Breathe Well, Sleep Well: Improving Ventilation in Cold-Climate Homes

EFFICIENCY VERMONT STUDY

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Executive Summary

Indoor air quality in homes affects human health in profound ways. When that quality is compromised, building occupants can experience health effects that range from immediate to long term. Both airborne pollutants and carbon dioxide contribute to those effects. Although the science is still uncertain about the effects of various levels of exposure to these substances, there is general agreement that improving indoor air quality is an important objective for home improvements.[1]

Vermont Energy Investment Corporation (VEIC), the operator of the statewide energy efficiency utility Efficiency Vermont, undertook a research project during the 2016-2017 heating season, to test CO_2 levels in a small sample of New England homes. The study specifically targeted nighttime bedroom CO_2 concentrations. The study tested construction industry and energy efficiency industry assumptions about ventilation and airtightness, and demonstrates potential health benefits when energy efficiency programs specify ventilation equipment in new and existing homes. This information can be a significant factor in helping homeowners and building professionals make decisions on homes and energy improvement projects.

Each of the participants' home bedrooms, when occupied, went above the CO_2 threshold for healthful indoor air quality—1,000 parts per million—on at least one of the four test nights. Several homes showed levels more than three times that. The results demonstrate that although heating system type and airtightness did not have a dramatic effect on CO_2 levels, the presence of a well-designed ventilation system was a significant factor in keeping CO_2 levels under the 1,000 parts per million threshold.

The literature is growing on correlations between indoor air quality and health. Current research links elevated CO_2 levels—within the range found in this study—with impaired cognitive function.[2] Researchers commonly use CO_2 levels as defensible indicators of harder-to-measure pollutants such as particulates (dust, dirt, soot, smoke) and volatile organic compounds (VOCs, found in paints, certain disinfectants, pesticides, and other household products).[3] These pollutants are generally associated with significantly worse health impacts that extend to respiratory illness, heart disease, and cancer.

[1] EPA (U.S. Environmental Protection Agency). n.d. "Introduction to Indoor Air Quality: Indoor Air Pollution and Health." https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality.

[2] See, for example, Allen, Joseph G., Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler. 2016. "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office workers: A Controlled Exposure Study of Green and Conventional Office Environments." Environmental Health Perspectives 124: 805-12. 10.1289/ehp.1510037.

[3] EPA. n.d. "Volatile Organic Compounds' Impact on Indoor Air Quality." https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality.

The information obtained in this research indicates that homeowners seeking energy improvements in their dwellings should use the opportunity to also make improvements to occupant health by making any necessary upgrades and appropriate design changes to ventilation systems. The information also reinforces the co-benefits to both health and energy efficiency when designers, energy efficiency experts, and building contractors follow the mantra, “Build tight, ventilate right.”

This study points to the need for further research to replicate VEIC’s findings, and to add to the literature in connecting energy efficiency work to improvements in health outcomes. Appropriately incorporating ventilation into homes should now be an objective of energy efficiency optimization in residential new construction and renovations of existing homes.

The Study

Airborne Pollutants in Buildings

Present-day energy codes and ventilation standards are designed to keep indoor pollutant levels to reasonable, healthful levels. Common pollutants that appear in all homes include carbon dioxide (CO_2), volatile organic compounds (VOCs), airborne particulates, and mold and mildew from undisturbed moisture. The effects of high levels of airborne pollutants in a home vary widely and range from a smell or feel of “stuffiness,” to conditions that promote mold on building components, to short- and long-term health effects from exposure to chemicals that promote or exacerbate respiratory illness.

The literature is growing quickly on health effects from these kinds of pollutants. For example, a 2016 Harvard study involving 24 office workers linked improved cognitive scores to work environments with lower CO_2 and VOC levels.[4] An earlier, seminal study tested 400 preschool-age children and found an association between elevated levels of a class of VOCs and asthma, rhinitis, and eczema.[5] Other research on CO_2 linked substantially lower decision-making performance with just 2.5 hours of exposure to elevated CO_2 levels.[6]

These pollutants exist in homes. When it comes to air quality in buildings, devices typically measure CO_2 because (a) it is relatively easy to obtain an accurate reading, and (b) all occupied spaces have a steady CO_2 source because people exhale it. So although CO_2 isn’t necessarily toxic at the levels found in houses, the home is a good location for measuring CO_2 and offers a valid proxy for other, harder-to-measure (and more dangerous) pollutants.

