The Breathe Easy Study: Air Quality, Health, and Energy Impacts of Ventilation Retrofits

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ABSTRACT

The interconnections between health, housing, and energy consumption are increasingly apparent, especially as COVID-19 has highlighted the importance of indoor air quality (IAQ) in homes. Furthermore, these connections are interwoven with, and contribute to, health disparities for communities of color and low-income communities, who experience higher rates of asthma alongside barriers to accessing energy efficiency and healthy home upgrades. Energy efficiency has a well-documented positive impact on household health including decreases in asthma and cardiovascular disease and improvements in IAQ, comfort, and well-being. In particular, mechanical ventilation systems can enhance healthy homes and improve IAQ, especially when combined with energy efficiency measures. This paper (1) shares insights from the literature on energy efficiency and its ability to address disparities in health and energy insecurity; (2) discusses the Breathe Easy study in Chicago-area homes that tested approaches to improving IAQ and reducing asthma symptoms with ventilation; (3) shares results of the health, energy, and IAQ outcomes from installing mechanical ventilation systems in existing homes; and (4) presents novel data on the relative benefits and trade-offs for three common approaches to mechanical ventilation retrofits in terms of IAQ and asthma outcomes. Integrating health improvements such as ventilation into energy efficiency programs will recognize and expand the benefits for vulnerable communities. Building and health experts should explore opportunities to increase their impact through innovative programs that reflect the established connections between energy, IAQ, and health.

Introduction

The Breathe Easy study was a >2-year pseudo-randomized, longitudinal, parallel group, intervention study designed to evaluate how three types of residential mechanical ventilation systems affect indoor air quality, residents' asthma symptoms, and energy use in 40 existing homes in Chicago, IL. By looking at these effects, the study fills a gap in the literature and provides a more holistic understanding of the costs and benefits of various ventilation systems under real-world conditions. The study compared the effectiveness of exhaust-only systems, central-fan-integrated-supply (CFIS) systems with and without electronically commutated motor (ECM) replacements, and balanced energy recovery ventilator (ERV) systems (also with and without ECM replacements in the central air handler).

Most of the study's work was completed before the COVID-19 pandemic in the U.S., between July 2017 and March 2020, when asthma was the most prevalent respiratory concern in the study area. U.S. EPA and the CDC recommend ventilating homes with outside air to reduce indoor air contaminants, including the virus that causes COVID-19. Both agencies have recommended a variety of interventions and, owing to the emergency of the pandemic and understanding that many face financial constraints, do not go so far as to state that new ventilation system upgrades are necessary. But both agencies also note that they may be helpful for those who can pursue them (US EPA 2022; CDC 2022).

In the U.S., over 25 million people have been diagnosed with asthma, or nearly 1 in 12 individuals. Asthma rates vary significantly by several socioeconomic and demographic factors, including race, gender, and income. In children, asthma is more common in boys than girls while in adults, it is more common in women than men. Asthma prevalence is 34-75% higher in African Americans and some Hispanic ethnicities (e.g., Puerto Rican) than in non-Hispanic Whites. And asthma is almost twice as prevalent in people with incomes below the federal poverty line than in people whose incomes are at or above 450% of the federal poverty line; this pattern can also be seen in environmental justice communities where the presence of polluting facilities may contribute to asthma prevalence or severity and where low-income families are more likely to live (NHIS 2019).

Air pollution is a well-known asthma trigger and has been shown to exacerbate asthma symptoms and severity (Koenig 1999; Brunekreef 2022; Leikauf 2002; Bernstein et al. 2004). And exposure to air pollutants can be worse indoors than outdoors, in part because of indoor sources of air pollutants such as smoking, gas stoves, wood stoves, and cleaning, and in part because of outdoor pollutants that infiltrate the building through cracks and leaks or through ventilation systems. Most human exposure to $PM_{2.5}$, PM_{10}, ozone, nitrogen dioxide, and carbon monoxide occurs indoors. In fact, "residential indoor air pollution exposures are estimated to account for 5-14% of the total non-communicable, non-psychiatric disease burden in the U.S" with "indoor exposures to hazardous pollutants $PM_{2.5}$, acrolein, formaldehyde, and ozone … account[ing] for the vast majority of this chronic disease burden," (Kang, McCreery, and Stephens 2020). Indoor exposure to allergens, pollutants, dampness, and molds "are consistently linked to exacerbation of asthma symptoms and increased asthma medication use," (Kang, McCreery, and Stephens 2020). And "concentrations of these pollutants are particularly problematic in low-income housing where excessive moisture and dampness, inadequate ventilation systems, and other issues lead to high exposures of indoor asthma triggers and other pollutants," (Kang, McCreery, and Stephens 2020).

