*Revised to include Labor Partners

BOARD OF EDUCATION OF THE CITY OF LOS ANGELES
GOVERNING BOARD OF THE LOS ANGELES UNIFIED SCHOOL DISTRICT

GREENING SCHOOLS & CLIMATE RESILIENCE COMMITTEE

333 South Beaudry Avenue, Board Room Los Angeles, CA 90017
4:00 p.m., Wednesday, March 26, 2025

Committee Members

Dr. Rocío Rivas, Chairperson
Ms. Sherlett Hendy Newbill, Board Member
Mr. Scott Schmerelson, Board Member

District Members

Krisztina Tokes, Chief Facilities Executive
Christos Chrysiliou, Chief Eco-Sustainability Officer
Jay Golida, Associate General Counsel

Board Secretariat Contact

Ebony Wilson
Tel: (213) 241-7002
Email: ebony.wilson@lausd.net

External Representatives

Lauren Ahkiam, Los Angeles Alliance for New Economy (LAANE)
Gloria Medina, Strategic Concepts in Organizing and Policy Education, SCOPE
David McNeill, Baldwin Hills Conservancy

Method for Accessing the Meeting and Providing Public Comment

There are three ways members of the public may access this Committee Meeting: (1) online (Granicus stream or join the zoom webinar), (2) by telephone by calling 1-888-475-4499 (Toll Free) and entering the Meeting ID: **815 1855 9131**, or (3) in person.

The Board of Education encourages public comment on the items on this agenda and all other items related to the District. Any individual wishing to address the Board must register to speak using the Speaker Sign Up website: https://boardmeeting.lausd.net/speakers, and indicate whether comments will be provided over the phone or in person. Registration will open 24 hours before the meeting. **15** speakers may sign up for general Public Comment, and each speaker will have **two** minutes to present. Each speaker will be allowed a single opportunity to provide comments to the Committee.

Speakers who do not register online to provide comments may use the following alternative methods to provide comments to Board Members:

- Email all Board Members at boardmembers@lausd.net;
- Mail comments via US Mail to 333 S. Beaudry Ave., Los Angeles, CA 90017; and
- Leave a voicemail message at (213) 443-4472, or fax (213) 241-8953. Communications received by 5 p.m. the day before the meeting will be distributed to all Board Members.

Speakers registered to provide public comments over the phone need to follow these instructions:

1. Call 1-888-475-4499 (Toll Free) and enter Meeting ID: **815 1855 9131** at the beginning of the meeting.
2. Press #, and then # again when prompted for the Participant ID.
3. Remain on hold until it is your turn to speak.
4. Call in from the same phone number entered on the Speaker Sign Up website. If you call in from a private or blocked phone number, we will be unable to identify you.
5. When you receive the signal that your phone has been removed from hold and/or unmuted, please press *6 (Star 6) to be brought into the meeting.

The Office of the Inspector General would like to remind you that they investigate the misuse of LAUSD funds and resources as well as retaliation for reporting any misconduct. Anyone can make a report via the OIG hotline on their website (https://www.lausd.org/oig), by telephone at 213-241-7778, or by emailing inspector.general@lausd.net. Reports are confidential, and you can remain anonymous if you wish.

Please contact the Board Secretariat at 213-241-7002 if you have any questions.

AGENDA

I. Welcome and Opening Remarks .... Dr. Rocío Rivas
Chairperson

II. Labor Partners

III. Presentations

a. Eco-Sustainability Office Updates .... Christos Chrysiliou
Chief Eco-Sustainability Officer

b. Maintaining Clean Air, Meeting Climate Goals, and
Student Achievement Wildfire Remediation Recommendations .... Fernando Ochoa
Political Director
SMART Local 105

Jeremy Zeedyk,
Special Projects Coordinator
Western States Council of SMART

Chris Ruch
Codes and Standards Representative
Western States Council of SMART

c. Cultivating Growth
The Impact of the Mindful Gardeners .... Esmeralda Marquez Garcia
Student, 8th Grade
Griffith STEAM Magnet Middle School

Victoria Chavez
Student, 7th Grade
Griffith STEAM Magnet Middle School

Hailey Heredia
Student, 6th Grade
Griffith STEAM Magnet Middle School

Mariah Lezo
Student, 9th Grade
Garfield High School

Nayeli Santos Torija
Student, 6th Grade
Griffith STEAM Magnet Middle School

Antonieta Garcia
Parent
Griffith STEAM Magnet Middle School

Stephanie Montoya
MSW Intern
Griffith STEAM Magnet Middle School

Christine Mariano
Psychiatric Social Worker
Griffith STEAM Magnet Middle School

IV. Public Comment

V. Adjournment

Requests for disability related modifications or accommodations shall be made 24 hours prior to the meeting to the Board Secretariat by calling (213) 241-7002.

Materials related to an item on this agenda distributed to the Board of Education are available for public inspection at the Security Desk on the first floor of the Administrative Headquarters, and at: https://www.lausd.org/boe#calendar73805/20250321/event/73509

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TAB 1

ECO-SUSTAINABILITY OFFICE

Greening Schools and Climate Resilience Committee Meeting

Christos Chrysiliou, FAIA, LEED AP
Chief Eco-Sustainability Officer

March 26, 2025

Sotomayor Magnet - From soil to structure: Climate literacy through Ado

Agenda

ESO Updates

- Solar Program Update
- Eco-Sustainability Plan
- Climate Literacy Updates

Canoga Park High School Solar Photovoltaics

LAUSD Eco-Sustainability Mission and Goals

Mission

The Los Angeles Unified School District is committed to being the most sustainable and environmentally-friendly large urban school district in the country.

Goals

Clean Energy

Transition LAUSD to 100% clean, renewable, energy resulting in healthier students and more sustainable, equitable, communities

Green Schools for All

Establish a minimum standard of 30% green space for all campuses

Climate Literacy

Enact a comprehensive Climate Literacy Program for LAUSD

Solar PV Program – Current

Overview

- School Sites: **63**
- Total System Capacity: **19 MW**
- Cumulative Energy Production (FY14-24): **240,244,703 kWh**
- General Fund Cost Avoidance (FY14-24): **$47.8 m**
- PV System Types:
  - Carport
  - Shade Structures
  - Rooftop

San Pedro High School Olguin Campus

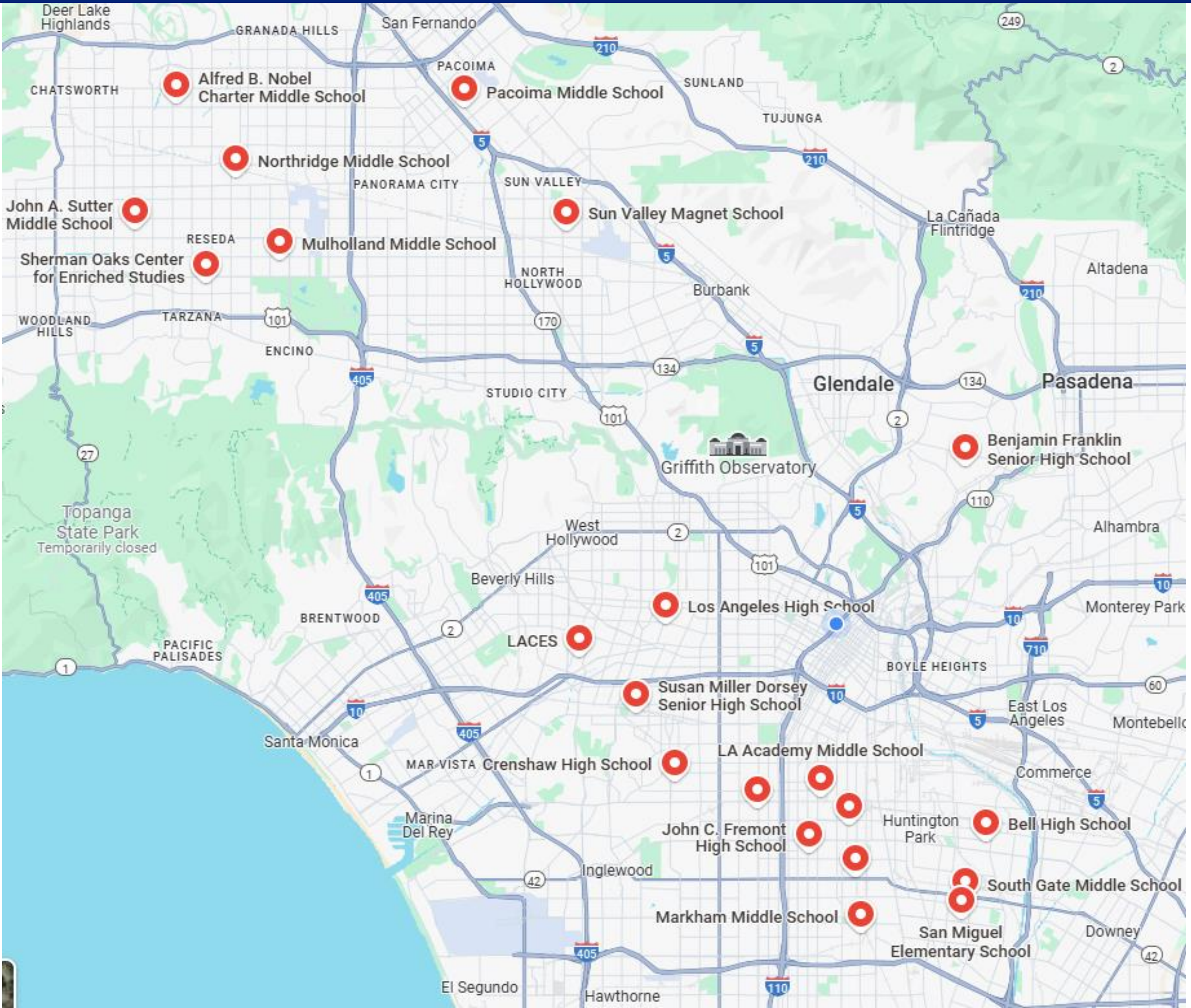
Solar PV Program

Program Updates

On February 11, 2025, the Board of Education authorized the design and installation of 21 Solar Photovoltaic (PV) projects. These projects will:

- Enable the District to significantly offset its energy costs over the 25-year equipment life of the PV systems
- Support District's goal to achieve 100% clean, renewable energy in its electricity sector by 2030 and in all energy sectors, including heating, ventilation, air conditioning (HVAC), cooking, and transportation, by 2040
- Installed within two different utility provider service areas, LADWP and SCE, to determine various delivery methods that could offer the greatest benefit for the PV system installations
- Provide an educational opportunity for students to learn about clean renewable energy technologies and real-world energy issues thereby furthering STEM education at these campuses

Solar PV Program – 21 School Sites



Overview

- Total System Capacity: **15 MW**
- Capital Budget: **$122.4 m**
  - Design, Construction, Management
- General Fund Budget: **$9.9 m**
  - O&M Services, Performance Guarantee
- Energy Production (25 Yrs.): **$178 m**
- Net Cost Avoidance (25 Yrs.): **$45.7 m**
- General Fund Cost Avoidance (25 Yrs): **$168 m**

Scope

- Rooftop, Carport and Shade Structures
- Level 2 EV Chargers at 13 sites
- Sites with new roofs or upcoming roof projects

Solar PV Program – Scope, Budget, Schedule

#	BD	REGION	School	PV* System Size (MW)	EV* Qty.	Project Budget	Est. 25 Yr. **Net Cost Avoidance	Est. 25 Yr. **General Fund Cost Avoidance	Const. Start	Const. End
1	5	East	Bell HS	0.959	0	$7,274,924	$4,453,097	$11,728,021	Q4-25	Q3-26
2	1	South	Crenshaw Magnet HS	1.207	12	$9,300,587	$5,237,009	$14,537,596	Q4-25	Q3-26
3	1	South	Dorsey HS	0.846	0	$6,862,632	$2,582,505	$9,445,137	Q3-26	Q1-27
4	7	South	Drew MS	0.691	8	$5,723,453	$2,086,869	$7,810,322	Q4-26	Q3-27
5	7	South	Edison MS	0.631	9	$5,215,047	$2,205,976	$7,421,023	Q4-26	Q3-27
6	2	East	Franklin HS	0.763	0	$6,529,607	$2,533,690	$9,063,297	Q4-25	Q3-26
7	7	South	Fremont HS	1.390	17	$10,296,032	$5,187,324	$15,483,356	Q4-26	Q3-27
8	7	East	Los Angeles Acad. MS	0.791	0	$6,117,889	$2,707,075	$8,824,964	Q4-26	Q3-27
9	1	South	Muir MS	0.612	0	$4,855,984	$1,944,445	$6,800,429	Q3-26	Q1-27
10	3	North	Northridge MS	0.674	2	$4,888,613	$2,084,279	$6,972,892	Q3-25	Q2-26
11	6	North	Pacoima MS	0.588	2	$4,237,615	$2,080,710	$6,318,325	Q3-25	Q2-26

**PV = Photovoltaic; EV = Electric Vehicle Chargers/Infrastructure*

***Net Cost Avoidance considers Bond funded project costs and General Fund Cost Avoidance does not.*

Solar PV Program – Scope, Budget, Schedule

#	BD	REGION	School	PV* System Size (MW)	EV* Qty.	Project Budget	Est. 25 Yr. Net Cost Avoidance	Est. 25 Yr. General Fund Cost Avoidance	Const. Start	Const. End
12	4	North	Sherman Oaks CES	0.527	2	$4,235,022	$1,631,772	$5,866,794	Q4-25	Q3-26
13	6	North	Sun Valley Magnet	0.423	2	$3,038,334	$1,722,549	$4,760,883	Q4-25	Q3-26
14	4	North	Sutter MS	0.510	2	$4,265,486	$1,326,346	$5,591,832	Q4-25	Q3-26
15	1	West	LACES	0.865	4	$7,416,368	$2,536,602	$9,952,970	Q4-25	Q3-26
16	1	West	Los Angeles HS	0.982	0	$7,707,349	$2,471,494	$10,178,843	Q1-26	Q4-26
17	7	South	Markham MS	0.706	5	$7,093,801	$1,052,827	$8,146,628	Q3-26	Q1-27
18	3	North	Mulholland MS	0.556	13	$5,973,080	$508,097	$6,481,177	Q1-26	Q4-26
19	3	North	Nobel Charter MS	0.590	0	$5,032,329	$1,039,133	$6,071,462	Q1-26	Q4-26
20	5	East	San Miguel ES	0.264	0	$1,681,284	$264,340	$1,945,625	Q3-26	Q1-27
21	5	East	South Gate MS	0.441	11	$4,660,987	$183	$4,661,170	Q1-26	Q4-26
			TOTALS:	**15.016**	**89**	**$122,406,423**	**$45,656,323**	**$168,062,746**		

**PV = Photovoltaic; EV = Electric Vehicle Chargers/Infrastructure.*

***Net Cost Avoidance considers Bond funded project costs and General Fund Cost Avoidance does not.*

Solar PV Program – Sample Project Site

Markham Middle School – 706 kW (90% offset of electricity consumption)

Roof Solar Array (typ.)

Carport Solar Array (typ.)

5 EV Charging Stations

Project Budget: $7,093,801

25-Year Cost Data:

Energy Production: $8,458,019

Net Cost Avoidance: $1,052,827

General Fund Cost Avoidance: $8,146,628

Solar PV Power Impact at LAUSD

25-Year Solar Power Generation

21 school sites to generate **15MW of solar energy** or approximately **23 million kWh** per year.

25-Year Total Avoided Energy Consumption:

556 million kWh

25-Year Total Avoided Greenhouse Gas Emissions:

280,000 $MTCO_2e$

That's Like:

Annually	Removing **2,766 personal vehicles** from the road	Enough to power **2,138 homes**	Diverting **4,190 tons of waste** from landfills	The amount of GHG emissions sequestered by **11,895 acres of forestland** or ~3 Griffith Parks

An Integrated Response Across LAUSD Divisions

Innovate! **Elevate!** **Accelerate!**

LAUSD Comprehensive Eco-Sustainability Plan

Supports the development and implementation of sustainable and renewable energy initiatives to reduce the District's carbon and water footprint and to achieve the District's operational efficiency and sustainability goals in alignment with the LAUSD Strategic Plan.