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[4] Allen et al., “Associations of Cognitive Function Scores.”

[5] Choi, Hyunok, Norbert Schmidbauer, Jan Sundell, Mikael Hasselgren, John Spengler, Carl-Gustaf Bornehag. 2010. “Common Household Chemicals and the Allergy Risks in Pre-School Age Children.” PLoS ONE 5, no. 10: e13423. 10.1371/journal.pone.0013423.

[6] Satish Usha, Mark J. Mendell, Krishnamurthy Shekhar, Toshifumi Hotchi, Douglas Sullivan, Siegfried Streufert, and William J. Fisk. 2012. “Is CO_2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO_2 Concentrations on Human Decision-Making Performance. Environmental Health Perspectives 120: 1671–77. 10.1289/ehp.1104789.

Researchers, engineers, and building code decision makers frequently use a CO_2 concentration of 1,000 parts per million (ppm) as a benchmark for “passable” indoor air quality, and as a set point for commercial demand-controlled ventilation systems. Energy efficiency professionals often target building upgrades, such as improved airtightness, which in turn can affect a building’s ability to dilute and remove pollutants. How does an energy efficiency effort offer an opportunity for not just lower energy use but also improved health if it can bring a building’s CO_2 ppm levels below the standard?

Efficiency Vermont, a statewide energy efficiency utility, sponsored new research in 2016 to investigate the overlap between energy efficiency and health in buildings. In it, the utility program tested CO_2 levels to evaluate the indoor air quality in rooms all people use for typically 7 to 8 hours a day—bedrooms. The test sample was 22 homes in northern Vermont during the 2016-2017 heating season.

Research Methods

In November 2016, 22 employees of a Burlington, Vermont, company participated in a ventilation study of their homes. Each received a house inspection that captured building age and a floorplan sketch, calculated home and master bedroom air volume, measured airtightness via a blower door test, and documented the ventilation system type and air flow rates. Each household then subjected its home to a continuous test of CO_2 in the primary bedroom over the course of four nights. On alternating nights, participants kept the bedroom door open or closed, so that the effect of the door’s position could be analyzed. The research team asked each participant to keep windows closed for the duration, and to log the number of sleeping people (with adjustments made for small children and pets) in the room each night. Also recorded were irregular events such as people entering or leaving the room during the night (and for how long), or a door opening / closing for other reasons. This testing period extended from November 2016 to April 2017, the winter months in Vermont, when windows are typically kept closed.

During this time, a data logger (TSI VelociCalc 9565-P) and CO_2 probe (TSI 986) recorded CO_2 measurements at one-minute intervals. Participants placed the loggers in draft-free locations approximately 3 feet above the floor (sleeping height), at least 3 feet from the nearest sleeping person, and at least 1 foot from walls. Researchers recalibrated the CO_2 probe approximately halfway through the testing period.

Home Statistics

The homes in the study spanned a wide range of size, age, airtightness, heating system type, and occupancy. Together, they represent a reasonable spectrum of existing homes in New England. Home size varied from 568 to 5,739 square feet. **Figure 1** presents data on the range of home age.

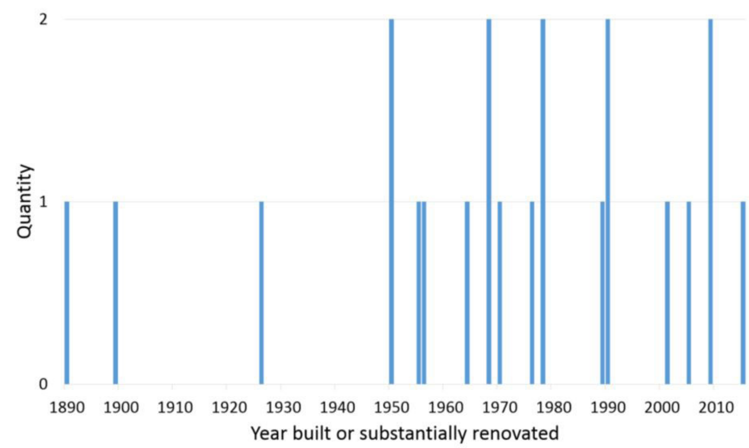


Figure 1. Construction year of homes in the study.