In addition to inequities in the prevalence of asthma, inequities exist in energy burden, the percentage of income required to pay energy bills in 48 of the largest U.S cities. Low-income residents in both single family and multifamily homes experience energy burdens significantly higher than non-low-income counterparts in the same type of housing. Renters typically experience higher energy burdens than those who own their homes. And African American and Latino households experience higher median energy burdens than households with a white head of household. In all of these cases, the groups with higher energy burdens experience this despite a smaller median home size (Drehobl and Ross 2016).

While results may vary by system configuration, ventilation systems are commonly used to dilute and remove pollutants from indoor air. However, studies of ventilation system performance have seldom combined a discussion of indoor air quality or health improvements with the costs of the systems themselves. This study provides the first known data in the U.S. holistically on IAQ, asthma outcomes, and energy use associated with different types of residential mechanical ventilation systems that are hypothesized to have highly varying impacts on indoor pollutant concentrations of both indoor and outdoor origin, environmental conditions, and ventilation rates. The study further compares energy use from CFIS and balanced ERV systems with and without ECMs. The ultimate goal is to inform the selection of ventilation systems with a more holistic understanding of their costs and benefits under real-world conditions and to provide useful information on customer satisfaction and related considerations for future pilots and programs.

Methods

The Breathe Easy study recruited 47 low and moderate income single-family and small multifamily homes in Chicago, Illinois. Each home had at least one occupant who had been diagnosed with asthma. Forty of the homes remained with the study to completion. Homes were self-reported to be non-smoking and were owner-occupied to reduce the likelihood of leaving the study and make it easier to get permissions for equipment installations. Participants agreed to complete 24 monthly surveys over a 2-year period and allowed data on indoor air quality to be collected for eight one-week periods over the 2-year study period. Twenty-seven of the 47 homes were Chicago bungalows, a masonry framed 1-1.5 story housing type with nearly identical size and construction characteristics and a widespread distribution around the City of Chicago and close-in suburbs (Kang, McCreery, and Stephens 2020). All of the homes were built before 1970, with the average year of construction being 1923 (Kang et al. 2022). Twenty-five of the homes participating in the study are in low-income census tracts (Kang, McCreery, and Stephens 2020). Of the seven homes that did not complete the study, four were excluded because they needed major health and safety repairs before ventilation systems could be safely installed (Kang, McCreery, and Stephens 2020). Two left the study before installation of the ventilation systems because of concerns about the amount of construction required and one left because they would be recovering from a very difficult respiratory-related surgery during construction and their doctor recommended forgoing the project to alleviate dust in the home during their recovery (Kang, McCreery, and Stephens 2020).

The study collected baseline survey data on household demographics, building characteristics, and indoor environmental conditions such as “bathroom fan use, stove fan use, presence of dampness, musty smell, and air freshener use in the last 12 months.” The same information was collected at the end of the study. Midway through the study, just after installation of the ventilation systems, study participants also completed surveys on “asthma triggers, interest and motivation in energy efficiency upgrades, and satisfaction with home temperatures, humidity, and energy bills,” (Kang, McCreery, and Stephens 2020).

We administered monthly Asthma Control Test^{TM} (ACT) surveys to assess asthma symptom control of participants throughout the study. Study staff from the Illinois Institute of Technology measured indoor and outdoor air quality data, including pollutant levels for particulate matter, ozone, nitrogen dioxide, formaldehyde, carbon dioxide, and carbon monoxide as well as temperature and relative humidity. The study team used research-grade instruments and designed, tested, and built custom cases for air quality field measurements. IAQ monitoring equipment was calibrated against reference equipment at quarterly intervals during the data collection period. Indoor and outdoor air quality measurements were taken for periods of 5-7 days each quarter for two years – up to four times in the year before the installation of ventilation measures and up to four times in the year after the installation. Twenty of the homes in the study did not, unfortunately, receive their final measurements because of the imposition of COVID-19 stay-at-home orders, but had measurements taken up until that last quarter. More details on field measurements, including air quality monitoring sensors and calibrations, are presented in our previous paper (Kang et al. 2022).

In addition to survey data, asthma control data, and air quality data, study participants allowed the collection of data on the performance of their central heating, ventilation, and air conditioning (HVAC) systems during the same data collection periods as the air quality data collection. To measure the system runtimes during all quarterly field visits (for a total of approximately 28 days before and after the interventions), we installed a Digi-Sense data logging vane anemometer on a conveniently accessible supply register to indicate whether the air handler fan was operating (the instrument logged at 30-sec intervals). We also estimated airflow rates through the central air handling units in fan-only and heating or cooling mode (depending on the season) at each visit using a DG-700 pressure gauge.