Sustainability Planning Process

Engage → Assess → Develop

12-14 Months

Proposals Received and Under Evaluation:
Anticipated Board Approval: May 2025

Engagement: Spring/Fall 2025

Assessment: Summer 2025

Plan Development: Fall 2025 – Spring 2026

An Eco-Sustainability Plan for all LAUSD

Scope:

- **ASSESS:** Collect and review District data
  - Establish a baseline of information and provide a gap analysis.
  - Identify climate risks and cascading risks
  - Identify infrastructure needs for all sustainability sectors

- **ENGAGE:** Stakeholder Engagement
  - Formulate engagement workplan
  - School/community engagement workshops at school sites
  - Involvement of all LAUSD Divisions

- **DEVELOP:** Development of Comprehensive LAUSD Eco-Sustainability Plan
  - A holistic plan with integrated, actionable solutions for all sustainability sectors. Measures that provide the greatest opportunities for resilience, emissions reductions, and student learning will take the highest priority.
  - Confirmation of Vision, Objectives, Goals, and Criteria for the plan
  - Roadmaps to address LAUSD's high-priority Eco-Sustainability goals and objectives








Eco-Sustainability Sectors

1 — Academic Excellence

Curriculum Integration
- Incorporate sustainability topics into general education and STEAM curriculum and into CTE programs

Climate Literacy
- Develop a comprehensive framework for a Climate Literacy curriculum

2 — Joy + Wellness

Healthy Food Initiatives
- Procurement of sustainable and locally sourced food
- School gardens

Outdoor Education + Greening
- Outdoor learning spaces, gardens, and nature trails to connect students with the environment and foster a sense of stewardship

Air Quality
- Low/No VOC product standards
- Low emission vehicles and fuels
- CO2 Monitors

Climate Resilience
- GHG Emissions Inventory
- Climate Action & Adaptation Plan
- Resiliency Plan
- Environmentally Preferable Purchasing

3 — Engagement Collaboration

Student Leadership
- Empower students to take on leadership roles as climate champions and environmental stewards

Community Engagement
- Partner with local organizations, businesses, government agencies, and the broader community to support sustainability initiatives at schools

4 — Operational Effectiveness

Energy + Water Infrastructure
- Energy Efficiency Projects
- Renewable Energy and Electrification
- Water Efficiency Upgrades
- Stormwater and Grey Water management

Transportation
- Conversion of fleet to hybrid and electric vehicles
- Subsidized transit passes
- Encourage walking, biking, carpooling

Waste Reduction
- Recycling and composting programs
- Minimize single-use plastics + packaging
- Surplus property repurposing/auction
- Construction waste diversion

Monitoring + Evaluation
- Metrics and assessments to track progress towards sustainability goals
- Green Building certifications

5 — Investing in Staff

Professional Development
- Provide training and resources for teachers and staff on sustainability practices and incorporate sustainability into professional development programs

O + M Staff Training
- Green Cleaning Program
- Native Landscape Maintenance Training
- O&M Best Management Practices

Working Group Representatives

Eco-Sustainability Sectors	Suggested Stakeholders/ Areas of Influence
Climate	Energy Services
	Transportation
Air Quality	Transportation
	Environmental Health and Safety
Energy	Energy Manager
	Facilities Director
Water	Utilities Management
	Wastewater Compliance
	Stormwater Compliance
Solid Waste	Solid Waste
	Facilities
Transportation	Transportation
	Fleet Manager
Food & Nutrition	Food Services
	Kitchen Staff
Procurement/Labor Compliance	Purchasing
	Contract & Budgeting Office
Education/ Engagement	Education Services
	Student Council Advisors
Construction	Facilities Management
	Capital Planning
Operations & Maintenance	Operations
	Facilities Management

Eco-Sustainability Priorities Survey

A roadmap to address LAUSD's high-priority eco-sustainability sectors

Sector	Category	Ranking
Climate	• Gas Emissions	
	• Climate Adaptation	
	• Climate Resiliency	
Air Quality	• Indoor Air Quality	
	• Air Pollutant Emissions (i.e.NOx)	
Energy	• Purchased Utilities	
	• On-Site Generation (Co-Generation, Generators, Solar)	
Water	• Potable Water	
	• Wastewater	
Stormwater/ Wastewater	• Stormwater Management	
	• Wastewater	
Solid Waste	• Municipal Solid Waste (Trash, Recycling, Organics)	
	• E-Waste	
	• Hazardous Waste	
	• Construction + Demolition Waste	
Transportation	• School Buses • Fleet Vehicles (white fleet)	
	• Employee Commuting	

Sector	Category	Ranking
Food + Nutrition	• Food Sourcing	
	• Nutrition Standards	
	• Nutrition Education	
Procurement	• Product Specifications	
	• Service Requirements	
	• Contracts	
Education / Engagement	• Sustainability Curriculum	
	• Staff Training	
	• Community Engagement	
Construction	• Sustainable Design Criteria	
	• Green Building Certification (i.e., CHPS, LEED, etc.)	
	• Green Construction Standards	
Operations + Maintenance	• Preventative Maintenance	
	• Building Management Systems	
	• Standard Operating Procedures	
	• Green Cleaning	

Climate Literacy Updates

HEROES for Zero 2023-24 Semi-Finalists, Ernest Lawrence Magnet 7th Grade Class

Overview

- Climate Literacy Task Force Update
- Climate Literacy Task Force Report
- Campus Greening Highlights
- Earth Month 2025

Ernest Lawrence Gifted Magnet 7th Grade Students

Climate Literacy Task Force

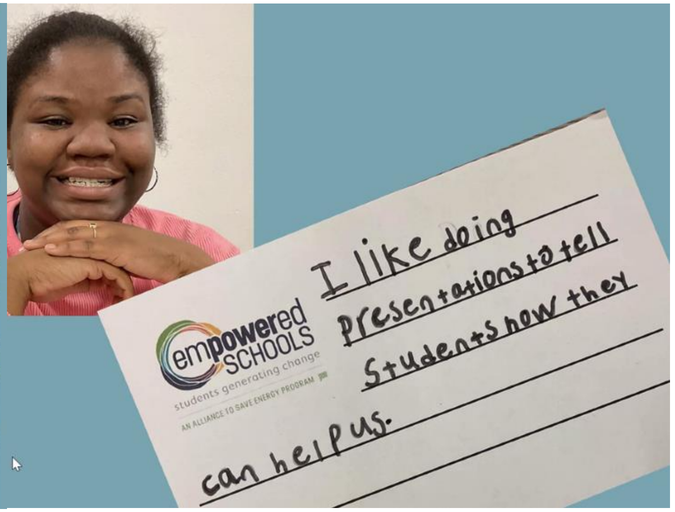

Garden at Jack London Continuation High

Climate Literacy Task Force Timeline

- **Meeting 1** - December 13, 2023 via Zoom
  - Introductions and reviewed Climate Literacy Resolution and LAUSD-UTLA MOU
  - Determined next steps for review of tasks and roles
- **Meeting 2** - February 27, 2024 @ Los Angeles Cleantech Incubator (LACI)
  - Tour of LACI and presentations from partners
- **Meeting 3** - April 16, 2024 @ Sotomayor Magnet
  - Tour of the Agriscience Program and updates on Task Force member findings
- **Public Meeting** – June 12, 2024 via Zoom
  - Shared preliminary recommendations & took comments
- **Meeting 4** – September 25, 2024 via Zoom
  - Draft report outline was shared and task force members began drafting their sections
- **March 2025** - Recommendations Report being finalized
  - For meeting details visit the CLTF website at lausd.org/cltf

Climate Literacy Task Force Report

Climate Literacy Champions '23-'24 professional development at the Tree Peoples Coldwater Canyon site.



CLTF Report Content

- Drafted in collaboration with the DOI & United Teachers of Los Angeles
- Division of Instruction Climate Literacy Champions program and Climate Literacy Leadership Team
- LAUSD Climate Literacy Schoology Group
- Social Emotional Learning (SEL) Programs and Resources
- Career Technical Education (CTE) Pathways
- Eco-Sustainability Office Programs
- Facilities Services Division
- K-12 Linked Learning
- Division of Adult & Career Education
- Stormwater & Water Quality
- Transportation, Solar, & EV Chargers
- Recommendations

Next Steps

- Detailed Report update to be provided at the May 2025 Greening and Climate Resilience meeting
- Issue Date: June 2025

Campus Greening Highlight


Alta California ES

Aeroponic Tower Gardens

- The Aeroponic Tower Garden Pilot Program is funded by the Los Angeles Department of Water and Power
- There are eight participating schools:
  - 20th St. ES
  - 107th St. ES
  - Alta California ES
  - Lake Balboa College Prep Magnet
  - Marina Del Rey MS
  - Polytechnic HS
  - Sotomayor Magnet HS
  - Valley Academy of Arts and Sciences
- The program supplies teachers with:
  - Materials for operating the tower gardens for three years
  - Training and technical support
  - Lifetime curriculum license integrating tower garden plant growth into multi-disciplinary lessons

Earth Month - April

Earth Month 2025 Campaign promotional poster

Earth Month 2025 Campaign

Digital ecosystem for environmental education

- website curriculum & activity hub with LAUSD and partner resources
- student showcase of sustainability efforts
- empowering educational videos for all grade levels

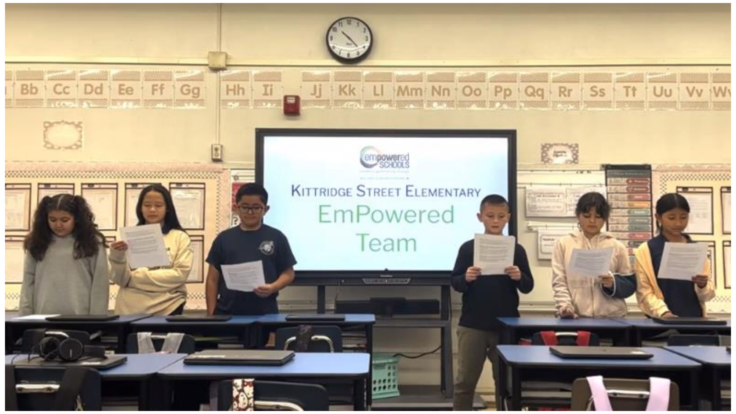
- **Kick off April 1, 2025**
- **The campaign will culminate in a vibrant, in-person celebration at the LAUSD Arts Festival: Saturday, May 3, 2025**
  - ESO and DOI will feature a climate literacy area with an opportunity for students to draw a school garden and families to adopt a tree!

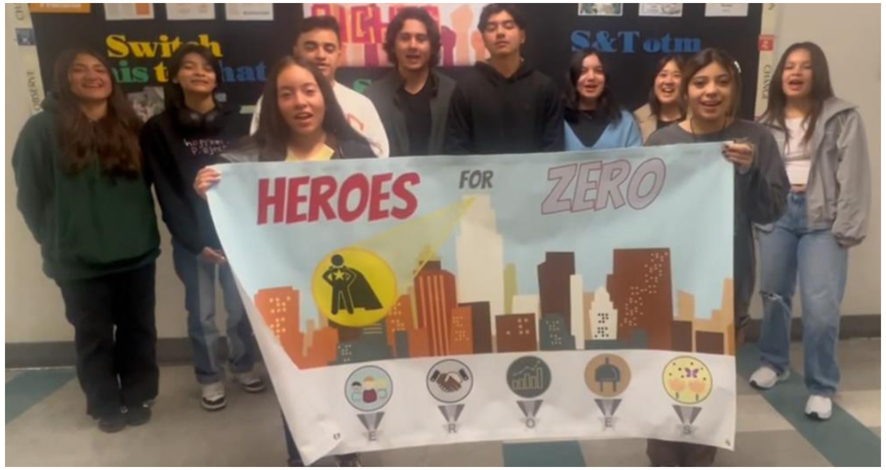
Climate Literacy Creator Highlight

- Incorporating feedback from 2024 to be more engaging
  - Videos about LAUSD and green careers are being created by an **LAUSD John F. Kennedy High School alumnus**. This work contributes to the District's **Climate Literacy** goal, aimed at increasing climate literacy and ensuring all students are 'READY FOR THE WORLD'.

Thank You!

Christos Chrysiliou, FAIA, LEED AP
Chief Eco-Sustainability Officer





TAB 2

RETURN FLEX BEFORE

AFTER

Maintaining Clean Air, Meeting Climate Goals, & Student Achievement - Wildfire Remediation Recommendations

WESTERN STATES COUNCIL OF SMART

MARCH 26, 2025

What is Western States Council of SMART?

“The HVAC Union”

Duct and HVAC Unit Cleaning

During wildfires, lead levels in air briefly increased 110 times just south of Eaton Fire, CDC says

By Denise Dador
Thursday, February 20, 2025

For several days during the fires, lead levels in the air just south of the Eaton Canyon Fire increased roughly 110-fold, a new CDC study shows.

LOS ANGELES (KABC) -- A new study by the Centers for Disease Control and Prevention shows that for several days during the fires, lead levels in the air just south

CDC Morbidity and Mortality Weekly Report (*MMWR*)
Search

Notes from the Field: Elevated Atmospheric Lead Levels During the Los Angeles Urban Fires — California, January 2025

Weekly / February 20, 2025 / 74(5);69–71

Notes from the Field

Elevated Atmospheric Lead Levels During the Los Angeles Urban Fires — California, January 2025

Haroula D. Baliaka[1]; Ryan X. Ward[1]; Roya Bahreini[2]; Ann M. Dillner[3]; Armistead G. Russell[4]; John H. Seinfeld[1]; Richard C. Flagan[1]; Paul O. Wennberg[1]; Nga L. Ng[4]

On January 7, 2025, the Eaton Canyon and Palisades fires blazed across the Los Angeles region, driven by exceptionally dry conditions and Santa Ana wind gusts approaching 100 mph (161 kph). The fires spread rapidly into densely populated neighborhoods along the wildland-urban interface, destroying approximately 16,000 structures. As of February 10, 2025, a total of 29 deaths had been identified.* In addition to the deaths and destruction of property, wildfires emit a complex mixture of air pollutants and contribute to elevated concentrations of fine particulate matter ($PM_{2.5}$; particulate matter with a diameter <2.5 μm), degrading air quality many miles downwind. Exposure to wildfire $PM_{2.5}$ has been linked to adverse health effects including increased asthma cases, respiratory symptoms, aggravated respiratory diseases, and increased overall mortality (*1–3*). Unlike conventional wildfires that primarily burn natural fuels (e.g., grasslands or forests), the Eaton Canyon and Palisades fires ignited significant portions of the built environment, in which painted surfaces, pipes, vehicles, plastics, electronic equipment, and the structures themselves became the fuel. This widespread combustion of synthetic materials has increased concerns about the toxicity of $PM_{2.5}$, because a large proportion of the structures affected by the fires were built before 1978, when use of leaded paint was still common. This report focused on measuring airborne $PM_{2.5}$ lead during the Los Angeles urban fires.

Investigation and Outcomes

The Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT)† is a new, nationwide, multi-institutional initiative funded by the National Science Foundation, to provide continuous measurements of $PM_{2.5}$ chemical components (organics, inorganics, metals, and black carbon) across 12 sites in the United States, including seven urban and five remote or rural areas.§ All ASCENT sites were operating and sampling ambient air as of May 2024.

The Los Angeles ASCENT site in Pico Rivera, approximately 14 miles (23 kilometers) south of the Eaton Canyon fire, has been operating since July 2023. During and immediately after the Los Angeles fires, southward winds transported the fire plume to the ASCENT site. Hourly $PM_{2.5}$ lead measurements recorded during and after the fires were reviewed to assess their contribution to atmospheric lead levels. Because this analysis consists of a review of routinely collected environmental data and does not include human subjects, human subjects review was not required by the authors' institutions.

During January 2–6, 2025, the average $PM_{2.5}$ lead concentration recorded at the Los Angeles ASCENT site was 0.00068 $\mu g/m^3$. From January 8 to January 11, $PM_{2.5}$ lead concentration increased approximately 110 times with an average concentration of 0.077 $\mu g/m^3$ (Figure). Recorded $PM_{2.5}$ lead concentration peaked at approximately 0.5 $\mu g/m^3$ on January 9. By the evening of January 11, $PM_{2.5}$ lead concentration had returned to levels similar to those before the fire. The presence of heavy metals such as lead is not unusual in urban fire emissions, particularly in California, where legacy pollutants from older infrastructure, industrial sources, and soils can be remobilized during fires (*2,4*). For example, during the 2018 Camp fire, monitors recorded ambient $PM_{2.5}$ lead concentrations that averaged 0.13 $\mu g/m^3$ during a period of 17 hours (*2*).