Air tightness ranged from approximately 1.5 to 10.0 air changes per hour at 50 Pa (ACH50),[7] as shown in **Figure 2**. Bedroom occupancy varied from 1 to 3, resulting in occupancy / volume ranging from 0.81 to 2.48 adults / 1,000 cubic feet. Children under the age of 4, and dogs, counted for 0.5 adults; this is a rough approximation, based simply on respiratory capacity.

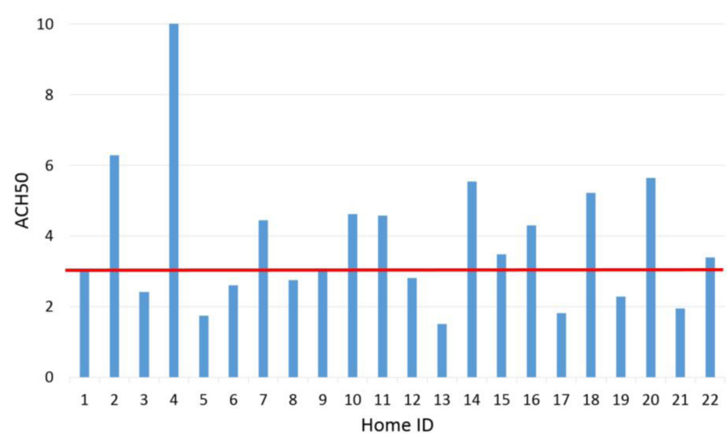


Figure 2. Airtightness of participating homes; red line indicates 3.0 ACH50, the prescriptive energy code requirement in Vermont.

Ten homes had forced-air heating systems, although not all had a supply or return in the tested bedroom. To differentiate this category from the houses with non-forced-air systems, the study included in this first category the houses that had non-ducted cold climate heat pumps. Twelve homes had non-forced-air systems.

Further, 19 homes were single-family detached dwellings; there were 2 single-family attached (multifamily) dwellings, and 1 duplex (half). Ventilation system types varied widely among the homes.

[7]Pascals, used to quantify negative pressure of the house during the blower door test.

The Results

CO_2 Levels

All 22 homes exceeded CO_2 concentrations of 1,000 ppm on at least one of the four nights of testing. Not surprisingly, the nights during which bedroom doors remained open had significantly lower CO_2 levels for most homes, although only 1 of the 22 homes stayed below 1,000 ppm on both nights in which the door was open.

Door-closed nights performed much worse: 86 percent of homes (19 of 22) exceeded 2,000 ppm—or double the 1,000 ppm CO_2 threshold—on at least one of the nights with the bedroom door closed. Another 32 percent (7 of 22 homes) had CO_2 levels that rose above 3,000 ppm. One home exceeded the measuring equipment maximum range of 5,500 ppm. **Figure 3** shows the performance.

