Nationwide Assessment of Energy Costs and Policies to Limit Airborne Infection Risks in U.S. Schools

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Abstract

Practices such as improved ventilation and air filtration are being considered by schools to reduce the transmission of Severe Acute Respiratory Syndrome Coronavirus 2 that causes the pandemic of coronavirus disease 2019 (COVID-19). Improved ventilation may significantly increase the energy cost of heating, ventilation, and air conditioning (HVAC), exacerbating financial challenges schools face amidst the worst pandemic in decades. This study evaluated HVAC energy costs for reducing COVID-19 airborne infection risks in 111,485 public and private schools in the U.S. to support decision-making. The average annual HVAC energy cost to maintain the infection risk below 1% for the schools in the U.S. is estimated at $20.1 per square meter or $308.4 per capita with improved ventilation and air filtration, where the private schools have higher costs than the public schools on average. The cost could be reduced by adopting partial online learning. It is also found that additional cost to control infection risk with increased ventilation and air filtration is significantly lower for PK-5 schools than that for middle and high schools in all states, indicating the possibility of remaining in-person instruction for PK-5 schools with necessary governmental assistance. Analyses of school HVAC energy cost to reduce airborne infection risk under different intervention scenarios provide important operational guidelines, financial implications, and policy insights for schools, community stakeholders, and policymakers to keep schools safe during the ongoing pandemic and improve preparedness for epidemics projected in the future.

Keywords:
HVAC; Energy Cost; Airborne Infection Risks; COVID-19; School Operation Policy

1. Introduction

About 55 million K-12 students and 7 million adults occupy more than 130,000 public and private schools in the U.S. [1]. Schools are known to be hotbeds for spreading infectious diseases among students and teachers, and subsequently to households and communities. School closures during the coronavirus disease 2019 (COVID-19) pandemic disrupt education, result in detrimental effects on the long-term wellbeing of children and parents, and lead to enormous economic and social costs [2]. Weighing the benefits of in-person schooling and health risks, schools in the U.S. have already reopened or plan to reopen. However, public concerns with school children contracting and spreading COVID-19 remain elevated, particularly at the time of a winter flu season, resurgent waves of COVID-19, and the emergence of more infectious COVID-19 strains in the U.S. [3]. Although school children may remain asymptomatic or experience mild symptoms, they are not less susceptible [4] and could make schools undesirable epicenters of community transmission as infections in children are rising faster than in other age groups [5]. Making matters worse is that no vaccine has been approved for use in children. Even vaccinated people could still be infected and transmit Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) to others [6]. The complexity highlights the necessity for schools to implement non-pharmaceutical mitigation measures to curb the spread of infection during the ongoing pandemic and in the events of future epidemics.

Airborne infectious pathogens including SARS-CoV-2 and influenza can be transmitted in the air and dispersed throughout school buildings, infecting those who even practice social distancing [7]. Improved ventilation and air filtration can dilute and/or displace airborne pathogens to reduce transmissions and occupant infection risks, and thus are being considered as important operational options along with other interventions such as de-densification via online learning [8]. Centers for Disease Control and Prevention (CDC) has established guidelines of ventilation requirements for schools and childcare programs, indicating that schools should increase outdoor air ventilation as much as possible, disable demand-controlled ventilation controls that may reduce air supply based on occupancy or temperature, consider running the HVAC system at maximum airflow rate two hours before occupying, and improve air filtration to the highest level [9]. However, improved ventilation with adequate outdoor air could significantly increase the energy costs for HVAC systems to maintain thermal comfort conducive for learning in school buildings. The financial costs for consistently adopting required ventilation are considerably high, and become a particular concern for U.S. schools that have already been heavily burdened with energy costs and budget restrictions exacerbated by the economic impact of the pandemic. Most schools are unable to assume the entire financial burden alone, and the federal and state governments should provide reasonable funding for schools to implement the mitigation measures required to maintain individual and community health and keep schools open. For instance, it is reported that California schools have been struggled to pay for the upgrading of ventilation systems with few guaranteed funding streams which is insufficient to cover necessary payments for ventilation improvements [10]. Therefore, it is imperative for schools and governments to be informed of the financial consequences of non-pharmaceutical interventions, particularly the energy costs associated with improved ventilation, which is critical to keep the schools open with reduced infection risks.

SARS-CoV-2 is not the first and certainly will not be the last airborne pathogen to cause outbreaks of infectious diseases. To combat the COVID-19 pandemic and other epidemics of similar nature, effective and affordable ventilation strategies are highlighted as a long-term precaution for infection control, particularly in mass-gathering school buildings. Despite the high infection risk and magnitude of energy consumption in schools, the energy cost to reduce infection risk associated with enhanced ventilation under various epidemiological and operational scenarios in schools remain elusive. Schools and governments lack insights regarding the reduced infection risks and increased energy costs to guide school operation and policymaking. Therefore, using the pandemic of COVID-19 to set the epidemiological context, this research conducts scenario analyses to examine increased energy cost for reducing infection risk using different intervention strategies in 111,485 public and private schools in the U.S. Employing the epidemiological modeling, infection risk prediction, energy simulation, and cost estimation, a series of important insights have been derived. First, by limiting the airborne infection risk under a threshold, i.e., 1%, the energy costs per square meter and per capita are assessed on national, state, and county basis for both public and private schools, establishing the first link between energy and health under various scenarios. Second, the impacts of air filtration and online learning on energy costs are quantified, providing the basis for coupled interventions to save energy costs while limiting infection. This study represents the first data-driven analyses of the HVAC energy cost associated with airborne infection risk control in US schools, providing important operation guidelines, financial implications, as well as policy insights to help schools and government adopt effective ventilation with other interventions to maintain low infection risk with affordable energy cost and limited funding support. Although explored under the COVID-19 context, the insights and implications derived from this study can be readily extended to future epidemics to keeps schools a healthy and conducive environment for learning.

2. Materials and Method

This study integrates infection risk modeling and energy consumption simulation into a holistic framework to evaluate the energy costs for schools associated with limiting infection risk using various intervention strategies under a given epidemiological scenario (Fig. 1). With the focus on airborne transmission, the infection risk in this study is defined as the probability of susceptible individuals being infected via airborne transmission after one-day attendance in schools. In order to limit the infection risk below a sufficiently low level (1% in this study), the required ventilation rate is first computed for each school via infection risk modeling considering school information (e.g., population, occupant density, etc.), epidemiological scenario (i.e., the prevalence of COVID-19 in the population), and different intervention strategies (e.g., filtration and partial online learning). Then, the resulting ventilation rate provides the HVAC operation schedule to simulate the school energy consumption given specific building and weather information. The energy cost is finally estimated by combining energy consumption and local utility price.

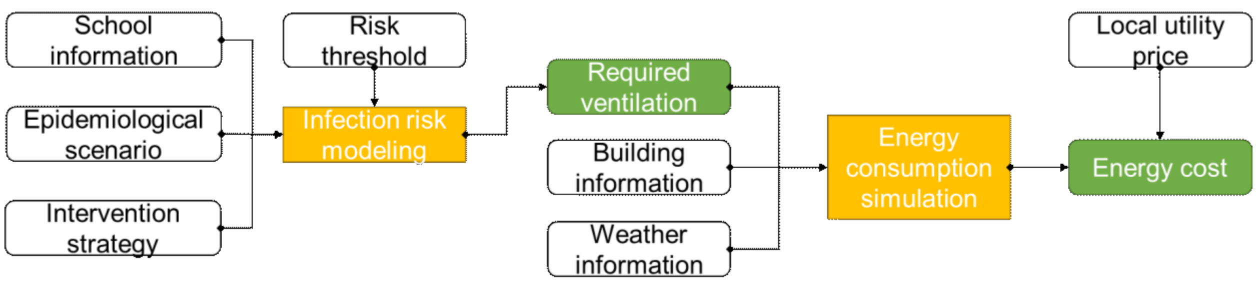

Fig. 1 Overview framework

2.1. Data Collection and Processing

A total of 111,485 public and private schools in the U.S. are analyzed in this study. The school information is collected from the NCES [11], including total enrollment, the number of teachers, school type and level, and school location. The schools are categorized into six levels based on the grades offered in each school, where public schools consist of prekindergarten, elementary, middle, high, and secondary schools, and private schools include elementary, secondary, and combined schools. The gross floor area for each school is estimated as the product of the total enrollment and occupant density (area per student). The descriptive statistics of school information is listed in Table 1.