Ventilation systems were assigned to homes based on the following factors: (1) feasibility of installation in the home, including the amount of construction needed for a particular type of unit, (2) expected cost of installation, and (3) health and safety risks that might result from the installation of a certain type of system. The required ventilation rates for each home were calculated using ASHRAE 62.2-2016, which bases ventilation rates on the occupied floor area and the number of bedrooms. In the end, the study installed thirteen continuous exhaust-only systems, fifteen CFIS systems (three systems without ECMs and twelve systems with ECMs), and twelve continuous balanced ERV systems (eight systems without ECMs and four systems with ECMs). Blower door tests were conducted in all homes except for one home where the test could not be conducted safely (results are below). All installed ventilation systems were initially sized to meet the ASHRAE 62.2-2016 standard, without accounting for any infiltration credit (i.e., the conditioned floor area and occupancy determined the target ventilation flow rate). The decision to avoid infiltration credits was driven by (1) a body of literature, chiefly from homes in Europe and Canada, demonstrating the health benefits of additional ventilation (Edwards et al. 2011; Kovesi et al. 2009; Lajoie et al. 2015; Woodfine et al. 2011; Wright et al. 2009), and (2) the understanding that 62.2 required minimum flow rates yield air change rates that are not particularly high (e.g., commonly only ~0.3 air changes per hour for a typical home. In addition to the installation of ventilation systems, we replaced their existing HVAC filters with a MERV 10 electrostatically charged filter, if a system had a low-efficiency filter, defined as less than approximately MERV 10 (Kang, McCreery, and Stephens 2020).

It should be noted that the study did have limited funding to use to remediate health and safety issues found during the study. Health and safety concerns were found in 78% of the study's homes, and while many were minor or unrelated to air quality (e.g. tripping hazards), 22 of the homes contained indoor air quality-related health and safety problems such as mold, asbestos, or improperly vented combustion appliances. Mold and asbestos problems were not remediated due to the lack of funding for such major problems, but these homes were allowed to continue as part of the study if the team determined that the ventilation systems could be safely installed without exacerbating the problem. For example, for homes with visible asbestos in the basement, we designated ventilation systems to avoid working or operating near the locations containing asbestos. One home was excluded from the study due to an active water issue in the basement, which would have to be addressed before installation could safely proceed. While the study team may have preferred to remediate these problems if it had had funding to do so, this approach allowed for comparison of ventilation systems under real-world conditions, including with homes that have existing and unremediated health and safety issues.

Breathe Easy Findings – Indoor Air Quality

As noted above, indoor air pollution is a significant source of exposure to a variety of air pollutants, leading to adverse health effects for residents. Residential ventilation systems have been shown to influence indoor air quality, with various studies showing reductions in carbon dioxide concentrations and humidity and other pollutants (Kang et al. 2022). US EPA (2022) and the CDC (2022) both recommend some form of augmented ventilation with outside air in residential buildings to dilute indoor airborne contaminants.

There are a wide variety of residential mechanical ventilation system options that builders, contractors, designers, homeowners, and housing agencies such as HUD have to choose from when prioritizing ventilation retrofits, but their operation affects indoor air quality in different ways. Ventilation systems may (or may not) filter air, they may run continuously or intermittently, and they may create pressure differentials between inside and outside the home, causing indoor air to vent to the outside or bringing outside air in and potentially delivering additional pollutants from outdoor air as it infiltrates through the building envelope and/or mechanical ventilation system (Rudd and Bergey 2014; Singer et al. 2017). The three types of ventilation systems tested in the study differ by how they deliver ventilation air into the home. The exhaust only systems ran continuously, bringing outdoor air into the home through leaks and other openings in the building envelope. The CFIS systems ran intermittently, bringing outdoor air in through a duct and passing it through an air handling unit with an air filter. The balanced ERV systems ran continuously, bringing outdoor air in through a duct and air handling unit with a MERV 10 air filter (Kang, McCreery, and Stephens 2020); five balanced ERV systems (out of twelve) were independently ducted while others were connected into the existing central forced air duct system.

Even in the same ventilation system group (i.e., exhaust-only, CFIS, or balanced ERV), not all homes received an as-installed ventilation system with the same ventilation rate, as the minimum ventilation rates of the ASHRAE Standard 62.2 were estimated based on the number of bedrooms and the floor area of each home. As reported previously in Kang et al. (2022), the continuously operating balanced ERV and exhaust-only systems were measured to deliver ventilation flow at or near 62.2 design rates; however, the intermittent CFIS systems varied in size across each home that received one. The reason is that because they operate intermittently, oversizing is ideal to be able to deliver more instantaneous flow but for shorter periods of time to ideally deliver the same total volume of flow throughout the year that ASHRAE Standard 62.2 requires. However, there were practical limits to how much each system could be oversized that generally scaled with home size and ventilation requirements; that is, in a home that might require 100 CFM of ventilation air running continuously, it is simply impractical to deliver three times that flow (i.e., 300 CFM) from an intermittent system operating 33% of the time. Thus, the intermittent CFIS systems delivered less total cumulative flow, and thus did not fully meet Standard 62.2 requirements. The project team and our installation contractors consulted with the manufacturers of the intermittent CFIS powered ventilators during the installation process. Based on these conversations, the practical constraints and the oversizing approach to installation were not out of the ordinary for real-world ventilation retrofits in existing homes.