Few data illustrate the health effects of lead from inhalation compared with other exposure routes. The ASCENT real-time measurements of airborne lead and other chemical constituents in $PM_{2.5}$ provide valuable $PM_{2.5}$ chemical composition data that can be combined with health data to examine health effects of individual smoke components from the Los Angeles fires.

Preliminary Conclusions and Actions

Lead is a toxic air contaminant that is distributed in multiple human tissues and accumulates in teeth and bones; it affects nearly every organ system, posing significant health risks, particularly for children, who are more vulnerable to its neurodevelopmental effects (*2,3,5*). Regulatory efforts, especially the U.S. Clean Air Act of 1970, have resulted in a sharp decline in airborne lead levels during the past 45 years.¶ The current National Ambient Air Quality Standard for lead in total suspended particles over a 3-month rolling average is 0.15 $\mu g/m^3$.** Measures including removing lead from gasoline

* https://www.fire.ca.gov/incidents/ (Accessed February 10, 2025).
† https://ascent.research.gatech.edu/
§ The seven urban areas are Atlanta, Georgia; Denver, Colorado; Houston, Texas; Los Angeles, California; New York, New York; Pittsburgh, Pennsylvania, and Riverside, California. The five remote or rural areas include Alaska, Cheeka Peak/Makah in Washington, and the Great Smoky Mountains, Joshua Tree, and Yellowstone National Parks.
¶ https://www.epa.gov/laws-regulations/summary-clean-air-act
** https://www.epa.gov/lead-air-pollution/national-ambient-air-quality-standards-naaqs-lead-pb

ARIZONA - CALIFORNIA - HAWAII - NEVADA
SMART WESTERN STATES COUNCIL

$PM_{2.5}$

$PM_{2.5}$ - Particulate Matter that is 2.5 microns (µg)

- **$PM_{2.5}$ is small enough to reach deep into the lungs (alveoli)**

Filters

MERV 8 Filters only remove ~50% of $PM_{2.5}$
MERV 13 Filters remove ~85% of $PM_{2.5}$

Table 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, µm			
	Range 1 0.30 to 1.0	Range 2 1.0 to 3.0	Range 3 3.0 to 10.0	Average Arrestance, %
1	N/A	N/A	$E_3 < 20$	$A_{avg} < 65$
2	N/A	N/A	$E_3 < 20$	$65 \le A_{avg}$
3	N/A	N/A	$E_3 < 20$	$70 \le A_{avg}$
4	N/A	N/A	$E_3 < 20$	$75 \le A_{avg}$
5	N/A	N/A	$20 \le E_3$	N/A
6	N/A	N/A	$35 \le E_3$	N/A
7	N/A	N/A	$50 \le E_3$	N/A
8	N/A	$20 \le E_2$	$70 \le E_3$	N/A
9	N/A	$35 \le E_2$	$75 \le E_3$	N/A
10	N/A	$50 \le E_2$	$80 \le E_3$	N/A
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$	N/A
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$	N/A
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$	N/A
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	N/A

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Asthma

Asthma is the most common childhood chronic disease in the United States, affecting more than 6 million (or nearly 1 in 13) school aged children[1,2]. Asthma is also a leading cause of absenteeism, resulting in about 13.8 million missed school days annually. [3]

Increasingly, studies link air pollution and poor indoor air quality exposure with the exacerbation of Asthma symptoms. [4,5]

However, evidence suggests that replacing inefficient filters with higher-efficiency filters can reduce the asthma burden. [6]

(1) Environmental Protection Agency. (2022, December 5). Why Indoor Air Quality is Important to Schools. EPA.
(2) "The Links Between Air Pollution and Childhood Asthma," US Environmental Protection Agency, 2018
(3) Zahran et al., "Vital Signs: Asthma in Children - United States, 2001-2016," 2018.
(4) EPA, Environmental Protection Agency
(5) Centers for Disease Control and Prevention. (2022, August 11). Hierarchy of controls. Centers for Disease Control and Prevention.
(6) Sheena E. Martenies and Stuart A. Batterman, "Effectiveness of Using Enhanced Filters in Schools and Homes to Reduce Indoor Exposures to PM2.5 from Outdoor Sources and Subsequent Health Benefits for Children with Asthma," Environmental Science & Technology 52, no. 18 (2018): 10767- 76

Health Benefits – Children Susceptibility

Students in the US spend about 1,000 hours per year at school, second only to their homes. (1)

"Children's bodies are different from adults' bodies. They are more likely to get sick or severely injured. They breathe in more air per pound of body weight than adults do." (2)

"The mean breathing rate over the first 12 years of life is almost twice as great relative to adult breathing rates" (3)

(1) Drew DeSilver, "School Days: How the US Compares with Other Countries," Pew Research Center, 2014
(2) Centers for Disease Control and Prevention. (2020, September 1). How are children different from adults? Centers for Disease Control and Prevention. Retrieved April 23, 2023
(3) Miller, Mark D., et al. "Differences between children and adults: implications for risk assessment at California EPA." International journal of toxicology 21.5 (2002): 403-418

Portable Air Cleaners?

- **Clean Air Delivery Rate (CADR) sizing**
- **Noise and power consumption**
  - ✓ According to ASHRAE, permanent central systems are more efficient than portable air cleaners however, in-room air cleaners can be supplemental when a central system cannot achieve the recommended objectives. (1)
- **Need for ongoing maintenance**
  - ✓ Air purifiers distributed during the pandemic often lack proper maintenance, with filters not replaced regularly. (2)
- **Potential for cross-contamination**
  - ✓ Air Cleaners can cause particles that haven't been filtered out to spread farther than they would if the cleaner wasn't there. (3)
- **Limitations to compounds that are filtered**

(1) ASHRAE . (2021). ASHRAE Position Document on Filtration and Air Cleaning - Developed by the Society's Filtration and Air Cleaning Position Document Committee.
(2) Fellowes. (2024), December 18). Educators speak out: 2024 survey on Classroom Air Quality . Fellowes Blog. https://fellowesblog.com/2024/12/17/educators-speak-out-2024-survey-on-classroom-air-quality/
(3) Salmonsmith, J., et al. (2025). The influence of mechanical ventilation and portable air cleaners upon aerosol spread in a hospital outpatients clinic. Aerosol Science and Technology. Doi.org/10.1080/02786826.2024.2446587.

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COMMENTARY

Facing wildfires and pandemics, California must invest in ensuring clean air in schools

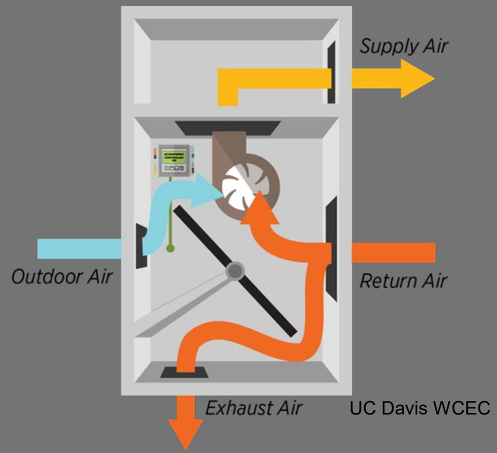
"Before the pandemic, schoolchildren in California had started to miss an increasing number of school days due to wildfires. Schools close for evacuation or because they lack the protocols and infrastructure to keep indoor air quality safe during poor air quality days."

"Learning loss and lost school days are a growing problem in California, with counties like Sonoma seeing upwards of 40 cumulative days lost. Since the state began collecting data in 2003, wildfires have accounted for two-thirds of school closures through 2018."

Are HVAC units achieving design intent and energy efficiency goals?

Before, During, and After an event.

What was the planned response during the recent wildfires?



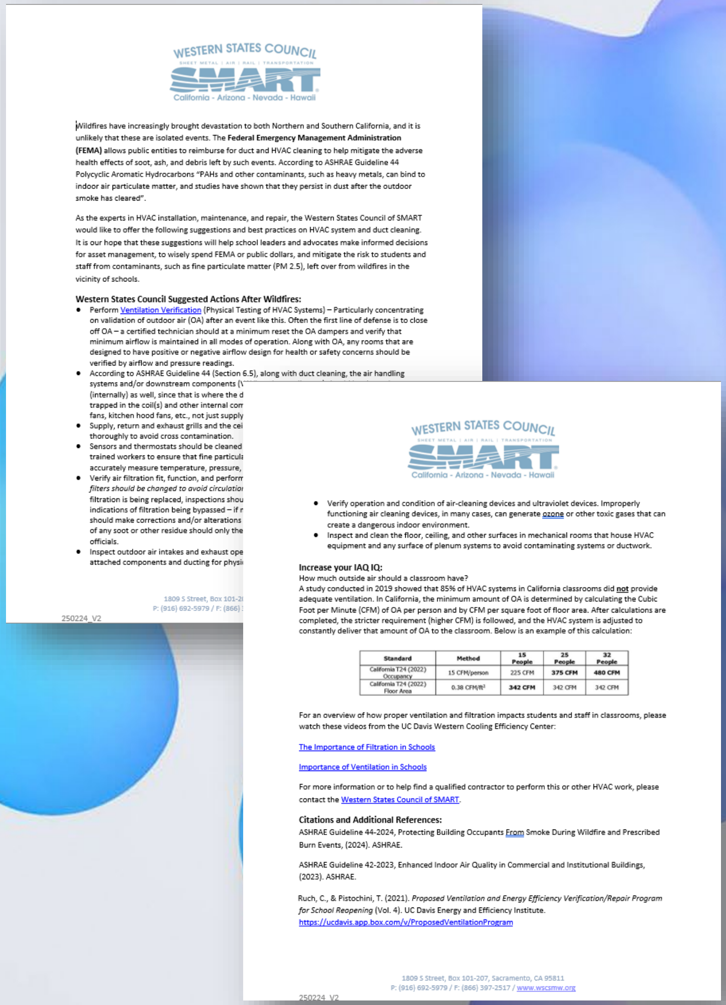
UC Davis WCEC

(1) Chan, et al, Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation, Building and Environment Journal 167 (2020)

(2) Commentaries, E. (2023, June 28). Commentary: Facing wildfires and pandemics, California must invest in ensuring clean air in schools. https://edsource.org/2021/facing-wildfires-and-pandemics-california-must-invest-in-ensuring-clean-air-in-schools/658730

Wildfire Remediation Recommendations

- **Step 1:Remediate HVAC Systems**
  - ✓ Units
  - ✓ Ducts
  - ✓ Filters
  - ✓ Sensors
- **Step 2: Ventilation Verification**
  - ✓ Identify Adjustments, Repairs, Replacements, or Upgrades
- **Step 3: Develop Emergency Mode(s)**
  - ✓ Utilizing ASHRAE Guideline 42, 44 & Standard 241
- **Step 4: Ongoing Maintenance**
  - ✓ Utilizing ASHRAE 62.1 Table 8.1



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Wildfires have increasingly brought devastation to both Northern and Southern California, and it is unlikely that these are isolated events. The **Federal Emergency Management Administration (FEMA)** allows public entities to reimburse for duct and HVAC cleaning to help mitigate the adverse health effects of soot, ash, and debris left by such events. According to ASHRAE Guideline 44 Polycyclic Aromatic Hydrocarbons "PAHs and other contaminants, such as heavy metals, can bind to indoor air particulate matter, and studies have shown that they persist in dust after the outdoor smoke has cleared".

As the experts in HVAC installation, maintenance, and repair, the Western States Council of SMART would like to offer the following suggestions and best practices on HVAC system and duct cleaning. It is our hope that these suggestions will help school leaders and advocates make informed decisions for asset management, to wisely spend FEMA or public dollars, and mitigate the risk to students and staff from contaminants, such as fine particulate matter (PM 2.5), left over from wildfires in the vicinity of schools.

Western States Council Suggested Actions After Wildfires:

- Perform Ventilation Verification (Physical Testing of HVAC Systems) – Particularly concentrating on validation of outdoor air (OA) after an event like this. Often the first line of defense is to close off OA – a certified technician should at a minimum reset the OA dampers and verify that minimum airflow is maintained in all modes of operation. Along with OA, any rooms that are designed to have positive or negative airflow design for health or safety concerns should be verified by airflow and pressure readings.
- According to ASHRAE Guideline 44 (Section 6.5), along with duct cleaning, the air handling systems and/or downstream components (\
  (internally) as well, since that is where the d
  trapped in the coil(s) and other internal com
  fans, kitchen hood fans, etc., not just supply
- Supply, return and exhaust grills and the cei
  thoroughly to avoid cross contamination.
- Sensors and thermostats should be cleaned
  trained workers to ensure that fine particula
  accurately measure temperature, pressure,
- Verify air filtration fit, function, and perform
  filters should be changed to avoid circulation
  filtration is being replaced, inspections shou
  indications of filtration being bypassed – if r
  should make corrections and/or alterations
  of any soot or other residue should only the
  officials.
- Inspect outdoor air intakes and exhaust ope
  attached components and ducting for physi

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- Verify operation and condition of air-cleaning devices and ultraviolet devices. Improperly functioning air cleaning devices, in many cases, can generate ozone or other toxic gases that can create a dangerous indoor environment.
- Inspect and clean the floor, ceiling, and other surfaces in mechanical rooms that house HVAC equipment and any surface of plenum systems to avoid contaminating systems or ductwork.

Increase your IAQ IQ:
How much outside air should a classroom have?
A study conducted in 2019 showed that 85% of HVAC systems in California classrooms did **not** provide adequate ventilation. In California, the minimum amount of OA is determined by calculating the Cubic Foot per Minute (CFM) of OA per person and by CFM per square foot of floor area. After calculations are completed, the stricter requirement (higher CFM) is followed, and the HVAC system is adjusted to constantly deliver that amount of OA to the classroom. Below is an example of this calculation:

Standard	Method	15 People	25 People	32 People
California T24 (2022) Occupancy	15 CFM/person	225 CFM	**375 CFM**	**480 CFM**
California T24 (2022) Floor Area	0.38 CFM/ft²	**342 CFM**	342 CFM	342 CFM

For an overview of how proper ventilation and filtration impacts students and staff in classrooms, please watch these videos from the UC Davis Western Cooling Efficiency Center:

The Importance of Filtration in Schools

Importance of Ventilation in Schools

For more information or to help find a qualified contractor to perform this or other HVAC work, please contact the Western States Council of SMART.

Citations and Additional References:

ASHRAE Guideline 44-2024, Protecting Building Occupants From Smoke During Wildfire and Prescribed Burn Events, (2024). ASHRAE.

ASHRAE Guideline 42-2023, Enhanced Indoor Air Quality in Commercial and Institutional Buildings, (2023). ASHRAE.