Table 1. Descriptive statistics of school information

School	Number of schools	Number of students		Number of FTE teachers		Occupant density (m^2/student)		Gross floor area (m^2)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
All schools	111485	427	432	30	25	14.93	5.45	6156	4744

Public	90160	538	440	33	25	14.99	5.07	7128	4696
Private	21325	192	250	16	21	14.72	6.60	2869	3175
Pre-k	1131	175	171	9	10	16.04	5.88	3567	1931
Elementary (K-5)	64998	396	246	25	15	14.19	5.00	6219	2869
Middle (Grade 6-8)	16087	595	350	37	21	16.52	5.54	9403	4360
High (Grade 9-12)	20785	717	743	43	41	16.11	5.60	11303	9221
Secondary (Grade 6-12)	2475	306	351	26	26	17.39	6.19	5682	4749
Combined (PK-12)	6009	242	356	24	31	15.90	7.07	2595	2595

In this study, the occupant density is estimated based on a selected set of schools with known population and gross floor area. Specifically, a total number of 1433 schools across different levels are used as representatives to estimate the occupant density for each school level. Schools are selected from the aforementioned 111,485 schools, following three criteria: 1) the number of buildings for the school can be determined; 2) the boundary of each building can be determined; 3) the number of floors can be determined for each building. The occupant density is computed as the ratio of gross floor area to the total enrollment of the school. The gross floor area of these schools is manually collected from Google Map, estimated as the sum of space in every school building. The space in each building is the product of the building area and the number of floors. The building area is measured using the area calculator tool in Google Map API, which can draw an enclosed area along the building boundary and calculate its area. The number of floors for each building is manually obtained from the street view of Google Maps. The total number of students for each school is obtained from the NCES [11]. The resulting occupant density for each school level is shown in Fig. 2.

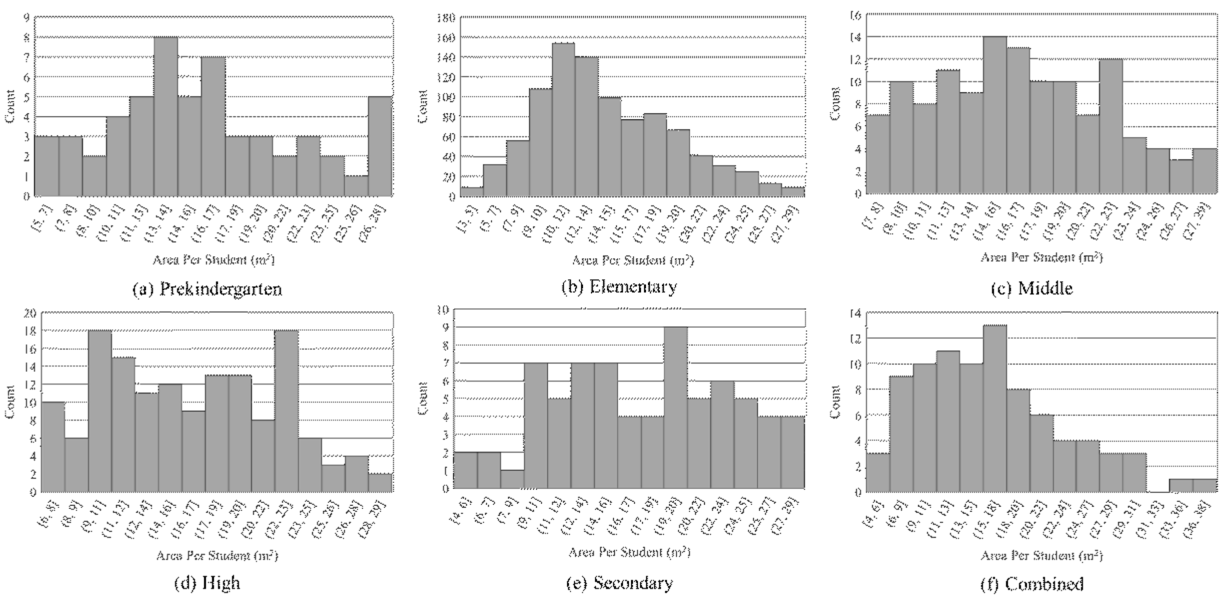

Fig. 2 Occupant density for each school level

2.2. Epidemiological Scenario Generation

The long-term projection model developed by [12] is adopted to establish the epidemiological context and estimate the prevalence of COVID-19 in the population during a one-year period. In [12], different pandemic scenarios are generated considering various seasonality and immunity characteristics of SARS-CoV-2. Specifically, this study uses a reference pandemic scenario with a moderate seasonality (i.e., R_0 in summertime is 0.8 of that in wintertime) and an immunity duration of 10 weeks considering the rapid decrease of SARS-CoV-2 antibody level and the short duration between reinfections [13–15]. The resulting prevalence of COVID-19 (i.e., number of infections per 1,000 people) is illustrated in Fig. 3.

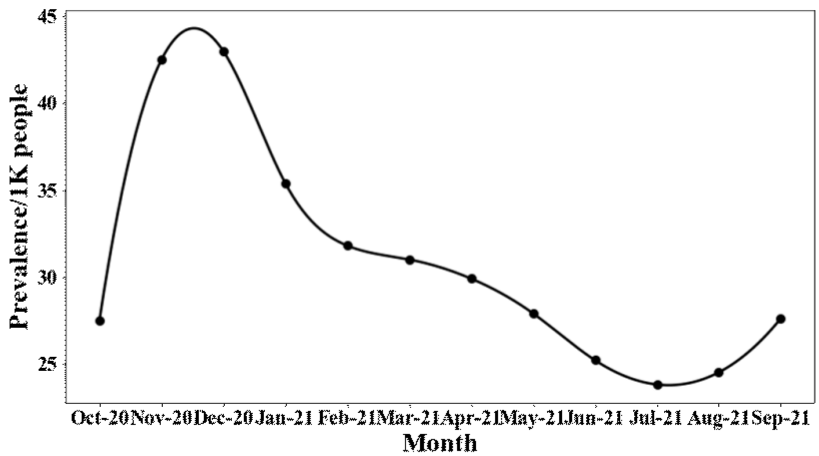

Fig. 3 Prevalence of COVID-19 in the population (generated based on [12])

2.3. Infection Risk Modeling

The airborne infection risk is computed using Gemmation-Nucci equation (G-N equation) [16], which is well adopted [16–20] to estimate the indoor infection risk of airborne pathogens including influenza, tuberculosis, and SARS-COV-2. G-N equation is developed based on the concept of "quantum of infection" proposed in an earlier model by Wells-Riley *et al* (W-R model) [21]. The probability of infection is determined by the intake dose of airborne pathogens in terms of the amount of quanta. The randomly distributed airborne infectious particles are described using Poisson distribution. To overcome the limitation of the W-R equation that assumes a steady-state of airborne pathogen concentration, the G-N equation depicts the concentration changes in quanta level using a differential equation to consider the time-weighted average pathogen concentration [22]. In the equation, the probability of susceptible individuals getting infected after a certain duration of exposure can be calculated using Eq. 1, where I is the number of infectors, V is the room volume (m^3), N is the total disinfection rate of environment (hr^{-1}), t is the exposure duration of susceptible individuals to infectors (*h*), p is the pulmonary ventilation rate (m^3/h), and φ is the quantum generation rate (quanta/h).

$$Risk = 1 - e^{-\frac{pI\varphi}{V}\left(\frac{Nt+e^{-Nt}-1}{N^2}\right)} \quad (1)$$

The number of infectors (*I*) is estimated as the product of school population and the prevalence of COVID-19 estimated in the previous section. The room volume (*V*) is estimated as the product of the gross floor area and the height of the classroom, where a height of 3 meters is assumed for all schools [23]. The exposure duration (*t*) is set as the number of hours in a typical school day, varying across different states according to [24]. The total disinfection rate of environment (*N*) considers a combined effect from outdoor ventilation and filtration (if applied in the HVAC system), computed as $N = \lambda_{ventilation} + k_{filtration}$, where $\lambda_{ventilation}$ is the outdoor air ventilation rate (hr^{-1}) and $k_{filtration}$ is particle removal rate due to filtration [18]. $k_{filtration}$ can be calculated using Eq. 2 [25].

$$k_{filtration} = \lambda_{recirculated}\eta_{filter} \quad (2)$$

where $\lambda_{recirculated}$ is the recirculation rate, set as 6.4 hr^{-1} [26]; η_{filter} is the filtration efficiency weighted by infectious particle size. ASHRAE specifies the method to determine the η_{filter} based on minimum efficiency reporting value (MERV) and particle size range [27], and has suggested that the filters with $MERV \geq 13$ are efficient at capturing airborne viruses [28]. The filtration efficiency for different HVAC filters is summarized in Table 2.