The study took extensive information on the homes' ventilation characteristics before installing the mechanical ventilation systems. Before the study, none of the homes had dedicated mechanical ventilation that met ASHRAE standard 62.2. Approximately 62% of homes had an exhaust fan in at least one bathroom, though 39% said they never used them. 90% of the homes had gas stoves and 38% had a kitchen exhaust fan, though only 23% had kitchen exhaust fans that vented to the outside. 37% replied that they sometimes used the stove fan. IAQ impacts of the study's interventions of mechanical ventilation systems and HVAC filter upgrades were examined primarily as a change in the indoor to outdoor concentration ratio (I/O ratio) of a variety of pollutants. This allows us to see not only absolute reductions in pollutants over time but reductions relative to the pollution levels in outdoor air that is infiltrating the home, which differ over time and by location. The study measured particulate matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}), ozone, nitrogen dioxide, carbon dioxide, and carbon monoxide (formaldehyde was only measured indoors). These are not the only indoor air pollutants that affect human health, but they occur both inside and outside the home and all except carbon monoxide “are known to be associated with asthma outcomes in various populations, are practical to measure, and … are plausibly influenced by the ventilation (and filtration) interventions,” (Kang et al. 2022).

The study found that average indoor concentrations for formaldehyde, carbon monoxide, carbon dioxide, nitrogen dioxide, ozone, PM_1, $PM_{2.5}$, and PM_{10} varied widely across homes and during all seasons. Study results supported the hypothesis that indoor pollutant concentrations and I/O ratios decrease after the installation of residential mechanical ventilation systems for carbon dioxide, PM_1, $PM_{2.5}$, PM_{10}, and nitrogen dioxide (Kang et al. 2022). Mean relative reductions in I/O ratios in the post-intervention period compared to the pre-intervention period were approximately 12%, 10%, 42%, 39%, and 33%, for carbon dioxide, nitrogen dioxide, PM_1, $PM_{2.5}$, and PM_{10}, respectively. Average formaldehyde concentrations, measured only indoors, also significantly reduced after the interventions, with an approximately 20-ppb reduction (although the reliability of the instrument used to measure formaldehyde limits our ability to draw firm conclusions from these data).

The study team went on to analyze the changes in pollutant concentrations across the three types of ventilation systems. Comparisons of I/O ratios suggest that there was a reduction in I/O ratios for all measured pollutants among all three ventilation system groups, on average, but with varying magnitude and levels of statistical significance. Reductions in I/O ratios for estimates of PM_1 and $PM_{2.5}$ were generally the greatest in magnitude compared to the other measured constituents, suggesting that there were benefits to combining increased ventilation and higher efficiency particle filtration (MERV 10), especially in homes with central HVAC systems. Moreover, there were apparent benefits to providing ventilation flow continuously rather than intermittently for reducing gaseous pollutants (e.g., carbon dioxide and nitrogen dioxide), which may be attributed to inconsistent timing between intermittent mechanical ventilation runtime and intermittent indoor pollutant sources and/or variability in the amount of ventilation flow delivered in the homes with intermittent CFIS systems (Kang et al. 2022).

Breathe Easy Findings – Health

The research team conducting the Breathe Easy study is continuing to analyze the data for conclusions about the health effects of installing the three types of mechanical ventilation. Based on the preliminary results, as expected, and in line with other studies, “statistically significant relationships were found between asthma control and age, race/ethnicity, annual income, and federal poverty levels,” (Kang, McCreery, and Stephens 2020). In addition, pre-installation air quality data showed that higher concentrations of nitrogen dioxide, emitted by gas appliances such as gas stoves, were associated with increased odds of poor asthma control.

Initial findings also indicate that there was a small but significant improvement in asthma control (approximately 1-point increase in ACT score) across the entire study population after the interventions were implemented, regardless of which system was implemented. It should be noted that a minimally important difference of the ACT score is 3-point (Schatz et al. 2009).

Figure 1 shows the average ACT scores before and after installation of the residential mechanical ventilation systems across all ventilation system types (i.e., “total”) and also for each of the three ventilation system types (i.e., exhaust-only system, CFIS system, balanced supply and exhaust system with an ERV). In general, an ACT score of 19 has been determined to be the optimal cut-off point for screening participants with asthma control problems, i.e., a score of >19 indicates "well-controlled asthma", while a score of ≤19 indicates "poorly-controlled asthma" (Nathan et al. 2004; Schatz et al. 2007). Mean and median ACT scores increased across the study participants and across all ventilation types after installation of the ventilation equipment. Mean ACT scores also increased in each of the three ventilation system types, while median ACT score were slightly lower for those receiving a balanced ERV system.