Ruch, C., & Pistochini, T. (2021). *Proposed Ventilation and Energy Efficiency Verification/Repair Program for School Reopening* (Vol. 4). UC Davis Energy and Efficiency Institute. https://ucdavis.app.box.com/v/ProposedVentilationProgram

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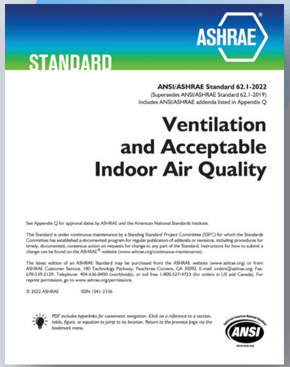
Minimum Ventilation



Sample requirement for a 900 square foot classroom

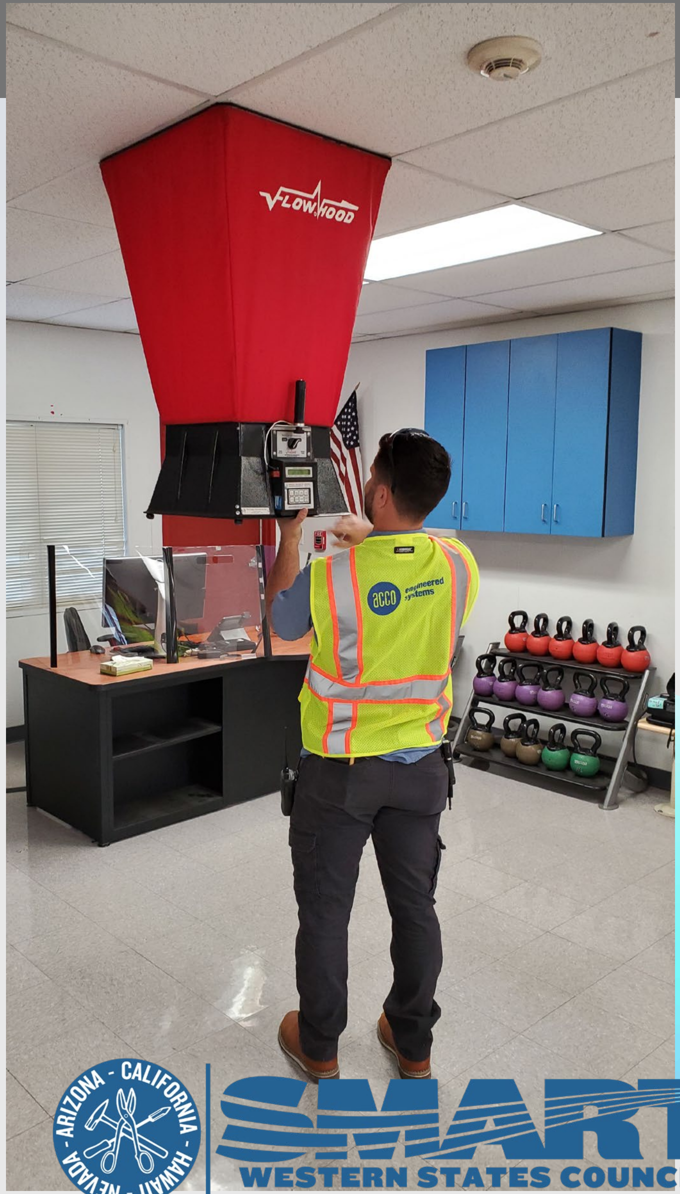
Standard	Method	15 People	25 People	35 People
ASHRAE 62.1 (2022)	$10\ CFM/person + 0.12\ CFM/ft^2$	258 CFM	358 CFM	458 CFM
California T24 (2022) Occupancy	$15\ CFM/person$	225 CFM	**375 CFM**	**480 CFM**
California T24 (2022) Floor Area	$0.38\ CFM/ft2$	**342 CFM**	342 CFM	342 CFM

CFM = Cubic Feet per Minute

(1) American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2022). Ventilation for acceptable indoor air quality: ASHRAE Standard 62.1 - 2022.
(2) International Code Council, 2022 California Energy Code: California code of regulations, Title 24, part 6 (2022). Washington, D.C.

Airflow & Pressure

- ✓ Ensure airflow patterns are measured, verified, and documented to provide maximize distribution and mixing but minimize occupant exposure to particles.
- ✓ Room pressure differentials and directional airflow help control airflow between zones.



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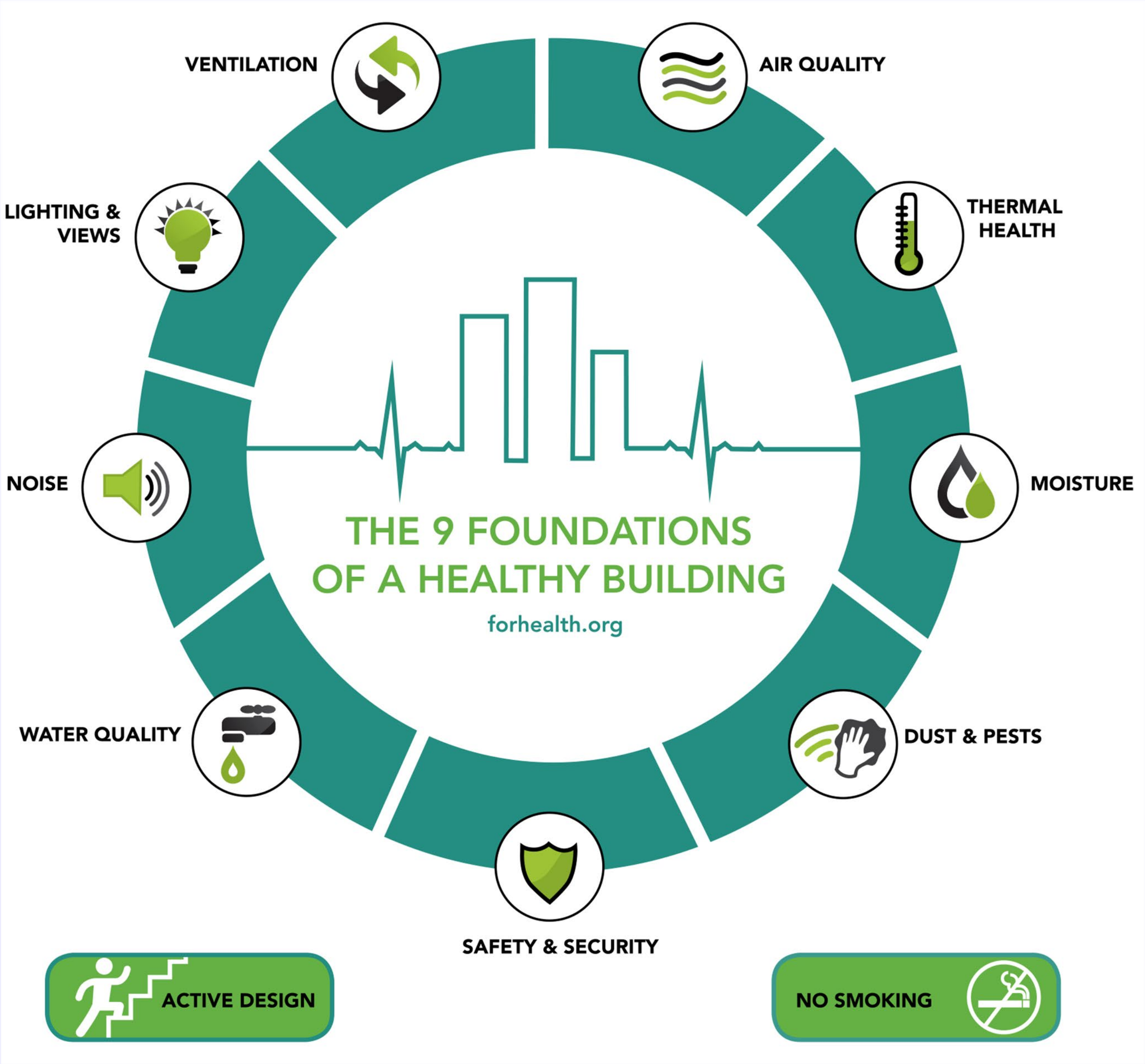
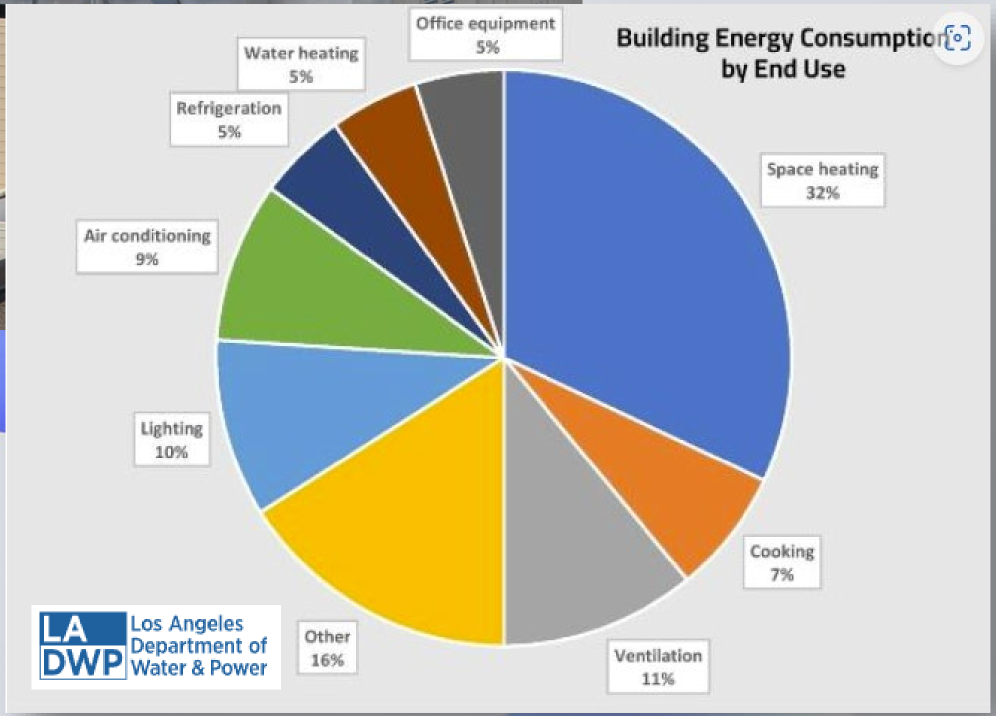


Source: forhealth.org
https://9foundations.forhealth.org/

Co-Benefits

Simultaneously achieving energy and health benefits

HVAC and Energy



- HVAC systems account for **52% of the energy** used in US K-12 schools. (3)
  - Compared to 11% for lighting

(1) Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS) Data
(2) Department of Energy September 2015, An Assessment of Energy Technologies and Research Opportunities, Ch.5: Increasing Efficiency of Building Systems and Technologies
(3) Emma Hines and Sara Ross, HVAC Choices for Student Health and Learning: What Policymakers, School Leaders, and Advocates Need to Know, RM I and Undaunted K12, 2023

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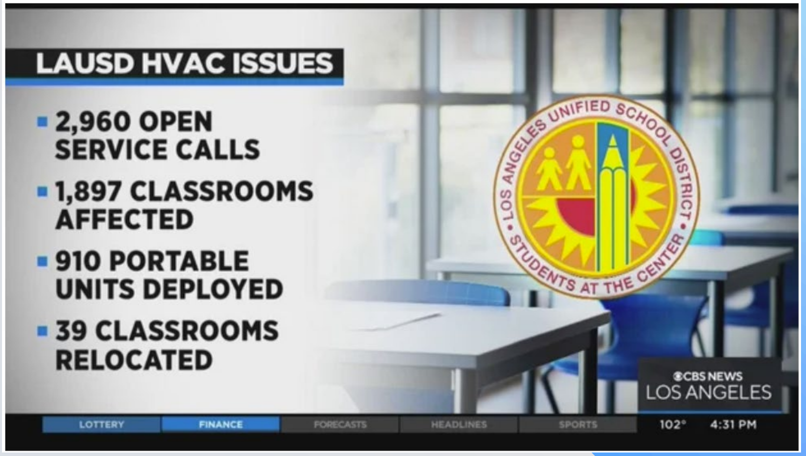
Results of Repairs, Adjustments and Upgrades

- Efficiency retrofits after energy audits can typically **reduce energy bills up to 30%** (1)
- Comprehensive retrofits can **reduce commercial building energy use up to 50%.** (2)



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(1) Department of Energy. 2013. Energy Saver 101 Infographic: Home Energy Audits. August 15. energy.gov/articles/energy-saver-101-infographic-home-energy-audits.
(2) York, D., S. Nadel, E. Rogers, R. Cluett, S. Kwatra, H. Sachs, J. Amann, and M. Kelly. 2015. New Horizons for Energy Efficiency: Major Opportunities to Reach Higher Electricity Savings by 2030. Washington, DC: ACEEE. P. 145
(3) Staff, K. N. (2022, September 2). *LAUSD struggling to keep aging A/C units on in some classrooms as temps continue to spike*. CBS News.

Health Benefits - Absenteeism

Indoor Air Quality

Study of over 3,000 individuals across 40 buildings found that that **57% of sickness** and **35% of short-term sick leave** can be **attributed to poor ventilation**. (1)

Educational Facility

A study of 162 classrooms for two years found a **1.6% decrease in absence** for each 2 cfm per person increase in ventilation rate. (2)

Increasing the ventilation rates of the classrooms to the state standard would **decrease illness absence rates by 3.4%.** (2)

(1) Milton DK, Glencross PM, Walters MD. Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints. Indoor Air. 2000 Dec;10(4):212-21. doi: 10.1034/j.1600-0668.2000.010004212.x. PMID: 11089326.

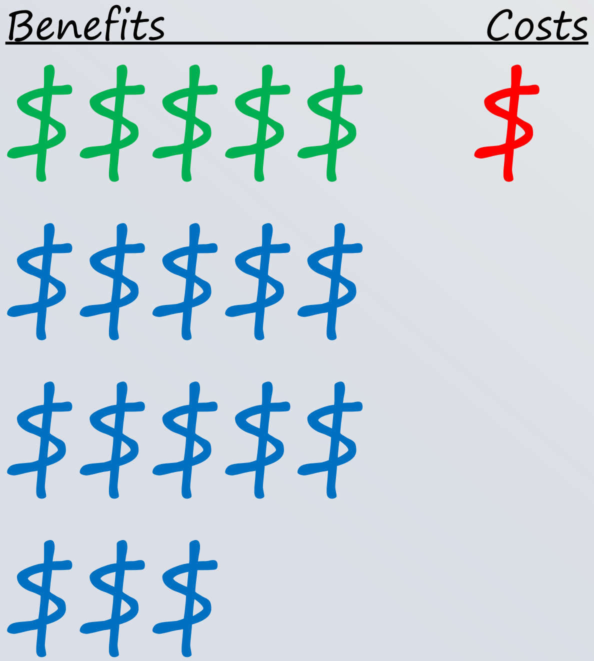
(2) Mendell MJ, Eliseeva EA, Davies MM, Spears M, Lobscheid A, Fisk WJ and Apte MG. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. Indoor Air 2013; 23: 515-528D.K.

Economic Benefits of Increasing California Classroom Ventilation Rates

If Current Average of 8.5 CFM per person was raised to Meet Code Requirement of 15 CFM per person

$33 million increase in school district revenue

$80 million reduction in care-giver costs



$6 million increase in energy cost

(1) Mendell et al. (2016) Indoor Air, 26: 546–557.

Student Performance

- 8 studies reported statistically **significant improvements** in some measures of **student performance** associated with increased ventilation rates or lower CO_2 concentrations, with performance **increases up to 15%.** (1)

- A 2007 paper published in the International Journal of Ventilation showed a **5% decrease in the "power of attention"** in classrooms with poor ventilation. This has the same effect as a child skipping breakfast. (2)

- A 2020 paper in the American Economic Journal found "Without air conditioning, a 1°F hotter school year **reduces that year's learning by 1 percent**. Hot school days disproportionately impact minority students, accounting for roughly **5 percent of the racial achievement gap."** (3)

(1) Fisk, W. J., The ventilation problem in schools: literature review, Indoor Air. 2017;27:1039–1051

(2) David A. Coley, RupertGreeves, and Brian K. Saxby, "The effect of Low Ventilation Rates on the cognitive function of a Primary School Class," International Journal of Ventilation 6, no. 2 (2007):107-112

(3) Park, R. Jisung, Joshua Goodman, Michael Hurwitz, and Jonathan Smith. 2020. "Heat and Learning." American Economic Journal: Economic Policy 12 (2): 306–39.