Table 2. Filtration efficiency for different HVAC filters

Minimum Efficiency Reporting Value (MERV)	Average particle size efficiency in size range		η_{filter}
	0.3 to 1 μm	1 to 3 μm	
13	50%	85%	67.50%
14	75%	90%	82.50%
15	85%	90%	87.50%
16	95%	95%	95%

Note: [29] indicates that more than half of the viral RNA of SARS-COV-2 are with aerosols smaller than 2.5 μm. In this study, it is assumed that half of the particles are in 0.3 μm to 1μm, and the other half are in 1 μm to 3 μm.

Because the pulmonary ventilation rate (p) varies with different age groups [30], different values are assigned to each school level (Table 3). The quantum generation rate (φ) for SARS-CoV-2 is estimated as a function of pulmonary ventilation rate using Eq. 3 according to [19].

$$ER_{q,j} = c_v c_i p(\sum_{i=1}^{4} V_{d,i} N_{d,i,j}) \quad (3)$$

where c_v is the SARS-COV-2 viral load in the sputum, set to be 10^9 RNA virus copies mL^{-1} [19]; c_i is a conversion factor between infectious quantum and infectious dose, set to be 0.02 [19]; p is the is the pulmonary ventilation rate based on school levels (m^3/h) ; $V_{d,i}$ is the volume of a droplet calculated by the droplet diameter D_i, and $N_{d,i,j}$ is the droplet concentration per cm^3 of different droplet diameter i and expiratory activity j, see Table 4 for details.

Table 3. Pulmonary ventilation rate of each school level based on student age groups

Parameter	Pre-k	Elementary	Middle	High	Secondary	Combined	Reference
Age	3-5	5-11	11-14	14-18	11-18	3-18	NCES[11]
Pulmonary ventilation rate (m3/day)	7.28	9.98	14.29	14.29	14.29	12.135	Literature[30]

Table 4. Droplet concentration (per cm^3) of different droplet size distribution during speaking activity (Adapted from [19])

Expiratory activity	D_1(0.8 μm)	D_2 (1.8 μm)	D_3 (3.5 μm)	D_4 (5.5 μm)
Voiced counting	0.236	0.068	0.007	0.011
Unmodulated vocalization	0.751	0.139	0.139	0.059

Note: for respiratory activity, speaking is considered as the main activity during school hour, and is considered as mean value between unmodulated vocalization and voiced counting.

2.4. Energy Cost Modeling

The energy consumption of school HVAC systems are estimated, including energy consumption for heating ($E_{heating}$), cooling ($E_{cooling}$), and fan operation (E_{fan}). It is assumed that electricity is used for indoor cooling and fan operation, while natural gas is used for indoor heating. EnergyPlus is used as the primary approach for building energy modeling and simulation, which requires input of building conditions, such as geometry, HVAC system, building materials, and schedule, as well as other information, such as system efficiency and weather conditions.

2.4.1. School Building information

In this study, the school is simplified as a one-story building with flat roof, with a height of 3 m, and is modeled as a single thermal zone. The floor area for each school is calculated based on enrollment and occupant density. The building footprint is extruded to the roof to create 3D building model. The window to wall area ratio (WWR) is set as 0.35 [31]. Building material, HVAC system, schedule, and load characteristics are set according to the U.S. Department of Energy (DOE) school reference buildings in different climate zones [32]. In addition, it is assumed all schools can implement certain strategies to achieve indoor heating, cooling, and ventilation requirements.

2.4.2. Weather information and Climate Change

The U.S. is divided into 16 climate zones for building energy simulation based on DOE commercial reference buildings [32]. The weather data in the most populous cities were selected to represent the corresponding climate zone. The hourly level weather data such as solar radiation, relative humidity, dry bulb temperature, and wind speed and direction are important inputs for energy simulation. Typical Meteorological Year 3 (TMY3) weather data [33] are used as weather input for each representative location, representing a collation of selected weather data derived from a 1976-2005 period of record.

To evaluate the influence of climate change on annual energy cost, the climate information in 2050 is modeled using the climate change world weather file generator (CCWorldWeatherGen) developed by Jentsch et al. [34]. The CCWorldWeatherGen tool adapts the “morphing” technique to generate future weather data based on the A2 emission scenario under HadCM3 Climate Scenario Data [35] and has been treated as a reliable approach for climate change modeling [36].

2.4.3. Simulation Details

A total of 111,485 schools in the 50 states and District of Columbia are simulated. For each school, the corresponding weather information and building materials in energy simulation are set based on its corresponding climate zone. The simulation period is set as one year to estimate annual energy consumption. The EnergyPlus parallel simulator is adopted due to its capability to run multiple simulations at the same time. Finally, the annual energy cost for each school is estimated based on energy consumption and utility price. The parameters used for energy cost estimation are listed in Table 5. The equipment operation schedule is estimated based on the 2012 Commercial Building Energy Consumption Survey (CBECS) for school buildings which consists of 755 K-12 schools nationwide [37]. The survey indicates that the average month in use for school buildings is 11.2, and the average operation hour is 8.5. Therefore, equipment operation time is approximated to 9 hours from 8 am to 5 pm every day of the year. The required ventilation rates of each school estimated from infection risk modeling are used as inputs of energy simulation.

Table 5. Parameters for energy consumption simulation

Parameter	Description	Reference
Equipment operation time	9 hours per day, 365 days per year	Estimated based on [37]
Average temperature (°F)	Hourly temperature varying across climate zones	TMY3[33]
Electricity unit cost (cents/kWh)	Average unit cost of electricity for each state (estimated from July 2019 to June 2020)	EIA[38]
Gas unit cost (dollars per thousand cubic feet)	Average unit cost of gas for each state (estimated from July 2019 to June 2020)	EIA[39]
Thermostat	21℃ - 24℃	DOE[32]
Heating efficiency	80%	ASHRAE[40]
Cooling efficiency	3.325	DOE[2]
Fan efficiency	0.596	DOE[2]

To validate the reliability of energy simulation, the energy use intensity (EUI) estimated via simulation was compared with that obtained from 2012 CBECS survey data [37] under baseline scenario with ventilate rate of 2 hr^{-1} [41], as shown in Fig. 4. The simulated average heating EUI is estimated as 0.172 GJ/m^2, and the national average is 0.280 GJ/m^2 in the 2012 CBECS survey. For the cooling usage, the simulation result is 0.043 GJ/m^2 and the survey result is 0.086 GJ/m^2. In general, the simulated results are compatible with the national school average, indicating the efficacy of the energy simulation model.