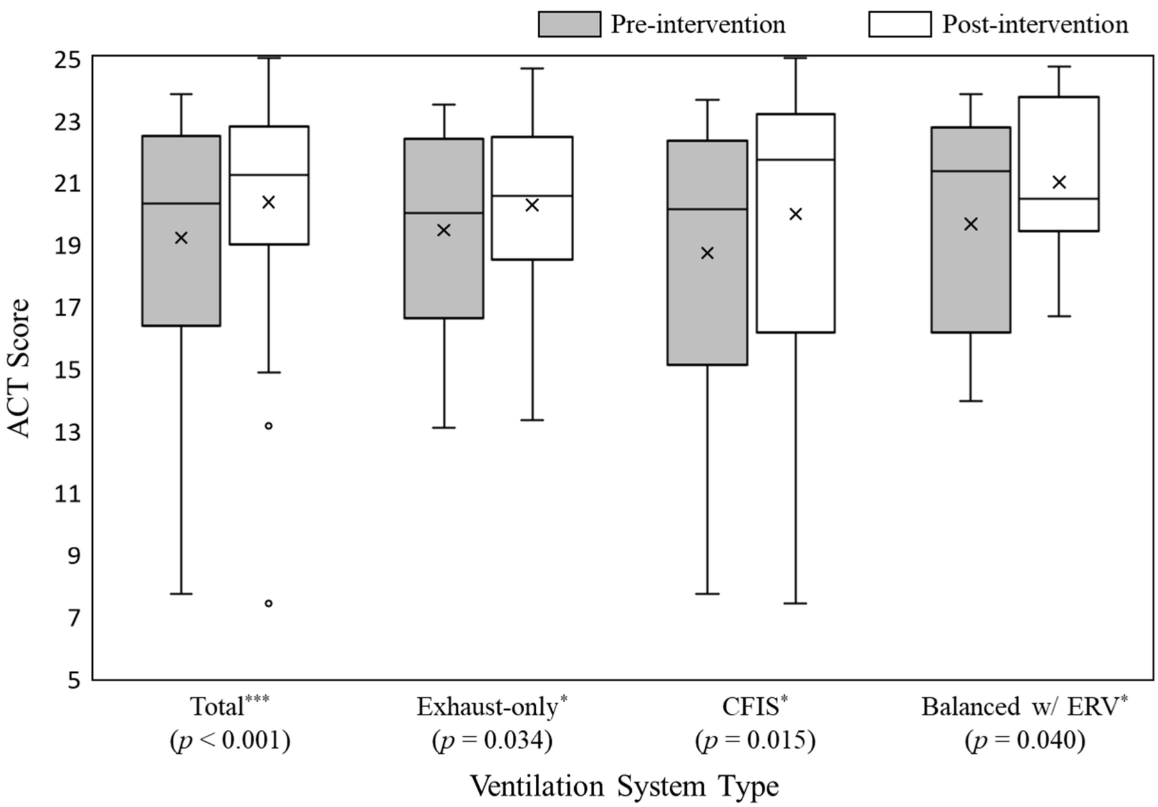

Figure 1. Asthma Control Test^{TM} (ACT) scores in pre- and post-intervention sources for any type of system (i.e., "total") and three ventilation system types.

Additionally, it is noteworthy that no survey participants noted that they had more difficulty breathing after the ventilation systems were installed. And four participants felt that their respiratory health had improved since installation, stating:

- "I am not as sick as before. Less respiratory infections,"
- "In general, we are both better than usual for this time of year!" "We are both doing better than we have been in a long time." "I am way better than I have been in years!" (3 separate comments from the same home)
- "Although we now have a cat (since October 2018) I've had less trouble breathing."
- "Spring is hard on my allergies. The air filter was installed, which has made sleeping better," (Kang, McCreery, and Stephens 2020).

Breathe Easy Findings - Costs

The present paper describes the preliminary results of cost analysis of the three types of mechanical ventilation systems “as-installed” in existing homes, while the research team is continuing to analyze the cost-benefit analysis of long-term health and environmental effects. It is important to note that here we provide cost estimates based on a range of measured and assumed values, with the goal of presenting a combination of upfront costs, installation costs, and estimates of average additional energy costs introduced by operating the newly installed ventilation systems in the average home in the study under assumed nominal operational conditions. The results are summarized in Table 1 and Figure 2 below.

Because ventilation systems bring unconditioned air (in the case of CFIS and exhaust only systems) or semi-conditioned air (in the case of balanced ERV systems) into the home, a ventilation system’s effect on home energy use is a function both the system’s own direct energy use and of the additional energy needed to heat or cool additional outside air.