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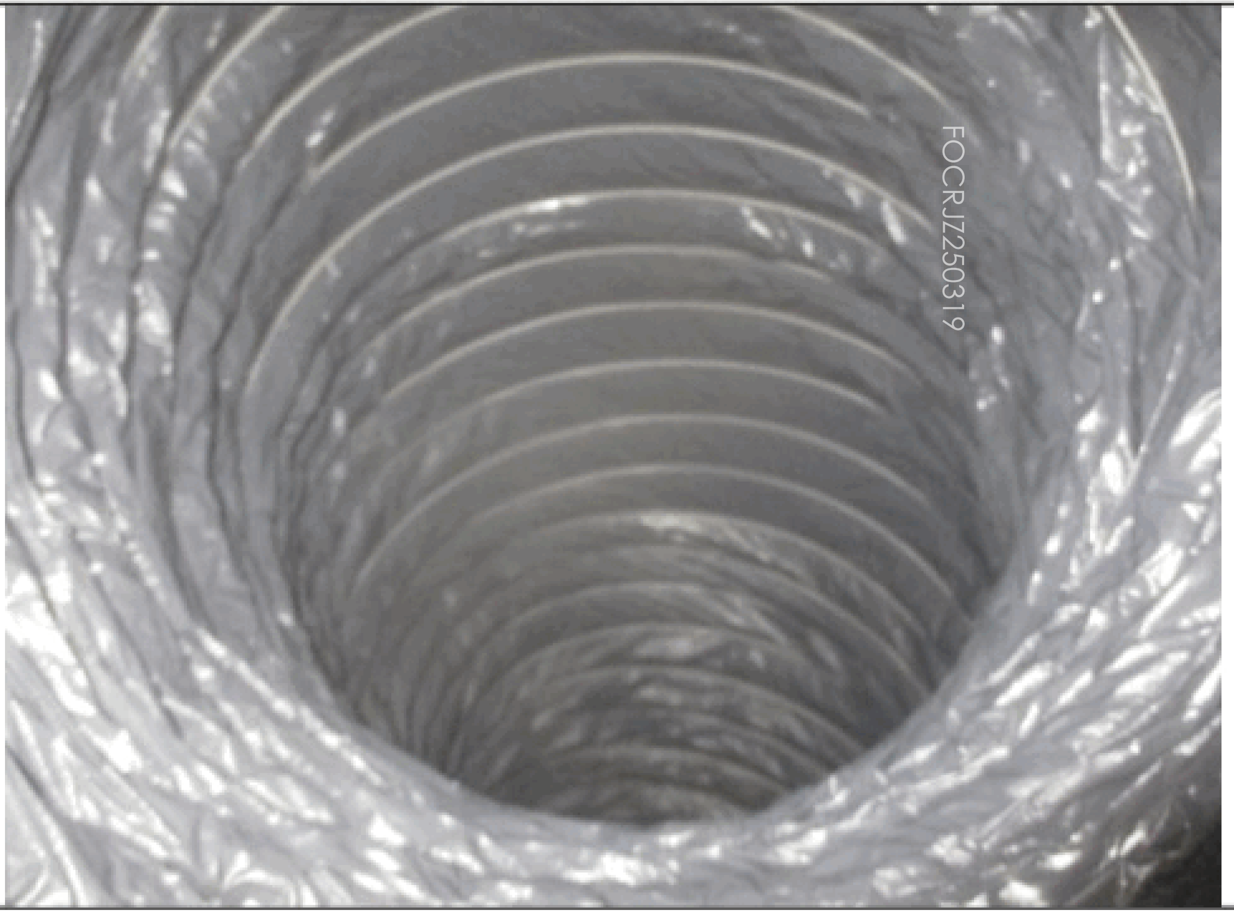

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Impacts of HVAC cleaning on energy consumption and supply airflow: A multi-climate evaluation

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ABSTRACT

Energy-efficiency interventions are crucial for sustainable building operations to accommodate emerging indoor air quality (IAQ) criteria into their engineering life cycles. While several studies have addressed building energy consumption and IAQ considerations separately, few provide integrated analysis of these aspects in response to building hygiene practices. In response, this study evaluates the effectiveness of routine heating, ventilation, and air conditioning (HVAC) cleaning on energy consumption and supply airflow patterns in non-residential public buildings. This study juxtaposes HVAC energy consumption and ventilation performance before, during and after routine HVAC cleaning, across buildings situated in four different climate zones, while operating in cooling mode. Each site had nearly identical HVAC systems serving similar architectural features and occupational loads; these were segregated into an intervention (cleaned HVAC system) that could be compared to an otherwise identically operating HVAC (control system), which was not cleaned. Following prescriptive cleaning, HVAC systems exhibited significant energy consumption reductions and delivered higher airflows compared to their uncleaned counterparts. On average, intervention systems saved between 41 % and 60 % on conveyance (fan/blower) energy, with one exception, and supplied 10 % and 46 % more airflow compared to their uncleaned counterparts. This research demonstrates how a new generation of low-cost HVAC system monitors can compile Internet of Things (IoT) archives to show immediate energy consumption benefits associated with cleaning HVAC components and their associated ductwork serving relatively high occupancy commercial and educational spaces.

1. Introduction

Building operations consume nearly one-third of total global energy output, accounting for a significant contribution to CO_2 emissions worldwide [1]. In the United States, commercial and residential buildings account for about 40 % of domestic energy consumption [2]. Such energy consumption trends in the building sector are expected to continue due to population growth, urbanization, increases in high-density building developments, rising comfort demands, and emerging indoor air quality (IAQ) concerns [3]. Furthermore, emerging guidelines for improving ventilation and indoor air quality [4-7] are expected to increase building energy consumption budgets in the foreseeable future.

In the context of building services, HVAC-associated energy consumption is significant, accounting for nearly 50 % of total energy usage in U.S. commercial and public buildings [8]. Given this substantial contribution, enhancing HVAC performance can lead to significant societal energy savings [9]. HVAC systems continuously manage thermal energy transfer while mixing and replenishing fresh air through occupied spaces. Energy is primarily consumed for heating, cooling, ventilation, air filtration, distribution, as well as by supporting auxiliary components such as chillers, boilers, backup fans, and variable frequency drives (VFDs). These systems employ various components and mechanisms to manage indoor environmental conditions.

HVAC systems are often operated to manage thermal comfort while maintaining indoor air quality through conditioning and (re)circulating filtered fresh air to occupied spaces. Given the amount of time people spend indoors, building environments can significantly impact occupant comfort and respiratory exposure; thermal management and indoor air

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quality are identified as one of the primary factors influencing the comfort, wellness, and productivity of building occupants [10-12]. Ducted HVAC systems with integrated filters help reduce the indoor load of ambient particulate matter (PM) in the environments they serve. Depending on the design and operation of these systems, in-line filters can further reduce the PM load associated with occupant shedding and indoor particle resuspension [13]. However, in some cases, the HVAC system itself can become both an acute and chronic source of PM and volatile organic carbon (VOC) emissions [14-16].

Conventional HVAC operations result in the gradual accumulation of particulate matter (PM) on the surfaces of different HVAC components [17,18], often reducing the energy efficiency of these systems over time; both heat transfer inhibition and cumulative airflow drag are responsible for this phenomenon [19,20]. While the PM fouling of any single HVAC component may lead to minor energy efficiency losses, the energy impacts can become significant when considering cumulative losses across all HVAC components, especially in larger buildings with expansive ductwork [21]. Moreover, design factors, faulty installation, operational paradigms and inadequate maintenance of HVAC system components can contribute to increased respiratory PM exposures, some of which can influence allergenic and hypersensitive responses from building occupants [22,23]. For instance, soiling of ductwork downstream of cooling coils and other areas that experience relatively high humidity or large humidity swings, often support microbiological deposition and activity, which can lead to negative operational and maintenance outcomes, including corrosion, odors, compromised insulation, and potential respiratory pathogen sources [24].

1.1. Review of Relevant literature

While numerous studies emphasize the importance of HVAC operation and maintenance for improving building energy performance [25-27], there is a lack for research investigating the effectiveness of building hygiene practices, in particular HVAC cleaning, on immediate and long-term energy savings potential for higher occupancy buildings. Since the U.S. Environmental Protection Agency (EPA) released the 1997 position paper on residential duct cleaning [28], only a limited number of studies have systematically examined the potential impacts HVAC system component cleaning can have on energy consumption patterns—a few of which included any accompanying IAQ survey.

Zhai and Johnson examined the effects of pressure drops within HVAC systems—caused by filter fouling, duct obstructions, and leakage—on fan energy consumption [29]. Using full-scale laboratory experiments, the authors observed that increased pressure drops, particularly from fouled filters, can raise energy consumption by up to 45.5 % when duct leakage is also present. To simulate increased pressure from fouling, the study introduced materials like linen sheets and wooden objects within the ductwork to mimic dust and obstructions, while foam board particles were added to elevate pressure drops across the filter. In a related study, Wilson et al. [30] examined the energy savings associated with cleaning coils and filters in constant air volume HVAC systems within single-family residential and small office buildings. Using a validated computer model to simulate varying levels of fouling in multiple climates, they found that while fouling affects both air conditioner and furnace energy use, anticipated energy savings are minimal for single-family residential buildings and may be negative for small office buildings based on fouling levels reported in the literature. They also emphasize the importance of regular cleaning and proper maintenance of constant air volume HVAC systems that introduce outside air for ventilation, to ensure that the systems maintain their designed ventilation rates.

In another study, Lin et al. [31] conducted an analysis of energy consumption patterns in United Arab Emirates buildings, with a specific focus on the operation and maintenance of building systems. Their findings indicate that, among other parameters, the cleanliness of air conditioning systems and the surface conditions of chillers are critical factors that significantly influence building energy consumption. In another study, Siegel and coworkers [32] critically examined particle deposition on evaporator coils and related effects of indoor particle and dust concentrations on coil fouling rates. Their results suggested that regular coil cleaning should be an integrated priority of residential air conditioning maintenance procedures to increase evaporator coil lifetimes and overall system energy efficiency. This observation likely extends to commercial HVAC hygiene as well.

While the quantity and thermodynamic properties of supply air have been the conventional focus of HVAC operations, the quality of air supplied to occupied spaces has received increased attention. Despite this, few studies have directly examined the effects of HVAC cleaning on indoor air quality. Ahmad et al. [22] looked at the effectiveness of three commercial HVAC duct cleaning processes in reducing airborne particulate matter (PM) and bioaerosols in residential homes. Results showed that during cleaning, PM and bioaerosol concentrations increased, suggesting that cleaning processes can disturb particle-associated pollutants. However, post-cleaning bioaerosol concentrations were significantly lower, indicating that cleaning has effectiveness on reducing subsequent respirable particle exposures over longer terms. In another study, Simbada et al. [16] analysed the bacterial DNA from HVAC filter dust collected in two university buildings. The results revealed the presence of potential pathogens, including the retention of antibiotic-resistant bacteria in HVAC systems, potentially posing health risk to occupants. They advised regular cleaning and disinfection of all HVAC systems to prevent potential pathogen accumulation and reduce occupants' potential respiratory exposures.

1.2. Contribution and research hypotheses

While existing literature highlights the potential of HVAC system management for enhancing energy savings, the actual effectiveness of HVAC system cleaning, and its influence on the interplay between energy consumption and indoor air quality should be considered [33]. Previous research has primarily relied on computer modelling and theoretical approaches to assess the effects of building hygiene practices on energy consumption, while an accompanying pool of actual field data are limited or not peer-reviewed if available. Studies often depend on controlled laboratory experiments, typically focusing on simulated cleaning processes for specific HVAC parts or components rather than on comprehensive, full-scale cleaning of ducts and other system elements. This approach may overlook key factors such as occupant activity, equipment aging, and actual duct conditions, including leaks—all of which can significantly impact HVAC performance. Additionally, previous studies on this topic have often focused on a limited sample of buildings, observed over relatively short durations within a single climate zone.

While existing literature predominantly focuses on residential and small office buildings, our study addresses medium-density commercial and public buildings. In response, this study demonstrates a scalable path to assess the effectiveness of HVAC system cleaning on energy consumption, concomitant with conditioned supply airflow monitoring, in medium-to-higher, non-residential buildings. By conducting our study in real-world settings, we aim to better capture actual building operation conditions and their effects on energy efficiency and supply airflow. A time-resolved examination of energy-related parameters and supply flow rates in buildings situated in four markedly different climate zones is reported— juxtaposing ventilation performance before, during and after staged HVAC cleaning using widely-accepted building hygiene practices. Each site chosen had nearly identical HVAC systems serving similar occupied areas, which were segregated into an intervention (cleaned system) for comparison with an otherwise identically operating control system that was not cleaned.

This report tests the hypotheses regarding the impact of building hygiene practices, specifically HVAC cleaning interventions, on energy consumption and indoor air quality as measured by supply airflow. We propose that cleaned HVAC systems will consume less energy than their uncleaned counterparts while delivering higher airflow rates. We report some of the immediate energy consumption benefits associated with full-scale HVAC system cleaning in a variety of medium-to-higher occupancy building types across several climate zones (in cooling mode). While the absolute energy consumption benefits are relative to each site, we observed consistently improved ventilation performance patterns across all sites. This suggests that beneficial effects can be realized by cleaning all HVAC system components, but notably including the conveyance system itself (ductwork) and enhanced VAV operational stability.

2. Methods

2.1. Site selection and system Specifications

Given the significant impact of physical geography, urban effects and local climate conditions on HVAC system behaviour and its energy consumption [34], this study selected four groups of buildings across the United States and Europe, each representing conditions in a major climate zone with a significant population: In the United States, Johnson, Vermont represents the temperate northeast climate (Zone 6A: Cold–Humid); Pearl, Mississippi represents the sub-tropical southeast (Zone 2A: Hot–Humid); Boulder, Colorado, represents the arid mountain west (Zone 5B: Cool–Dry); and Pavia, Italy represents a temperate climate, 4A (Mixed–Humid) [35]. Studies have revealed that building type [36] and occupant activity [37] can affect HVAC system loads and dynamics. In this study, building functionalities span a diverse range of medium-to high occupancy settings, from an office building in Johnson, Vermont, to a daycare/gym facility in Pearl, Mississippi, as well educational spaces in Boulder, Colorado and Pavia, Italy. Fig. 1 displays locations of the buildings analysed in this study. Both occupied and unoccupied conditions were considered.

For this study, two nearly identical Air Handling Units (AHUs) were deliberately selected at each site for practical comparative analysis (control vs. intervention). The site selection was guided by the following criteria: first, they had to possess a minimum quantity of ducts with varying lengths and turns, in order to be generalized to an average medium-density service system duct system. Additionally, access to blueprints or simplified drawings of the HVAC system was required. It was also essential that the chosen systems did not incorporate variable speed fans, or if they did, the ability to operate them at a fixed speed for the duration of the study was mandated. Furthermore, a duplicate or a similar system in immediate proximity, serving a similar architectural space, was necessary for comparative analysis. Moreover, the systems had to be free of excessive nuances or variables like numerous reheat coils or inline restrictions. Finally, the location of these sites had to be dependable to ensure uninterrupted access throughout all scheduled phases of a cleaning response study. The cooling capacities of the HVAC systems ranged between approximately 10 tons (at the Vermont site) to 30 tons (at the Italy site).

To maintain consistency during this cleaning intervention study, any Variable Air Volume (VAV) controllers, where present, were deactivated (locked open). Ensuring that filter conditions did not impact the measurements in either control or cleaning intervention systems, any existing filters were replaced with new filters of the same type, before commencing cleaning protocols. Other key considerations encompassed formal facility manager engagements, scheduling all monitor installations, cleaning and subsequent operations in collaboration with building owners and managers. Furthermore, it was imperative that

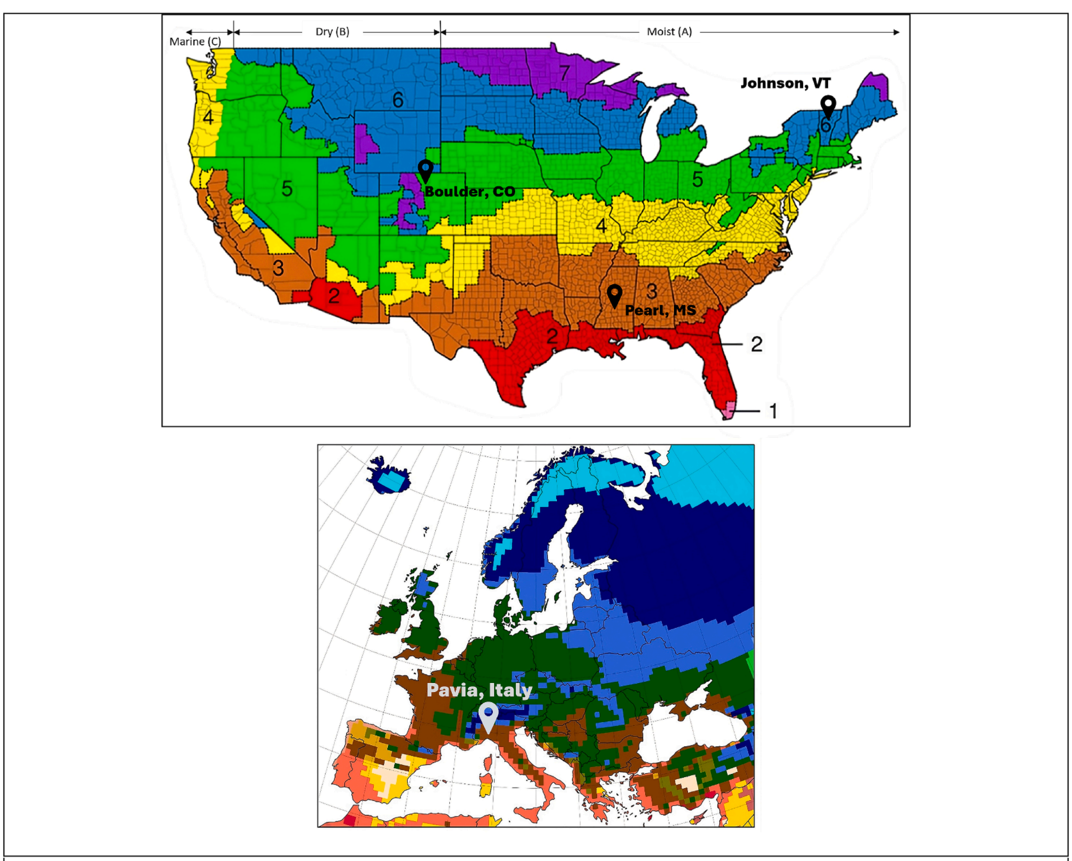


Fig. 1. Building sites participating in this study superimposed on a climate zone map as designated by ASHRAE [35]. Top: United States climate zones with three study sites including Boulder, Colorado (Zone 5b, Cold/Dry); Johnson, Vermont (Zone 6A, Cold/Humid); Pearl, Mississippi (Zone 3A Warm/Humid). Bottom: Europe climate zones, Pavia, Italy (Temperate/Warm).

cleaning contractors possessed the necessary training to install HVAC system energy monitors, sensors and accurately measure supply airflows at the registers. During the cleaning process, the supply and return duct systems, including registers, were thoroughly cleaned, ensuring that any dampers were left in their pre-cleaning positions. All HVAC system components, including fans/blowers, heat exchangers, and evaporator/condenser coils, were cleaned following industry standards [38]. The study timeline, along with a summary of climatic conditions at the building sites participating in this study, is listed in Table 1. Cleaning schedule staging and details for each site are available in the Supplementary Materials (A 1–A 4).