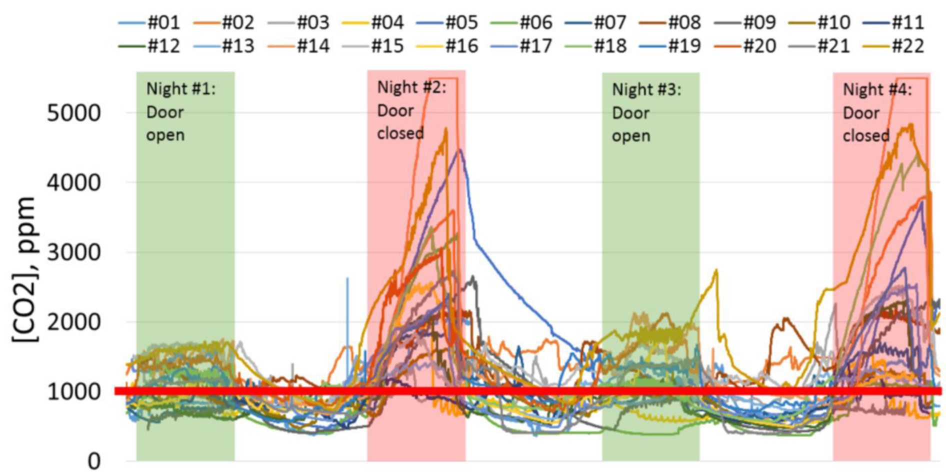


Figure 3. CO_2 concentrations for each of four nights, among 22 homes. Shaded regions correspond to nighttime periods of 9 p.m. to 7 a.m. Red line indicates acceptable building code norm of 1,000 ppm.

Correlations

It was obvious that closing bedroom doors had an enormous effect on CO_2 levels for most of the participants' homes. The most logical explanation is that with doors open, bedroom air with noticeable concentrations of CO_2 exhaled by sleeping humans and animals is diluted by air (with lower concentrations of CO_2) in the rest of the home. Closing the bedroom door has the effect of trapping air, including exhaled CO_2, inside the room.

Clearly, however, some homes performed far worse than others. Occupant behavior can also affect results, as shown in **Figure 4**. But overall, behavior did not account for the dramatic differences in performance that occurred between homes.

Figure 4. CO_2 concentrations and occupant behavior for one home, per night.

The study evaluated four variables for correlation to CO_2 concentrations: (a) airtightness, (b) heating system type, (c) occupant density in the bedroom, and (d) ventilation systems. Items the study did not investigate were stack effect, outdoor temperature, and wind / wind exposure.

Airtightness

A common misperception in the construction industry is that "you have to build a building that breathes" (that is, build a home so that it leaks and thus provides adequate air exchange for good respiratory health). Concurrently, there is a prevailing mantra among energy efficiency experts to "build tight, ventilate right." If one supports the theory that buildings should be built to "breathe," it should follow that the leaky (and older) homes in this study would perform better in terms of lower CO_2 concentrations. Interestingly, however, there was actually little apparent correlation between airtightness of homes and CO_2 levels. **Figure 5** contains an illustration (on the left) showing "tight" homes, whereas the "leaky" homes are on the right. If anything, the data show the leaky homes performed worse.

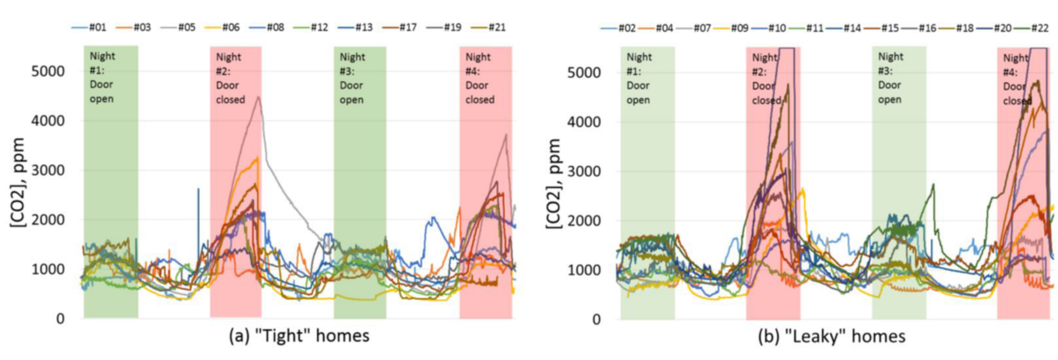


Figure 5. CO_2 concentrations, by night, for (a) 10 homes with fewer than 3.0 ACH at 50 Pa depressurization (ACH50), and for (b) 12 homes with ACH50 of 3.0 or greater.

Heating System Type

Comparing homes with heating systems that mechanically move air (for example, furnaces and cold-climate heat pumps) with those that do not (for example, boilers with hydronic distribution) yielded similar results. That is, heating system type did not clearly predict “better” indoor air quality, as shown in **Figure 6**.