The direct energy costs of each ventilation system (i.e., the powered exhaust, CFIS, or ERV fans) were estimated using either direct measurements of power draw, or, where measurements were unavailable, estimates of power draw (i.e., Watts), multiplied by either measured or assumed nominal runtime (i.e., hours). For the exhaust-only systems, the system runtime was set by design to 100% in all homes (i.e., continuous operation, which was also confirmed by periodic measurement using Digi-Sense data logging vane anemometers attached to the exhaust grilles), and the power draw was estimated to be 7.7 W at an average airflow rate of 110 CFM (this was not directly measured but estimated from manufacturer’s data). For the balanced ERV systems, we also assumed 100% runtime (i.e., continuous operation, also confirmed by periodic measurement using Onset Plug Load Data Loggers), and the power draw was measured using Onset Plug Load Data loggers deployed during every quarterly visit (the average ERV power draw was ~75 W).

For the CFIS systems, we estimated direct energy costs of the powered ventilator fan using an assumed average nominal system runtime of 33% (i.e., the design target intermittent operation setting of 20 mins per hour), and the average power draw was measured to be 67 W using Onset Plug Load Data Loggers deployed during each quarterly visit. We intentionally did not factor in any assumed additional power draw of the air handler fans that could have been attributed to increased air handler runtime to meet ventilation needs in excess of normal operation to meet heating and cooling need because our periodic measurements of air handler runtime suggested there was not actually an increase in the total system runtime. This was likely due to lower-than-expected runtimes of the CFIS powered ventilator, as the logic on the controller shuts the system off at extreme (both high and low) ambient temperature conditions (Kang et al. 2022).

The amount and cost of energy needed to condition (heat and cool) the additional outside air introduced by the ventilation systems into the average home was estimated using estimates (or measurements) of ventilation system runtimes multiplied by measured ventilation flow rates, multiplied by the specific heat of air (0.24 BTU/lb·°F), density of air (0.075 lb/ft^3), and heating and cooling degree days (3752 and 850 °F-days, respectively), and divided by the average coefficient of performance (COP) of a typical air conditioner (3.0) (for cooling) and by the average annualized fuel utilization efficiency (AFUE) of a typical furnace (0.8) (for heating). We also assumed electricity rates of $0.14/kWh and gas rates of $9.41/MMBTU over a period of 10 years (with no escalation rate assumed) in Illinois’ average climate.

Table 1. Estimates of annual energy use for each type of mechanical ventilation system in the average home

Ventilation system	Exhaust-only	CFIS	Balanced w/ ERV
Manufacturer (Model)	Broan (ZB110)	AprilAire (8140)	Broan (ERV110)
System runtime	8,760 hours (100% continuous)	2,891 hours (33% intermittent)	8,760 hours (100% continuous)
Average power draw	7.7 Watts	67 Watts	75 Watts
Fan energy (cost)	67 kWh ($10)	194 kWh ($28)	657 kWh ($94)
Measured outdoor airflow rates, mean ± SD	105 ± 26 (cfm)	166 ± 30 (cfm)	100 ± 23 (cfm)
Estimated outdoor air volume delivered per year (million ft^3)	55.2	28.8	52.6
Heat recovery efficiency	N/A	N/A	Heating (sensible): ~68% Heating (latent): ~48% Cooling: ~53%
Additionally required heating energy (cost)	6,070 kWh ($195)	3,172 kWh ($102)	1,853 kWh ($60)
Additionally required cooling energy (cost)	237 kWh ($34)	124 kWh ($18)	106 kWh ($15)
Total additionally required heating and cooling energy (cost)	6,307 kWh ($229)	3,296 kWh ($120)	1,959 kWh ($75)
Total estimated cost	$239	$142	$166
Total estimated cost per total volume of ventilation air delivered by as-installed mechanical ventilation system	$4.33 per million ft^3	$4.93 per million ft^3	$3.16 per million ft^3

Overall, Table 1 shows that the balanced ERV systems had the lowest total additional annual energy costs per amount of ventilation flow delivered. This arises from the significant savings assumed to be achieved by pre-conditioning outside air through the ERV. The intermittent CFIS system had the lowest estimated annual cost on an absolute basis, but since these systems under-ventilate compared to 62.2 requirements (due to practical factors mentioned previously), operating an assumed only 33% of the time, and because they did not pre-condition outside air through an ERV, these systems actually had the highest estimated additional energy cost when normalized for the total estimated volume of outside air delivered on an annual basis. The exhaust-only systems were only slightly lower total cost than the intermittent CFIS systems but were able to deliver continuous ventilation flow and thus meet 62.2 requirements. It is important to reiterate here too that these estimates are made using our unique retrofit installations and are subject to a number of practical factors and assumptions inherent to this study. Many of these practical factors would be expected in real-world deployment of these ventilation systems in existing homes, so in practice the CFIS system would have the smallest cost impact on actual household budgets if these systems were included as a measure for a large-scale program.