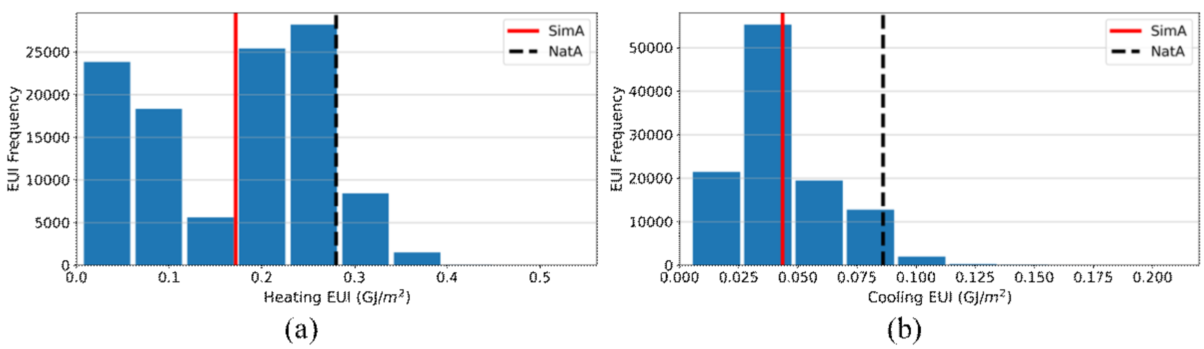

Fig. 4 Comparison of EUI between energy simulation and the 2012 CBECS school survey data. SimA represents simulated average EUI using 111,485 schools. NatA represents national average of school EUI from survey data.

3. Results

3.1. Required Ventilation Rate for Limiting Infection Risk

To limit the infection risk below a sufficiently low threshold, 1% in this study, the required ventilation rate throughout the year is first determined for each school using Eq. (1), considering school parameters, intervention strategies, and COVID-19 prevalence in different months of the year. Fig. 5 illustrates the required ventilation rates throughout the year of different student populations with different mitigation measures. Modeling results show that PK-5 (prekindergarten and elementary) schools can limit the infection risk below 1% by modestly increasing ventilation rates with air filtration. In contrast, the 1% infection risk could not be achieved in middle and high schools without unrealistically high ventilation rates even with the use of air filtration. The results indicate that these schools may consider additional infection control measures such as de-densification by implementing partial online learning to maintain infection risk at acceptable levels and lower the required ventilation rates to save energy costs. These required ventilation rates under different scenarios serve as the ventilation schedule to compute the energy cost for schools.

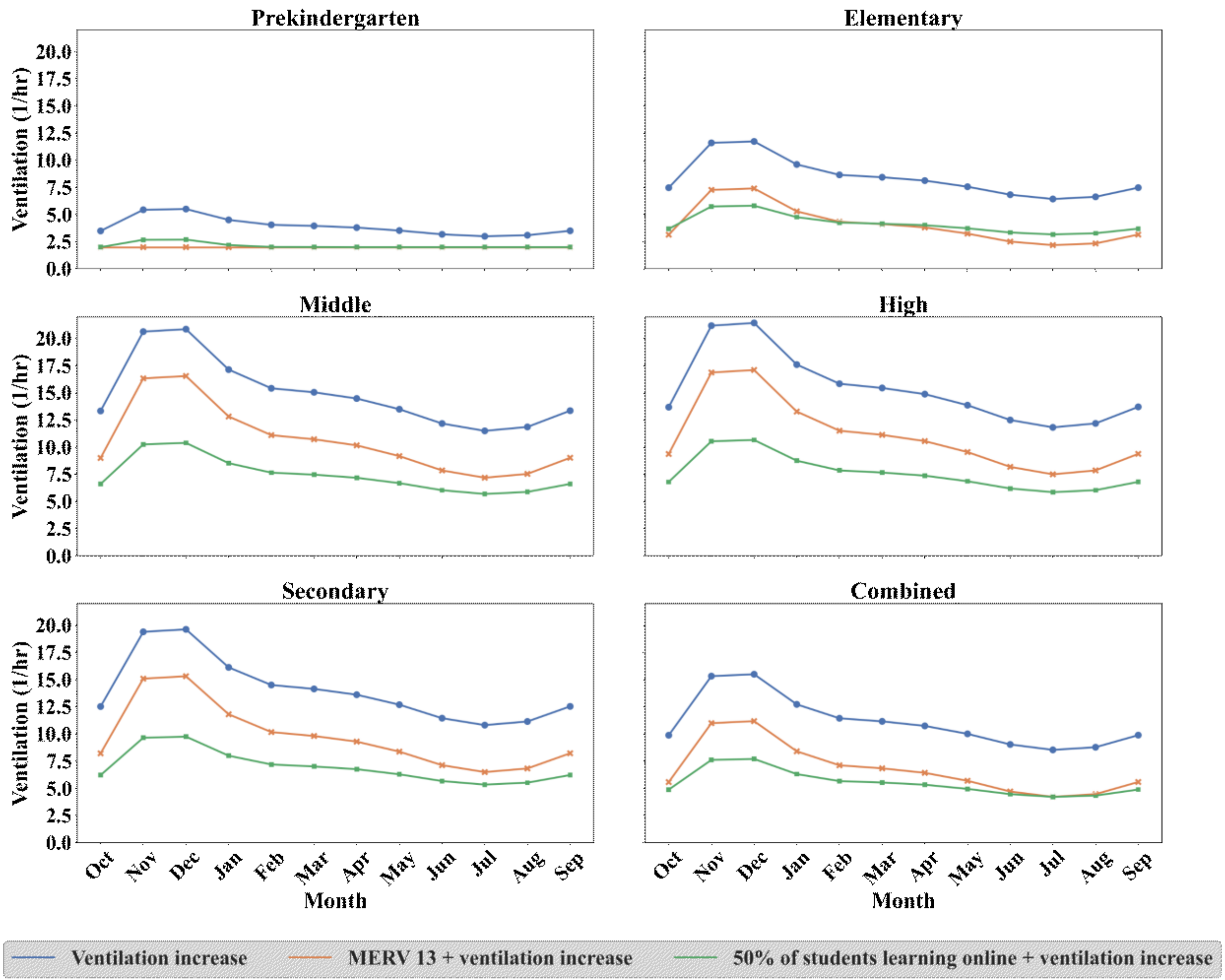

Fig. 5 Required ventilation rate in different schools to limit infection risk below 1%

3.2. Unit Energy Costs and Implications

Different cost measures have different implications for decision-making. Cost per square meter and cost per capita under various mitigation strategies are useful for guiding school operations. Total cost at the national and state level could help federal and state governments to assess funding gaps and prioritize funding allocation to limit infection risk. Under the baseline scenario with ventilate rate of 2 hr^{-1} [41], the nationwide average annual school HVAC energy cost is \$3.98 per square meter and \$60 per capita, setting the basis for comparison. It is noted that Hawaii and Alaska are separately analyzed due to their extreme climate and high utility rate.

Fig. 6 presents the additional energy costs per square meter to limit infection risk below 1% by implementing different mitigation measures: ventilation increase only, ventilation increase with air filtration, and ventilation increase with partial online learning. Solely improving ventilation to limit infection is not affordable in most schools, as the average additional cost amounts to \$24.18 per square meter. Coupled intervention has significant impacts on saving energy costs while maintaining low infection risks, but exhibits different effects. The use of air filters could significantly reduce energy costs. Considering the additional costs for advanced filters MERV 14-16, MERV 13 with ventilation is a feasible solution to consider. Limiting the number of students present in schools via online learning also significantly reduces the HVAC energy cost, with median value shifting to the low end and variance decreasing, representing a more aggressive measure in infection control and potential energy saving during the pandemic. However, limiting in-person schooling could have other impacts such as hindering learning productivity, exacerbating educational inequality, and thus its adoption should be carefully considered by schools and governments.