2.2. Data collection

The monitoring and data collection process was consistent and uniform for both control and intervention systems at each site. The following sensors were deployed in both intervention and control sides across at the four different sites (Fig. 2).

R&T-500 Series (T&D) sensors [39] were used at the Vermont and Mississippi sites for measuring energy (RTR-505-P) and pressure (RTR-505-mA, with 0.05 mA + 0.3 % of reading inaccuracy) values. Data from these sensors were accessed via the vendors' cloud server, T&D WebStorage Service [40]. Measurements from the sensors were reported at an hourly frequency.

At the Colorado site, a Dwyer Series 607 Differential Pressure Transmitter [41] was used to assess pressure drop, the Keyence FD-R Series Clamp-on Flow Meter [42] measured flow rate (temp accuracy = ±3 °C, flow accuracy = ±2 %), the Dwyer Series RHP Humidity and Temperature Transmitter [43] monitored humidity (±2 % inaccuracy) and temperature (±0.3 °C inaccuracy), and the WND series WattNode Wide-Range Modbus [44] served as the electric power meter (±0.5 % inaccuracy). Data from these sensors were accessed through the vendor's cloud server, Attune [45], with a data reporting frequency of every minute.

At the Italian site, the SmartDHOME [46] sensor family was utilized to measure energy consumption, providing real-time data monitoring capabilities through MyVirtuoso Home [47] software. The Ultrasonic Heat/Cool Meter was deployed to measure the flowrate and temperature of cooling water (±1 % inaccuracy). The energy consumption of fans (blowers) was measured using a three-phase inductive energy meter. For monitoring differential pressure, temperature, and relative humidity, as well as capturing real-time photos from the interior of HVAC system ducts and AHUs, REMOTAIR [48] sensors were utilized. Equipped with cameras installed in AHUs and ducts, REMOTAIR sensors captured photos multiple times per day, enabling the ongoing tracking of particle deposition conditions within the HVAC system.

At all sites, an industry standard method was used to measure and record the volumetric flow through each supply register using a four-quadrant measurement or flow hood. While the energy consumption and differential pressure within the HVAC systems were continuously measured, supply airflow was intermittently measured before, during, and after the cleaning process, with data recorded for both control and intervention systems. Measurements were conducted according to the National Environmental Balancing Bureau (NEBB) "Procedural Standards for Testing, Adjusting, and Balancing of Environmental Systems" [49]. Similar to the energy and air quality sensors, the supply airflow measurement process was consistent and uniform for both control and intervention systems at each site, ensuring the basis for stringent statistical comparisons.

Table 1
Table summarizing climatic zone and project timeline at the building sites participating in this study.

Location	Climatic condition	ASHRAE climate zone	Start date	End date
Johnson, VT	Temperate Northeast	6A: Cold – Humid	Jul 17, 2019	Sep 1, 2019
Pearl, MS	Sub-Tropical Southeast	2A: Hot – Humid	Jul 17, 2020	Oct 10, 2020
Boulder, CO	Arid Mountain West	5B: Cool – Dry	Aug 17, 2022	Oct 5, 2022
Pavia, Italy	Temperate	4A: Mixed – Humid	Jun 15, 2023	Aug 4, 2023

2.3. Data analysis

Both descriptive and inferential statistical methods were applied to analyse energy consumption and ventilation performance data. This analysis was structured to investigate the energy-related response of routine HVAC system cleaning, as well as to identify common patterns in system performance dynamics within these non-residential public buildings. Statistical analyses were conducted utilizing the R programming language within the RStudio environment [50], with visual presentations generated using R-compatible libraries [51].

The data analysis procedures were standardized across all locations. For the primary analysis, data collected from 8 am to 6 pm (local time zone) on regular working days were incorporated into the study. Sensor data from public holidays and system cleaning days were omitted from the analysis. Additionally, instances of technical malfunctions in either the control or intervention systems, such as refrigerant leaks, necessitated immediate attention from maintenance personnel, resulting in the shutdown of either the entire system or specific faulty components. Data collected on these days were also excluded from the analysis. Data from both the control and intervention (cleaned) systems were collected during all the different cleaning phases, which were consistently staged to isolate cleaning effects on the heat transfer equipment, conveyance system (ducts) and fans (blowers). Differential pressure across the HVAC system was continuously measured. Data obtained prior to cleaning served as foundational baseline(s).

Cumulative daily energy consumed by fans, blowers, and cooling equipment, alongside differential pressure values, were computed for both the control and intervention systems. The trends of these variables over the duration of the project were analysed using widely accepted statistical regression practices. A reporting model was constructed using the linear model function in base R to identify trends in energy consumption and ventilation performance variables [52]. This function formulates regressions with variance. In the context of this study, the regression model described linear relationships between the energy usage for cooling, air conveyance, and differential pressure (outcome variables) and the observation days across the project timeline (predictor variable). This model was individually fitted to the variables of interest in both the control and intervention systems, which were then compared.

To assess whether HVAC components in control and intervention systems at each site differ significantly, an analysis of covariance (ANCOVA) was conducted across the respective cleaning stages at each site. ANCOVA is a statistical technique that combines analysis of variance (ANOVA) with linear regression [53] for normally distributed data, which applies to the present study. In the context of examining regression variances between control and intervention systems, ANCOVA tests determined whether observed distinctions remain significant after accounting for covariates, thereby offering a more refined comprehension of the relationship between any independent and dependent variables. A significant interaction term between the experimental condition and the covariates indicates that the regressions for the control and intervention groups are not parallel, suggesting disparate relationships between the independent and dependent variables across the two groups. In this case, the ANCOVA fitted a linear model to predict energy consumption based on the observation day, system type, i.e., control or intervention, and the interaction between these two factors, i.e., observation day and system type. Eq. (1) shows an example of how the ANCOVA model was constructed in R for the value of interest:

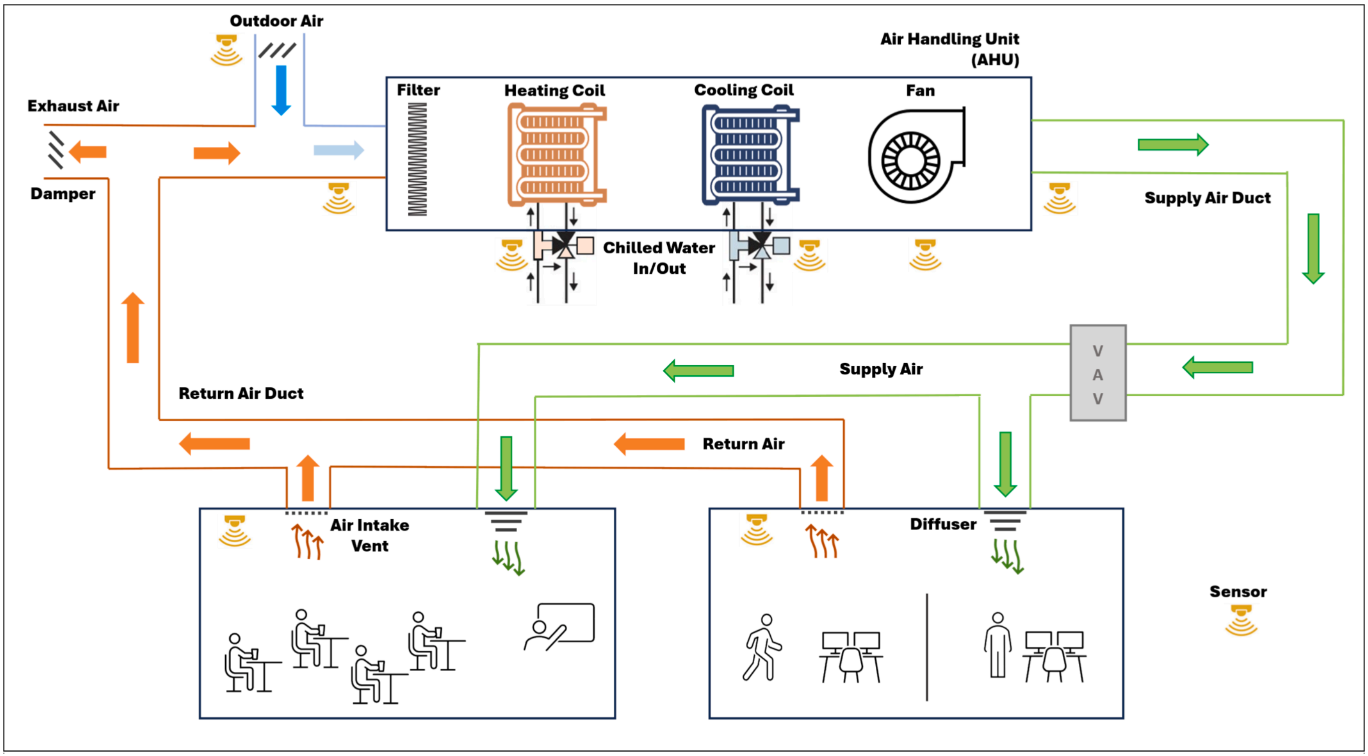


Fig. 2. Schematic of air handling units (AHU), sensor networks, duct work and occupied spaces of that typically observed in this study. Energy consumption sensors were installed on all fans and heat transfer equipment. Pressure sensors were installed in ductwork immediately upstream and downstream of the AHU. Thermodynamic sensors (T and RH) were installed in the occupied spaces and immediately adjacent to outdoor (fresh) air intake.

$$ANCOVAModel = LinearModel\begin{pmatrix} DependantVariable \\ ObservationDay + SystemType \\ +ObservationDay{*}SystemType \end{pmatrix}\# \quad (1)$$

The significance levels for the linear regression models were classified as follows: highly significant ($p < 0.001$), very significant ($p < 0.01$), significant ($p < 0.05$), marginally significant ($p < 0.1$) and not significant ($p \geq 0.1$). The p-value in this context indicates the probability of observing the difference in slopes between the control and intervention groups, assuming there is no true difference between them, with smaller p-values suggesting stronger evidence against the null hypothesis.

Additionally, we compared the daily energy required for air conveyance (i.e., fans and blowers) in both the intervention and control systems on each observation day, and adapted a method similar to that of Zhai and Johnson [29] to calculate the percentage of potential relative energy savings, as shown in Eq. (2):

$$PercentofRelativeEnergySaving = (Energy_{control} - Energy_{intervention})/Energy_{control} \quad (2)$$

To assess the impact of HVAC system cleaning on supply airflow, measurements from the control side were subtracted from those of the intervention side and plotted over the time for each project site. This enabled monitoring of how differences between intervention and control measurements changed throughout each cleaning phases. To better quantify the difference between the control and intervention systems following each stage of cleaning, we calculated the percentage increase in supply airflow rates using Eq. (3) [30]:

$$PercentofRelativeIncreaseinSupplyAirflow = (FlowRate_{intervention} - FlowRate_{control})/FlowRate_{control}\# \quad (3)$$

Changes in supply airflow at each stage of the cleaning compared to the previous cleaning stage was also studied to identify the cleaning stage that were most impactful as judged by supply airflow rates.

3. Results

The influence of routine HVAC system cleaning on energy use and supply airflow in public, non-residential buildings was studied. A detailed, time-resolved analysis was conducted on energy and airflow metrics in buildings grouped in the various climate zones is reported below. This section details the observed patterns in energy consumption, changes in supply airflow rates, and other overall impact of the HVAC cleaning practiced here. The structure of the Results and Discussion section is as follows: The impact of HVAC cleaning on energy consumption at each site is presented chronologically. Next, an analysis of supply airflow across all sites is provided. Other unanticipated benefits arising from the cleaning process, i.e., system stability, are then discussed.

3.1. Energy consumption

An overall reduction in energy consumption in fans and cooling energy was anticipated and quantified, primarily due to the decreased cooling loads resulting from the transition to cooler outdoor temperatures as the studies progress from summer to fall seasons at all sites. This expectation also applies to differential pressure reductions. The cleaning process commenced during the peak load of HVAC systems, coinciding with the peak of warmest season in each location. The sites and associated results are res described in the order studied, during summers of 2019, 2020, 2022 and 2023 (2021 was a study hiatus due to COVID-19 building shutdowns).

3.1.1. Johnson, VT

The analysis of the first location (2019), Vermont, examined the cumulative daily energy consumption of the blower, cooling, and daily average differential pressure over the duration of this project. The daily energy use by blowers in both control and intervention systems, calculated based on the methodology in Eq. (2), indicates that daily relative energy savings ranged between 43 % and 50 %, with an average of 44 % over the study duration.

Parallel regression analysis of data from both the control and intervention systems suggests that although the cumulative daily energy consumption of the blower in the intervention system increased at a higher rate compared to the control system, the respective increases were not statistically significant. The relatively high p-values in both groups and the ANCOVA analysis indicated that routine HVAC system cleaning did not significantly impact the blower's energy consumption in this setting (Table 2).

For the energy consumption used for cooling by the main compressor, both the control and intervention systems exhibited negative slopes, indicating a decrease in energy consumption over the season observed. These data indicate that while there is a statistically significant decrease in energy consumption for cooling in both systems, which is consistent with the prevailing weather pattern, the routine cleaning of the HVAC system did not result in a significant consumption rate differences when comparing the control and intervention thermodynamic heat transfer performance. Additionally, the analysis showed a slight decrease in the daily averaged differential pressure in the cleaned system over time. However, no significant difference between the control and intervention systems was observed.

In summary, the primary system results from the Vermont office site location suggest that routine cleaning of HVAC systems did not significantly affect the energy consumption patterns of the conveyance or the cooling system, nor did it significantly impact the differential pressure in the system. The lack of significant energy performance differences between control and intervention systems implies that other factors may play a more crucial role. At the Vermont site, this manifest in differences in the number and duration of back up compressor recalls between the cleaned and control systems.

Here, both the control and intervention air conditioning systems featured a backup compressor, which were frequently brought into supplementary service to meet cooling demand. A notable observation following HVAC cleaning was the reduced startup frequency of backup equipment in the intervention (cleaned) side (Fig. 3). A comparison between the control and intervention systems revealed that the backup compressor in the intervention side was activated 47 % less frequently than its counterpart in the control side. This reduction in back-up system startup frequency could potentially extend equipment lifetime and reduce maintenance costs.

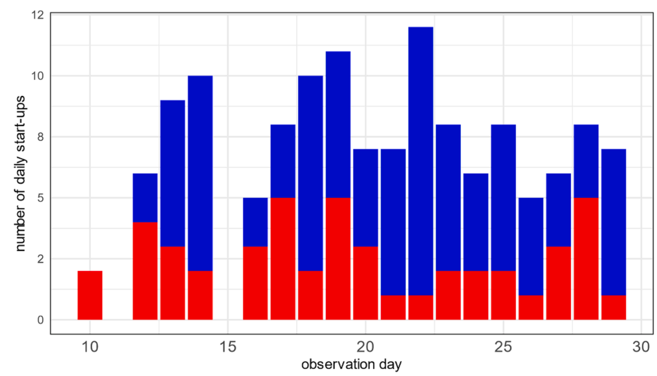


Fig. 3. Daily service recall frequency of back up air conditioning compressors supporting control (■) system and intervention system (■) in response to HVAC system cleaning in Johnson, VT office building.