It is also worth noting that upgrading the fan motors in the central air handling units of any of these systems that utilize a central air handler (or in any homes that have central forced air, regardless of whether the systems are also used for ventilation) to ECMs can further reduce total system energy costs by reducing the fan motor's energy use. Upgrading to ECMs would allow customers to receive the improvements to indoor air quality, and potentially better health outcomes, with a smaller change in operating costs (Kang, McCreery, and Stephens 2020).

Energy costs in Table 1 were also combined with the cost of the ventilation system and its installation to arrive at a lifecycle cost comparison, summarized in Figure 2. Upfront and installation costs of exhaust only and balanced systems with ERVs eclipsed those of CFIS systems. Consequently, when all costs are combined, the CFIS system, particularly with ECM retrofits, provides the lowest lifecycle cost of the three types of ventilation systems tested in the study (Kang, McCreery, and Stephens 2020). However, it must be acknowledged again that the lower cost of the intermittent CFIS systems comes with a tradeoff – that is, they led to under-ventilating homes in our study compared to the exhaust-only and balanced with ERV systems. The same values in Figure 2 could also be normalized by the total amount of ventilation flow and yield essentially opposite conclusions. However, it is also worth noting that asthma control was slightly improved regardless of system type whereas measures of IAQ were impacted differently by each system, so the net cost/benefit calculation can vary depending on which outcome is assessed.

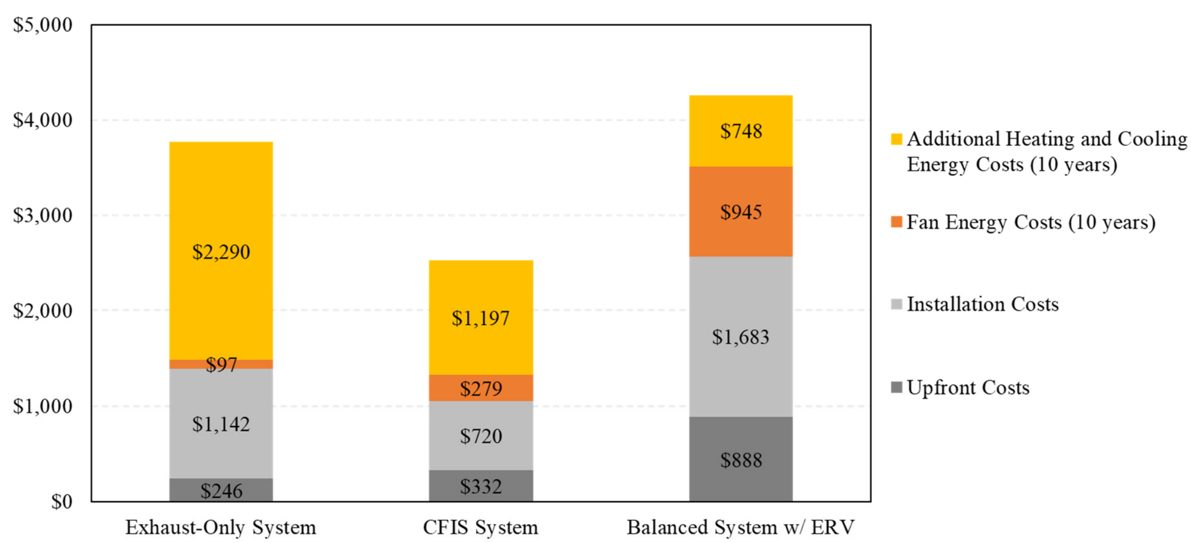

Figure 2. Comparison of life-cycle costs over 10 years in a hypothetical home. *Source:* Kang, McCreery, and Stephens 2020.

Breathe Easy Findings – Customer Satisfaction

The study collected survey data on customer satisfaction for two months after ventilation system installations and again at the end of the study period. In five homes, the surveys were completed by multiple adults living in the home. 74% of respondents noticed changes in their home after installation, with 42% noticing improvements in air quality. Two homes noticed a potential degradation in air quality, specifically odors coming in from outdoors. For both homes field measurements showed improved indoor air quality post-intervention despite the outdoor odors, however field measurements did not include all potentially odor-causing pollutants (e.g. volatile organic compounds can be the source of some odors and were not measured in this study). By definition well-ventilated homes have more outdoor air that enters the living space, and even with filtration this could potentially increase outdoor odors in some homes. Respondents in 8 homes out of the 40 noticed colder temperatures (systems were installed toward the end of a Chicago winter, when significant heating is still needed). While this is a small group of homes, all but one of them were CFIS and exhaust-only systems, which bring in outdoor air without conditioning, indicating that they are more likely to result in uncomfortable temperature changes than balanced ERV systems.