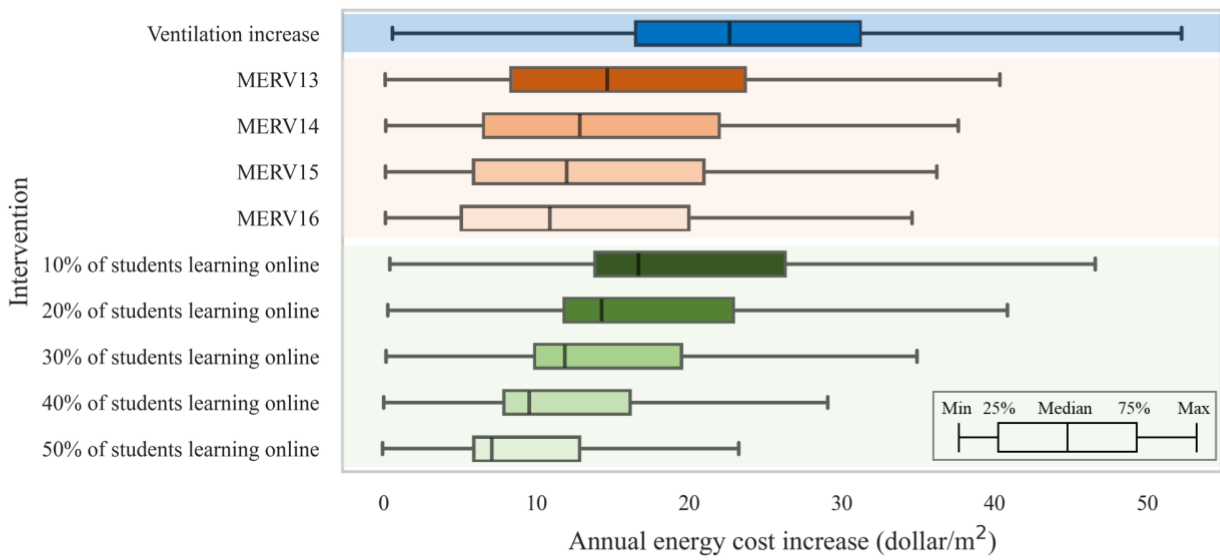

Fig. 6 Extra annual school HVAC energy cost under different interventions

Because most school districts are associated with counties, and budget allocation and school policies are usually determined by local and state governments, the results are aggregated to county and state levels. The average additional annual energy cost for each county under different interventions is presented in Fig. 7, which provides high-resolution energy cost information for schools across the U.S. For all counties, solely improving ventilation to limit infection risk below 1% will lead to an average cost increase of $23.39 per square meter. Adopting MERV 13 filter will reduce the average cost increase to $15.89 per square meter, and having half of the students learning online will reduce the cost increase to $9.67 per square meter. Counties in the northeastern and southeastern U.S. and California will have greater cost increases due to their climate conditions. Climate change will have different impacts on the cost increase in different states, ranging from $-6.10 to $8.41 per square meter. The extra energy cost for infection control in California and the northeastern U.S. will be further elevated, while that for the western U.S. will be reduced. Schools can identify appropriate interventions to control risk considering their energy budget, geospatial locations, and the potential influence from climate change.

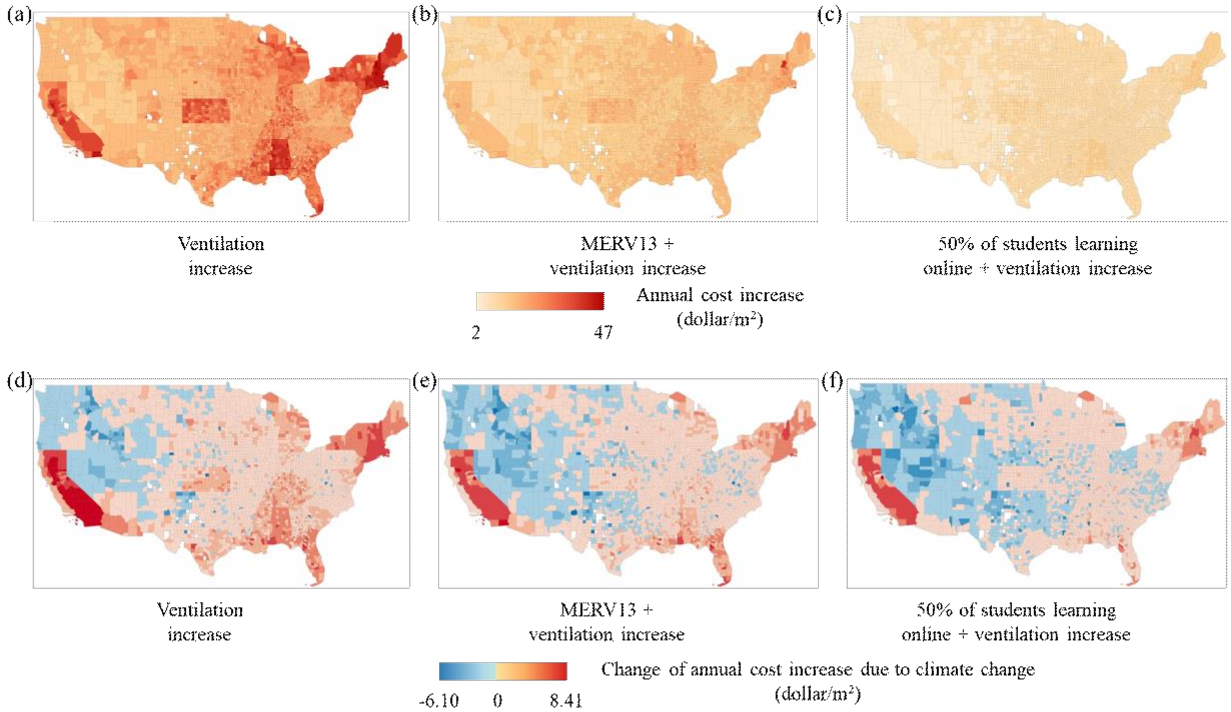

Fig. 7 Average extra energy cost for schools at county level and under climate change

Fig. 8 presents the energy costs per square meter and per capita for both public and private schools for the states in the United States, showing the differences across states and between public and private schools. To facilitate the analyses, costs are calculated for the scenario of improving ventilation with MERV-13 to limit infection risks for all students below 1%. Note that, the energy costs per square meter and per capita is first calculated for each school. Then, for schools in the same state, their energy costs are averaged to represent state-level costs. The average extra annual HVAC energy cost is \$15.04/ m^2 for public schools and \$20.55/ m^2 for private schools nationwide. The additional energy cost is \$234.74 per student for public schools and \$306.29 per student for private schools. The average enrollment in private schools (192 students) is lower than public schools (538 students), resulting in smaller gross floor area and thus a higher energy cost per unit area. For public schools, the extra energy costs per student represent 1.17% to 3.38% of the expenditures spent on each student in each state in 2018 [42] (Fig. 9). Considering the loss in revenue due to decreased enrollment and additional expenditure on online learning during the pandemic, public schools need public funding support and private schools need to identify potential revenue sources to cover the costs to consistently implement the mitigation measures. The states have different average extra HVAC energy cost and cost variance, which are affected by a variety of factors such as state climate and schools in the state. The extra costs per square meter and per capita across the states represent different patterns for public and private schools. Given the varying conditions in the states in U.S., the results could inform both the schools and governments of energy costs to reduce infection risks.