Table 2
Table summarizing analyses of variance outcomes of selected energy consumption and differential pressure comparisons at the different sites. The significant codes used are as follows: *** indicates $p < 0.001$, ** indicates $p < 0.01$, * indicates $p < 0.05$.

Location	Parameter	System	Slope	Intercept	ANCOVA slope difference
Johnson, VT	Blower energy	Control	8.76	49706.08 ***	NS
		Intervention	14.10	27687.89***	
	Cooling energy	Control	−231.93*	23299.07***	NS
		Intervention	−231.36*	22036.38***	
	Cooling energy (backup)	Control	−48.30	4053.25***	*
		Intervention	−212.05***	5477.13***	
	Differential pressure	Control	0.00057	6.40***	NS
		Intervention	−0.0020	5.85***	
Pearl, MS	Blower energy	Control	1.73	528.63***	**
		Intervention	−6.58***	436.43***	
	Cooling energy	Control	−11.80*	1738.63***	*
		Intervention	−32.85***	1822.80***	
	Differential pressure	Control	−0.0041**	4.76***	*
		Intervention	−0.010***	4.73***	
Boulder, CO	Fan energy	Control	−0.95	4397.56 ***	***
		Intervention	33.17***	5208.38***	
	Fan energy (after hours)	Control	−4.73	3764.25***	***
		Intervention	−55.77***	6842.88***	
	Cooling energy	Control	−171.03***	6576.50***	*
		Intervention	−329.43***	17810.20***	
	Cooling energy (after hours)	Control	0.17	209.40**	***
		Intervention	−27.02***	2366.48***	
	Differential pressure	Control	0.00037	1.42***	***
		Intervention	0.011***	1.17***	
Pavia, Italy	Fan energy	Control	2592.6**	117184.1***	***
		Intervention	−38.09	57732.24***	
	Cooling energy	Control	−32.49	10821.42***	NS
		Intervention	−16.24	17407.68***	

Furthermore, considering the energy consumption of backup equipment (Supplementary Material, A 5), the comparison of power between the control and intervention systems revealed a significant energy consumption difference: the compressor on the intervention side demonstrated a substantially greater reduction in energy consumption compared to the control. These energy consumption patterns suggest that routine HVAC system cleaning may have a notable impact on the energy usage of backup compressors on these otherwise identical systems with similar architectural features and occupancy.

3.1.2. Pearl, MS

A similar analysis was done on the daily cumulative energy consumption of the blower and cooling systems, as well as the daily average differential pressure in the Pearl, Mississippi location. The intervention group included two blowers, while the control group had three blowers; additionally, both control and intervention HVAC systems were equipped with two compressors each. For the blower energy consumption, the intervention system exhibited a significant energy consumption decrease, while the control system showed no such performance changes

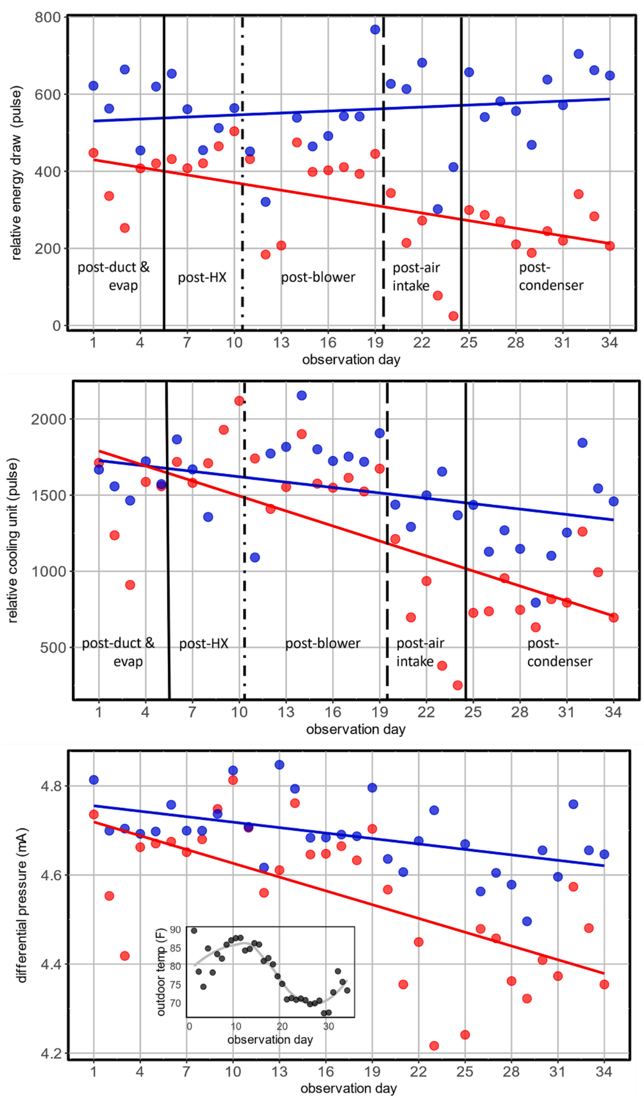


Fig. 4. Relative HVAC performance of control (-●-) system and intervention system (-●-) in response to stages of HVAC system cleaning in a Pearl, MS day care school building. **Top:** relative fan energy draw (normalized voltage pulses); **Middle**: relative cooling energy draw (normalized voltage pulses); **Bottom:** differential pressure across heat transfer equipment (normalized current (mA)); **Bottom inset**: outdoor temperature during observation period.

(Fig. 4). The daily energy use by blowers in both control and intervention systems, calculated with the methodology in Eq. (2), indicates that daily relative energy savings ranged between 4 % and 94 %, with an average of 41 % over the study duration. ANCOVA analysis also revealed a significant energy consumption difference between the control and intervention systems ($p < 0.01$), indicating that the routine HVAC cleaning resulted in a notable reduction in energy consumption (Table 2).

For the energy consumption patterns associated with the air cooling equipment, both systems showed significant decreases over time, consistent with the prevailing weather pattern; however, the intervention system demonstrated a steeper decrease compared to the control system. ANCOVA analysis confirmed a significant difference in slopes ($p < 0.05$), suggesting that routine cleaning led to a more pronounced reduction in cooling energy consumption.

In terms of daily average differential pressure (supply and outdoor air), both systems exhibited significant decrease over time, with the intervention system showing a steeper decrease compared to the control system. ANCOVA analysis indicated that routine cleaning resulted in a substantial reduction in differential pressure following individual stages of the cleaning process as well as the cumulative outcome.

The results from the Mississippi location demonstrate that routine cleaning of HVAC systems can significantly reduce energy consumption for both the blower and cooling systems, as well as lowering the differential pressure across this system.

3.1.3. Boulder, CO

In the analysis of the Colorado location, the daily cumulative energy consumption for the fan and cooling systems, as well as the daily average differential pressure, were examined for both the control and intervention systems. Cooling for this location was provided by a remote water-chiller system.

Concerning blower energy consumption, the intervention system demonstrated a significant increase over time and used between 20 % to 37 % less energy compared to control system on daily basis (Eq. (2). Meanwhile, the control system exhibited a non-significant decrease (A 6). Despite the increase in blower energy consumption, the intervention system showed a greater reduction in cooling energy consumption over time. Both systems showed significant decreases in terms of cooling energy consumption, consistent with the prevailing weather pattern, with the intervention system demonstrating a steeper decrease compared to the control system. ANCOVA analysis suggested that routine cleaning could be associated with a more pronounced reduction in cooling energy consumption at this location (Table 2).

Regarding daily average differential pressure, both systems exhibited significant increases over the study period, with the intervention system showing a much steeper increase compared to its control. Although the differential pressure (DP) of the intervention system remained lower than that of the control over an extended period, it increased toward the end of the cleaning phase and into the heating season (as indicated by outdoor air temperature data), allowing the system to provide conditioned air more effectively. An examination of supply air temperature and humidity revealed that the control system was unable to provide an appropriate temperature of conditioned air to the indoor spaces it served, while the cleaned system was capable of supplying air at desired conditions (A 7). This discrepancy may explain why the cleaned system consumed more conveyance (fan) energy compared to the control system, as the control system was unable to meet the load demand (A 8).

Unlike the other locations, the Colorado site HVAC systems remained fully operational during both occupied and unoccupied periods. Therefore, both occupied and unoccupied air conditioning data from the Colorado site was included for this aspect of the analysis. The HVAC system in Colorado featured integrated VAV controllers, which were initially deactivated ("locked open") during the primary study to maintain consistent airflow rates into the rooms. VAV terminal boxes modulate VAV damper positions to regulate both the supply airflow and a "reheat" region to help better maintain local zone temperatures. Recent research indicates that VAV configurations can influence fan power cycles as well as cooling and heating energy consumption [25]. As a result, VAV boxes were initially deactivated during and after the cleaning process. However, once sufficient post-cleaning data was collected to compare sensor measurements between intervention and control systems, they (VAVs) were subsequently (re)activated and monitoring continued assess the system's performance in regular operational mode, i.e., with all VAVs activated.

Regarding fans energy and cooling, the intervention system at the Colorado site exhibited a steeper negative slope compared to the control (Fig. 5, A 8). The comparison of slopes between the control and intervention systems yielded significant differences. The intervention group, apparently benefiting from cleaning, displayed a substantially greater reduction in energy usage compared to the control system when considering the prevailing weather pattern. This finding underscores the potential efficacy of routine cleaning in improving energy efficiency considering both occupied and unoccupied hours.

3.1.4. Pavia, Italy

Similar analysis was done on the daily cumulative energy consumption of the blowers and cooling system in University of Pavia buildings. For blower energy consumption, the control system exhibited a significant positive slope, indicating an increasing trend in energy usage over this seasonal time. In contrast, the intervention system displayed a negative slope (Fig. 6). The comparison of slopes between the control and intervention groups yielded statistically significant differences considering the prevailing weather pattern during the end of the cooling season (Table 2). The differences in daily energy use by blowers in control and intervention systems at the Pavia site, calculated based on Eq. (2), shows that daily relative energy savings ranged between 39 % and 67 %, with an average of 60 % over the study duration (Fig. 6).

For the energy consumption used for cooling, both the control and intervention groups exhibited insignificant changes over time. While routine HVAC system cleaning demonstrated a significant reduction in blower energy consumption, its impact on cooling energy consumption was not significant (A 9). These findings highlight the importance of considering all system characteristics and environmental factors when evaluating the efficacy of cleaning interventions.

3.2. Supply airflow

In this study, a systematic method was used to measure and document the supply air from each supply register at each site (in cubic feet per minute, or CFM). Supply air measurements were obtained before, during, and after the cleaning process, with data recorded for both control and intervention systems. All sites had non-operable windows

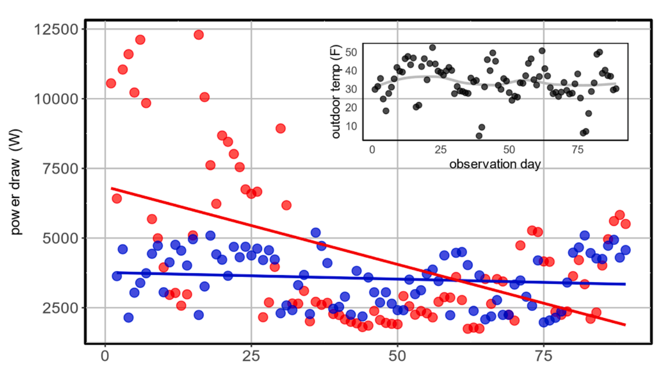
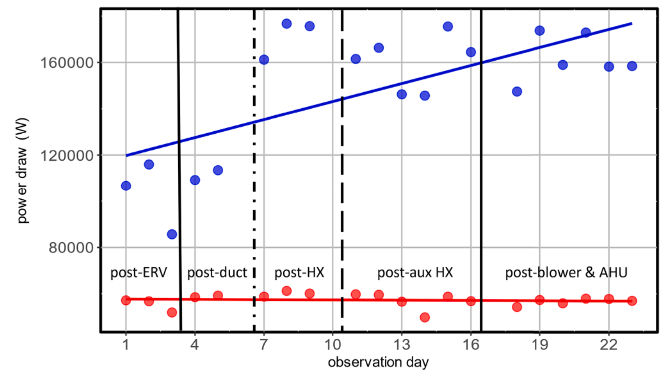


Fig. 5. Power draw of supply air HVAC fans operating in control (-●-) system and intervention system (-●-) in response to HVAC system cleaning in a Boulder, Colorado University classroom and office building. **Inset:** outdoor temperature during observation period.



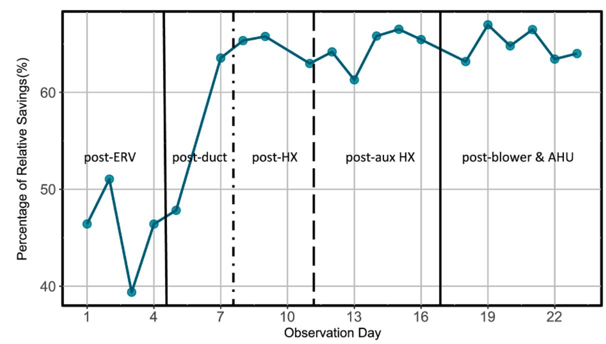


Fig. 6. Top: Power draw of supply air HVAC fans operating in control (-●-) system and intervention system (-●-) in response to stages of HVAC system cleaning in a Pavia, Italy, classroom and office building. **Bottom:** The percentage of relative energy savings over the duration of study.

and self-closing mechanical doors which were shut during these supply air measurements. Measurements were taken on the same days for both control and intervention systems. As shown in Fig. 7, the increase in supply airflow differences generally exhibits a positive slope, indicating the cumulative effect of cleaning on conditioned air flow to the occupied space. In all cases except one, the supply flow differences between control and intervention systems increased over time. Notably, the disparity in supply airflow rates between intervention and control systems rose by over 40 % in Colorado and Italy from pre-cleaning to post-cleaning. The Mississippi site showed a remarkable increase of 174 %.

Initially, the control system at the Mississippi site showed higher pre-cleaning measurements than the intervention system. However, as the cleaning progressed, the intervention measurements surpassed those of the control side. Further examination of the Mississippi site data shows (Fig. 8) that the intervention site had the dirtiest ducts among all the sites, despite having the shortest duct length and the smallest surface area cleaned. Notably, the evaporator coils in Mississippi were in better condition than those at other locations. The positive impact of duct cleaning on supply airflow rates at this site was evident in the data shown in Fig. 7.

In Vermont, both the ducts and coils were relatively clean. The primary issue was the presence of leaves and large debris in the air handling unit (AHU), which was located outside the building on the ground in the open air. An improvement in supply airflow was observed after cleaning the AHU box during the final stages of the cleaning process. This situation might also explain the minimal difference in energy savings between the control and intervention systems at this location, as the main obstruction was large debris rather than dust both in ductwork and cooling/heating equipment.

As judged by conditioned supply airflow, we were able to isolate a clear ventilation performance benefit in response to routine duct cleaning. The greatest change from the previous cleaning phase was an 89 % increase in conditioned supply airflow at the Italian site and 76 %

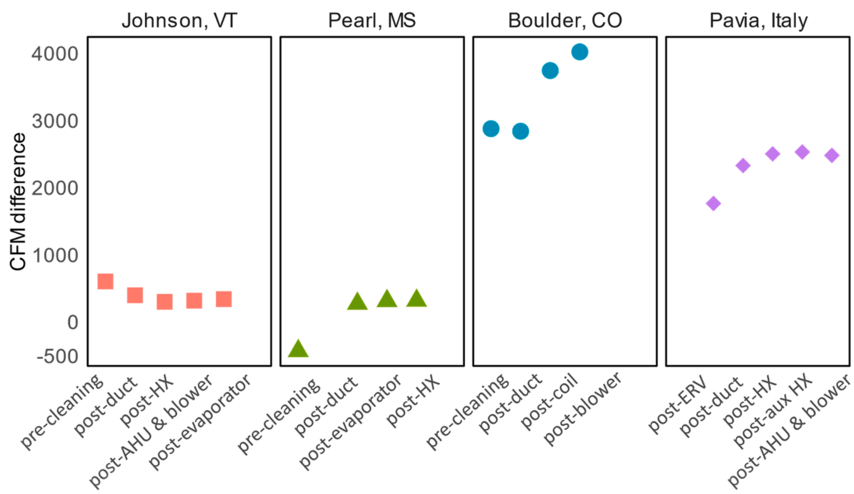


Fig. 7. Difference in supply air flow (ft^3/min) to occupied spaces in response to different cleaning stages at the respective sites: office building, Johnson, VT (■); day care school building, Pearl MS (▲); University classroom building, Boulder, CO (●) and University classroom and office building, Pavia, Italy (◆).

