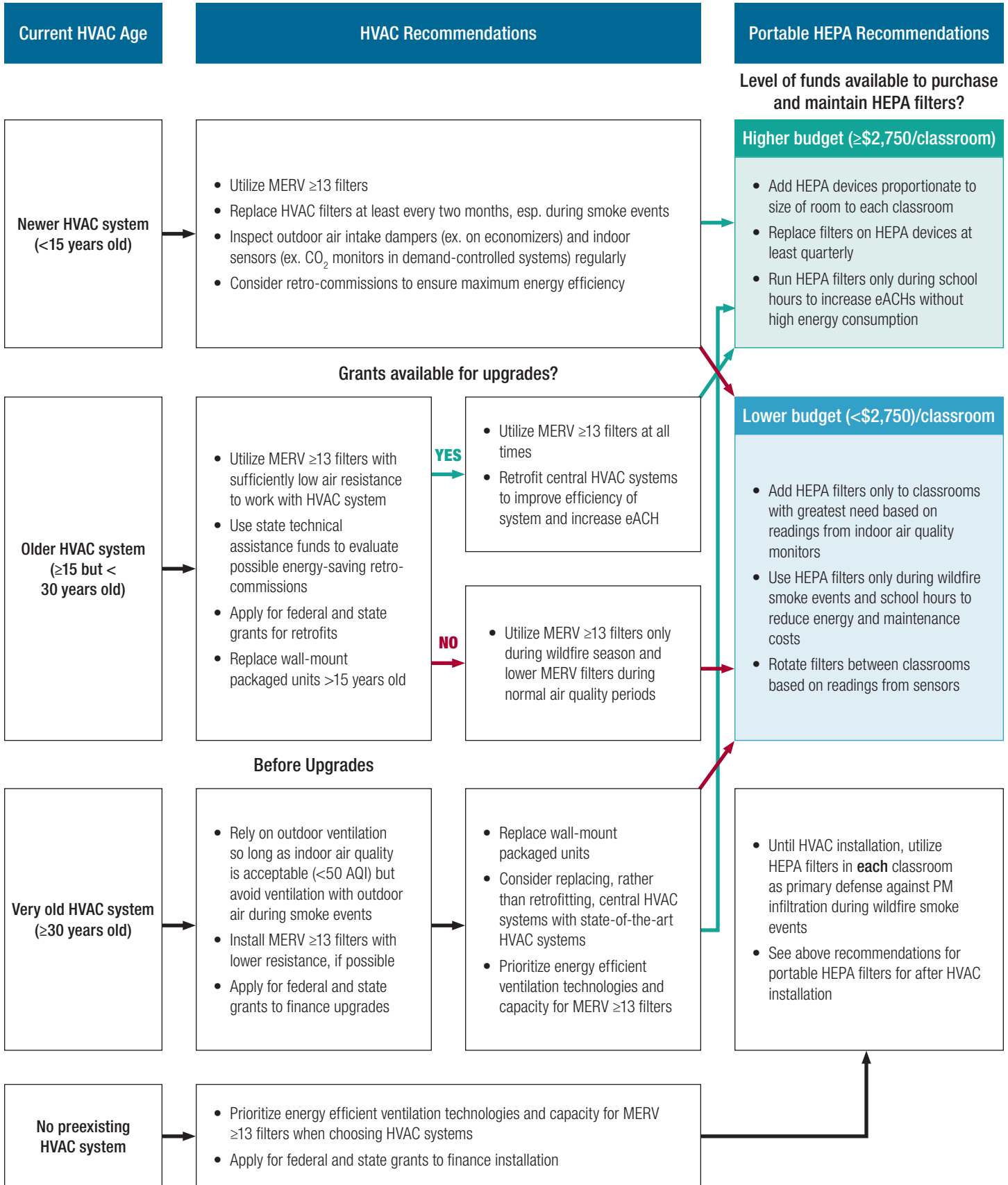
64 "When to Replace Your Commercial HVAC System," *Oliver Heating & Cooling*, <https://www.oliverheatcool.com/about/blog/mechanical-service-experts/when-to-replace-your-commercial-hvac-system/>; "6 Signs It's Time to Replace Your Commercial HVAC System," *The Cooling Company*, July 1, 2019, <https://thecoolingco.com/6-signs-its-time-to-replace-your-commercial-hvac-system/>; "Commercial HVAC Repair vs. Replace Decisions: What to Consider When Making the Call," *CMI Mechanical HVAC & Refrigeration*, <https://coloradomechanical.com/commercial-hvac-repair-vs-replace-considerations/>.

65 The calculation for this decision map also assumes that the cost of energy is California's average (\$0.31/kWh), filters are running for 8 hours per day and 9 months out of the year, and a labor cost of \$30/hour.

66 Isobel Anwyn Nairn and Greg Zegas, "LAW808D Policy Practicum: Smoke: Wildfire Science and Policy Lab Final Paper," Autumn 2022. See also their Google Sheets form to generate cost estimates for air quality monitoring and portable HEPA filters: https://docs.google.com/spreadsheets/d/17ypWc1rL3yOxiZ5nVmsQwK3urEIG15FL_Si6AJ92Ubw/edit#gid=0

For schools with very old HVAC systems, the acceptable ambient air quality index recommendation is derived from the US EPA's recommendations that an AQI of 50 or greater is "moderate" and may pose a risk for some people who are especially sensitive to air pollution, such as children. Because students are exposed to this indoor air throughout the day, it is important to keep this indoor air quality within the "good" zone of an AQI less than 50.⁶⁷ Schools should also use indoor and outdoor air quality sensors to get a better sense of particulate infiltration during wildfire smoke events to fine tune the measures that they should take. This decision tool is meant to be a starting point for upgrades to and maintenance of air quality filtration and ventilation infrastructure to prepare for wildfire smoke events. For more detailed information about each type of system and recommendations for how to operate these systems during wildfires for maximum protections, see the corresponding sections of the report.

67 See section IV of the report for a more complete rationale for this recommendation. "Air Quality Index (AQI) Basics," *AirNow*, <https://www.airnow.gov/aqi/aqi-basics/>.





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This report was produced by the Climate and Energy Policy Program (CEPP) within the Stanford Woods Institute for the Environment. CEPP operates at the interface of policy analysis, academic research and education, with a focus on informing decision making on climate and energy law and regulation. For more information visit:

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