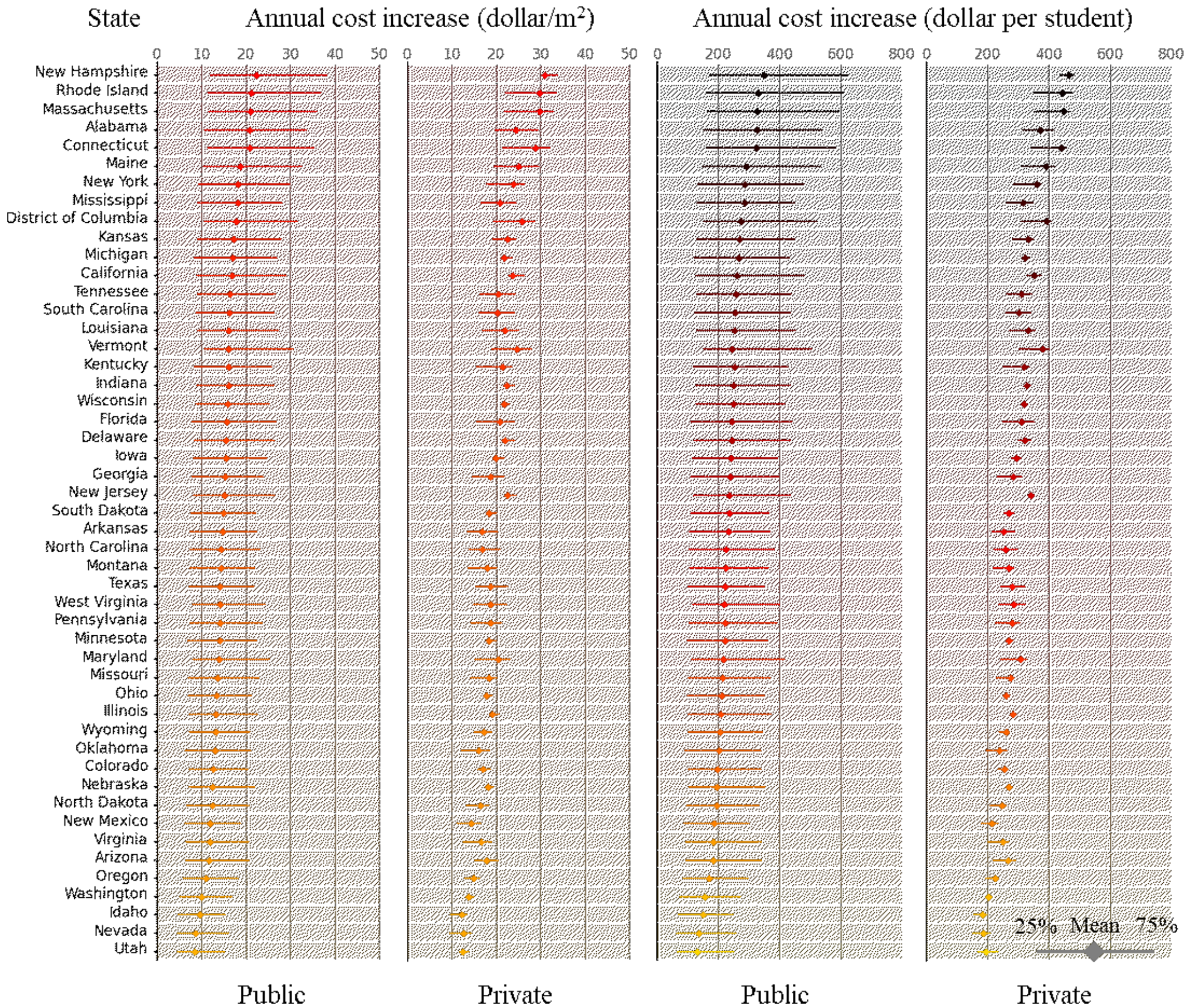

Fig. 8 Annual extra HVAC cost for public and private schools in each state to limit infection risk below 1% with improved ventilation and MERV-13

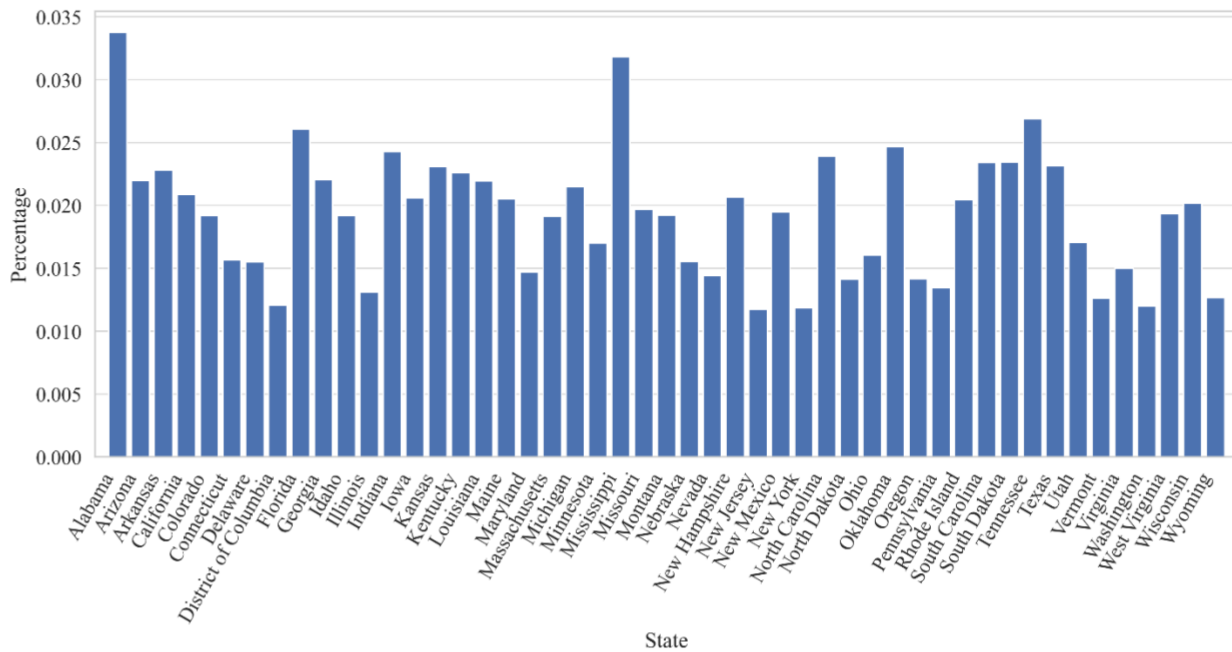

Fig. 9 Percentage of additional costs per capita with respect to annual expenditure per student in public schools

Note: The annual expenditure per student in public schools is obtained in [42]. The percentage is 4.53% in Hawaii and 2.17% in Alaska.

3.3. Total Energy Costs and Implications

The annual total HVAC energy costs are assessed at the national and state level (see Table 6). The annual total costs for improving ventilation with MERV-13 to have all students attending schools range from $26.67 million to $2.43 billion for all states with an average of $351.86 million. For states such as California and Texas, the expected costs are very high, and complementary interventions (such as online learning) might need to be implemented to maintain low infection risks and save energy costs. For states such as Wyoming, the costs seem to be affordable depending on the state fiscal conditions.

Table 6. Total annual energy cost in each state to control infection risk below 1% with MERV 13 and improved ventilation

State	Annual energy cost (million dollar)		
	Total	Public	Private
Alabama	316.27	292.06	24.21
Arizona	268.24	253.48	14.76
Arkansas	143.31	136.60	6.71
California	2429.90	2229.67	200.23
Colorado	242.67	229.84	12.83
Connecticut	265.07	240.26	24.81
Delaware	52.22	46.28	5.94
District of Columbia	36.91	31.43	5.48
Florida	1069.84	944.08	125.76
Georgia	604.08	566.16	37.92

Idaho	61.48	58.46	3.02
Illinois	640.75	572.41	68.34
Indiana	406.87	365.38	41.49
Iowa	173.86	159.99	13.87
Kansas	182.75	168.62	14.13
Kentucky	246.33	224.56	21.77
Louisiana	257.11	216.40	40.71
Maine	82.25	75.01	7.23
Maryland	332.08	291.64	40.44
Massachusetts	505.15	453.60	51.55
Michigan	533.79	490.10	43.69
Minnesota	282.04	258.53	23.51
Mississippi	176.09	162.41	13.68
Missouri	295.02	263.81	31.22
Montana	45.62	42.98	2.65
Nebraska	99.94	88.76	11.19
Nevada	103.54	98.74	4.79
New Hampshire	101.74	91.04	10.70
New Jersey	526.64	466.84	59.80
New Mexico	83.64	79.95	3.70
New York	1118.68	974.46	144.22
North Carolina	484.04	454.73	29.31
North Dakota	31.19	29.04	2.14
Ohio	517.56	461.96	55.60
Oklahoma	179.01	172.02	6.99
Oregon	141.08	129.99	11.09
Pennsylvania	577.49	512.04	65.45
Rhode Island	80.15	72.45	7.70
South Carolina	277.36	260.00	17.36
South Dakota	43.58	40.27	3.31
Tennessee	362.69	337.50	25.19
Texas	1626.83	1552.98	73.84
Utah	125.58	121.76	3.82
Vermont	33.30	29.71	3.59
Virginia	379.28	350.05	29.24
Washington	258.52	238.85	19.67
West Virginia	90.24	86.18	4.06
Wisconsin	322.58	279.57	43.01
Wyoming	26.67	26.07	0.61
Total	**17241.02**	**15728.68**	**1512.34**

Fig. 10 present the additional energy costs required for different levels of public schools across the states in U.S. The results suggest that the energy cost for reopening PK-5 schools and keep them open with low infection risk for all students seems to be affordable in many states. The insights could guide the federal and state government in assessing the financial resources needed to cover the costs, particularly energy costs for schools to operate with mitigation practices during pandemics and epidemics.