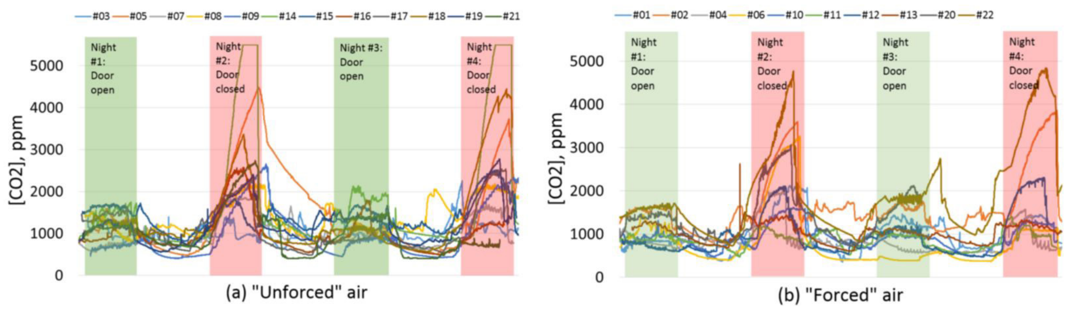


Figure 6. CO_2 concentrations, per night, for (a) 12 homes without mechanically moved air heat, and (b) 10 homes with mechanically moved air heat.

Occupant Density

CO_2 data supported a predictable result: that CO_2 peaked at higher levels for homes that had more occupants per bedroom, in terms of room air volume. However, there was no direct correlation (for example, doubling the occupant density did not double CO_2 levels), and occupant density cannot account for the wide differences in CO_2 levels among homes.

Ventilation Systems

The one variable (besides door-open / door-closed status) that had a large and obvious effect on CO_2 levels was the ventilation system. Two homes had balanced ventilation with heat recovery through which various rooms receive fresh air, while removing air from places like bathrooms and kitchens. This type of ventilation is considered a “best practice” in modern (and energy-efficient) building construction. Seven homes had exhaust-only ventilation with automatic controls. That is, fan(s) operate throughout the day without relying on a person to turn them on (for example, for a certain number of minutes each hour, or for programmed periods of time throughout the day). The balance—13 homes—had either no ventilation or ventilation that operated only via manual switches.

None of the 22 homes in this study would pass current (2015) Vermont energy code ventilation requirements, were it constructed today. Ten homes would fail the requirement for spot ventilation (50 cubic feet per minute [cfm] for bathrooms with bathtubs or showers, lowered to 20 cfm if they run 24 hours / day). All but 1 home—that is, 21 homes—would fail the whole-house requirement for adequate ventilation air flow rate (based on home size and occupancy). The single home that passes this requirement would not meet code because it does not have sufficient spot ventilation in one bathroom.

However, the three homes that came closest to meeting code requirements for ventilation—fitted with automatic controls and having a whole-house flow rate within 50 percent of the ASHRAE 62.2-2013 standard—clearly fared better than the other 19 homes. The category of 19 poorly performing homes includes Home 5, which had a balanced ventilation system, but did not have a supply or exhaust register in the bedroom. **Figure 7** compares the 13 homes that have no ventilation—or ventilation only on manual switches—with the 3 that came close to meeting code.

