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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 (SARS-CoV-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-makings. 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 was 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, indicating the possibility of remaining in-person instructions for PK-5 schools with necessary governmental assistance. Analyses of school HVAC energy costs to reduce airborne infection risks 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.

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 well-being 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 2 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 struggling 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 keep 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, occupancy 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.

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.

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

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**Fig. 1.** Overview framework.
resulting occupant density for each school level is shown in Fig. 2.

2.2. Epidemiological scenario generation

The long-term projection model developed by Ref. [12] is adopted to establish the epidemiological context and estimate the prevalence of COVID-19 in the population during a one-year period. In Ref. [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 1000 people) is illustrated in Fig. 3.

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 ($m^3/hr$), and $\phi$ is the quantum generation rate (quanta/h).

![Table 1](image)

| 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    | 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 |

![Fig. 2](image)

Fig. 2. Occupant density for each school level.

![Fig. 3](image)

Fig. 3. Prevalence of COVID-19 in the population (generated based on [12]).
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 1 μm, and the other half are in 1 μm to 3 μm.

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 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 time is 8.5. Therefore, equipment operation time is approximated to 9 h from 8 a.m. to 5 p.m. every day of the year. The required ventilation rates of each school estimated from infection risk modeling are used as inputs of energy simulation.

To evaluate 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 ventilation rate of 2 hr⁻¹ [41], as shown in Fig. 4. The simulated average heating EUI is estimated at 0.172 GJ/m², and the national average is 0.280 GJ/m² in the 2012 CBECS survey. For the cooling usage, the simulation result is 0.043 GJ/m² and the survey result is 0.086 GJ/m². In general, the simulated results are compatible with the national school average, indicating the efficacy of the energy simulation model.
ventilation rates with air filtration. In contrast, the 1% infection risk
schools can limit the infection risk below 1% by modestly increasing
Modeling results show that PK-5 (prekindergarten and elementary)
year of different student populations with different mitigation measures.
the year. Fig. 5 illustrates the required ventilation rates throughout the
intervention strategies, and COVID-19 prevalence in different months of
variance decreasing, representing a more aggressive measure in infec
tion 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
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.

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 miti-
gation 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
variability decreasing, representing a more aggressive measure in infec
tion 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.

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.

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

| Parameter                        | Pre-k | Elementary | Middle | High | Secondary | Combined | Reference |
|----------------------------------|-------|------------|--------|------|-----------|----------|-----------|
| Pulmonary ventilation rate (m3/day) | 7.28  | 9.98       | 14.29  | 14.29| 14.29     | 12.135   | NCES [11] |

Table 4
Droplet concentration (per cm³) of different droplet size distribution during speaking activity (Adapted from Ref. [19]).

| Expiratory activity | D₁ (0.8 μm) | D₂ (1.8 μm) | D₃ (3.5 μm) | D₄ (5.5 μm) |
|---------------------|-------------|-------------|-------------|-------------|
| Voiced counting     | 0.236       | 0.068       | 0.007       | 0.011       |
| Unmodulated         | 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.

Table 5
Parameters for energy consumption simulation.

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

Fig. 4. Comparison of EUI between energy simulation and the 2012 CBEC survey data. SimA represents simulated average EUI using 111,485 schools. NatA represents national average of school EUI from survey data.
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. 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/m² for public schools and $20.55/m² 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%–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.

### 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.

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.

#### 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).

### 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-h exposure, leading to energy consumption of 265
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 Ref. [42]. The percentage is 4.53% in Hawaii and 2.17% in Alaska.
insights and recommendations. Energy cost of K-12 schools, and have derived the following managerial infection mitigation measures to provide a nationwide assessment of 44 conclusions 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

### Table 6

| 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    | 260.07 | 240.26 | 19.81 |
| 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  | 88.75  | 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       | 111.68 | 97.46  | 14.22 |
| 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 | 172.92 | 6.09  |
| Oregon         | 141.08 | 129.99 | 11.09 |
| Pennsylvania   | 577.49 | 512.04 | 65.45 |
| Rhode Island   | 80.15  | 72.45  | 7.70  |
| South Carolina | 277.26 | 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 | 248.45 | 10.07 |
| West Virginia  | 90.24  | 86.18  | 4.06  |
| Wisconsin      | 322.58 | 297.43 | 43.01 |
| Wyoming        | 26.67  | 26.07  | 0.60  |

| Total          | 17241.02 | 15728.68 | 1512.34 |
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

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