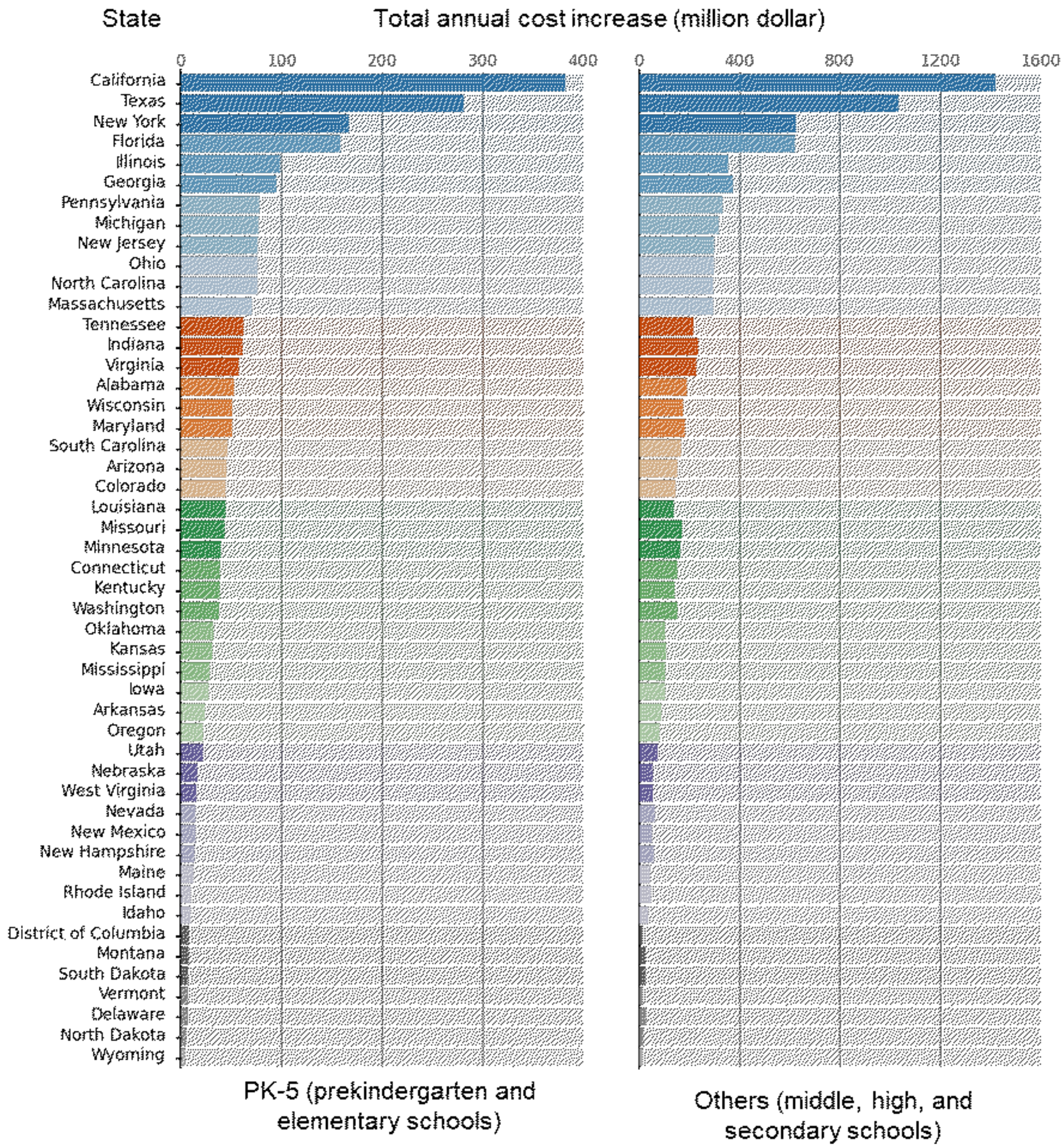

Fig.10 Additional funding needed for public schools to have all students attending schools with MERV 13 and improved ventilation to limit infection risk

3.4. Energy Cost in Hawaii and Alaska

Due to extreme climate and high utility price, the energy costs for schools in Hawaii and Alaska are much higher than other states in U.S., and thus analyzed separately. Under the baseline ventilation, the average annual HVAC energy cost is $13.31 per square meter and $198.49 per student in Hawaii, and $7.36 per square meter and $110.13 per student in Alaska. To control infection risk below 1% with MERV 13 and improved ventilation, the average annual energy cost increase is $50.71 per square meter in Hawaii and $25.75 per square meter in Alaska, which will further increase by 30.3% and 14.6%, respectively, under climate change. The additional cost per capita in public schools amounts to $690.5 and $384.3 in Hawaii and Alaska, accounting for 4.5% and 2.2% of annual expenditure per student. The cost increase under other interventions can be found in Fig.11. Furthermore, to have all students attending schools while limiting infection risk below 1% with MERV 13 and improved ventilation, a total amount of $220.71 million and $53.88 million is needed for energy cost in Hawaii and Alaska. The additional funding needed to keep K-5 public schools open seems to be more affordable in Hawaii and Alaska, i.e., $32.07 million and $10.56 million respectively (Fig. 12).

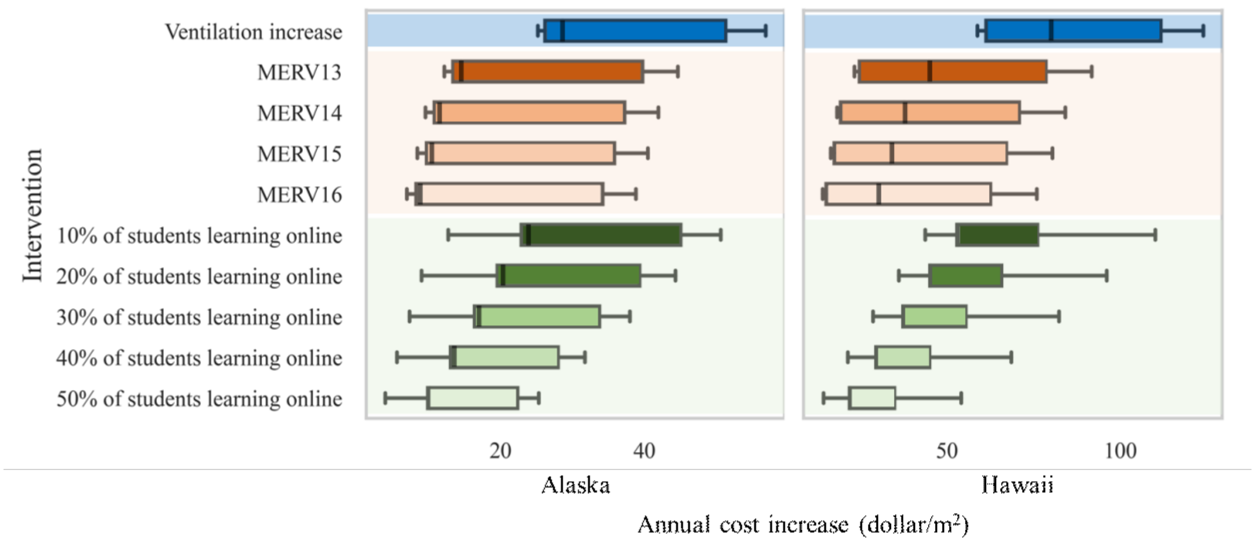

Fig. 11 Annual cost increase in different interventions in Hawaii and Alaska

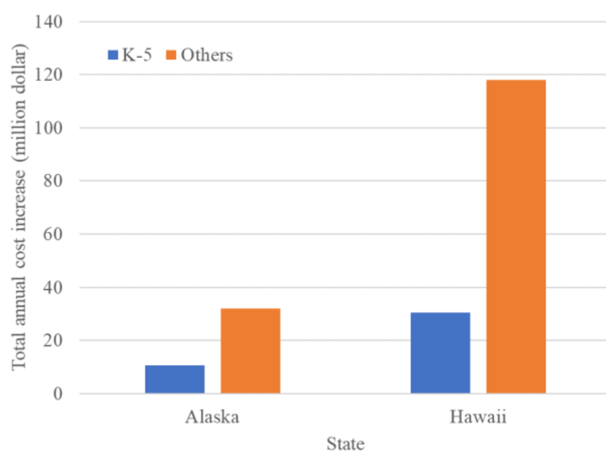

Fig. 12 Additional annual energy cost for public schools in Hawaii and Alaska to control infection risk below 1% with MERV 13 and improved ventilation