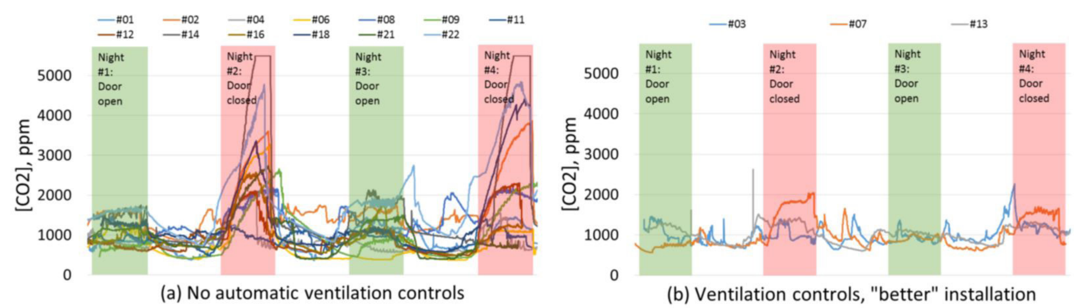


Figure 7. CO_2 concentrations, by night, for (a) 13 homes with no ventilation or ventilation only on manual switches, and (b) 3 homes with automatic controls and ventilation within 50 percent of the ASHRAE 62.2-2013 whole-house flow rate. Home 13 has balanced ventilation and supply air delivery in the tested bedroom.

Discussion

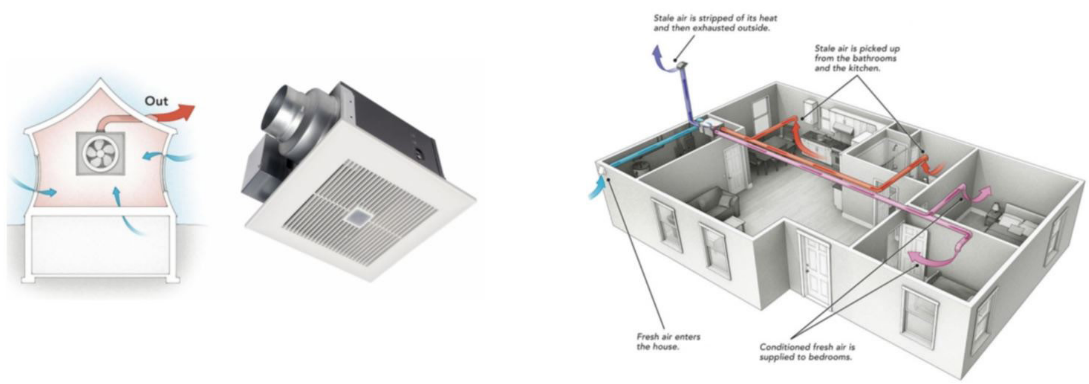
CO_2 levels in the 1,000 to 5,000 ppm range in this study are not usually considered immediately dangerous; for example, the Occupational Safety and Health Administration (OSHA) exposure limit for CO_2 over an 8-hour workday is 5,000 ppm. However, the studies listed above (and others) have linked CO_2 exposure in this range to reduced cognitive function, and some individuals may experience headaches, fatigue, and a sense of air "stuffiness" at these levels.

Worse, perhaps, is that as an indicator of inadequate ventilation, elevated CO_2 can indicate that if sources of VOCs, particulates, moisture, and other pollutants are present in the home, they might be present at elevated levels. Many of these pollutants are potentially much more serious to human health than is CO_2 alone. For example, high VOC levels can lead to headaches, and to damage to the liver, kidneys, and the central nervous system. VOCs are also linked to certain cancers. Excess, trapped moisture can lead to the development of mold, adversely affect long-term building durability, and exacerbate the impacts of VOCs. Particulates are associated with asthma, allergies, and coronary and respiratory problems.

[8] A brief description of common VOCs and their respective cancer risks can be found at Lawrence Berkeley National Laboratory Indoor Environment Group. "VOCs and Cancer." n.d. Indoor Air Quality Scientific Findings Resource Bank. https://iaqscience.lbl.gov/voc-cancer.

[9] EPA, "Introduction to Indoor Air Quality."

Fortunately for homeowners, a wide range of effective and efficient ventilation solutions already exists. The "old" strategy is exhaust-only ventilation (EOV; **Figure 8**), which depressurizes a home and relies on replacement or "make-up air" to come in through intentional passive vents (rare) or via leaks in the building shell (common). Meanwhile, balanced ventilation by design neither pressurizes nor depressurizes a home. Instead, it removes air from rooms where pollutants are likely to be generated (for example, kitchen and bathrooms) and brings new air into areas where people spend the most time. Important questions for **Figure 8** are: "Where is the 'fresh' air to my bedroom / living room coming from?" and "How does my current ventilation system ensure that fresh air gets to where I want it to go?"