Before ventilation systems were installed, several homeowners also reached out to the study team with questions about the type of system that would be installed, operating costs, and the extent of construction required. Several participants had a number of questions, indicating some level of anxiety about the installation process. After installation, two participants were disappointed that they had received exhaust only systems, citing concerns related to unfiltered outdoor air, as one lived near a pollution source and the other experienced severe outdoor allergies. Both participants were switched to a balanced ERV system without continuous exhausting. Three participants were concerned about colder temperatures, which were addressed through a combination of system adjustments and homeowner education.

Participant satisfaction was measured on a scale of 1-4 across several variables soon after installation and again at the end of the study. Tellingly, as seen in Figure 3, below, satisfaction at the end of the study was higher on every variable measured, indicating that residents adjust to the new equipment over time.

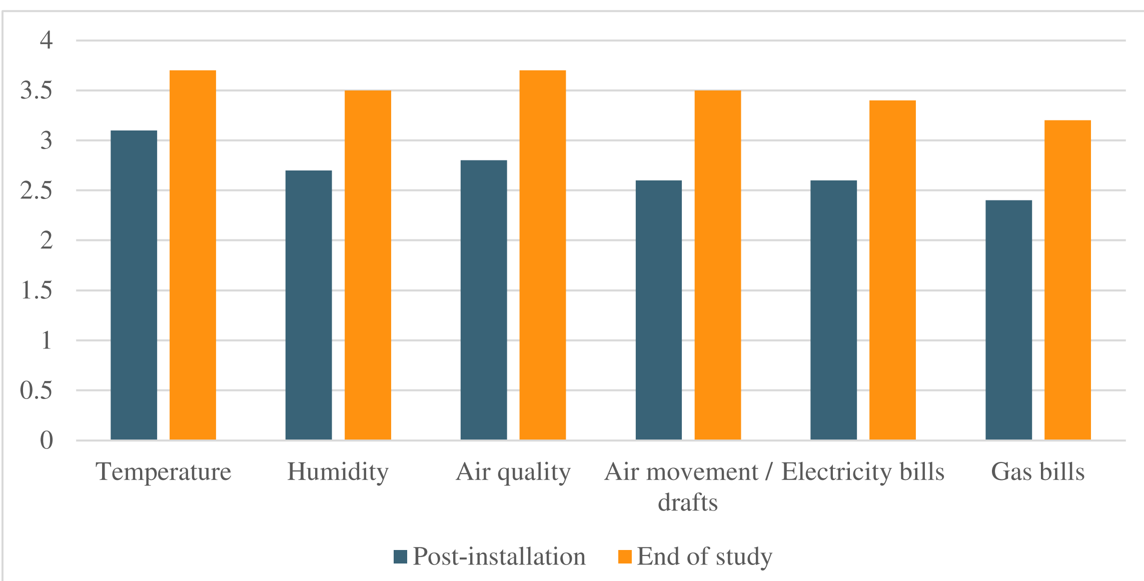

Figure 3. Participant satisfaction with home conditions, shortly after ventilation installation versus at the end of the study. *Source*: Kang, McCreery, and Stephens 2020.

The final customer satisfaction survey indicated that there was no appreciable difference in customer satisfaction, across any of the variables measured, between types of ventilation systems.

Communications with participants, whether by survey or customer-led interactions, indicates that customer satisfaction is increased by ensuring that customer questions are answered, contractors understand customer needs, and post-install quality control is carefully managed. High quality customer service will help customers understand how construction will affect their home and why a ventilation system may affect temperatures and will work with customers to make needed adjustments as they become accustomed to the new system.

Recommendations

The study's results highlight several ways to improve energy efficiency programs. First, efficiency and weatherization programs should consider including ventilation to improve indoor air quality and occupant health. Currently, most weatherization programs do not include mechanical ventilation measures, or only do so rarely. However, mechanical ventilation can have substantial non-energy benefits, including improved indoor air quality and associated health improvements. The benefits are likely to be greater for residents with respiratory health issues such as asthma, and a combined program could facilitate energy efficiency improvements like ECMs that are not always widely deployed in existing programs.

Second, homeowner education is paramount. Study participants had a lot of questions, but continuing discussions often overcame their initial hesitation to participate by helping them understand the process of installation and avoid surprises due to construction or a change in operations. Customers also need to be educated on the health benefits of ventilation, and COVID-19 has opened many people's eyes to that issue, making this a good time to begin incorporating these discussions into customer communications. Discussions of health benefits may even lead customers to take energy efficiency measures they had not otherwise considered.

And finally, to ensure customer satisfaction when installing ventilation systems, contractors need both relevant technical skills and strong customer service and organizational skills for scheduling, homeowner education and reassurance.

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