4. Discussion

The ongoing COVID-19 pandemic reveals the significance of improved ventilation and air filtration to reduce the airborne infection risk, which could lead to considerably high energy costs. Several recent studies have explored the energy consumption of HVAC systems in different buildings when maintaining a low risk of COVID-19 transmission. For instance, Sha *et al*. [43] investigated the relationship between increased ventilation rate and energy consumption in high-rise buildings, and found a ventilation rate of 5.2 ACH is required to maintain infection risk under 1% when conducting social distance and wearing masks for 8-hour exposure, leading to energy consumption of 265 MWh for chiller system, and 252 MWh for fans. Wang *et al*. [44] found that the standard minimum airflow rate is insufficient to maintain the infection risk at low level, and the energy consumption can reach up to 2.9 kWh for 1-hour exposure when limiting the infection risk below 2%. Mokhtari *et al*. [45] analyzed the impact of occupant distribution on energy consumption and infection risk using a university building as a case study. The result indicated that with the increase of ventilation rate, the number of infected people decreases exponentially, with a near-linear increase in energy consumption. In accordance with our study, the above relevant studies have illustrated the excessive energy consumption to control infection risks when solely improving ventilation. However, apart from existing studies that only focus on ventilation strategy for a specific building example, our study considered different infection mitigation measures to provide a nationwide assessment of energy cost of K-12 schools, and have derived the following managerial insights and recommendations.

Schools serve manifold purposes for the communities and school closures result in ripple effects. District leaders and school administrations are wrestling with the complex and high-stakes decision of balancing public health risks, in-person schooling benefits, and mitigation costs for opening and operating schools as the pandemic persists and future epidemics may emerge. Based on the results of this study, the energy costs for implementing the recommended ventilation practices are high. Given the importance of in-person interaction for learning and development, districts should prioritize offering full-time, in-person instructions in grades PK-5 who are still developing the skills to regulate their behavior, emotion, and attention and thus cannot be best served by online learning. The results also suggest that the infection risks in most PK-5 schools are low and costs required for ventilation with air filtration are affordable with governmental assistance. For middle and high schools, the required ventilation rate is difficult to achieve or cost-prohibitive, thus online learning should be practiced, and full in-person learning could be resumed when the infection risk is low, which balances the infection risk and energy cost. The schools should also adopt other strategies together with mitigation measures to control infection risks and save energy consumptions. For example, turning off unnecessary lighting to save energy for improved ventilation, and practicing social distancing and wearing masks to further limit pathogen transmission and reduce infection risks could be considered by schools.

Schools alone, particularly public schools will not be able to take on the entire financial burden for implementing the mitigation strategies, and are not warranted to shift the costs to households, further exacerbating the burden and inequality. Private schools relying on tuition as the main revenue need additional funding sources or raise tuition to cover the expenditure. Schools are the quintessential public good, and thus federal and state governments should provide significant resources to districts and schools to enable them to implement the suite of measures required to maintain individual and community health and allow schools to remain open. The costs per square meter, per capita, and total costs, as well as the total costs for different levels of schools vary across different states. Comparing the additional costs per capita with the annual expenditure per student across states, the percentages range from 1.17% to 3.38%, implying plausible justification given the benefits. For states with affordable costs, opening schools and offering in-person instruction with government support to cover expenditure are feasible, for other states, coupled interventions should be in place to maintain health and safety with a limited budget. Decision-makers should consider the trade-off between infection risk and energy cost based on disease prevalence, climate condition, and utility costs within the state, as well as consider the pandemic and energy disparities that may persistently devastate some communities. Due to the economic impact of the pandemic, state budgets are shrinking and the education budgets are being cut, making it even more difficult for schools and districts to obtain the funding. The costs for PK-5 schools in most states are relatively affordable, and thus priority for additional energy budget approval could be given for these schools.

To maintain healthy school environments, governments should also consider school maintenance and retrofit to save energy costs in the long run. Poor facilities will need additional financial support to improve facilities to basic health and safety standards, requiring high upfront costs as estimates on HVAC system repair amounts to about $32 for a school building square meter and replacements estimated to be about $108 per building square meter [46]. In addition, the government should continue energy efficiency program for schools to be energy-efficient, as energy has important implications for student health, school, and even community and society functions.

5. Conclusions

This study performed a data-driven scenario-based analysis to assess increased energy cost associated with reducing airborne infection risk of SARS-CoV-2 under different mitigation measures, including increased ventilation, air filtration, and online learning, in 111,485 public and private schools in the U.S. The epidemiology scenario is used to derive the infection risks and energy costs to inform response and preparedness for the ongoing pandemic and the inevitable emergence of the next pandemic. There are three main findings that could lead to managerial insights at different levels.

First, to limit the airborne infection risk below 1%, the energy costs per square meter and per capita are estimated on national, state, and county basis for both public and private schools for different ventilation and intervention strategies. The impacts of increased ventilation, air filtration, and online learning on energy costs are quantified, providing the basis for coupled interventions to save energy costs while limiting infection. To ensure in-person schooling, solely improving ventilation is cost-prohibitive with an average additional annual cost of $24.2 per square meter and $369.6 per capita. The costs could to a large extent be reduced by adding air filtration, but are still not affordable for many schools. Thus, for some schools, in-person schooling should be compromised to limit infection risks and also save energy costs. The insights provide the basis for schools to implement different and coupled interventions during and after the pandemic. In addition, the private schools have higher costs than the public schools on average, requiring deliberate decisions for them to cover the costs.

Second, the unit and total costs vary significantly across the states in the U.S. to provide all students in public schools with in-person learning. The unit costs range from $11.09 to $28.92 per square meter and from $170.64 to $447.74 per capita, and the total costs range from $26.07 million to $2.23 billion, providing unprecedented information for state governments to assess funding needs and allocate limited funding to maintain school operation during the pandemic and beyond. Besides, with increased ventilation and air filtration, the total annual additional energy costs to control infection risk below 1% is significantly lower for PK-5 schools than that for middle and high schools in all states. In such situation, PK-5 schools may consider remaining fully in-person instruction with governmental assistance, whereas, for middle and high schools, partial online learning could be practiced to balance the infection risk and energy cost.

Third, examining from a long-term perspective to maintain healthy school environments, the impact of climate changes on energy costs has also been explored, demonstrating climate-induced spatial variance for the energy costs. The findings will help design guidelines to upgrade HVAC systems as well as develop school operation practices to accommodate infection control needs and control energy costs to facilitate a healthy and sustainable school environment.

There remain several limitations. First, as a nationwide assessment of energy cost, schools are simplified as one-story buildings due to the unavailability of detailed information (e.g., building story and layout) for every school in the U.S., as well as the high computation cost for national-scale energy simulation. With detailed information for specific schools, more sophisticated models can be developed to improve the accuracy of energy simulation. Second, for the estimation of indoor airborne transmission, the assumption of our study was based on the well-mixed assumption of the school without room separation, which aligns with the mathematical model (G-N equation) used to compute infection risk. Other approaches (e.g., agent-based simulation) are need with both human behavior and detailed building information incorporated, to more accurately simulate the airborne infection risk in specific buildings.

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