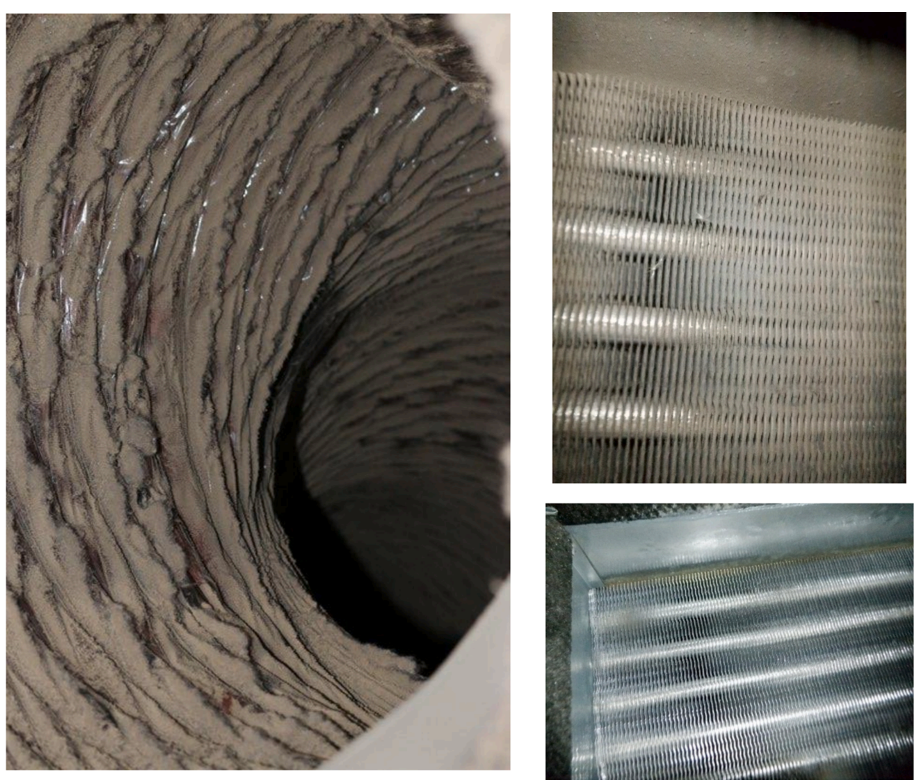


Fig. 8. Left: An image of the spiral duct taken before system cleaning at the study location in Pearl, MS. **Right:** A before (top) and after (bottom) system cleaning images of evaporator coils at the study location in Boulder, CO.

in Mississippi, following duct cleaning. In Italy, HVAC coils were not significantly dirty, however the ducts were visibly soiled, notably including large areas of dust accumulation. In Colorado, the most significant effect was observed after coil cleaning, with a 110 % increase in conditioned supply airflow compared to the previous phase, followed by a 20 % increase after blower cleaning. The coils in Colorado were visibly soiled (Fig. 8). Cleaning these coils led a notable increase in supply airflow compared to the control system, highlighting the importance of maintaining clean coils for optimal system performance.

A critical evaluation of conditioned supply airflow measurements shows that airflow rates consistently and significantly increased in cleaned systems compared to their uncleaned counterparts (Eq. (3). Across the different cleaning stages, the average relative increase in supply airflow (CFMs) were as follows: 46 % for the Italian site; 35 % for Colorado site; 19 % for Mississippi site; and 10 % for the Vermont site. Comparative analysis suggests that the larger cleaned duct area, correlates with a greater relative increase in supply airflow. The two sites with the largest improvements, Italy and Colorado, had the greatest duct surface areas cleaned and the highest duct surface-to-serving area ratios. They also had the largest cooling capacities. Details on duct length, duct surface area, area served by the HVAC system, and the cleaned surface-to-served area ratio for each project location are provided in Supplementary Material (A 10).

3.3. Complementary findings on system performance

Our study supports a conclusion that additional (unanticipated) benefits may be associated with HVAC cleaning process. Analysis of the system differential pressure at the Colorado site suggests system stability benefits can result from HVAC cleaning where VAV control is enabled. Fig. 9 illustrates system differential pressure when Variable Air Volume (VAV) boxes were subsequently activated following cleaning intervention; these results suggest improved stability resulted from HVAC cleaning. Notably, the occurrence and range of pressure fluctuations is markedly smaller in the intervention system operation where compared to the control group – a condition which remained apparent for several months after cleaning. This reduction in pressure variability can positively impact system control, particularly considering the influence of (large and capricious) pressure differences on various system components.

It is important to note here that those systems with the longer duct work reaches (Pearl, MS and Pavia, Italy (A-7)), benefited in large supply air flow increases, in response to isolating the duct work cleaning alone.

4. Discussion

Significant energy savings in larger buildings with medium-density occupancy could be realized and verified by implementing the coupled cleaning & monitoring approach described here. Due to differences in system characteristics across the four climatic locations—such as variations in ductwork size and equipment type— direct comparisons of energy savings and supply airflow improvements could not be applied here. However, despite this diversity, net energy consumption significantly decreased during and after HVAC system cleaning, though the degree of impact following each cleaning stage (fans, ducts, heat transfer equipment, etc.) varied by site. Only at one site did the blower energy increase in the intervention system; further analysis indicated that the associated control system was in poor condition, unable to perform adequately in supplying conditioned air at the desired set points.

Our analysis also indicated that larger systems, in terms of ductwork

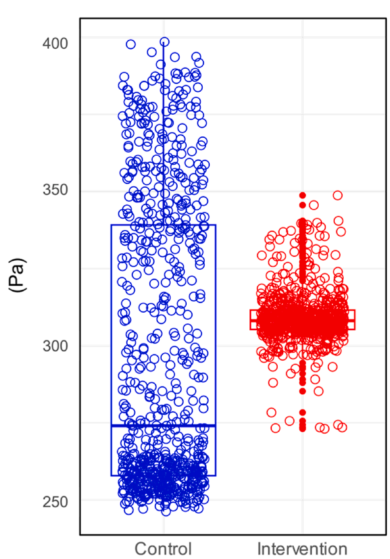


Fig. 9. Distribution of differential pressure (inches water) across filter/cooling coil complex operating in control (-○-) system and intervention system (-○-) in response to HVAC system cleaning in a Boulder, Colorado University classroom and office building with VAV systems engaged. Bottom line of boxes represents 25th percentile; center line of boxes represents 50th percentile; upper line of boxes represents 75th percentile.

conveyance and cooling capacity, benefited more from cleaning than their smaller counterparts. Examination of all cleaned HVAC systems suggests that a larger cleaned duct area is associated with a greater relative increase in supply airflow. In smaller systems, the larger relative energy benefit is realized from coil cleaning, as cleaner evaporative coils enhance heat exchange efficiency by increasing the effective area for heat transfer. Additionally, clearing the limited flow passage area within coils can further improve flow rates.

Accurate and affordable energy consumption measurements are complex, particularly in larger systems. However, a new generation of IAQ and energy sensors, such as those employed here, now offer affordable detail to energy consumption patterns in response to building hygiene interventions beyond conventional BAS. Additionally, in cases where multiple faults are present within the HVAC system, implementing a maintenance schedule, such as HVAC system cleaning, may offer only potential for system performance diagnosis that was not previously available without on-site inspections [54]. The methods outlined in this study present an advance in leveraging modern monitoring IoT networks for demonstrating the efficacy of HVAC hygiene. Modern energy monitors are accurate and account for energy "losses and gains" in the specific context of short- and long-term seasonal weather changes. Future work can consider extending the post-cleaning data monitoring time to study the re-accumulation of dust (and biofilms) in-and-on HVAC components to better evaluate the longitudinal effects of cleaning.

At this time, we were unable to find a study in scope or design similar to that reported here. To meet rising societal expectations for indoor environment improvements, integrating strategies and analysis for the concomitant management of indoor air quality and maintenance of energy-efficient HVAC systems is essential. In this context, building hygiene costs, notably including periodic HVAC system cleaning, should be weighed in a comprehensive benefits analysis that considers longitudinal energy savings, improved ventilation performance and associated indoor air quality factors.

5. Conclusions

The advent of post-pandemic indoor air quality guidelines suggests that building hygiene will gain increased attention as systematic part of building maintenance portfolios. This study demonstrates how a new generation of affordable IAQ and HVAC system monitors can compile secure IoT archives into an evidence base that enables building mangers to leverage HVAC hygiene into operational scenarios that help optimize energy consumption to help maintain optimal supply airflow rates.

Here we analysed ventilation performance in response to HVAC cleaning in moderately aged buildings (less than 20 years) in four markedly different climates. This study shows that statistically significant improvements in HVAC energy consumption and conditioned air supply can be realized following staged, systematic cleaning of different HVAC systems during the peak of cooling season. On average, intervention systems saved between 41 % and 60 % in conveyance (fan/blower) energy (with one exception) and were able to supply 10 % to 46 % more airflow compared to their uncleaned counterparts. This study demonstrates that the cleaning of HVAC systems can yield significant co-benefits, including enhanced energy efficiency and improved supply airflow rate. These outcomes emphasize the role that facility managers can play in reducing the carbon footprint associated to their building operations. Policies mandating routine, rather than episodic HVAC system maintenance can facilitate the implementation of these measures.

It is important to note that HVAC cleaning can offer additional benefits beyond energy efficiency and fresh air delivery rates. Cleaned HVAC systems presented greater system stability in operational conditions, characterized by decreased fluctuations in system differential pressure. Moreover, the cleaned HVAC systems show decreased dependence on backup equipment, implying possible cost savings in longer-term operational and maintenance expenses.

Maintaining adequately conditioned supply airflow is essential to ensure both comfort and appropriate indoor air quality [55]. We observed the important benefit of significantly increasing conditioned air flow in response to all stages of HVAC cleaning—notably including cleaning the ductwork itself. Lower airflow rates can lead to poor mixing conditions and uneven distribution of conditioned air, resulting in inadequate ventilation and spatial–temporal enthalpy inconsistencies. At the same time, studies have shown that higher airflow rates result in increased fan energy and total annual energy consumption [56]; thus, an optimum balance between minimum air quality considerations, room air mixing regimes and HVAC energy consumption is an important operational goal; indeed, routine HVAC hygiene may help achieve this goal. Only through thoughtful monitoring can such optimization be achieved and confirmed.

CRediT authorship contribution statement

Nasim Ildiri: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Emma Biesiada:** Writing – review & editing, Methodology, Investigation, Data curation. **Tullio Facchinetti:** Writing – review & editing, Visualization. **Norma Anglani:** Writing – review & editing, Visualization, Data curation. **Nouman Ahmed:** Writing – review & editing, Data curation. **Mark Hernandez:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.115147.

Data availability

Data will be made available on request.

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Wildfires have increasingly brought devastation to both Northern and Southern California, and it is unlikely that these are isolated events. The **Federal Emergency Management Administration (FEMA)** allows public entities to reimburse for duct and HVAC cleaning to help mitigate the adverse health effects of soot, ash, and debris left by such events. According to ASHRAE Guideline 44 Polycyclic Aromatic Hydrocarbons "PAHs and other contaminants, such as heavy metals, can bind to indoor air particulate matter, and studies have shown that they persist in dust after the outdoor smoke has cleared".

As the experts in HVAC installation, maintenance, and repair, the Western States Council of SMART would like to offer the following suggestions and best practices on HVAC system and duct cleaning. It is our hope that these suggestions will help school leaders and advocates make informed decisions for asset management, to wisely spend FEMA or public dollars, and mitigate the risk to students and staff from contaminants, such as fine particulate matter (PM 2.5), left over from wildfires in the vicinity of schools.

Western States Council Suggested Actions After Wildfires:

- Perform Ventilation Verification (Physical Testing of HVAC Systems) – Particularly concentrating on validation of outdoor air (OA) after an event like this. Often the first line of defense is to close off OA – a certified technician should at a minimum reset the OA dampers and verify that minimum airflow is maintained in all modes of operation. Along with OA, any rooms that are designed to have positive or negative airflow design for health or safety concerns should be verified by airflow and pressure readings.
- According to ASHRAE Guideline 44 (Section 6.5), along with duct cleaning, the air handling systems and/or downstream components (VAV's, reheat coils, etc.) should be cleaned (internally) as well, since that is where the dirty air that makes it through the filter can be trapped in the coil(s) and other internal components. This should also be done on any exhaust fans, kitchen hood fans, etc., not just supply-side fans.
- Supply, return and exhaust grills and the ceiling spaces near them should also be cleaned thoroughly to avoid cross contamination.
- Sensors and thermostats should be cleaned per manufacturers' suggestions by skilled and trained workers to ensure that fine particulates are not affecting the ability of the sensor to accurately measure temperature, pressure, humidity, etc.
- Verify air filtration fit, function, and performance. Per ASHRAE Guideline 44 (Section 6.5) "*Dirty filters should be changed to avoid circulation of odors that may remain from the smoke*". When filtration is being replaced, inspections should be made to determine if there are physical indications of filtration being bypassed – if noted, a skilled, trained, and certified workforce should make corrections and/or alterations to reduce or eliminate any bypassing. Final cleaning of any soot or other residue should only then be done per the established protocols of health officials.
- Inspect outdoor air intakes and exhaust openings, bird screens, louvers, dampers, and other attached components and ducting for physical condition and buildup of dirt and debris.
- Verify operation and condition of air-cleaning devices and ultraviolet devices. Improperly functioning air cleaning devices, in many cases, can generate ozone or other toxic gases that can create a dangerous indoor environment.

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- Inspect and clean the floor, ceiling, and other surfaces in mechanical rooms that house HVAC equipment and any surface of plenum systems to avoid contaminating systems or ductwork.

Increase your IAQ IQ:

How much outside air should a classroom have?

A study conducted in 2019 showed that 85% of HVAC systems in California classrooms did **not** provide adequate ventilation. In California, the minimum amount of OA is determined by calculating the Cubic Foot per Minute (CFM) of OA per person and by CFM per square foot of floor area. After calculations are completed, the stricter requirement (higher CFM) is followed, and the HVAC system is adjusted to constantly deliver that amount of OA to the classroom. Below is an example of this calculation:

Standard	Method	15 People	25 People	32 People
California T24 (2022) Occupancy	15 CFM/person	225 CFM	**375 CFM**	**480 CFM**
California T24 (2022) Floor Area	0.38 CFM/ft^2	**342 CFM**	342 CFM	342 CFM

For an overview of how proper ventilation and filtration impacts students and staff in classrooms, please watch these videos from the UC Davis Western Cooling Efficiency Center:

The Importance of Filtration in Schools

Importance of Ventilation in Schools

For more information or to help find a qualified contractor to perform this or other HVAC work, please contact the Western States Council of SMART.

Citations and Additional References:

ASHRAE Guideline 44-2024, Protecting Building Occupants From Smoke During Wildfire and Prescribed Burn Events, (2024). ASHRAE.

ASHRAE Guideline 42-2023, Enhanced Indoor Air Quality in Commercial and Institutional Buildings, (2023). ASHRAE.

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Return to Agenda

TAB 3

Cultivating Growth

The Impact of the Mindful Gardeners
Griffith STEAM Magnet Middle School

Mission Statement

The Mindful Gardeners are a group of ambitious and dedicated middle-school students from Griffith STEAM Magnet Middle School in search of change and leadership, addressing conflicts in our school environment and community. More specifically we focus on the dilemma of increasing mental health awareness in our community of East Los Angeles.

Self-Care Activities for Students & Parents

Short Term and Long Term Impact

Accomplishments

Accomplishments

Accomplishments

Community Partnerships

How East L.A. middle school students use gardening to spread mental health awareness

Known as the Mindful Gardeners, this dedicated school-based group at Griffith STEAM Magnet Middle School meets regularly to discuss mental health, plan engaging activities, and share accessible resources with the East Los Angeles community.

Our School’s Garden and the Impact of the Mindful Gardeners

How our Social Work Team leads the Mindful Gardeners

Future Goals & Conclusion