Exhaust-only ventilation

Balanced ventilation

Figure 8. EOV versus balanced ventilation, Source: Green Building Advisor[10]

Many jurisdictions already have code language designed to reduce the ventilation challenge that this research highlights. For example, the state of Minnesota's 2015 energy code mandates "balanced mechanical ventilation system that is + / - 10 percent of the system's design capacity and meets the requirements of International Energy Conservation Code® (IECC) Section R403.5.5, which establishes the continuous and total mechanical ventilation requirements for dwelling unit ventilation," including specifications for heat and other energy recovery, fan efficacy, and airflow verification.[11] Another cold-climate locale, the Canadian province of Manitoba, amended its energy code in early 2015 to require heat or energy recovery ventilators.[12] And a United States Department of Energy (DOE) proposal for the 2018 IECC would mandate heat or energy recovery ventilation for climate zones 6, 7, and 8.[13]

[10] A publicly available version of the article in which these images first appeared in Green Building Advisor (subscription only) can be found in Groom, Sean. 2014. "Breathe Easy with Balanced Ventilation." Fine Homebuilding: 54-58.
Photos are credited to the manufacturers. http://www.greenbuildingadvisor.com/sites/default/files/021242054.pdf.
[11] Minnesota Department of Labor and Industry. n.d. The Minnesota State Building Codes. http://www.dli.mn.gov/ccld/codes15.asp.
[12] Manitoba Building Code. 2015. The Buildings and Mobile Homes Act (CCSM c. B93). Registered April 27. https://web2.gov.mb.ca/laws/regs/annual/2015/052.pdf.
[13] DOE (U.S. Department of Energy). 2015. R-3 DOE Proposal for 2018 IECC; Heat Recovery Ventilation (R403.6). https://www.energycodes.gov/sites/default/files/documents/iecc2018_R-3_final.pdf.

To optimize both ventilation effectiveness and energy efficiency, best-practice norms advocate achieving balanced ventilation by installing a heat recovery ventilator (HRV) or energy recovery ventilator (ERV) for new construction and retrofits. This practice also offers an additional benefit: high-efficiency filtration such as HEPA or MERV 13 or better in homes occupied by individuals with allergies or other sensitivities. Optimal HRVs or ERVs offer:

- **High efficiency.** A sensible recovery efficiency (SRE) of at least 75 percent gives warmer delivered air temperature in winter and reduces energy bills.
- **Electrically commutated motor (ECM).** ECMs operate efficiently at all speeds and help avoid over-ventilation by enabling low-speed operation.
- **Swappable ERV / HRV core:** Although this feature is not a must-have, it gives the owner the option to change cores later, since core type can affect moisture balance in the home.
- **Capability for a MERV 13 or HEPA filter upgrade:** Provides high filtration for sensitive individuals.
- **Easy accessibility and simple controls**

Note that just installing an HRV or ERV "machine" is not enough. Proper design and commissioning of such systems, including ventilation directly to bedrooms, are very important.

It is not always possible or feasible to install an HRV or ERV in existing homes. However, the Efficiency Vermont research data suggest that retrofitting exhaust fans with automatic controls and ensuring flow rates in accordance with energy codes and ventilation standards are also an effective strategy for improving CO_2 levels in bedrooms.

If a homeowner is unable to undertake any of these measures, at the minimum, an open bedroom door at night is a smart first step.

Acknowledgements

- *Mike Duclos, DEAP Energy Group, LLC*
- *A condensed report on this research appeared as an article in* BuildingEnergy*, Fall 2017: 30-32. http://www.nxtbook.com/naylor/ENEB/ENEB0217/index.php#/32.*

[13] SRE values help predict heating season performance of an HRV or ERV unit. The higher the percentage, the more efficient the performance of the unit. For a full definition and description of this measure and its value, see HVI. 2010. Heat Recovery Ventilators and Energy Recovery Ventilators (HRV / ERV), Section III. https://www.hvi.org/proddirectory/CPD%20Files/Sec3_cover.pdf.